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PHOSPHATE AND POTASH FERTILISER
RECOMMENDATIONS FOR CEREALS:
CURRENT ISSUES AND FUTURE NEEDS

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PHOSPHATE AND POTASH FERTILISER RECOMMENDATIONS FOR CEREALS: CURRENT ISSUES AND FUTURE NEEDS

by

P J A WITHERS

ADAS Bridgets, Martyr Worthy, Winchester, Hants. SO21 1AP

Executive Summary

Inputs of inorganic phosphorus (P) and potassium (K) fertilizers to cereal crops cost the UK agricultural industry about £185 million per year. With cereal prices falling well below £100/tonne and increasing EU, commercial and public pressure to farm in a manner which will not cause a risk to human health or cause a deterioration in environmental quality, there are strong economic and environmental arguments to reduce or omit P and/or K fertilizer inputs where they cannot be justified. As P is the more expensive fertilizer nutrient, and with increasing concern over the link between P and eutrophication of watercourses, and the build-up of cadmium in the soil from application of P fertilizers, there is a particular need to manage P inputs more efficiently. In contrast, K is the cheapest of the major nutrients and has no known deleterious effect on the environment.

Reductions in P and K fertilizers can be achieved by taking full account of the PK fertilizer value of organic manures and on soils which are oversupplied with nutrients, especially since cereal crops are not generally responsive to fresh PK inputs once residual soil PK levels have reached a critical level. However, the consequences of reducing or withholding PK fertilizer from modern high-yielding cereal varieties have not been adequately quantified. Better targeting of crop PK needs requires a level of precision which the current recommendation system was not developed for. Recent evidence from long-term field experiments and farmer experience indicates that standard soil PK tests and 'maintenance PK policies' are not performing adequately on all soil types. Soil types and their physical and chemical characteristics have a large influence on critical PK concentrations above which yield response is unlikely, on the amounts of fertilizer PK required to achieve and maintain a critical level, on the potential availability and uptake by crops of the pool of P and K in the soil which is not measured by standard soil tests, and on the risk of P loss in land run-off, yet these are not presently taken into account in currrent advice.

Protocols for plant sampling and analysis have recently been defined to help farmers assess adequacy or oversupply of plant nutrient supply but plant analysis has less predictive value than soil analysis in assessing fertilizer need. Information on the release and retention of P and K by readily and slowly exchangeable soil PK fractions on different soil types (topsoil and subsoil), the relative importance of crop rooting patterns and weather factors

influencing crop uptake and the development of novel techniques for improving the efficiency of PK fertilizer use are required to help develop accurate decision support systems for farmers. Such systems should encompass both short-term and long-term impacts of fertilizer strategies on soil PK levels and crop yields, nutrient budgeting and include an economic appraisal. Intelligent zoning of farm and/or field areas is recommended as a means of using soil type information for better targeting of P and K inputs and improving nutrient and land management practices to maintain economic production levels and avoid accelerated P loss in land run-off. With the recent introduction of national guidelines to restrict P use in UK agriculture, there is increasing justification for more precise information on PK fertilizer strategies for economic and environmental sustainability.

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1. INTRODUCTION

Usage of phosphate (P_2O_5) and potash (K_2O) fertilizers in the UK is currently estimated at about 400,000 and 450,000 tonnes, respectively (FMA, 1996). Surveys of fertilizer practice in Britain indicate that of these totals, about 40% of P and 33% of K is used on cereal crops each year (Fig. 1). These PK inputs represent 10-15% of the variable costs of cereal production on individual farms and cost the cereals industry a total of about £185 million annually. Over the last 25 years, actual field application rates have increased slightly, for example for winter wheat from 53 to 67 kg P_2O_5/ha and from 48 to 73 kg K_2O /ha. Typical average application rates currently vary from 48-67 kg P_2O_5/ha and 62-73 kg K_2O/ha, although only about 75% of cereal crops in any one year receive these rates in England and Wales (Burnhill *et al.,* 1997).

Ever since the Second World War, cereal growers have recognised the beneficial effect of PK fertilizers on yields of cereals grown on soils of poor fertility. Regular fertilizer use has greatly improved soil PK fertility in arable and ley/arable farming systems as measured by the standard soil tests used in routine advisory work (MAFF, 1986; MAFF, 1994). For example, the most recent results from the Representative Soil Sampling Scheme (RSSS) indicate that 80% of soils in arable cultivation in England and Wales have extractable soil P and K Indices of 2 or above, and indeed very similar figures have been obtained since 1969 when the present survey began (Church and Skinner, 1986; Skinner *et al.,* 1992). Data from Scotland also shows that 70-90% of soils in arable cultivation have adequate, or more than adequate, extractable soil P and K levels (MLURI/SAC, 1987). However, the need for such generous use of inorganic fertilizers is now being questioned due to economic pressures to reduce variable costs and environmental concerns over eutrophication.

An HGCA-funded review of the PK requirements of cereals, based on 30-35 years of field trials data, concluded that cereal crops are not very responsive to fresh PK inputs on most soils with adequate (Index 2) soil PK fertility (Arnold and Shepherd, 1990). As a consequence, modern fertilizer policies on many arable farms aim to maintain soil PK fertility by replacing only what comes off in the harvested product over a rotation (MAFF, 1985; MAFF, 1994). Current usage of inorganic PK fertilizer therefore closely matches the offtake of P_2O_5 and K_2O in average yielding arable crops, and the data from the RSSS quoted above suggest that previous fertilizer PK applications have maintained an adequate

extractable soil PK concentration over the last 20 years. Similar conclusions were drawn by Salter *et al*. (1997).
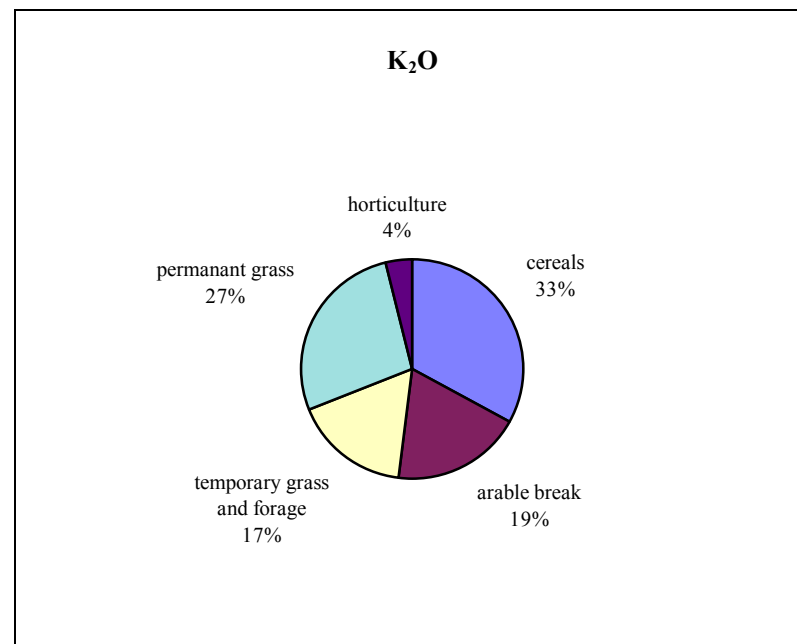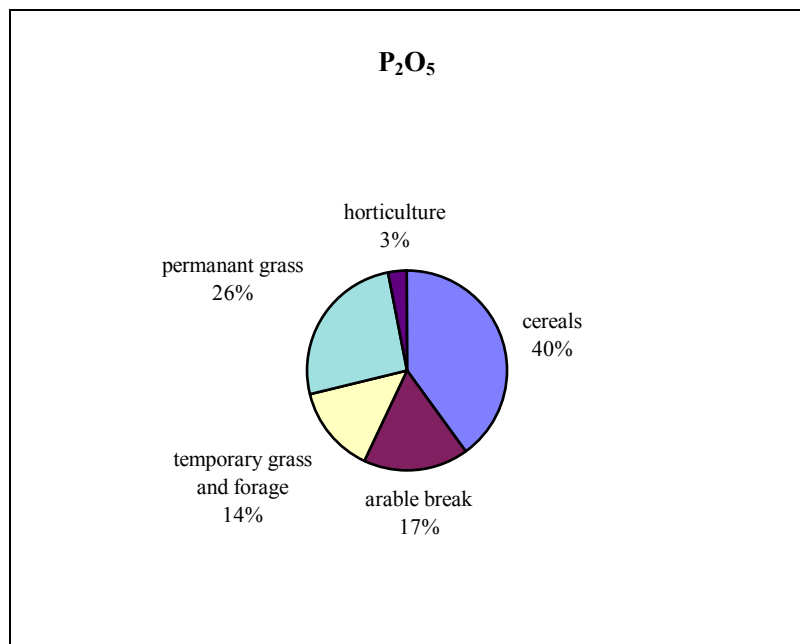
Figure 1. *Proportions of phosphate and potash fertilizer used on different crops in Britain (based on 1993 MAFF census and Survey of Fertilizer Practice data).*

However, there can be considerable deviation from this general picture on individual fields. For example, the above data ignore the inputs of P_2O_5 and K_2O in livestock and other manures applied to agricultural land; the majority of which is spread onto arable land (Smith *et al.,* 1998). Hence, about 17% of the arable land in the UK receives approximately 150,000 tonnes of P_2O_5 and K_2O each year (not the same land area each year), but little account is taken of these inputs in planning fertilizer programmes (Table 1). Consequently, most arable fields receiving manure probably have a P and K surplus. Since there is some evidence to indicate that manure P and K becomes totally available over a crop rotation (Van Dijk and Sturm, 1983; Smith and Van Dijk, 1987), there is clearly scope to reduce dependence on imported PK fertilizer and save on fertilizer bills. Conversely, data from the RSSS also suggests that there still fields which have inadequate soil P and K fertility for optimum crop yields, and these will clearly need to be generously fertilized to build-up residual soil P concentrations.

Table 1. *Overall rates of PK fertilizer applied to various arable crops in Britain which do or do not receive additional PK in manure. (The data have been summarised for 1992-96 from Burnhill et al., 1997).*

Crop	Arable fields receiving manure[1] (% of total)	Application rate (kg/ha)			
		P_2O_5		K_2O	
		Without manure	With manure	Without manure	With manure
Winter wheat	11	51	44	50	45
Spring barley	28	37	32	49	41
Oilseed rape	12	52	29	50	34
Potatoes	38	195	180	267	260
Sugar beet	31	59	41	124	118
Field beans	6	34	29	33	30
Forage Maize	86	50	34	57	29
All arable	17	51	48	58	65

[1]During one year

Much of the data reviewed by Arnold and Shepherd (1990) were from field experiments undertaken during the 1960's and 1970's with low yielding crops of spring barley. Also, soil analysis methods which were developed during the 1950's and 1960's to provide information in order to help build-up soil fertility may no longer be the most appropiate for fertile soils, for example in measuring the potential for release of P in land run-off to water (Withers and Sharpley, 1995). There are increasing indications, both in discussion with farmers by this

author, and in long-term field trials (Withers *et al.,* 1994; Bhogal *et al.,* 1996; Richards *et al.,* 1998), that current fertilizer policies and/or the results of standard soil PK tests may not be performing adequately on individual fields. This does not just relate to the maintenance of soil PK levels but also the use and interpretation of soil analysis data. With the sharp increase in cereal yields during the 1980's and the dominance of winter wheat with higher nutrient demand, there is a need to better define sustainable levels of soil PK fertility for modern systems of production and how they might be maintained. Against a background of possible restrictions on total P inputs in the future, and/or the use of economic instruments to encourage lower P fertilizer use, it is important to understand the significance of this unreliability in order that farmers can continue to farm cost-effectively. Better quantification of P and K offtake in harvested produce on different soils may also be required since this is a fundamental component of any PK fertilizer strategy.

Recent reforms of the price support mechanism for cereals, trends towards protocol farming and concerns over the transfer of P from agricultural land to water causing eutrophication are issues which may also significantly affect decisions on PK usage on individual farms. Current fertilizer policies for P and K are therefore coming under increasing scrutiny due to a) the economic and market pressures on farmers to omit PK inputs where these are not essential, b) the environmental pressures to manage P inputs more accurately and c) the need to understand the nature of variation in soil PK supply and offtake more precisely in modern 'precision farming' systems. The aim of this project was to:

1. Review the adequacy of current PK fertilizer recommendations to cereal crops including the use of soil analysis and plant analysis and the development of decision support systems.

2. Appraise environmental aspects of PK usage in UK agriculture and assess implications for future management of PK inputs to cereals.

3. Provide guidelines on future R&D requirements relating to PK usage on cereals taking account of economic and environmental requirements.

2. CURRENT FERTILIZER POLICIES

2.1 Soil PK reactions

Efficient and sustainable PK fertilizer use requires an understanding of the different forms of P and K in soil, the transfers between them and their relative significance with respect to availability to crops and to the wider environment. There are fundamental differences in the behaviour of P and K in the soil, in the amounts available in solution for crop uptake, their function in crop growth and their environmental impact, which are summarised in Table 2.

Table 2. *Characteristics of phosphorus and potassium in soils and crops.*

Property	Phosphorus	Potassium
Soil content (kg P_2O_5 and K_2O/ha to 25 cm depth)		
Total (median value)[1]	5700	17940
Olsen-extractable (median vlaue)[1]	141	507
Soil concentrations (mg P and K/l)		
Extractable concentrations (Index 2)[2]	16-25	121-240
Solution concentrations	<1	1-10
Soil reactions		
Form of ion in solution	HPO_4^{2-}, $H_2PO_4^-$	K^+
Form of reaction	Anion sorption	Cation exchange
Diffusion rate in solution	Slow	Rapid
Crop Uptake (kg P_2O_5 and K_2O/ha)		
Mean offtake (8 t/ha wheat crop, straw removed)	70	94
Crop recovery of fresh fertilizer (%)	<10	<30
Mode of uptake	Regulated	Luxury
Function in crop	Root establishment	Water regulation
	Energy transfers	Flowering
National UK surplus (inputs-offtakes) kg P_2O_5/ha	37[3]	?[3]
Environmental impact	Major	None

[1]McGrath and Loveland (1992). [2]MAFF (1994). [3]Edwards and Withers (1998). A value for K_2O has not been calculated for the UK.

Soils naturally contain large quantities (tonnes) of P and K within normal plough depth, the amounts of K exceeding the amounts of P threefold. There are similar differences in the amounts extracted by standard soil testing procedures, although as a proportion of the total content, extracted amounts are very small (2-3%) for both nutrients. Consequently, concentrations of K in the soil solution are an order of magnitude greater than for P despite

similar crop uptake values (Table 2). Long-term experimental plot data from Rothamsted indicate that only about 15% of the fertilizer P and 40% of fertilizer K applied to crops is recovered in soil-extractable form (Arnold and Shepherd, 1990; Johnston and Poulton, 1992; Johnston, 1997). Long-term experiments on a number of commercial crops carried out by ADAS during the 1960's and 1970's suggested slightly lower values; a net P_2O_5 and K_2O fertilizer input (ie inputs minus crop offtake) of 100 kg/ha raised the Olsen-extractable P concentration (0-15 cm) by *c.* 3 mg/l and the ammonium nitrate-extractable K concentration by *c.* 10 mg/l (Tytherleigh, 1988a,b), changes which are barely detectable by routine soil sampling and analysis.

What is clear is that extractable soil PK concentrations change only slowly in response to changes in annual net PK inputs. The efficiencies with which fertilizer P and K are used by cereal crops can be quite variable according to the amount of readily-exchangeable PK reserves in the soil and crop growing conditions, but, generally, the recovery of fertilizer P by the crop in the year it is applied is often <10% whilst the recovery of fertilizer K is generally larger (30%), A. Johnston (pers. comm.). This reflects the different amounts present in solution and the ability for K to be taken up in quantities which exceed immediate requirements ie luxury uptake.

