HGCA

PROJECT REPORT No. 137

PLANT TESTING TO DETERMINE THE P AND K STATUS OF WHEAT

JANUARY 1997

PRICE £10.00

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by

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This is the final report of a four year project which started in September 1991. The work was funded by a grant of £259,119 from the Home-Grown Cereals Authority (Project No. 0050/1/91).

CONTENTS

1 SUMMARY

British farmers spend about £22/ha annually on P and K fertilisers for wheat crops (equivalent to nearly £40M nationally), but have limited means of assessing how well a particular fertiliser strategy is doing or of fine tuning P and K inputs to crops.

Soil testing is the established method of assessing if P and K supplies are adequate for crop needs. The problem with soil testing is that critical concentrations of extractable soil P and K for maximum grain yield depend on soil type and few farmers, if any, know the critical values for their fields. This can lead to prophylactic applications of P and K fertiliser.

Plant testing could be used to diagnose the P and K status of wheat crops, but little use is made of this at present. This is because very little information is available on critical P and K concentrations in wheat under UK conditions, and the interpretation of conventional plant test results, that is tests based on total nutrient concentration in plant dry matter, is complicated by the effects of plant development and interactions between growth factors. The most important criteria for a plant test are that it must be quick and easy to carry out and critical concentrations should be stable, i.e. unaffected by crop growth stage or by soil type, weather and management (site/season variation).

A 4-year collaborative project by IACR-Rothamsted and ADAS in the period 1992-95 investigated the use of conventional and new plant testing procedures for diagnosing the P and K status of winter wheat crops. As well as conventional dry matter testing of whole shoots, the use of the newest fully expanded leaf blade, expression of concentrations on a tissue water basis, and the use of inorganic storage pools were investigated. In all, twelve different approaches to plant testing for P and K were evaluated.

Field experiments were conducted at Rothamsted in Hertfordshire, at Ropsley in Lincolnshire and on three commercial farms in East Anglia. Winter wheat (cv. Mercia) was grown at Rothamsted and Ropsley on soils having extractable P and K levels ranging from deficient to abundant. At the East Anglian farms various wheat varieties were grown on K deficient soils to which a range of fertiliser K rates was applied.

Typical grain yield penalties as a result of soil P and K deficiency were 1-2 t/ha. Critical soil concentrations of extractable P and K for maximum yield changed little between years on the

same soil, but varied with soil type. At Rothamsted, critical topsoil P and K for 95% maximum grain yield were 10 and 80 mg/kg, respectively. At Ropsley, critical topsoil P was 16 mg/l. Topsoil K was not a reliable guide to the likelihood of a grain yield response to fresh fertiliser K on the three East Anglian farms.

Plant testing can be used to diagnose the P and K status of wheat crops. Problems associated with conventional plant testing can be reduced by specifying crop growth stage, by choosing indicator organs of a fixed physiological age, by targeting specific nutrient pools, and by expressing concentrations on a tissue water basis. The greatest variation in critical concentrations between sites and seasons was generally during tillering and at anthesis, consequently the best time to assess the P and K status of wheat is during stem elongation, GS 31-39.

For diagnosing plant P status, the recommended test is based on %P in dry matter in the newest fully expanded leaf blade (leaf(1)). Critical %P in leaf(1) was in the range 0.28-0.38% (average 0.32%) during stem elongation (GS 31-39). Alternatively, tests based on inorganic phosphate (Pi) in whole shoots, either in dry matter or tissue water, can be used. In dry matter, critical shoot %Pi was in the range 0.05-0.07% (average 0.06%) during stem elongation (GS 31-39). In tissue water, critical shoot Pi was in the range 4-6 mM (average 5 mM) during stem elongation (GS 31-39).

For diagnosing plant K status, the newest fully expanded leaf blade (leaf(1)) should be used. Critical leaf(1) K concentrations depended on yield. For crops yielding up to 8.5 t/ha, critical %K in leaf(1) dry matter was in the range 1.6-2.5% (average 1.9%) during stem elongation (GS 31-39), and critical K in leaf(1) tissue water was in the range 130-170 mM (average 150 mM) during the period GS 31-61. For a crop which yielded 9.5 t/ha, the corresponding critical values were 2.5-3.2% (average 2.9%) and 170-230 mM (average 200 mM), respectively.

Further work is required to refine tests based on leaf, tissue water and P storage pool concentrations. In particular, the effects of leaf age and position, and N and water supply on critical concentrations need further investigation. There is a good possibility of using *in-situ* techniques for measuring Pi and K concentrations in plant tissue water, and this also merits investigation.