Phosphorus is present in soils as inorganic ions within or attached to soil particles, discrete inorganic compounds (Ca/Fe/Al-P precipitates) and organic complexes (Frossard *et al.,* 1995). Potassium does not enter readily into organic combination and is largely present in inorganic form in the soil (Syers, 1998). In most well-fertilized, cultivated mineral soils, P in the soil solution is dominated by inorganic forms, whilst in soils which have not been regularly fertilized, or which contain or receive appreciable amounts of organic matter, then organic P becomes more important as an indirect nutrient source for crops. For example, Edwards (1993) found that soluble organic P compounds dominated the soil solution of upland grassland soils in Scotland.

Although there are fundamental differences between the forms and quantities of P and K in the soil, the processes by which soils maintain a concentration of each nutrient in solution are conceptually similar (Fig. 2). Crops take up P and K in dissolved form (HPO_4^{2-}, $H_2PO_4^-$ and K^+) directly and rapidly from the soil solution. As the concentration of the nutrient in solution becomes depleted, PK ions which were previously in exchangeable forms, move into solution to replenish dissolved ion supplies. The mechanism for this is diffusion, whereby ions move from areas of high concentration to areas of low concentration until an equilibrium

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is reached. The lower concentration of P in solution compared to that of K reflects differences in the rate of diffusion between the two nutrients. The rate of P and K exchange between the soil and the solution depends on how tightly (P), or accessibly (K), ions are held within the soil. Ions which are loosely held exchange easily, whilst ions which are strongly adsorbed (P), or held within clay lattices (K), exchange only slowly (Fig 2).
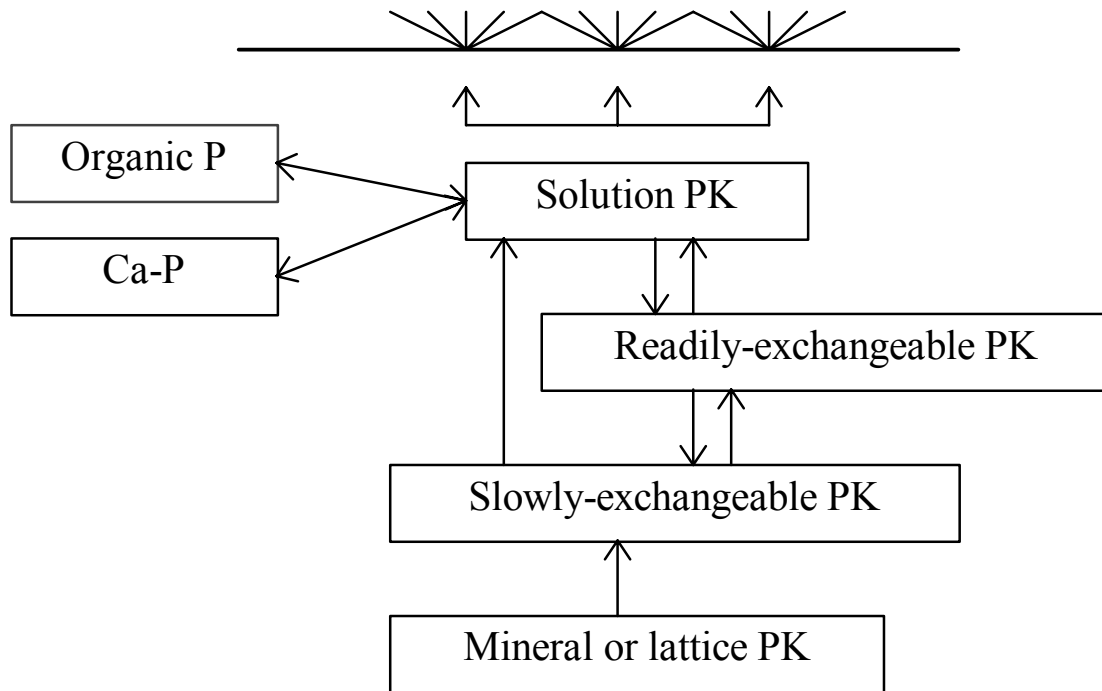
Figure 2. *Conceptual diagram of of P and K transformations in the soil.*

In calcareous soils, Ca-P precipitates also release or immobilise P depending on the concentrations of Ca and P in solution, and their solubility products. A significant proportion of total soil P and K is held very tightly in the primary mineral soil matrix (lattice PK) and is only very slowly released to slowly-exchangeable PK forms by weathering processes, therefore remaining largely unavailable to crops. Solution and readily-exchangeable forms are often referred to as 'labile', whilst slowly-exchangeable forms are sometimes referred to as the non-labile or fixed. Losses of P and K from the soil occur both in particulate form due to erosion and in soluble form due to leaching. Soluble P losses of up to 10 kg/ha have been recently measured passing 90 cm depth in soils with excessive Olsen-extractable P (Index 8)

concentrations (Smith *et al.,* 1998), whilst Shepherd (1997) reports soluble K losses of up to 30 kg/ha from sand soil lysimeters at ADAS Gleadthorpe, irrespective of K fertilizer inputs.

The size of the readily-exchangeable PK pool (and the degree of Ca saturation for P) governs the *intensity* with which P and K are available in solution for uptake, whilst the size of the slowly-exchangeable PK pool governs the *buffering capacity* of the soil to maintain the supply route. The intensity and capacity factors differ for different soil types, depending on the nature of the soil (particle size distribution including stone content) and the history of fertilization. For example, sandy soils generally maintain a large, readily-exchangeable pool (ie high soil test P) but often have a low capacity to maintain this pool compared to soils with an appreciable clay content which build up slowly-exchangeable PK reserves. Intensity and capacity factors are both low for K on sandy soils and require regular fertilization. There are some soils which need to maintain a high intensity factor, whilst others may supply adequate P or K in solution under a lower soil test value because they have a high buffering capacity. Soils which have been regularly fertilized for long periods build up large reserves of nutrient in both the readily and slowly-exchangeable pools, and the concentration of P and K in solution remains relatively high. As more fertilizer is added and the readily-exchangeable pool becomes saturated, PK ions move into more slowly-exchangeable forms. The different forms of P and K in soil can therefore be seen to be in dynamic equilibrium.

2.2 Soil test procedures and current recommendations

Standard soil testing procedures used in routine advisory work in the UK were largely developed during the 1950's and 1960's to help predict both the need for fresh applications of PK fertilizer and how much should be applied to help boost soil fertility. Soil test values were compared with the amounts of fertilizer required to achieve optimum crop yields based on extensive field experimentation. The soil tests have been slightly modified over the years, but all attempt to quantify the readily-exchangeable soil PK reserves potentially available for crop uptake; a summary of the main methods used in the UK is given in Table 3. Examination of this early work, which compared a variety of methods for both P and K, clearly shows that soil analysis is not a totally reliable method of predicting fertilizer requirement, especially for K, and for less responsive crops such as cereals (Boyd and Frater, 1967; Boyd, 1965; Williams and Cooke, 1965).

Table 3. *Routine soil test methods for phosphorus and potassium currently used in advisory work in the UK.*

Organisation	Extractant	Extraction conditions	Soil:solution ratio	Reference
Phosphorus				
ADAS	0.5 M sodium bicarbonate ($NaHCO_3$)	pH 8.5, 30 mins at 20°C	1:20	Olsen *et al.* (1954), MAFF (1986)
SAC	0.5M ammonium acetate/acetic acid	pH 4.5, 30 mins at 20°C	1:5	Edwards, pers com.
Levington	5ml anion exchange resin	16 hours at 20°C	1:50	Hislop and Cooke, 1968
Potassium				
ADAS	M ammonium nitrate	30 mins	1:5	MAFF, 1986
SAC	0.5M ammonium acetate/acetic acid	pH 4.5, 30 mins at 20°C	1:5	Edwards, pers com.
Levington	M ammonium nitrate	30 mins	1:5	MAFF, 1986

On average, the Olsen (sodium bicarbonate) method for P performed best, especially on neutral and alkaline soils, whilst no one method was outstanding for K, reflecting the significant contribution of slowly-exchangeable K forms, and subsoil K, to crop uptake on some soils, especially those with micaceous clays. Also, these methods were developed at a time when crop yields and N inputs were much lower than at present; the introduction of new varieties with higher yield expectations, better soil management and hence better crop rooting, and moves towards intensification and specialisation, raise doubts about whether the relationships established during the 1950's and 1960's still hold.

There appears to be general agreement that the methods currently used are the best current guide to the likelihood of a yield response to fresh PK fertilizer on most soils (Arnold and Shepherd 1990; Johnston and Poulton 1992; Syers, 1998). In current recommendations, the likelihood of a yield response has been summarised as probable at Index 0, possible at Index 1 and unlikely at Index 2 (MAFF, 1985; MAFF, 1994). However, it is likely that farmers and agronomists have too much faith in the accuracy of soil sample results and crop response. For example, Boyd (1965) found that Olsen-P concentrations accounted for less than 50% of the variance in response to freshly applied P fertilizer, whilst Arnold and Shepherd (1990) concluded there was a generally poorer relationship between readily-exchangeable K and yield response to K fertilizer than was the case for P. Soil analysis is also of limited value in characterising the amount of PK nutrient release from the soil, and therefore more accurately quantifying fertilizer need. In reviewing the adequacy of soil testing for predicting fertilizer requirements, Beringer (1985) concluded 'Routine soil testing methods are excellent tools for monitoring soil fertility but will frequently fail to predict optimum fertilizer requirement. Soil test methods must become more comprehensive with regard to the rates of nutrient supply and the magnitude of the nutrient reserves'.

Standard soil tests in the UK attempt to predict relative PK availability during a growing season or over a rotation, and do not measure what the crop will take up from a soil. This is because a) different soil test methods extract different amounts of exchangeable P depending on the reagent used and the extraction conditions, for example see Edwards *et al.* (1997), b) the soil test method does not measure the amounts of slowly exchangeable PK which may become available for uptake, either directly, or indirectly via the exchangeable pool, and c) crop roots may explore a greater or lesser soil volume than is included in the standard soil sampling depth. With the recent interest in precision agriculture, soil PK analysis is becoming increasingly used to help explain variation in crop yield within fields, and used

together with field maps, to form the basis for more precise site specific application of P fertilizer - a level of accuracy which is perhaps unjustified. As pointed out by Tunney *et al.* (1997), the soil sample is only 1 part in 10 million of the bulk field soil it is considered to represent, only 1-5 g of the sample is actually analysed and inconsistencies may arise in each step of the sampling and analysis procedure (Table 4).

Table 4. *Opportunities for inconsistencies in soil sampling and analysis procedures (from Edwards et al., 1997).*

SAMPLE COLLECTION	Taken by advisor or farmer Soil core size and depth taken Number and pattern of sub-samples Time of year samples taken
SAMPLE PREPARATION	Drying time and temperature Method of grinding and sieving Method of sub-sampling
SAMPLE EXTRACTION	Weight or volume of soil taken Ratio of soil to extractant solution Shaking time and temperature
SAMPLE ANALYSIS	Method of determination in filtered extract Expresssion of concentration
INTERPRETATION	Concentration or Index Soil type (parent material, texture, subsoil PK) Crop rotation, fertilizer/manure history Time of year the sample taken Time since P application

Fundamental differences in the ability of different soil types to replenish PK in solution (ie buffering capacity) are not taken into account in the UK, although their importance is well recognised in other countries (Tunney *et al.,* 1997). For example, soils differ in the amounts of fertilizer PK required to raise or maintain a critical level of P and K in the soil. In the long-term ADAS experiments described by Tytherleigh (1988a,b), a net fertilizer input of 100 kg P_2O_5 or K_2O/ha raised soil test P and K values by between 2 and 7 mg P/l and 6 and 12mg K/l, respectively between sites. A lower amount of Olsen-extractable P is generally required to maintain crop growth in a clay soil than in a sandy soil, but the amount of fertilizer P initially required to raise Olsen-P concentrations is greater in a clay soil. The dissolution of calcium phosphates is also sensitive to solution Ca concentrations which could vary greatly with soil type. Hence, crops require quantities of P and K which may be poorly characterised by a concentration measured in an extract of 0-15 cm soil sample in the laboratory.

There are other reasons why the inclusion of additional soil properties can help with the interpretation from soil tests. One example is the stone content of the soil profile; the general inert nature of stones, the dead space they occupy and the reduced volume of soil exploitable by plant roots. It should also be remembered that all advisory soil tests are usually performed upon the <2.0 mm soil fraction, so stones are discarded. Extrapolation from a concentration (mg/l) to an amount (kg/ha) requires knowledge of soil bulk density, which the presence of stones influences. For example, in two soils with the same soil test P, more P would be present in the soil without stones (Table 5). Similarly if the same amount of fertilizer P is applied to these soils, then the expected increase in extractable P would be positively related to the stone content, since the amount of soil is reduced with increasing stone content. Large differences in bulk density also occur between peat and mineral soils. Fundamental differences in topsoil cultivation depth between clays (20 cm) and sands (30 cm) affect the rate of soil PK accumulation for a given input of total PK nutrient, and the type of subsoil can have a major influence on nutrient uptake, especially K.

Table 5. *Hypothetical example of the possible influence of stone content on extractable P.*

Stone content (%)	Tonnes of soil (<2.0 mm)[1]	Total quantity extractable P (kg P/ha)[2]	Concentration of Extractable P mg P/kg[3]
0	1500	30	27
15	1275	25.5	28.5
30	1050	21	30

[1]Soil present in topsoil (0-15 cm) [2]Calculated amount of extractable P present in one ha of soil assuming all have a similar Olsen P concentration of 20 mg/kg. [3]Calculated concentration of Olsen-extractable P after a net P addition (input-offtake) of 25 kg P_2O_5/ha.

Until recently, soil type differences were incorporated into fertilizer recommendations in Scotland based on the work of Reith *et al.* (1987), who found that soil type had as large an influence as the soil test extraction method in identifying critical levels of available P in soils. Cox (1994) concluded that the effectiveness with which fresh fertilizer P changed soil test P was highly dependent on clay content, and extremely important in making fertilizer recommendations. In particular, he considered that a lack of awareness and appreciation of the important influence of soil type had led to some extremely high concentrations of extractable P in soils low in clay in the USA. Unnecessary use of fertilizers is economically wasteful and increases the potential transfer of P in land run-off to watercourses. Russell

(1971) considered shallow soils over limestone could supply 30 kg K_2O/ha/year for 20 years from natural soil reserves, and Goulding and Loveland (1986) classified soils into three groups based on their ability to supply K. Subsoils rich in micaceous clays can release substantial quantities of K to crop roots (Goulding and Loveland, 1986).

Various attempts have been made to characterise the amount of slowly-exchangeable K in the soil, because this is known to make a potentially large contribution to crop K uptake, but depending on the level of redily-exchangeable K in the soil (Syers, 1998). For example, Goulding and Loveland (1986) used Ca-resin and concentrated hydrochloric acid to distinguish the reserve of slowly-exchangeable K in a number of UK soils. They concluded that cropping history and fertilization history were as important as soil type in explaining the large differences obtained in the amounts measured. A 'Reserve Potash Analysis' service developed by Levington agriculture also found that clay content and fertilization history greatly influenced amounts of slowly-exchangeable K in soils, as measured by 10N nitric acid. These approaches have value in targeting K fertilizer requirements much more precisely and avoiding the wastage associated with applying K fertilizers when they are not needed, for example in the use of compounds containing nil or low K where slowly-exchangeable K reserves are high, although they have not been commercially expoited to-date. Similar opportunities exist to measure slowly-exchangeable forms of P, although their contribution to plant P uptake is less than for K.

2.3 Are existing recommendation systems adequate?

Whilst it is recognised that routine soil tests must be rapid and cheap to use, it is perhaps not surprising that there are instances when soil testing, or fertilizer recommendations, fail to adequately predict the need for fresh P fertilizer, and/or allow soil test PK levels to run-down. This may be partly a reflection of the variability in nutrient offtake within and/or between fields compared to the average figures for P and K offtake in crops (Withers, 1991; Dawson, 1996; PDA, 1997). However, examination of long-term experiments in the UK, where annual offtake is being measured, have also indicated that existing recommendation systems may not always be appropiate on all soils. In reviewing Swedish experiments, Bertilsson and Forsberg (1997) found that a 'replacement' policy was not appropiate for some soils. They concluded that whilst the concept of replacement might serve as a starting point for developing farm P fertilizer policies, there was a need to adjust P inputs according to knowledge on soil nutrient release characteristics so that the efficiency of P fertilizer use could be improved.

Withers *et al.* (1994) reported two experiments on calcareous soils in England with initially adequate and high soil PK levels, respectively, which examined the effect of withholding phosphate and potash fertilizer for periods of up to 11 years on the yield of cereal crops. Two key points emerged: firstly P and K inputs designed to match crop offtake were not sufficient to maintain the extractable soil PK levels at the start of the experiment, and (b) yield responses were obtained at one of the sites when soil P and K levels were well above Index 2. In reviewing other experiments on calcareous soils, these authors found other evidence to indicate that fertilizer P inputs needed to exceed crop offtake in order to maintain a given level of Olsen-extractable P because of the gradual transfer of P from readily-exchangeable forms to slowly-exchangeable or fixed P forms (Withers *et al.,* 1994). In experiments as far back as 1960, Eagle (1974) found that soil P concentrations on a silt soil at Terrington declined unless the amount of P fertilizer applied exceeded the quantity removed by about 25%. Under current recommendations there is no way of distinguishing these sites, although it is recognised that when soil analysis is carried out regularly and consistently by the same laboratory, it provides useful information on adequacy of long-term fertilizer policies.

In a long-term experiment at Ropsley in Lincolnshire, a rotation of winter wheat, sugar beet and spring barley received rates of phosphate between 1977 and 1985 which were either equal to (L) or 50% in excess of (H) expected crop demand, with control plots (N) receiving no phosphate fertilizer (Bhogal *et al.,* 1996; Hatley *et al.,* 1997). Since 1985, applications of 0, 70, 100 kg P_2O_5/ha were superimposed on these fertilizer policies. Mean Olsen-extractable soil P values in 1985 were 15, 19 and 28 mg l^{-1} for the N, L and H policies respectively. Since 1985, Olsen P has fallen where no P has been applied, the rate of decline being dependent on the initial soil P levels: declines of 4, 7 and 14 mg/l were recorded for the N, L and H policies respectively. Applications of 70 kg P_2O_5/ha were sufficient to slightly increase Olsen P for the N policy but only maintain the L policy. The highest P fertilizer rate increased Olsen P values for N and L policies, but neither 70 nor 100 kg P_2O_5/ha additions maintained the Olsen P levels on the H policy.

Marked 'seasonal' variations in Olsen P values were observed over the full range of treatments at Ropsley, although this was not correlated with simple parameters such as crop offtake or soil moisture status. Allowing for this variation, a linear model describing changes in Olsen P indicated an overall fixation of P from 12 years annual additions of 100 kg P_2O_5/ha to previous H policy plots of approximately 700 kg P_2O_5/ha. Clearly it is not

economic to maintain a high P level on these soils, but the data illustrates the capacity of different soils to fix P. The level of fixation was reduced where higher rates of N were applied indicating an influence of higher nutrient demand (Bhogal *et al.,* 1996). Where no P was added, the crop extracted an additional 450 kg P_2O_5/ha from sources other than those identified by Olsen extraction. For this site, also, a 'balance' approach to P fertilization was not appropriate.

Richards *et al.* (1998) examined the effect of four rates of P fertilizer (0, 22, 45 and 90 kg P_2O_5/ha) on soil and crop P during 1968-1996 at a site in Cornwall cropped each year with barley. The optimum rate of P application for yield was 69 kg P_2O_5/ha which was greater than the average P offtake (39 kg P_2O_5/ha). It was calculated that adopting a maintenance policy under current recommendations would have reduced grain yields by 0.2 t/ha/year, although extractable soil P levels would have been maintained on this soil, which was developed over shale. Barraclough *et al. (*1997) found soil analysis was of no value in predicting K fertilizer needs of cereals grown at 3 sites; there was no yield response to added K despite deficiency levels of extractable K in the soil. Syers (1998) also considered that there were a number of soils where the release of slowly exhangeable, or fixed K, might sustain crop growth at low levels of readily-extractable K as measured by standard soil tests. Under current recommendations there is no way of distinguishing these sites.

2.4 Effects of withholding PK fertilizer on cereal yields

Where soil PK concentrations are above the critical values considered necessary for optimum crop growth, there is clearly opportunity to omit or reduce phosphate and potash fertilizer use. However, there is little up-to-date information on the effect of withholding P and K fertilizer inputs to commercial high yielding cereal crops on PK rich soils. Experimental data outside of Rothamsted is limited and largely restricted to field experiments conducted during the 1970's on low yielding cereal crops and on soils of low rather than high soil fertility status. However, these experiments do illustrate the large variation in response to PK omission on different soils (Tables 6 and 7).

Table 6. *Mean yield response (t/ha) to fresh fertilizer during each build-up year at different sites (adapted from Tytherleigh, 1988a, b).*

Site	Initial soil level (mg/l)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Phosphorus															
Gleadthorpe (1966)	34	0.20	0.19	0.20	0.07	0.03	0.34	0.14							
High Mowthorpe (1965)	21	0.11	-0.19	0.15	0.59	0.23	1.03	0.36	0.05	1.02	1.05	0.94	0.66		
Thurgarton (1966)	17	ley	ley	0.71	0.64	0.56									
Deerhurst (1965)	12	0.11	0.24	0.66	1.02	ley	ley	0.43	-0.27	0.12					
West Lydford (1965)	18	-0.12	0.00	-0.61	-0.7	0.71	0.56	-0.64	0.48						
Stonehouse (1966)	10	0.03	1.14	0.48	0.82										
Pamington (1966)	9	-	-	ley	ley	ley	0.21	0.57	1.07	0.85	ley	ley	ley	1.16	1.98
Enford (1973)	14	0.01	0.70	0.32	1.11	1.24	1.23	1.01	1.17	-0.05					
Mere (1974)	10	0.49	-0.28	0.86	0.72	-	-	-	0.07						
Stapleford (1976)	18	-0.01	-0.06	-0.09	ley	0.08	0.25	ley	ley	1.15	0.54	1.07	2.22		
Tetbury (1981)	49	0.16	-.010	0.10	0.26	0.28	0.31	0.31	0.23						
Potassium															
Gleadthorpe (1966)	109	0.11	0.26	0.32	0.22	0.19	0.34	0.20							
High Mowthorpe (1965)	126	0.10	0.13	0.25	-0.04	-0.12	0.22	0.86	-0.06	0.40	0.24	0.75	0.38		
Brakenhurst (1966)	284	-0.38	-0.30	-0.18	-0.02	-0.22									
Marston Magna (1970)	170	Ley	nd	0.32	0.05	-0.14	-0.20								
Shapwick (1970)	298	0.17	0.13	nd	ley	ley	ley	ley							
Ramsbury (1975)	96	0.10	-0.09	0.08	-0.07	0.12	ley	ley	2.58	0.23					
Stapleford (1976)	239	0.13	0.01	-0.07	ley	-0.10	-0.05	ley	ley	0.26	0.08	0.6	0.16		
Tetbury (1981)	363	-0.02	-0.04	0.06	-0.06	-0.04	0.19	-0.01	-0.11						

The "Number of years fertilizer withheld" heading spans columns 1 through 14.

Table 7. *Changes in soil test P and K over the build-up phase and yield response to fresh PK fertilizer on plots receiving no PK fertilizer during the build-up phase (adapted from Tytherleigh, 1988a, b).*

Site	Soil Series	Soil test value (mg/l)		Years PK	Test	Yield response
		Initial	Final	withheld	year	t/ha (85% dm)
Phosphorus						
Gleadthorpe	Newport	34	32	7	1973	+0.19
High Mowthorpe	Andover	21	8	12	1977	-0.16
High Mowthorpe	Andover	21	8	13	1978	+0.39
Thurgaton	Worcester	17	14	5	1971	+0.40
Deerhurst	Evesham	12	5	9	1974	+0.11
West Lydford	Evesham	18	7	8	1973	+0.44
Stonehouse	Evesham	10	9	4	1970	+1.49
Pamington	Evesham	9	3	14	1980	-0.14
Enford	Upton	14	9	9	1982	+0.59
Mere	Icknield	10	8	8	1982	+1.16
Potassium						
Gleadthorpe	Newport	109	107	7	1973	+0.18
High Mowthorpe	Andover	126	81	12	1977	+0.37
High Mowthorpe	Andover	126	91	13	1978	+0.39
Brackenhurst	Worcester	284	218	5	1971	+0.08
Marston Magna	Evesham	170	175	6	1976	+0.29
Shapwick	Evesham	298	309	7	1977	-0.13
Ramsbury	Upton	96	81	9	1984	+0.78

These experiments investigated a build-up phase testing 0, 50, 100, 150/250 kg P_2O_5 or K_2O /ha over a number of years, which varied between sites, and a testing year where yield response to added nutrient was superimposed on each of the build-up plots. Differences in yield between plots receiving PK (meaned across all PK rates) and those receiving no PK fertilizer for each year of the build-up phase are shown in Table 6. Large yield differences were observed after only a few years of withholding P, for example at Enford (1 year), High Mowthorpe (3 years) and West Lydford (4 years), but the initial extractable P concentrations at these sites was low. The two sites with high soil P fertility (Gleadthorpe and Tetbury) did not show large yield differences, although at Tetbury, the small yield differences obtained after the third year were consistant and significant (Withers *et al.,* 1994). Clare and Caldwell (1972) found litttle yield reduction during a 4-year run-down period of soil P on a calcareous clay loam soil. For K, large yield differences were observed after 6 years on the chalk soil at High Mowthorpe (although not consistant) and coincided with a sudden sharp drop in soil test K. Similarly at Ramsbury, a very large yield difference was observed after a grass ley

break, 7 years after the start of the experiment. At sites with very high initial soil test K values (Brakenhurst and Shapwick) there was no positive response to added K. Similarly, at Stapleford and Tetbury, there was no response to fresh potash fertilizer for at least 10 and 6 years, respectively (Table 6).

In the testing year, Olsen-extractable P concentrations had fallen to Index 0 at most sites and yield responses to fresh fertilizer P were generally large, although not consistently so (Table 7). Similarly, those sites where soil extractable K values had fallen over the build-up period showed the largest yield responses. However, there were some sites (eg Gleadthorpe for P, Gleadthorpe, Brackenhurst, Marston Magna and Shapwick for K) which maintained the same level of extractable P and K on nil fertilized plots throughout the experimental period. This did not appear to be related to the initial soil test value for the site. With increasing economic pressures to reduce unnecessary variable costs, further information is required on the effect of soil PK rundown on cereal yields, and the causes of variability in response between different sites, especially under modern farming methods with high-yielding varieties.

2.5 Critical nutrient levels

Relationships between grain yield and the amount of residual soil PK potentially available for crop uptake, as measured by standard soil tests, have indicated there is a threshold or critical level of residual soil PK fertility above which it is not economically worthwhile exceeding. These critical levels define the point at which PK fertilizer policies can switch between build-up and maintenance. Although often assumed to be the same, this critical level of residual soil PK fertility is not necessarily the level above which or below which yield responses to fresh P and K will not or will occur, respectively. For example, at Woburn, Johnston *et al.,* (1976) found that the critical level for yield response to fresh P was lower than that for yield response to residual P. This difference reflects the influence of factors other than soil test PK levels;

1) Experimental error larger than yield differences in field experiments
2) Growing conditions (light, temperature, moisture) during the season
3) Soil conditions and crop rooting patterns affecting accessibility to nutrient reserves
4) Availability of PK from soil reserves not measured by standard soil tests (eg fixed K)
5) Uptake of PK from the subsoil

Hence, critical levels of residual soil PK maybe independent of season but critical levels for response to fresh PK tend to be more variable; in the absence of other growth limiting factors the two can be considered synonymous. As reviewed by Arnold and Shepherd (1990) and more recently demonstrated by Barraclough *et al.* (1997), there are numerous examples of a lack of response to fresh PK at soil PK levels well below what might be considered an adequate level of soil fertility (Fig. 3).
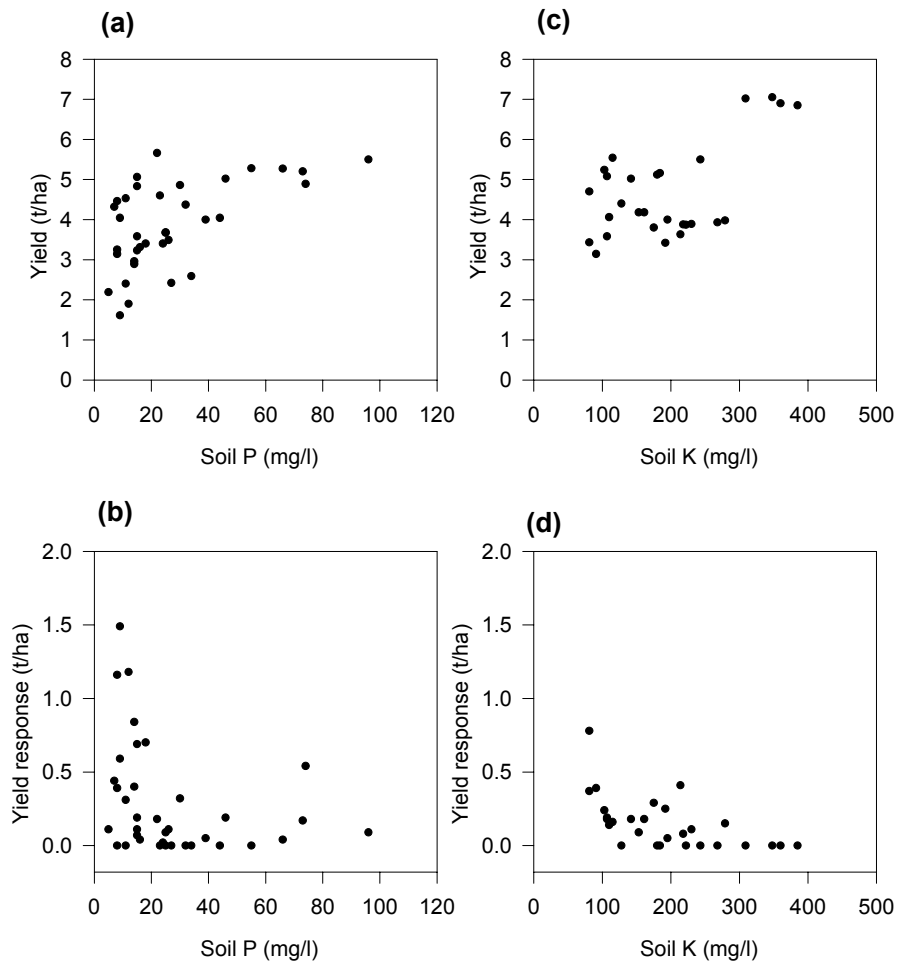
Figure 3. *Relationships between readily-extractable soil PK concentrations (0-15 cm) and both yield level without fresh inputs of fertilizer, and the yield response from fresh fertilizer PK, for spring barley.*

Critical levels of residual soil PK fertility for cereals have been determined by field experimentation at only a limited number of sites, especially for wheat (Tytherleigh, 1988a,b; Johnson and Poulton, 1992; Barraclough *et al.,* 1997; Syers, 1998). Johnston and Poulton (1992) found a critical value of 20 mg/kg Olsen-extractable P for winter wheat on a sandy clay loam soil at Saxmundham in one year, whilst Barraclough *et al.* (1997) found values closer to 10 mg/kg on a deep clay loam soil at Rothamsted during 1992-1995. Johnston and Poulton (1992) also report a value of 25 mg/kg for spring barley receiving 63 kg N/ha, but this increased to 33 mg/kg when 96 kg N/ha was applied to the crop. In contrast, Johnston *et al.* (1998) report values for winter wheat at Saxmundham decreasing from 29 to 18 mg/kg as N rate increased from 80-200 kg/ha. At Rothamsted, Johnston *et al.* (1998) report values for spring barley of 15 mg/kg between 1986 and 1990. Similar values have been suggested in experiments at a deep loam site in Lincolnshire (Ropsley) for winter wheat in recent years (ADAS unpublished).