2 TERMINOLOGY

P	- Phosphorus
Pi	- P as inorganic orthophosphate ($H_2PO_4^-$)
P_2O_5	- Fertiliser "phosphate" ($P = P_2O_5 \times 0.4364$)
Soil P	- soil extractable P (mg/kg or mg/l)
%P	- total P concentration as % of plant dry matter
Pw	- total P concentration in plant tissue water (millimolar, mM)
%Pi	- Pi concentration as % of plant dry matter
Piw	- Pi concentration in plant tissue water (mM)
K	- Potassium
K_2O	- Fertiliser "potash" ($K = K_2O \times 0.8301$)
Kex	- soil exchangeable K (mg/kg)
Kext	- soil extractable K (mg/l)
Knex	- soil non-exchangeable K (mg/kg)
%K	- plant K concentration as % of dry matter
Kw	- plant K concentration in tissue water (mM)
DM	- dry matter
FM	- fresh matter
TW	- tissue water (fresh weight minus dry weight)
Leaf(1)	- youngest mature leaf blade (collar visible)
Leaf(2)	- next youngest mature leaf blade
Shoot	- single stem plus leaves
Mainstem	- first or primary shoot
Tiller	- side shoot
Whole Shoots	- mainstem plus tillers
GS	- Growth Stage (Zadoks *et al.*, 1974). (N.B. Reported growth stages are those observed on the day of sampling and not the actual dates on which particular growth stages were reached).
DFS	- days from sowing
JD	- Julian days (days from 1st Jan)

3 INTRODUCTION

3.1 P and K fertiliser policy

The P and K fertiliser policy followed on many UK arable farms is essentially one of soil build-up and maintenance checked by occasional soil analysis. However, the boundary between deficiency and sufficiency in soil P and K for most crops is not known precisely for individual fields (soil types), so growers cannot accurately assess where a field lies on the response curve. At present growers have no reliable means of checking on the efficacy of a particular fertiliser policy for individual crops and fields. Arnold and Shepherd (1990) in a review of P and K requirements of cereals stated that it was important for farmers to be able to recognise when it was safe to switch from build-up to maintenance dressings, when a maintenance regime was working, and when not even maintenance dressings were needed. They recognised the shortcomings of soil testing for achieving this and recommended that more attention should be given to plant testing which is little used on arable crops at present.

3.2 P and K fertiliser use on winter wheat

British farmers grew about 1.7 M ha of winter wheat in 1993 with typical annual applications of phosphate and potash of 23 kg P/ha (52 kg/ha of P_2O_5) and 41 kg K/ha (49 kg/ha of K_2O) (Burnhill *et al.*, 1994). Assuming P_2O_5 costs 27p/kg and K_2O 17p/kg, the annual cost to farmers of P and K for winter wheat in 1993 was £22/ha, and the national bill was £38M per annum.

3.3 Response of cereals to P and K fertiliser

Numerous field trials carried out over the last 40 years have shown that cereals are not very responsive to fresh P and K dressings on most UK soils (Arnold and Shepherd, 1990). The response of a crop to fertiliser depends on the amount of nutrient already present in the soil, its availability to plants, and growing conditions. Clearly response to fertiliser will vary from site to site and year to year. Responses to fresh fertiliser are only likely on soils low in available nutrients. On soils very deficient in P or K, yield reductions can be substantial. In the classical winter wheat experiment on Broadbalk field at Rothamsted for example, typical yield reductions due to extreme soil P and K deficiency are 45% and 30%, respectively.

3.4 Soil testing

Soil testing is the established method of assessing if soil P and K supplies are adequate for crop needs. It is the basis of P and K fertiliser recommendations for all crops in the UK

(MAFF, 1994). Standard chemical extraction procedures are used to rank soils according to plant nutrient availability (MAFF, 1986; Westerman, 1990). Soil analysis indicates the potential availability of nutrients and has the advantage of allowing remedial fertiliser dressings to be applied for the coming crop.

The problem with soil analysis is that critical concentrations for maximum yield are not known for individual crops and fields (soil types). Little evidence is available on factors affecting critical soil concentrations, but these may include crop species, soil type, availability of unmeasured nutrient supplies (e.g. nutrients in the subsoil), availability of other nutrients and factors which affect soil nutrient availability such as rainfall, temperature and root growth. Critical soil values are therefore likely to vary between crops, sites and seasons.