In reviewing work on yield response to applied K at Rothamsted, Syers (1998) reports a linear relationship between readily-exchangeable K (measured by ammonium acetate rather than the ammonium nitrate used in routine soil testing), and grain yield of winter wheat below 100 mg/kg, whilst there was no such relationship for spring barley above 80 mg/kg exchangeable K in the soil. When comparing across sites, the data are more variable. For example, there was too much scatter in the data from the long-term field experiments carried out on spring barley by ADAS on a range of sites during the 1970's to allow a statistically significant curve-fit for identifying critical soil test PK values for optimum yield (Fig. 3). The number of application rates tested was not sufficient to identify critical PK levels at individual sites or in individual years. Hence, it is not clear to what extent lower critical PK values may be appropiate on soils which have built up slowly-exchangeable PK reserves and/or under modern farming systems.

Withers *et al.* (1994) found consistently large cereal grain yield responses (up to 2 t/ha) to fresh P fertilizer at a shallow chalkland site (Stapleford) in Wiltshire only once Olsen-extractable P levels dropped to 8 mg/l (10 mg/kg). At the shallow chalk site in Wiltshire, a yield response to fresh K (50 kg K_2O/ha) occurred when the soil test K level dropped to 120 mg/l, but there was no response the following year at the same site. In more recent experiments by Barraclough *et al.* (1997), there was no yield response to fresh K fertilizer at 3 sites even though soil test K levels were very low (ranging from 32-79 mg/l). The data in

Tables 6 and 7 also indicate yield responses to fresh P and K are not consistent even at low soil PK fertility status.

These data indicate that whilst there is often a good relationship between the amount of readily-exchangeable P and/or K in the soil and crop yield at an individual site in the absence of other seasonal growth limiting factors, there is considerable variability in the critical concentration of extractable P and K in the soil necessary for optimum yield between different sites. Much of this variation is due to soil properties (clay, sesquioxide (Fe/Al), organic matter, depth over parent material, stone content), and a better understanding of the effect of soil type on PK release would help to more precisely define optimum residual PK levels. Other growth limiting factors may influence crop behaviour within individual years, in particular the ability of the crop to explore sufficient rooting volume for water and nutrients. Clearly where crop rooting is restricted due to compaction or drought, a higher critical concentration is required to compensate for the lack or rooting volume. Winter cereals may therefore require a lower critical concentration than spring cereal crops, but current recommendation systems do not allow for this. The use of precise critical values is perhaps questionable bearing in mind the errors introduced during commercial field sampling, as discussed above, and in routine advisory work, threshold indices which span a range of soil-extractable PK concentrations have conventionally been used to define PK fertilizer recommendations (MAFF, 1985; MAFF, 1994; MISR/SAC, 1985). However, even using an Index system, there are a number of instances where crops may be under or over-fertilized with P and/or K (Fig. 3).

2.6 Plant analysis

Plant analysis has been used for many years in advisory work as a quick and convenient method of assessing crop nutrient status and diagnosing nutrient deficiencies where these occur. Crop concentrations are typically reported on a dry matter (DM) basis and can vary according to the crop being grown, crop growth stage, crop growing conditions (light, temperature and moisture) and the part of the plant sampled. For cereals, for example, P and K concentrations will be greater in leaf tissue than in shoot or whole plant samples, and will decline as vegetative growth increases during the season reaching a minimum usually at anthesis (Gregory *et al.,* 1979; Bollons and Barraclough, 1997). Accurate interpretation requires crop, soil and weather information and plant analysis has only ever be used to

provide a 'snapshot' of crop nutrient status at the time of sampling. Critical values which have been commonly used in advisory work by ADAS for deficiencies of P and K in leaf tissue of cereal crops at anthesis are 0.2% and 2.0%, respectively.

In view of this inherent variability, plant tissue testing has had limited use as a means of checking whether annual fertilizer applications, or rotational fertilizer policies, have been less, or more than adequate, to meet crop P and K requirements. Whilst soil analysis gives a prognostic guide to the potential reserves of PK available to crops, regular plant analysis does have the advantage of providing information on actual PK uptake during a particular season, although this information comes too late to correct the current crop. A recent HGCA-funded project has helped define more precisely a sampling and analysis blueprint for assessing the P and K status of cereals (Barraclough *et al.,* 1997). This project concluded that conventional analysis of total P and K concentrations (in the DM) in young fully expanded leaves between growth stages 31 and 39 was the best overall indicator of crop PK status. Recommended critical concentrations for P and K at different growth stages are given in Table 7; for K, critical concentrations were related to yield level.

Table 7. *Critical concentrations of P and K at different growth stages in cereals.*

Growth stage	Total nutrient in the dry matter (%)		
	Deficient	Borderline	Adequate
Phosphorus			
GS 22-30	<0.28	0.28-0.45	>0.45
GS 31-39	<0.28	0.28-0.38	>0.38
GS39-65	<0.25	0.25-0.30	>0.30
Potassium			
Crop yield <8.5 t/ha			
GS 22-30	<2.0	2.0-2.9	>2.9
GS 31-39	<1.6	1.6-2.5	>2.5
GS 39-65	<1.2	1.2-1.7	>1.7
Crop yield >8.5 t/ha			
GS 22-30	<3.0	3.0-3.5	>3.5
GS 31-39	<2.5	2.5-3.2	>3.2
GS 39-65	<1.8	1.8-2.0	>2.0

Concentrations of P and K during tillering were variable; also K values at anthesis varied due to the effect of moisture stress. An alternative technique measuring PK concentrations in tissue water was found to reduce the variability in P and K in whole shoots due to seasonal

differences in growing conditions within and between sites, but was no better than conventional analysis in identifying under or over-supply of PK. Hence, whilst determination of tissue water K concentrations in the youngest fully expanded leaves was the least variable parameter, conventional analysis of K levels in the DM was also very satisfactory, and better combined with P analysis. No extensive analysis of second and third leaves was undertaken.

2.7 Variation in P and K offtake

The offtake of P and K in the harvested crop is an important component of fertilizer planning since it determines minimum maintenance requirements to ensure adequate soil PK fertility for the following crop. Grain yield largely determines P offtake since there is relatively little P found in straw (Withers, 1991), whereas straw K concentrations are somewhat larger and straw K offtake typically represents >50% of the total K offtake in grain and straw. Hence, Froment *et al.* (1997) found that grain yield explained 60% of the variation in P offtake and only 30% of the variation in K offtake within a field. Thorne *et al.* (1988) found grain P and K concentrations were relatively constant on the Broadbalk field at Rothamsted from 1969-84. Analysis of 400 samples of cereal grain as part of the HGCA Wheat Quality Survey undertaken in 1992 (Chaudri *et al.* 1997) indicated that wholemeal flour P and K concentrations in 80% of samples varied only by about 0.1% or 8 kg/ha for a 8t/ha crop. Mean values were 0.34% for P and 0.5% for K. Although there was statistically significant differences in grain P and K between wheat varieties, the differences were small (± 0.05% in the dry matter) and the authors considered them not agriculturally important.

   Much larger variation in P and K concentrations occurs in straw, especially K. In a survey undetaken during 1986-1988, Withers (1991) measured P and K concentrations in cereal straw dry matter ranging from 0.01-0.28% (mean 0.08%) and 0.05-2.8% (mean 1.05%), respectively. There were significant differences in straw PK concentrations between wheat and barley and between spring-sown crops and winter-sown crops. Average variance in P and K concentrations between different varieties of wheat and barley straw at 5 sites in 1986 represented about 30% (± 0.013% for P and ± 0.15% for K) of the average PK concentration. Application rate of N, and rainfall in the 3-week period before harvest also influenced cereal straw K concentrations. Froment *et al.* (1997) report similar variation for both grain and straw within specific fields.

Existing information on the relationship between soil PK levels and crop yield, or PK offtake, within commercial field crops is limited. Froment *et al.* (1997) reported data for three fields showing no significant relationship with crop yield and poor correlations (r^2 0.2-0.3) with total PK offtake. Johnston *et al.* (1998) suggests soil PK analysis is reliable for assessing yield variation, but limiting factors other than soil P and K level clearly influence crop yields and crop PK offtake within commercial fields. In the wheat and barley straw straw survey (Withers, 1991), variation in the PK content could only partly be explained (r^2 0.2-0.3) by soil PK index; but multiple correlation with other site variables did not improve the regression, although subsoil PK was not included. It must also be remembered that differences in annual offtake are too small to make any detectable difference in the amounts of readily-exchangeable PK in the soil.

Significant variation in P and K offtake between and within fields can be related to soil, crop, weather and management factors. Grain yield is clearly a major factor and precision farming technology is now available to more precisely monitor yield levels within fields and over time. Differences in straw yields are also important if the straw is removed, especially for K, although these are not measured precisely. Existing data indicates that differences in P and K concentrations are most likely to be related to soil type and soil PK fertility, and a better understanding of the extent of variation across different soil types would improve current fertilizer recommendations, especially in view of the recent restrictions on P inputs to match crop P offtake above P Index 3 in the Code of Good Agricultural Practice for the Protection of Water. Other factors such as crop rooting patterns, growing conditions, and weather patterns at harvest may also affect the uptake of potentially available P and K supplied by the soil and their influence needs to be better quantified as part of a modelling approach to PK fertilization (Table 8).

Table 8. Some **f***actors influencing the supply of P and K from the soil and uptake by crops.*

Soil supply	Crop uptake
Mineralogy	Soil PK status
Texture	Crop type
Organic matter	Yield potential
Depth	Rooting pattern
Stone content	Growing conditions
Fertilization history	Weather patterns

2.8 Fertilization models

The current fertilizer recommendation system (MAFF, 1994) can be viewed as a simple model which uses routine soil analysis to predict soil PK supply, average figures of crop PK offtake to maintain soil PK levels, average figures for PK inputs in organic manures and the PK fertilizer responsiveness of the crop being grown based on field experimentation. As discussed above, this approach lacks the precision with which to fine tune fertilizer applications, and more detailed approaches which take account of the ability of different soil types to retain and supply P and K in relation to crop demand during the growing season have been developed. Physiologically, the amount of P and K uptake by cereal crops is a function of the amount of exchangeable nutrient in the soil, the crop rooting pattern at critical growth stages (eg winter v spring) and the rate at which nutrients diffuse to the root surface as influenced by soil moisture conditions and the uptake of nutrients as affected by the composition of the soil solution, particularly Ca. Rather than rely on a single soil analysis test to predict fertilizer need, there have been recent advances in our understanding of how nutrients behave in soil and/or the development of mechanistic models to describe nutrient uptake (Jones *et al.,* 1984; Costigan, 1987; Wolf *et al.,* 1987; Barraclough, 1990; Rengel, 1993; Greenwood and Karpinets, 1997).

   This approach is best illustrated by Greenwood and Karpinets (1997), who have developed a model to describe the effects of K fertilizer on crop growth, K uptake by different crops and the change in easily and slowly exchangeable K forms in the soil. The model was developed to better characterise the supply of K to vegetable crops on different soil types and has been used to provide useful information on the level of extractable K in the soil above which there was no contribution from fixed K reserves; their critical value was 167 mg/l. The model also uniquely involves a feedback mechanism to describe the inhibition of K uptake when the tissue K contents reaches the saturation value of 200 mM (Leigh and Johnston, 1983; Barraclough *et al.,* 1997). Further work is still required to model nutrient uptake of P by crops. The ability of a model to describe the impact of fertilizer strategies both on crop production and in terms of the short and long-term impacts on soil PK reserves is also central to the development of the 'Outlook' model.

2.8.1 The 'Outlook' model

The 'Outlook' model is a decision support system for fertilizer use on pastoral agriculture in New Zealand. Initially designed to quantify P transfers within farms, the model also intends
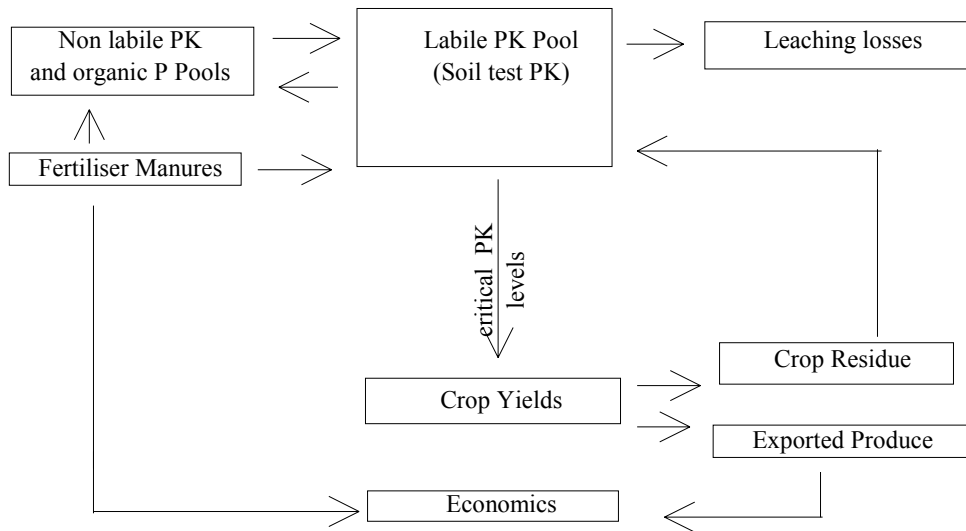
to incorporate both K and S, which are important major nutrients for grass production, as for cereals. The model was developed on the principle that decisions on fertilizer use must be based on a sound knowledge of the fate of fertilizer nutrients in different soil types, information on the soils and management of the farm and an economic appraisal. The outline concept of the model, adapted for use in cereal production in the UK, is shown in Fig. 4.

The model predicts changes in the size of a *pool* of readily-available (referred to as labile) nutrient as a result of inputs (fertilizers, organic manures, crop residues, mineralisation, non-labile soil reserves), outputs (harvested and sold products) and losses (erosion, leaching, immobilisation into organic matter, soil fixation). The size of the labile pool is determined by soil analysis and compared to a critical level for optimum crop production on different soil types. This critical level is defined according to the relationship between extractable soil nutrient level and crop production for different soil groups. For example, although there is a wide range of soil types in New Zealand, field experiments have shown that they could be grouped into 4 major classes with respect to P buffering capacity. Hence, volcanic soils in New Zealand require twice as much P fertilizer and half as much K fertilizer to raise soil-test PK concentrations by 1 unit compared to sedimentary soils, even though the critical level of soil PK for optimum pasture production is very similar for both soils. The critical level is broadly equivalent to the ADAS Index 2 but refined according to soil type; below the critical level, fertilizer inputs are required to build up soil fertility, whilst reductions in fertilizer use are allowable above the critical level; the exact amounts varying with soil type.

Following decisions on the amounts of fertilizer required to maintain both soil fertility and crop production, the model assesses the economic consequences. The economic analysis is based on the impact of the cost of nutrient purchases on the gross margin (ie sales minus variable costs). A distinction is made between the short-term cost impacts of nutrient use and the longer-term cost impacts of cumulative annual decisions; for example the depletion of soil fertility, impacts on soil nutrient levels and production and the capital costs of building fertility back up again. This economic analysis is a useful development, for example in calculating a long-term economic strategy; the model might suggest that the best option is to spend capital on a basal fertilizer dressing to raise soil nutrient status to the critical level for long-term production and apply maintenance dressings thereafter. The farmer can also nominate a maximum spend on fertilizer in any year, a maximum rate to apply in any year or set production targets, and the model will calculate the impacts on soil P levels and production. The farmer can also compare his own fertilizer strategy with that recommended

by the model. The benefits of this approach are illustrated by the example of the farmer growing cereals on Cotswold limestone whose soil test P levels fell from Index 2 to Index 0 despite applying maintenance PK fertilizer dressings and now has a substantial capital cost to restore soil P fertility.

```
  Non labile PK            Labile PK Pool              Leaching losses
and organic P Pools  →   (Soil test PK)      →

                     ←

         ↑

  Fertiliser Manures  →                          ←

                          critical PK
                             levels

                                              Crop Residue

                          Crop Yields    →

                                              Exported Produce

                          Economics     ←
```

Figure 4. *The principles of the 'Outlook' model*

The model is sensitive to changes in the input variables; for example maintenance requirements are affected by soil type, slope and stocking rate for ley/arable systems and gross margins. Sensitivity analyis has indicated that for every set of inputs, 'Outlook' will provide a suite of outputs with precision down to 1 kg. Uncertainty analysis has also indicated that the model is able to predict maintenance fertilizer requirements to within 5 kg of those determined by field experiment, whilst it is recognised that the amounts of fertilizer required to raise soil P levels to a critical value may have more error. There is also scope to improve the model; for example to take account of differences in the type of fertilizer (slow or fast release), changes in management affecting the efficiency of utilisation of P and the impacts of fertilizer use on other farm inputs affecting gross margin (fungicides etc). The Outlook model can be seen as a useful development of our current fertilizer recommendation system taking into account soil type.

3. ENVIRONMENTAL ISSUES

Potassium constitutes no hazards to human health and has no known deleterious effect on water quality. However, there are environmental concerns with respect to P fertilizer use because of the link between phosphorus and the undesirable symptoms of eutrophication in surface waters, and the accumulation of heavy metals in soils receiving derivatives of phosphate rock.

3.1 Eutrophication

Under optimal conditions of light and temperature, the accelerated enrichment, or eutrophication, of rivers, lakes, canals and reservoirs with nutrients (primarily, P and N) produces a number of undesirable symptoms which either interfere with water use for amenity, conservation or recreational purposes and/or pose a hazard to human and livestock health. These symptoms are most commonly observed as algal blooms, excessive growth of aquatic weeds, reduced water flow, or transparency, and localised fish kills or reduced fish populations. Perhaps the most famous example is that on Rudyard Lake in 1989, when toxins produced from a bloom of blue-green algae killed grazing livestock. A subsequent survey of 686 standing waters undertaken by the UK National Rivers Authority (now known as the Environment Agency) indicated that 169 waters contained potentially hazardous populations of blue-green algae with a 60-70% chance of them containing toxins (NRA, 1990). Recent surveys in Northern Ireland indicate a high proportion of small lakes in the province are eutrophic (Gibson *et al.,* 1995), and there is increasing concern over the effects of diffuse pollution on fish populations in some UK rivers (Huggins, 1999).

The extent of eutrophication in freshwaters is most commonly related to the concentration of P, since this is the nutrient which is usually in least supply (ie growth limiting), and when P inputs to water increase, this can have a large impact on its eutrophication status. Only very low concentrations of P are required for eutrophication symptoms to appear, such that changes in P inputs do not have to be large to cause a significant deterioration in water quality. Many of the eutrophication problems in the UK have historically been linked to anthropogenic inputs from an expanding population, usually discharged as sewage effluent from a single point, the sewage treatment works (STW).

The precise contribution of agricultural activities has not always been clear, largely because they are much more difficult to identify and quantify due to their diffuse nature. As STW point sources become more effectively controlled under existing EU directives (Urban Waste Water Directive, 1991), more attention is focusing on the contribution from agriculture. There is good evidence to indicate that the intensification of agriculture in recent decades has increased the loads and concentrations of P in land run-off (Foy and Withers, 1995; Johnes et al., 1996), and recent evidence from the MAFF-funded R&D programme on phosphorus loss from agriculture confirms that these are sufficient to cause eutrophication problems (Withers, 1996). There is still much to learn about the impact of agriculturally-derived P on water quality, but at some stage in the future, there maybe be controls over agricultural P inputs, and/or in the way land is managed, in some areas in an attempt to minimise P loss to water. In the UK, concern over the contribution of agriculture to eutrophication has prompted new guidelines which recommend that no inorganic P fertilizer should be applied to soil with Olsen-extractable P levels of Index 4 and above (> 45 mg l^{-1}) and that at Index 3 and above (>25 mg l^{-1}), application rates of organic manure applications should match crop P offtake rather than crop N offtake (MAFF, 1998).

As a result of the MAFF R&D programme, our understanding of the mechanisms of P loss has improved. The transfer of P in land run-off occurs in association with soil particles (particulate P or PP) due to *erosion*, in dissolved form (DP) as a result of the *leaching* of soil solutions, and when storm events follow applications of fertilizers and manures which have had too little time to be incorporated into the soil (*incidental loss*). These three mechanisms transport P either in surface run-off as overland flow or in sub-surface run-off either through tile drains or to shallow groundwaters, as summarised in Fig 5. The potential for P loss in erosion and leaching is strongly influenced by the residual P content of the soil, whilst the potential for incidental loss is related to the rate, timing, form and method of fresh P applications. During transport and on entering the water, the amounts of DP and PP continually change as 'new' sources continually become transported from different areas within the field, farm and catchment. Research suggests that the largest losses may be derived form a small number of fields in the catchment.

3.1.1 Erosion

Erosion is the main process of P loss from cultivated fields and is considered to have increased as a result of modern farming techniques (Spiers and Frost, 1985; Evans, 1988). In particular, the increase in the area sown to winter cereals, the introduction of tramlines which concentrate and increase the velocity of water flow, the removal of hedgerows which increases the length of slope, and the reduced soil stability arising from continuous cultivation are major contibuting factors. For example, in a survey of 80 fields susceptible to erosion monitored during 1989-1994, 80% of the erosion events were on land cropped to winter cereals (Skinner and Chambers, 1996; Chambers, 1997). However, the development of rills and gullies at the surface is not the only form of erosion from agricultural fields. Significant losses of PP also occur through tile drains both from arable and grassland. For example, recent monitoring of P loss from a small mixed arable/grass catchment in Herefordshire (ADAS Rosemaund) indicated that most of the loss occurred as PP transported through tile drains rather than in surface run-off (Hodgkinson and Withers, 1995). Winter cereal crops are therefore a high risk crop in terms of P loss to water where erosion occurs.
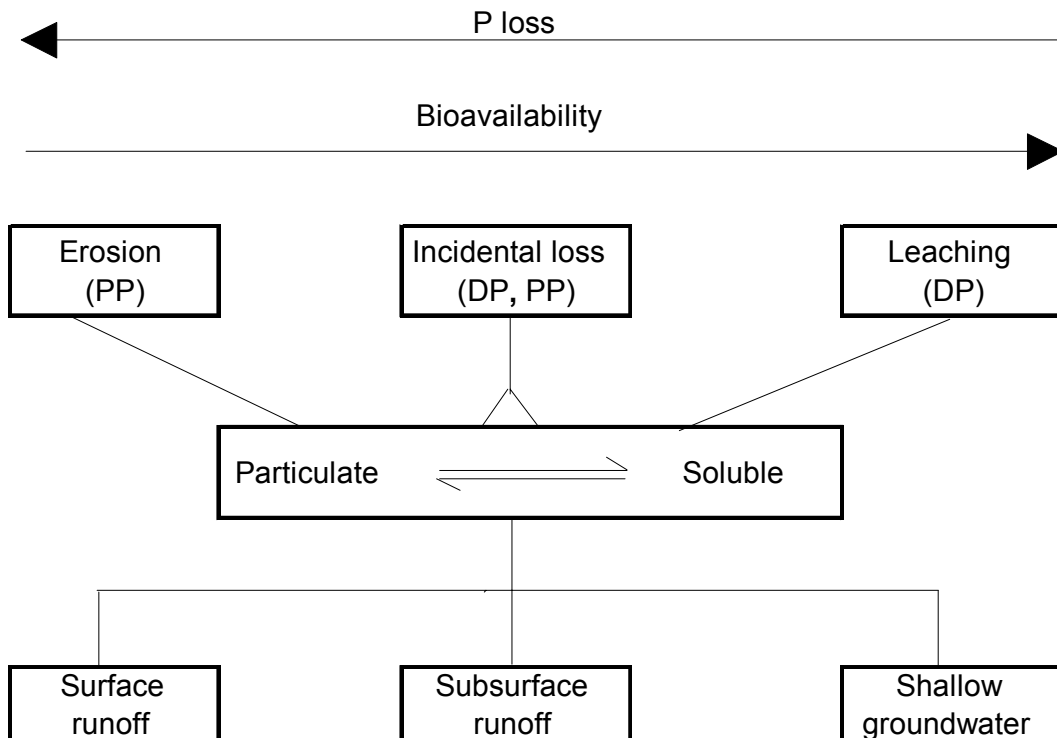
Figure 5. *Mechanisms of P loss from agricultural land to water.*

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Inputs of P in fertilizers and manures can influence the amount of P loss in erosion due to the build-up of P in the soil above what might be considered the 'natural' P content due to weathering of the soil parent material. Additionally, the P content of the eroding soil particles is generally greater than the bulk field soil because only the finer silt and clay particles usually leave the field, and these are enriched with P because of their greater surface area. Since only about 15% of the applied P is retained in an Olsen-extractable form in the soil, the drive towards adequate soil P fertility for optimum crop yields has required large amounts of total P inputs in the past. Since erosion transports both extractable and non-extractable P forms, it is the total P content which is most relevant with regard to diffuse P transfer and eutrophication. Where soil test P levels are allowed to increase beyond Index 2/3, then the influence of soil total P content becomes proportionally much greater.

Nationally, P inputs in feeds and fertilizers exceed the outputs of P in sold farm products by about 178,000 tonnes (Fig. 6). When spread over the area of productive arable and grassland in the UK, this P surplus equates to 16 kg P/ha/year (37 kg P_2O_5/ha/year). If imports of fertilizer P were banned, there would be no surplus P in the UK, but fertilizers are needed to grow crops in areas which have no livestock. Hence, the uneven redistribution of livestock manures is the main cause of P surplus, but data from the Survey of Fertilizer Practice also indicates that this could be reduced from current levels if farmers take full account of the P fertilizer value of livestock manures (Table 1). The main risk of P surplus on cereal farms is therefore with those in ley/arable farming where livestock manures are recycled, particularly those with pig and poultry enterprises which generate far more manure than can be sensibly recycled to land without causing potentially acute environmental problems in the future.

3.1.2 Leaching

Leaching can also be viewed as a process of DP transfer not only to groundwater, but also encompasses the loss of DP in surface run-off, or through tile drains. Although conventionally regarded as negligible, there is increasing evidence that environmentally significant P leaching losses can occur in land run-off, especially on over-fertilized soils (Heckrath *et al,* 1995; Smith *et al.,* 1998). Conceptually, there is a strong link between the amount of readily-exchangeable P in the soil and the amount of DP in the soil solution. As the readily-exchangeable soil P content increases, the amount of P in solution in equilibrium increases and the risk of transfer during storm run-off is consequently greater, but depending on the

degree (depth and time) of interaction between the incoming rain and the soil. In practice, the relationship between loss of DP and the soil P content has not been adequately quantified for different UK soils and the specific processes are not well understood.
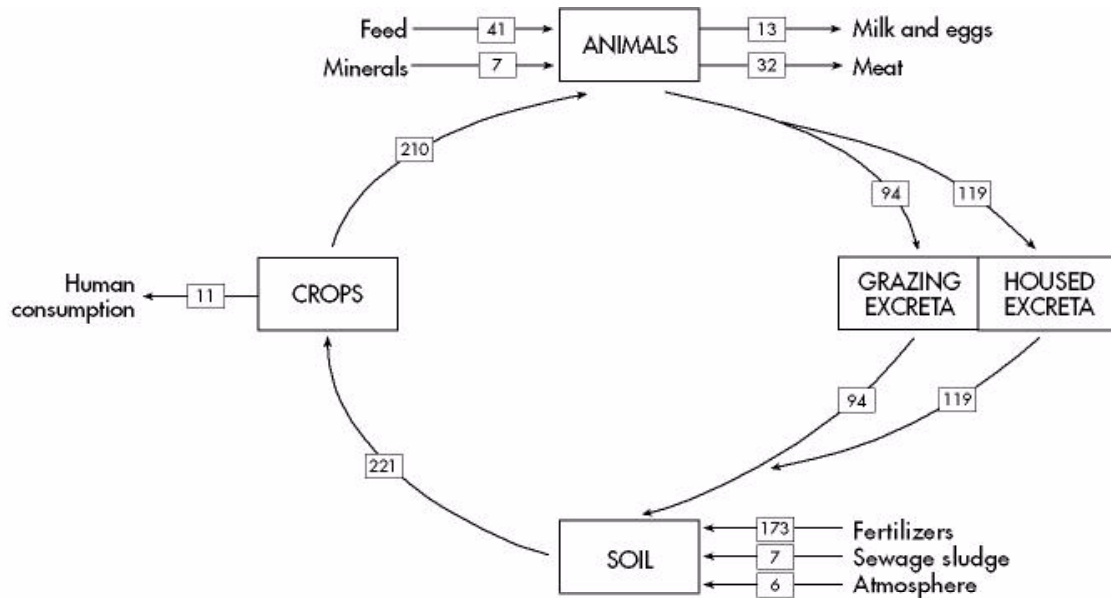
Figure 6. *A phoshorus balance sheet for UK agriculture.*

Work at Rothamsted has suggested there is a critical soil test P level above which the loss of DP in drainflow maybe greatly accelerated; for the soils on their Broadbalk plots, this critical level was c. 60 mg/kg. However, it is not clear whether the standard soil test (method or sampling depth) used on farms is adequate to predict DP loss in different run-off pathways or whether other environmental soil tests may be more sensitive. What is clear is that continued P inputs above requirements will eventually lead to increased P leaching losses which are hard to control; soil P levels change only slowly and soils will continue to leach long after P inputs in fertilizers and manures have ceased. Accurate nutrient budgeting is therefore required now to avoid sustained eutrophication problems in the future (Withers and Jarvis, 1998).

3.1.3 Incidental losses

When fertilizers and manures are applied to the surface of the soil, there is a risk of loss in storm run-off, especially if applied to soils already at field capacity, to frozen soils or to cracked or recently underdrained soils. However, even under normal soil conditions, P concentrations in run-off generally increase after fertilizer or manure application; for a number of recent examples from the MAFF R&D programme see Withers (1996). Although the amounts of P lost are generally very small (<5%) in relation to the total P amounts applied, the concentrations are well above those required for eutrophication to occur (Withers and Sharpley, 1995). In recent field experiments, a triennial application of triplesuperphosphate to a growing cereal crop in spring increased the P loss in surface run-off threefold compared to a control receiving no P fertilizer, and increased the dissolved inorganic P concentration in the run-off from 0.14 to 6.5 mg/l (Withers, 1998). Minimum losses occurred when P fertilizer was incorporated into the soil rather than surface-applied. Recent experiments with surface applications of manure to the soil surface have indicated that the dry solids loading had the greatest influence on P loss (Smith *et al.,* 1998), and confirmed the need for farmers to apply manure at rates recommended by the Code of Good Agricultural Practice for the Protection of Water (MAFF, 1991). The Code has been revised with recommended upper limits for P accumulation in soils (MAFF, 1998).

These considerations point the need for information on alternative P fertilizer strategies; in particular, a) effects of withholding P on soils which are already too high in extractable P b) effects of reducing P inputs rather than omitting altogether and improving the efficiency of P use. For example, through the use of seed dressings, placement techniques and/or foliar sprays. The adequacy of these techniques for maintaining PK supply needs investigation.

3.2 Cadmium accumulation in soils

Phosphate rock, and the fertilizers manufactured from it, are known to contain metal impurities which can accumulate in the environment and be either phytotoxic (Zn, Cu, Ni), or hazardous to human health (Cd, Pb, U). Of particular concern is cadmium (Cd) because background concentrations in unfertilized soils are usually low (0.2 mg/kg, Rothbaum *et al.,* 1986) and regular addition of P fertilizers can lead to a build-up of Cd in the soil, increased uptake by agricultural crops and/or accumulation in animal tissues (Williams and David,

1973; Ryan *et al.,* 1982; Bramley, 1990). Long-term exposure to even low concentrations of Cd are considered deleterious to human health and, currently, there are proposals to reduce the statutory limit for the content of Cd in foods from 1 mg/kg to either 0.1 or 0.2 mg/kg. In a national HGCA survey of British wheat grain, 4% of samples contained > 0.12 mg Cd /kg in 1982 and 1983, whilst only 2% exceeded this limit in 1993 (Chaudri *et al.,* 1995). Although these data indicate that the majority of British wheat grain is safe to eat, it is important to identify the soil properties and agronomic conditions under which grain Cd levels are, or may become, elevated.

The impact of Cd inputs in P fertilizers in the UK on Cd uptake by cereals and the proportion that is translocated to the grain has not been widely investigated; the limited available data indicates little or no effect. Johnston and Jones (1995) found little increase in the grain Cd of grain of wheat and barley crops grown with P fertilizer applications between 1877 and 1984. Mortvedt *et al.* (1981) observed no increase in the Cd content of wheat grain after 50 years of P fertilizer application at soil pH 5.8 and above. Richards *et al.* (1998) also report no evidence of Cd enrichment of either soil or crop after 29 years of superphosphate application (equivalent to 96 g Cd/ha at the highest application rate), although background levels on unfertilized plots were already high at the start of the experiment (1.2 mg/kg). Impacts will clearly depend on the background soil Cd concentration, the inputs of Cd both from the atmosphere, and in P fertilizers, and the soil factors affecting the availability of added P for uptake by crops. Some soils such as those developed over shale, will contain relatively high Cd concentrations. A survey of nearly 700 agricultural soils in England and Wales showed a mean Cd concentration of 0.6 mg/kg but with 46% of samples containing over 1 mg/kg (Archer and Hodgson, 1987). Data from the National Soils Inventory suggests soil total Cd concentrations vary from <0.2 - 40.9 mg/kg with a median value of 0.7 mg/kg; 25% of samples containing over 1 mg/kg (McGrath and Loveland, 1992). Availability of soil Cd is reduced at high pH and low organic matter (Johnston and Jones, 1995).

In long-term studies in the USA, Mortvedt (1987) suggested negligible effects on crops if the Cd content of the fertilizer was < 10 mg/kg. Syers *et al.* (1986) report Cd concentrations in different types of phosphate rock ranging from 2-100 mg/kg of material, but this type of fertilizer is little used in the UK now and most P fertilizer is imported as soluble derivatives (phosphoric acid and ammonium phosphates). Recent surveys of commercial P fertilizer products indicate Cd levels ranging from 0.1-42 mg/kg of product (0.3-185 mg/kg P_2O_5, with a median value of 30 mg/kg P_2O_5, (Table 9).

Table 9. *Trace contaminants in phosphatic fertilizers used in the UK (from Marks, 1995).*

Element	Amount (mg/kg P_2O_5)			
	Range	Median	Mean	SD
Arsenic (As)	1.1-415	22.0	41.6	61.1
Cadmium (Cd)	0.3-185	30.6	39.6	37.4
Chromium (Cr)	4.7-12740	319.0	467.0	1276.0
Copper (Cu)	16.7-4175	93.6	233.0	588.8
Fluorine (F)	1197-146500	37647	45631	33642
Lead (Pb)	1.7-340	10.5	24.8	43.2
Mercury (Hg)	0.02-4.0	0.10	0.21	0.43
Molybdenum (Mo)	0.4-129.4	21.8	33.4	34.2
Nickel (Ni)	0.8-413.3	63.1	77.1	60.6
Selenium (Se)	0.02-42.2	5.0	9.0	10.7
Uranium (U)	10.0-655	158.2	174.6	119.3
Zinc (Zn)	7.2-10400	654.0	944.0	1408.0

It is currently estimated that P fertilizers contribute about one third of the total Cd input to agricultural land each year, equivalent to 1.6 g/ha/year. Atmospheric inputs have been measured at 1.8 g/ha/year (range 0.9-3.6 g/ha, Alloway, 1998), with very small inputs nationally from sewage sludge and livestock manures. Locally, the latter may be significant. With crop offtake estimated at no more than 1.5 g/ha for cereal grain plus straw (for example, see Richards *et al.,* 1998), there is an overall net accumulation of Cd in agricultural soils. Where straw is not removed, grain Cd offtakes are low (0.2 - 0.3 g/ha). Highest accumulation rates can be expected where sewage sludge, industrial by-products and to a lesser extent animal manures are applied on a regular basis (Alloway, 1998). The time period over which soil Cd concentrations can be allowed to increase before significant increases in crop uptake occur is not known, but will vary on different soils depending on soil pH, clay and organic matter content.

4. PRECISION FARMING

Developments in field mapping technologies have focused attention on the within-field variability in crop yields and soil nutrient status. There is potential, through variable rate fertilizer application equipment, to match P and K inputs according to the spatial variability in soil PK levels in different parts of the field, provided these can be mapped accurately. As pointed out by Froment *et al.* (1997), treating the field as a whole may lead to increasing divergence between areas which may be under-fertilized, causing financial loss in reduced yields, and those which are over-fertilized, allowing financial gain in omitting PK fertilizer but also leading to increased risk of P leaching. There is also commercial interest in precisely matching PK inputs to crop offtake using standard offtake figures and within-field yield data which are easily obtained.

Variation in extractable P and K levels within fields can be large over very short distances. Becket and Webster (1971) concluded that the variation in nutrients mapped over 1 ha could also be found within 1 m^2, and it is this fine scale variation which hinders the accurate identification of spatial trends for precision farming (Sylvester-Bradley *et al.,* 1997). In a study of 78 arable fields in England, the average range in soil P and K levels in samples taken on a 60-100 m^2 grid was 38 and 213 mg/l, respectively. In many fields, the range in PK values was twice the mean value for the field (Table 10); the greater the history of fertilization, the greater the variation in concentrations across the fields. The percentage of sample results within the mean Index of the whole field was 53% for soil P and 69% for soil K.

Table 10. *Comparison of the mean soil PK concentrations (mg/l) for 6 fields sampled on a grid basis or as a whole field (from Froment et al., 1995).*

Field	Phosphorus		Potassium	
	Whole field	Grid (Range)	Whole field	Grid (Range)
1	32	30 (13-101)	73	101 (50-224)
2	13	17 (13-22)	43	68 (51-98)
3	19	19 (10-35)	99	92 (56-157)
4	29	29 (19-42)	106	118 (82-255)
5	49	49 (26-83)	239	190 (93-357)
6	27	38 (20-58)	187	226 (131-358)

As current fertilizer recommendations are based on the Index system, this data indicates that 47% and 31% of a field might be incorrectly fertilized with P and K, respectively. Interestingly the mean values of P and K from the grid sampling were generally very similar to the mean value for the field sampled conventionally (Table 10). Hence the value of more intensive sampling lies in being able to identify the areas where soil PK levels are sufficiently low to inhibit yield or sufficiently high to save on fertilizer or cause pollution.

There is now growing concensus that grid sampling at an intensity well below $100m^2$ is needed to accurately identify true patterns in soil PK variation, yet this is not economically worthwhile (Webster and Oliver, 1992; Sylvester-Bradley *et al.,* 1997; Froment, 1998; Oliver and Frogbrook, 1998). Schepers *et al.* (1998) found that sampling at different intensities produced different patterns in soil P variation across a field in the USA causing problems in interpretation with respect to PK fertilizer policies; the different grid sampling intensities used did however pick up a hotspot in soil P related to a buried village. Similar evidence for P and K is presented by Oliver and Frogbrook (1998). Clearly, the methodology of soil nutrient mapping still requires development, but it appears that it would be far more appropiate to carry out intelligent zoning of the fields based upon existing knowledge (Sylvester-Bradley *et al.,* 1997), and/or use existing knowledge to help define the intensity of mapping required to allow sampling strategies to be modified so that fields can be more adequately represented by a bulk sample (Oliver and Frogbrook, 1998).

5. FUTURE PERSPECTIVES AND OPPORTUNITIES FOR RESEARCH AND DEVELOPMENT

5.1 Cost-effective fertilizer use

The profitability of cereal production in the UK has declined considerably as grain prices have decreased to levels associated with world markets. Further economic pressures on cereal production may follow as concern grows over the impact of agriculture on the environment and food safety. A tax on P fertilizers, the introduction of cross-compliance measures as part of commodity reforms under Agenda 2000 and the imposition of fines on excessive nutrient imbalance are all examples of economic instruments which are being used or being considered within EU countries as part of a drive towards more environmentally sustainable agriculture (DETR, 1997; Archer and Marks, 1997). For example, in Sweden, there ia a tax on P fertilizers depending on the level of Cd they contain, and in The Netherlands fines are imposed on farmers exceeding certain P surplus thresholds. The level of tax required to effectively reduce fertilizer consumption is not clear, and it is generally recognised that their uniform adoption would unfairly penalise farmers on poorer soils and farmers who already farm efficiently at the expense of those farmers who over-fertilizer with P. However, there also seems little doubt that farmers will increasingly need to identify more precisely the conditions under which fertilizer inputs are economically justified than is possible under current recommendations.

There are three ways in which farmers could make more cost-effective use of PK fertilizers. Firstly, through improved budgeting of the PK fertilizer value of organic manures applied over the rotation. There is much evidence to show that farmers take little account of the PK contained in manures, yet this a valuable nutrient resource which can contribute to residual soil PK fertility. Secondly through better quantification of critical levels of soil test PK, the fertilizer inputs needed to sustain them and the variability in the amounts of P and K removed in harvested produce. A better understanding of the ability of different soils to retain and release P and K and of crop and seasonal factors influencing crop uptake would provide a scientific base on which farmers can take informed decisions on minimum fertilizer inputs for sound economic production. For example, soil mineralogy, texture, organic matter content, depth and stone content are all inherent soil properties which influence soil PK supply. Thirdly, the development of techniques which might improve the efficiency of P use,

allowing lower amounts to be used without impairing profitability. Such methodologies might include seed dressings, placement techniques and/or foliar applications.

5.2 Eutrophication control

Soil parent materials and their physical and chemical properties also have a large influence on the transport of P in land run-off causing eutrophication, not only in terms of their ability to retain and release dissolved P during storm-flow, but also in their susceptibility to particulate P loss in soil erosion. Guidelines on upper limits of P accumulation in soils have already been issued as part of the revised Codes of Good Agricultural Practice for the Protection of Water (MAFF, 1998). However, there is no scientific justification for treating all P inputs the same as regards potential for P loss to water, neither is it scientifically justified to take all soils as having the same P pollution risk above a certain threshold (Index 3 in the new Code); a single Index may not be approiate for all soils, as is the case with current fertilizer recommendations. In order to ensure that any future restrictions on P inputs do not unduly affect farm incomes, there is a need to identify the relationship between critical P concentrations for agronomic production and those which cause accelerated loss of P in land run-off on different soil types. Land management is also a key area for control over diffuse P transfer to water. Increasingly farmers will need to identify those areas on the farm which contribute the most run-off and target better management of P inputs in order to control accelerated or unacceptable P loss during storm events. As with fertilizer inputs, there is potential to classify soils in terms of their suitability to receive PK inputs in relation to the risk of accelerated P loss to water under existing management practices.

5.3 Present and future R&D opportunities

This review indicates that farmers require better and more up-to-date information on the economic and environmental consequences of poor PK fertilizer management, how they can make more effective use of PK inputs whilst maintaining economic output and how they can apply them in a manner which will avoid environmental problems associated with eutrophication. Soil type is a principal unifying factor which governs both the precise need for PK fertilizer and the potential for P loss in agricultural run-off to watercourses within any given farming system yet this is not taken into account in any structured way in current advice (Fig. 7).
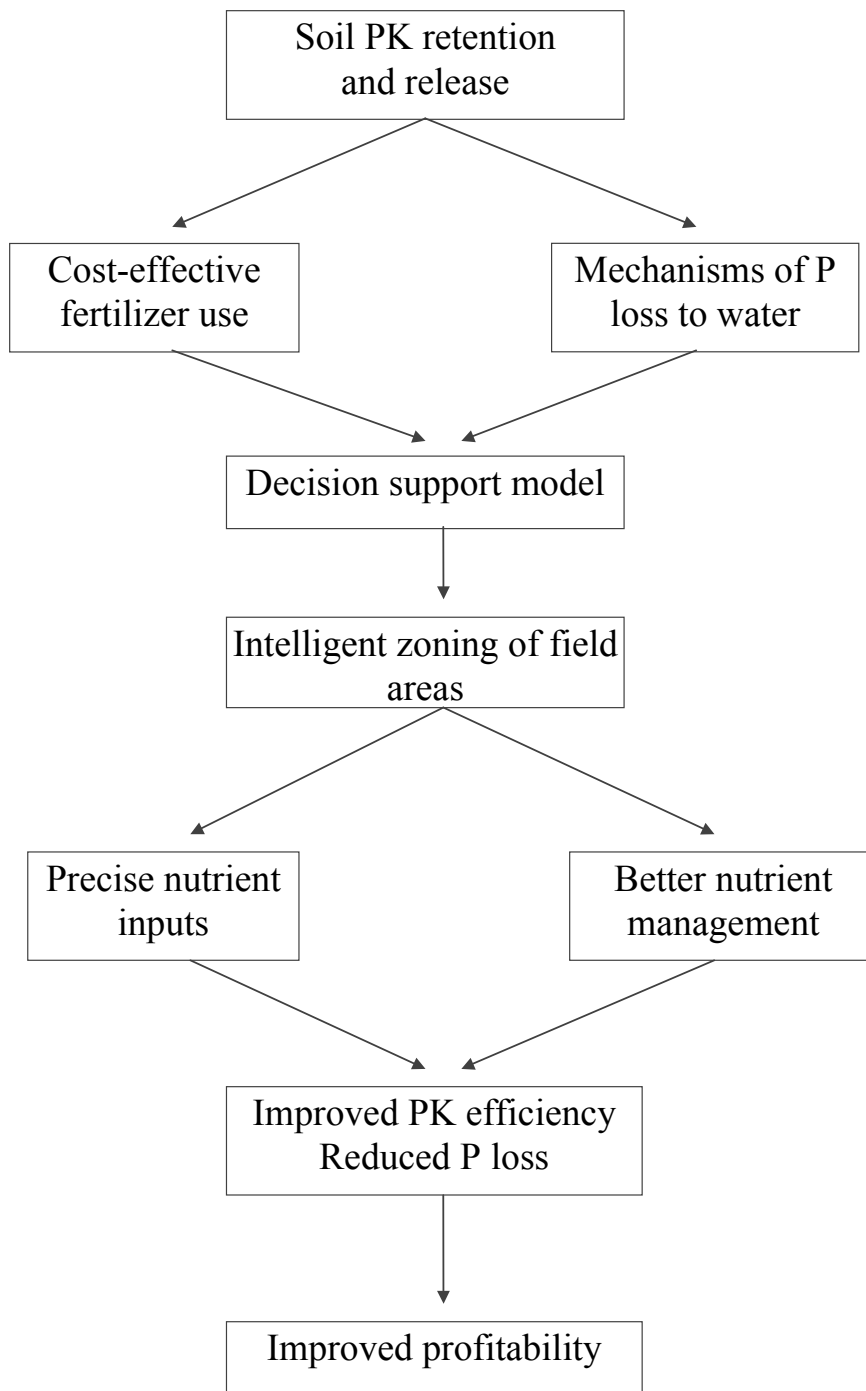
Figure 7. *Conceptual diagram illustrating the usefulness of specific soil type information.*

For example, there is potential to classify soils according to their PK release characteristics and identify which soils might be over or under-fertilized under the current

recommendation system. This information would benefit farmers wishing to adopt precision farming technology both in terms of identifying field zones for differential PK application and explaining the variability in soil nutrient levels observed in such zones. Farmers switching to organic production also require information on the short-term and longer-term supplying power of soils (ie buffering capacity) in the absence of the readily-available P sources which maintain conventional systems. The physical and chemical properties, and management of soil, are more likely to be critical in organic systems. The development of the concept of management of PK inputs within different zones within fields is also applicable to the management of nutrients and land to avoid eutrophication risk.

Key issues which require addressing are:

1. A better understanding of the influence of soil parent materials and their chemical and physical properties affecting PK retention and release for crop uptake and/or P loss to watercourses.
2. Identification of critical areas or zones within fields, or within the farm, for improved P input and land management.
3. Identification of techniques for improving the efficiency with which PK inputs are utilized.
4. Development of farm management tools (decision support systems) which enable accurate calculation of nutrient budgets and can predict the consequences of short-term and long-term fertilizer strategies on farm profitability.

Currently there is a gap in R&D funding which examines how farmers can use P and K fertilizers more discriminately both from an economic and environmental viewpoint. There are therefore opportunities for HGCA-funded R&D to provide improved guidelines on identifying minimum PK fertilizer inputs for sound economic production in collaboration with government-funded R&D aimed at identifying agricultural practices which accelerate the transfer of nutrients (P) and methods to reduce diffuse P loss. Currently there is no government-funded research aimed at improving the the efficiency of fertilizer PK usage on arable crops through improved decision making, other than the current drive to improve awareness of the PK fertilizer value of organic manures. Potential funding bodies other than HGCA include MAFF, DETR, Fertilizer Indistry, Water Authorities, PDA, MGA.

MAFF Rural and Marine Environment Division (RMED) are funding a research programme (NT10 - Phosphorus loss from agriculture) 'to better define the agricultural contribution to eutrophication in order that effective control options can be identified'. The programme includes plot, field and catchment experiments investigating the amount, form, timing, processes and pathways of P loss from agricultural land. Information from this programme will help identify the risk of P loss in land run-off under different regions, agricultural systems and practices. Similarly the Department of the Environment, Transport and Regions (DETR; Water Quality Division) are planning a research programme on diffuse pollution but this is still at the review stage. MAFF are currently funding R&D projects to utilise organic manures more effectively to reduce nutrient losses, and to transfer knowledge on PK cycling in soil in conventional farming systems to assist organic producers.

Additionally an EU COST Action aimed at 'Quantifying the Agricultural Contribution to Eutrophication' has a Working Group devoted to the feasability of unifying decision support systems for P inputs in different farming systems and the quantification of minimum P inputs for economic and environmental sustainability. The relationship between soil test P required for profitable production and that causing unnecessary P loss is a main component. The 'COST Action is scheduled for 5 years starting in 1997. However COST does not fund R&D but only provides money for travelling expenses for scientific experts to attend working group meetings. A UK research programme would help to underpin UK involvement in this group.

Specific areas for future funding include:

1. Classification of UK soil types in terms of their ability to maintain adequate P and K in solution for economic production under different fertilizer policies, including identification of those soils where current recommendations lead to over or under-fertilization, and the opportunities for omission or reduction in PK fertilizer use without affecting yields.

2. Further development of PK fertilization models to include better characterization of soil, crop and seasonal factors affecting PK uptake by cereal crops and better quantification of the variability in PK offtake at harvest.
3. Methodologies for identifying upper limits of soil P accumulation from different sources and their relationship to soil test P for optimum crop production.

4. Development of a decision support package for intelligent zoning of land areas for improved input and land management based on economic and environmental goals.

5. Development of novel management practices to maximise efficiency of P use.

6. Technology transfer programme centred around the influence of soil type and soil properties on P input management and the promotion of the decision support package.

The benefits of R&D in these areas are:

1. Increased awareness of the potential impact of agricultural P management on water quality.

2. Improved precision in optimising P and K inputs for economic production.

3. Avoidance of eutrophication problems through identification of high P loss risk areas on the farm for improved P management.

4. Provision of information on the suitability of land areas to receive recycled PK inputs (livestock manures, sewage sludge and industrial wastes) and/or transition to organic production.

5. Identification of best management practices to maximise efficiency of P use and avoid accelerated P transfer to water using local farm information.

6. Provide information to defend the agricultural industry against future regulation on agricultural P management.

Fundamentally, current fertilizer recommendations require further development to meet the economic and environmental demands of modern farming.

6. CONCLUSIONS AND RECOMMENDATIONS

1. Cereal prices have fallen dramatically in recent years and are now well below £100/tonne. If such prices continue, there is a strong argument to reduce or omit fertilizer PK inputs where they are not economically justified. There are two main areas where reductions may be justified on present knowledge:

a) Farmers take little account of the PK nutrients contained in organic manures, yet these are known to become available over a rotation. It is estimated that the PK in manures applied to arable land is worth about £65 million and there is clearly scope to reduce dependency on PK fertilizer in cereal crops receiving manure.

b) There is no economic justification for maintaining soil extractable P and K levels above critical levels for production, and, once identified, fertilizer programmes can be tailored to maintain a critical level. However, the effects on yields of modern cereal crops of reducing, or withholding, fresh PK inputs on soils with high test PK, and the time period over which such reductions can be continued, have not been adequately quantified.

It is recommended that cereal farmers are better informed about the fertilizer value of organic manures in arable and ley-arable farming systems and the potential savings associated with short-term reductions in fertilizer inputs of P and K on PK rich soils. More experimental data illustrating the PK fertilizer value of different types of manure for cereal production are also required.

Further work is required to assess whether lower critical PK values are now adequate for modern production systems and the short and long-term consequences of reducing or withholding PK fertilizer on soils of high PK status, both on cereal yields and soil PK levels. Novel techniques to reduce P inputs whilst maintaining adequate soil P supply on soils of high P loss risk also require investigation.

2. Soil analysis provides a useful basis for PK fertilizer recommendation systems for cereals and should continue to do so. However, there is increasing evidence, largely from long-term

field experiments but also from farmer experience, that not all soils are similar in respect of their optimum soil test PK status for production, or in the way soil PK levels change under different fertilizer policies. Currently there is too much unreliability in terms of critical concentrations for winter cereals on different soil types, and too much uncertainty over the fate of PK fertilizer on different soil types, to formulate P reduction strategies and better cost-effective targeting of PK inputs. An improved understanding of the effect of soil type would help to:

a) identify more precisely critical soil test PK levels for optimum crop yields and therefore better target crop requirements.
b) quantify more precisely the amounts of PK fertilizer required to raise or reduce soil PK levels to their critical status allowing more cost-effective fertilizer use.
c) identify where further soil tests may be helpful in identifying the potential availability of fixed PK reserves, for example in organic farming systems.

Further work is required to develop the current fertilizer recommendation systems through characterisation of different soil types and their ability to release and fix P and K in order to provide a scientific basis for cost-effective use of PK fertilizers. This information will be of particular benefit to those farmers interested in both precision and organic agriculture, and will help avoid eutrophication problems associated with mismanagement of P inputs. This is probably best achieved by classifying soil types in terms of their PK retention and release properties (eg buffering capacity), and the development of additional soil testing methods and field experimentation to help define these properties locally.

3. Plant analysis has a useful role in confirming adequacy or over-supply of P and K to cereal crops now that deficiency thresholds have been more precisely identified for different growth stages. Recent HGCA-funded work has shown that young fully-expanded leaves should be sampled between GS31 and GS39 and their P and K content determined on a dry matter basis. Crop offtake in harvested produce is an important component of current fertilizer advice but variation in P and K concentrations in grain and/or straw may confound accurate fertilizer planning.

Plant sampling is currently being commercially exploited and no further work on plant analysis on cereals is required. However, further work is required to more develop PK fertilization models for use in cereal-based rotations taking account of soil, crop and seasonal factor affecting PK uptake during the growing season and P and K offtake at harvest.

4. In the past, generous application of P fertilizers has been actively encouraged in order to optimise crop production. However, attention is now focusing on the link between the intensity of agricultural production and eutrophication problems associated with the transfer of P in land run-off to water. There is no doubt that the agricultural industry will come under increasing pressure to improve the standard of P nutrient management on farms and minimise the risk of P transport in run-off and erosion.

It is recommended that cereal farmers are better informed of the environmental issues relating to P fertilizer use and the general ways in which P losses to water can be avoided through nutrient budgeting and better land management.

Information is needed on the soil P concentrations above which accelerated P loss to water may occur on different soil types and under different farming systems and how these relate to those required for optimum crop production.

5. There is increasing concensus that the intensity of soil sampling required to produce accurate maps of residual PK fertility on which to base the application of variable rates of fertilizer is too fine to be economically viable. However, it is likely to be profitable to identify broad zones within fields for variable fertilizer application based on a knowledge of soil type, fertilization and management history. Identification of variable management areas is also an important principle with regard to avoidance of P loss in storm run-off from agricultural land.

It is recommended that the concept of management of field or farm zones is developed to enable not only improved precision of PK fertilizer inputs for economic production, but also better nutrient and land management to avoid pollution of watercourses with agricultural P.

6. As economic and environmental constraints on cereal production increase, there is a need to develop decision support systems which will help cereal farmers identify the best fertilizer policy to adopt for their particular soil types, economic conditions and localities in respect of risk of environmental pollution. These factors are best resolved through balance sheet modelling of PK transfers on the farm, as demonstrated by the OUTLOOK model in New Zealand. This would represent a useful development of the present system.

Following a better understanding of the influence of soil type on the availability of P and K to cereal crops, and the risk of P transfer in land run-off to watercourses, it is recommended that this knowledge is incorporated into a decision support system for cereal growers incorporating the concept of farm, or field, zone management.

7. Cadmium concentrations in cereal grain are of concern with respect to human health and new concentration limits are being considered within the EU. Phosphorus fertilizers contribute about one third of the input of Cadmium (Cd) to agricultural soils, which exceeds the removal of Cd in the harvested produce. As soils accumulate Cd, there is a long-term risk of increased uptake by crops, with the amounts depending on soil type and pH. The potential for Cd transfer from soils to water, and their impact, is unclear. Inputs of other potentially hazardous contaminants in P fertilizers are less of a concern due to high background levels in soils.

Further information is required to better quantify the relationship between soil Cd content, Cd in solution and plant uptake, and potential loss of Cd on different soils.

7. ACKNOWLEDGEMENTS

8. REFERENCES

Alloway, B.J. (1998). The vulnerability of soils to pollution by heavy metals. *Final Project Report OC9325*. Minsitry of Agriculture, Fisheries and Food.

Archer, F.C. and Hodgson, I.H. (1987). Total and extractable trace element contents of soils in England and Wales. *Journal of Soil Science* **38**, 421-431.

Archer, J. R. and Marks, M. J. (1997). Control of nutrient losses to water from agriculture in Europe. *Proceedings of the Fertilizer Society No. 405*, York.

Arnold, P.W. and Shepherd, M.A. (1990). Phosphorus and potassium requirements of cereals. *HGCA Research Review No. 16.* Home-Grown Cereals Authority, London.

Barraclough, P.B. (1990). Modelling K uptake by plants from soil. In: *Development of K-Fertilizer Recommendations.* International Potash Institute, Basel, pp. 217-230.

Barraclough, P.B., Bollons, H.M., Chambers, B.J., Hatley, D. and Moss, D.P. (1997). Plant testing to determine the P and K status of wheat. *HGCA Project Report No. 137*, Home-Grown Cereals Authority, London.

Beckett, P.H.T. and Webster, R. (1971). Soil variability - a review. *Soils and Fertilizers* **34**, 1-15.

Beringer, H. (1985). Adequacy of soil testing for predicting fertilizer requirements. *Plant and Soil* **83**, 21-37.

Bertilsson, G. and Forsberg, C. (1997). Sustainable phosphorus management in agriculture. In: H. Tunney, Carton, O.T., Brookes, P.C. and Johnston, A.E. (Eds), *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, pp 273282.

Bhogal, A., Young, S.D., Ralph, R., Sylvester-Bradley, R. and Craigon, J. (1996). Modelling the residual effects of phosphate fertilizer in the Ropsley (UK) field trial 1978-1990. *Fertilizer Research* **44**, 27-36.

Bollons, H.M. and Barraclough, P.B. (1997). Plant testing for assessing the adequacy of P supply in winter wheat crops. *Aspects of Applied Biology* **50**, 173-180.

Boyd, D.A. (1965). The relationship between crop response and the determination of soil phosphorus by chemical methods. II. In: *Soil Phosphorus*, MAFF Technical Bulletin No. 13, Ministry of Agriculture, Fisheries and Food Publications, HMSO, London, pp. 94-102.

Boyd, D.A. and Frater, A. (1967). Analytical methods for potassium and their correlations with crop response. In: *Soil Potassium and Magnesium*, MAFF Technical Bulletin No. 14, Ministry of Agriculture, Fisheries and Food Publications, HMSO, London, pp. 55-62.

Bramley, R.G.V. (1990). Cadmium in New Zealand agriculture. *New Zealand Journal of Agricultural Research* **33**, 505-519.

Burnhill, P., Chalmers, A.G., and Owen, L. (1997). *Fertilizer Use on Farm Crops for Crop Year 1996.* British Survey of Fertilizer Practice, The Stationary Office, Edingburgh.

Chalmers, A.G., Withers, P.J.A. and Chambers, B.J. (1997). Optimising P and K inputs to cereals by soil analysis. *Aspects of Applied Biology* **50**, 155-164.

Chambers, B.J. (1997). Guidelines to reduce the risk of water erosion on susceptible soils used for arable cropping. *MAFF Final Report for Project SP0401*. Ministry of Agriculture, Fisheries and Food.

Chaudri, A.M., Zhao, F.J., McGrath S.P. and Crosland, A.R. (1995). The cadmium content of British wheat grain. *Journal of Environmental Quality* **24**, 850-855.

Chaudri, A.M., McGrath, S.P., Crosland, A.R. and Zhao, F. (1993). Mineral status of British wheat. *Aspects of Applied Biology* **36**, 347-354.

Church, B.M. and Skinner, R.J. (1986). The pH and nutrient status of agricultural soils in England and Wales 1969-83. *Journal of Agricultural Science, Cambridge* **107**, 21-28.

Clare, R.W. and Caldwell, T.H. (1972). Annual versus a large single application of phosphate for a 5-year cereall rotation. *Experimental Husbandry* **22**, 69-77.

Costigan P.A. (1987). A model to describe the pattern of availability of broadcast phosphorus fertilizer during the growth of a crop. *Plant and Soil* **101**, 281-285.

Cox, F.R. (1994). Predicting increases in extractable phosphorus from fertilising soils of varying clay content. *Soil Science Society of America Journal* **58**, 1249-1253.

Dawson, C.J. (1996). Implications of precision farming for fertilizer application policies. *Proceedings of the Fertilizer Society, No. 391*. The Fertilizer Society, York.

DETR (1997). *Economic Instruments for Water Pollution, Consultation Document*. Department of the Environment, Transport and Regions, London.

Eagle, D.J. (1974). Long term phosphate manuring experiment on a silt soil. *Experimental Husbandry* **26**, 28-36.

Edwards, A.C. (1993). Factors influencing plant availability of P from acid soils. *Phosphorus in Agriculture* **3**, 1-12.

Edwards, A.C. and Withers, P.J.A. (1998). Soil phosphorus management and water quality: a UK perspective. *Soil Use and Management* **14**, 124-130 (Supplement).

Edwards, A.C., Withers, P.J.A. and Sims, T.J. (1997). Are current fertilizer recommendation systems for phosphorus adequate? *Proceedings of the Fertilizer Society No. 404*. The Fertilizer Society, York.

Evans, R. (1988). *Water Erosion in England and Wales 1982-1984*. Soil Survey and Land Research Centre, Silsoe, Bedfordshire.

FMA (1996). *Fertilizer Review 1996*. Fertilizer Manufacturers Association, Peterborough.

Foy, R.H. and Withers, P.J.A. (1995). The contribution to agricultural phosphorus to eutrophication. *Proceedings of the Fertilizer Society No. 365*. The Fertilizer Society, York.

Froment, M.A. (1998). Analysis and interpretation of yield mapping, soil and crop parameters as a component of precision farming. *MAFF Final Report for Project AS0107*, Ministry of Agriculture, Fisheries and Food.

Froment, M.A., Dampney, P.M.R. and Goodlass, G. (1997). Managing P and K applications to cereals within fields based upon variability in soil nutrient status and crop nutrient content. *Aspects of Applied Biology* **50**, 165-172.

Froment, M.A., Dampney, P.M.R., Goodlass, G., Dawson, C. and Clarke, J. (1995). A review of spatial variation in nutrients in soil. *MAFF Final Report for Project CE0139*, Ministry of Agriculture, Fisheries and Food.

Frossard, E., Brossard, M. Hedley, M.J. and Metherell, A. (1995). Reactions controlling the cycling of P in soils. In: *Phosphorus in the Global Environment, SCOPE 54*. H. Tiessen (ed.), John Wiley & Sons, Chichester, pp. 107-138.

Gibson, C.E., Wu, Y., Smith, S.J. and Wolfe-Murphy, S.A. (1995). Synoptic limnology of a diverse geological region: catchment and water chemistry. *Hydrobiologia* **306**, 213-227.

Goulding, K.W.T. and Loveland, P.J. (1986). The classification and mapping of potassium reserves in soils of England and Wales. *Journal of Soil Science* **37**, 137-154.

Greenwood, D.J. and Karpinets, T.V. (1997). Dynamic model for the effects of K fertilizer on crop growth, K-uptake and soil K in arable cropping. 1. Description of the model. *Soil Use and Management* **13**, 178-183.

Gregory, P.J., Crawford, D.V. and McGowan, M. (1979). Nutrient relations of winter wheat. 1. Accumulation and distribution of Na, K, Ca, Mg, P, S and N. *Journal of Agricultural Science, Cambridge* **93**, 485-494.

Hatley, D.L.J., Johnson, P.A. and Ellis, S. (1997). The effects of phosphate additions on soil phosphate reserves in a long term experiment at Ropsley, UK. In: *Proceedings of the 11th World Fertilizer Congress* 7-13 September, Ghent, Belgium.

Hodgkinson, R.A. and Withers, P.J.A. (1996). Non-point source phosphorus loss from small agricultural catchments. In: *Diffuse Pollution and Agriculture*, A.M. Petchey, B.J. D'Arcy and C.A. Frost (eds), Scottish Agricultural College, Aberdeen, pp. 120-126.

Huggins, R. (1999). The Landcare project. In: Diffuse Pollution II. T. Petchey *et al.* (ed.), The Scottish Agricultural College, Aberdeen, UK (In press).

Johnes, P., B. Moss, and G. Phillips. (1996). The determination of total nitrogen and total phosphorus concentrations in freshwaters from land use, stock headage and population data: testing of a model for use in conservation and water quality management. *Freshwater Biology* **36**, 451-473.

Johnston, A.E. (1997). Fertilizers and agriculture: fifty years of development and challenges. *Proceedings of the Fertilizer Society No. 396.* The Fertilizer Society, York, pp. 19-48.

Johnston, A.E., Barraclough, P.B., Poulton, P.R. and Dawson, C.J. (1998). Assessment of some spatially variable soil factors limiting crop yields. *Proceedings of the Fertilizer Society No. 419.* The Fertilizer Society, York.

Johnston, A.E. and Jones, K.C. (1995). The origin and fate of cadmium in soil. *Proceedings of the Fertilizer Society No. 366.* The Fertilizer Society, York.

Johnston, A.E., Mattingly, G.E.G. and Poulton, P.R. (1976). Effect of phosphate residues on soil P values and crop yields. I. Experiments on barley, potatoes and sugar beet on sandy soils at Woburn. Rothamsted Experimental Station Report for 1975, Part 2, pp. 5-35.

Johnston, A.E. and Poulton, P.R. (1992). The role of phosphorus in crop production and soil fertility: 150 years of field experiments at Rothamsted, United Kingdom. In: *Phosphate Fertilizers and the Environment*, J.J.Schultz (ed), International Fertilizer Development Centre, Muscle Shoals, USA, pp. 153-180.

Jones, C.A., Cole, C.V., Sharpley, A.N. and Williams, J.R. (1984). A simplified soil and plant phosphorus model: I. Documentation. *Soil Science Society of America Journal* **48**, 800-805.

Leigh, R.A. and Johnston, A.E. (1983). Concentrations of potassium in the dry matter and tissue water of field grown spring barley and their relationships to grain yield. *Journal of Agricultural Science, Cambridge* **101**, 675-685.

MAFF (1985). *Phosphate and Potash for Rotations*. Bulletin 2496, Ministry of Agriculture, Fisheries and Food Publications, HMSO, London.

MAFF (1991). *Code of Good Agricultural Practice for the Protection of Water*. MAFF Publications, London.

MAFF (1994). *Fertilizer Recommendations for Agricultural and Horticultural Crops,* Reference Book 209, Ministry of Agriculture, Fisheries and Food Publications, HMSO, London.

MAFF (1998). *Code of Good Agricultural Practice for the Protection of Water, 2nd edition.* London: Her Majesty's Statinary Office.

Marks, M.J. (1995). *Survey of the Trace Contaminants in Phosphatic Fertilizers*. Report for Project CS0201/CS0202, Ministry of Agriculture, Fisheries and Food.

McGrath, S.P. and Loveland, P.J. (1992). *The Soil Geochemical Atlas of England and Wales*. Blackie, Glasgow.

MISR/SAC (1985). *Advisory Soil Analysis and Interpretation*. Bulletin 1, MaCaulay Institute for Soil Research and Scottish Agricultural College Liaison Group, 13pp.

MLURI/SAC (1987). *Scottish Soil Fertility Information System No. 1*. SAC, Aberdeen.

Mortvedt, J.J. (1987). Cadmium levels in soils and plants from some long-term soil fertility experiments in the United States of America. *Journal of Environmental Quality* **16**, 137-142.

Mortvedt, J.J., Mays, D.A. and Osborn, G. (1981). Uptake by wheat of cadmium and other heavy metal contaminanats in phosphate fertilizers. *Journal of Environmental Quality* **10**, 193-197.

NRA (1990). *Toxic Blue-Green Algae* (Water Quality Series No. 2, National Rivers Authority, Bristol, UK.

Oliver, M.A. and Frogbrook, Z.L. (1998). Sampling to estimate soil nutrients fro precision agriculture. *Proceedings of the Fertilizer Society No. 417*. The Fertilizer Society, York.

PDA (1997). *Phosphate and Potash Removal by Crops*. Potash Development Association, Carmarthen.

Reith, J.W.S., Inkson, R.H.E., Scott, N.M., Caldwell, K.S., Ross, J.A.M. and Simpson, W.E. (1987). Estimates of soil phosphorus for different soil series. *Fertilizer Research* **11**, 123-142.

Rengel, Z. (1993). Mechanistic simulation models of nutrient uptake: A review. *Plant and Soil* **152**, 161-173.

Richards, I.R., Clayton, C.J. and Reeve, A.J.K. (1998). Effects of long-term fertilizer phosphorus application on soil and crop phosphorus and cadmium contents. *Journal of Agricultural Science* (In press).

Rothbaum, H.P., Goguel, R.L., Johnston, A.E. and Mattingly, G.E.C. (1986). Cadmium accumulation in soils from long-continued applications of superphosphate. *Journal of Soil Science* **37**, 99-107.

Russell, R.D. (1971). Residual potash experiments on the Sherborne Soil Series. In: *Residual Value of Applied Nutrients*, MAFF Technical Bulletin 20, Her Majestys Stationary Office, London, pp. 265-269.

Ryan, J.A., Pahren, H.R. and Lucas, J.B. (1982). Controlling cadmium in the human food chain. A review and rationale based on health effects. *Environmental Research* **27**, 251-302.

Salter, J.L., Higgs, B. and Dawson, C.J. (1997). The impact of fertilizer strategies on the phosphorus status of arable soils in England and Wales. In: H. Tunney, Carton, O.T., Brookes, P.C. and Johnston, A.E. (Eds), *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, pp. 452-454.

Schepers, J., Varvel, G.E. and Schlemmer, M.L. (1998). Site specific considerations for managing phosphorus. In: *Practical and Innovative Measures for the Control of Agricultural Phosphorus Losses to Water*. Proceedings of an OECD Workshop 16-19 June 1998, Belfast, Northern Ireland, pp.24 (Abstract).

Shepherd, M.A. (1997). Leaching of nutrients other than nitrogen from an arable sandy soil: long-term lysimeter data. *Final Project Report NT1314*. Ministry of Agriculture, Fisheries and Food.

Skinner, R.J. and Chambers, B.J. (1996). A survey to assess the extent of soil water erosion in lowland England and Wales. *Soil Use and Management* **12**, 214-220.

Skinner, R.J., Church, B.M. and Kerhaw, C.D. (1992). Recent trends in soil pH and nutrient status in England and Wales. *Soil Use and Management* **8**, 16-20.

Smith, K.A. and Van Dijk, T.A. (1987). Utilisation of phosphorus and potassium from animal manures on grassland and forage crops. In: *Animal Manure on Grassland and Fodder Crops*, H.G. Van De Meer et al. (Eds), Matinus Nijhoff Publishers, Dordrecht, pp. 88-102.

Smith, K.A., Chalmers, A.G., Chambers, B.J. and Christie, P. (1998). Organic manure phosphorus accumulation, mobility and management. *Soil Use and Management* **14**, 154-159.

Spiers, R.B. and Frost, C.A. (1985). The increasing incidence of accelerated soil water erosion on arable land in the East of Scotland. *Research and Development in Agriculture* **2**, 161-167.

Syers, J.K. (1998). Soil and plant potassium in agriculture. *Proceedings of the Fertilizer Society No. 411*. The Fertilizer Society, York.

Syers, J.K., Mackay, A.D., Brown, M.W. and Currie, L.D. (1986). Chemical and physical characteristics of phosphate rock materials of varying reactivity. *Journal of the Science of Food and Agriculture* **37**, 1057-1064.

Sylvester-Bradley, R., Lord, E.I., Scott, R.K., Clare, R.W., Basford, W.D., Bryson, R.J., Clark, W.S., Clarke, J.H., Dampney, P.M.R., Froment, M.A., Goodlass, G., Orson, J.H., Parker, W.E., Paveley, N.D., Spink, J. and Wiltshire, J.J.J. (1997). The potential of precision farming from an agronomic perspective. *Research Review No. 37*. Home-Grown cerals Authority, London.

Thorne, G.N., Darby, R.J., Day, W., Lane, P.W., Welbank, P.J. and Widdowson, F.V. (1988). Variation between years in growth and nutrient uptake after anthesis of winter wheat on Broadbalk field at Rothamsted, 1969-84. *Journal of Agricultural Science, Cambridge* **110**, 543-559.

Tunney, H., Breeusma, H., Withers, P.J.A. and Ehlert, P.A.I. (1997). Phosphorus fertilizer strategies: present and future. In: H. Tunney, Carton, O.T., Brookes, P.C. and Johnston, A.E. (Eds), *Phosphorus Loss from Soil to Water*. CAB International, Wallingford, pp177-203.

Tytherleigh, A. (1988a). Long term phosphate experiment. *ADAS Internal Paper.*

Tytherleigh, A. (1988b). Long term potash experiment. *ADAS Internal Paper.*

Van Dijk, T.A. and Sturm, H. (1983). Fertilizer value of animal manures on the continent. *Proceedings of the Fertilizer Society No. 220,* The Fertilizer Society, London, pp45.

Webster, R. and Oliver, M.A. (1992). Sample adequately to estimate variograms of soil properties. *Journal of Soil Science* **43**, 177-192.

Williams, C.H. and David, D.J. (1973). The effect of superphosphate on the cadmium content of soils and plants. *Australian Journal of Soil Research* **11**, 43-56.

Williams, R.J.B. and Cooke, G.W. (1965). Measuring soluble phosphorus in soils, comparison of methods and interpretation of results. In: *Soil Phosphorus*, MAFF Technical Bulletin No. 13, Ministry of Agriculture, Fisheries and Food Publications, HMSO, London, pp. 84-93.

Withers, P.J.A. (1991). Removal of phosphorus and potassium from the soil in wheat and barley straw. *Journal of Agricultural Science, Cambridge* **117,** 221-224.

Withers, P.J.A. (1996). *Phosphorus Loss from Agriculture: A Review of the MAFF R&D Programme (NT10).* A Report to the Ministry of Agriculture, Fisheries and Food.
Withers, P.J.A. (1998). Phosphorus in run-off from agricultural land receiving sewage sludge. In: *Practical and Innovative Measures for the Control of Phosphorus Loss to Water,* proceedings of an International Workshop, 16-19 June, Belfast, Northern Ireland, pp. 5 (Abstract).

Withers, P.J.A. and Jarvis, S.C. (1998). Mitigation options for diffuse phosphorus loss to water. *Soil Use and Management* **14,** 186-192.

Withers, P.J.A. and Sharpley., A.N. (1995). Phosphorus Fertilizers. In: *Soil Amendments and Environmental Quality*, J.E. Rechcigl (ed), Lewis Publishers, Boca Raton, pp. 65-107.

Withers, P.J.A., Unwin, R.J., Grylls, J.P and Kane, R. (1994). Effects of withholding phosphate and potash fertilizer on grain yield of cereals and on plant-available phosphorus and potassium in calcareous soils. *European Journal of Agronomy* **3**, 1-8.

Wolf, J., de Wit, C.T., Janssen, B.H. and Lathwell, D.J. (1987). Modelling long-term crop response to fertilizer phosphorus. I. The model. *Agronomy Journal* **79**, 445-451.