Boundaries between soil deficiency and sufficiency, i.e. critical values, in current advice schemes have been set on the basis of numerous field experiments across crops, sites and seasons. Thus the ADAS soil analysis classification (based on results obtained by standard procedures (MAFF, 1986)) groups soil test results into nine indices for the purpose of deciding if responses to fertiliser are likely or not. Responses by cereals are probable at Index 0, possible at Index 1, and unlikely at Index 2 and above. Each Index covers a relatively wide range of values (see Appendix 1).

The MAFF Representative Soil Sampling Survey (1983-88) showed some 14% of arable soils in England and Wales were at P Index 0 or 1, 31% at Index 2, and 55% at Index 3 and above (Skinner *et al.*, 1992). Equivalent figures for K were 28%, 52% and 20%, respectively. As yield responses by cereals to fertiliser are only likely on Index 0 or 1 soils (less than 15 mg P/l or 120 mg K/l), the potential exists to make short-term savings on some soils by witholding or reducing P and K fertiliser inputs.

Soil analysis could be improved as a predictor of crop response by taking soil type and subsoil nutrients into account. Even if this were to be done however, critical values would still need to be determined for the most common soil types at least, and subsoil testing would add to the cost considerably. The main use of soil analysis should be to check on trends in soil nutrient status over time and to categorise a soil as either deficient, border-line or abundant. Plant testing could then be used to provide a more precise indication of soil nutrient status for a particular crop and soil.

3.5 Plant testing: Conventional approaches

It is important to define what is meant by "plant testing" and other commonly used terms associated with it, such as plant analysis, foliar analysis, tissue testing, sap testing, and spot, quick or snappy testing. Conventional "plant analysis" involves the measurement of total nutrient concentrations in whole plant dry matter, and "foliar analysis" is a variant of this involving just leaf blades. "Tissue testing" normally means the extraction and analysis, usually from stems and petioles but also leaves, of unassimilated soluble nutrient fractions (nitrate, phosphate, sulphate and potassium) and expression of concentrations on a dry or fresh weight basis. "Sap testing" is a variant of this involving the extraction of sap, usually from stems and petioles, and analysis for soluble nutrients. Sap concentrations are normally expressed in millimoles per litre (i.e. millimolar or mM). "Spot", "quick" or "snappy" testing are variants of sap testing in which the tests are conducted *in-situ* in the field. In this report, the term "plant testing" is used to refer to all these methods.

A considerable world literature has built up over the last 50 years on "plant testing" (plant/foliar analysis and tissue/sap/spot testing). There are numerous review articles (Ulrich, 1952; Smith, 1962; Bates, 1971; Bouma, 1983), guides to visible deficiency symptoms (Wallace, 1951; Schering Agriculture, 1989; Bennett, 1993),and comprehensive interpretation manuals (Reuter and Robinson, 1986; Benton Jones *et al.*, 1991). Most information relates to conventional plant analysis, but foliar analysis and tissue/sap/spot testing have been widely used on perennial and horticultural crops.

Plant testing provides a means of checking whether crop nutrient requirements are actually being met, although a deficiency in the plant does not automatically mean that soil supply is deficient. Nutrients may be present in the soil but unavailable due to impaired root growth or dry soil for example. Plant test results may also come too late for remedial action to be taken for the current crop, but they will indicate the need for increased fertiliser use for following crops.

The ideal plant testing method should be quick and easy to perform, sensitive to nutrient supply, and selective for the nutrient in question. Critical values for maximum yield need to be stable during growth and between sites and seasons, i.e. universally applicable. In theory, critical nutrient concentrations in plants should be intrinsic physiological parameters independent of growing medium and growing conditions. In practice, the above criteria are met to different extents by different methods.

In annual crops, total plant nutrient concentrations in shoot dry matter decrease with plant age and depend on growing conditions, especially the supply of other nutrients which affect dry matter production independently. The decline in concentration with plant age is due to an increase in the amount of structural materials such as cellulose and lignin, which contain little or no mineral nutrients, relative to metabolic materials. In cereals this is particularly marked during stem elongation. Thus it is necessary to know the stage of growth of the plant in order to interpret total nutrient concentrations in shoot dry matter with confidence.

Foliar analysis and the use of nutrient ratios can get round some of the above problems. Sampling leaves is generally more practical than sampling whole shoots, and analysis of leaves of a fixed age should reduce plant ageing effects. Nutrient ratio analysis was developed to reduce nutrient interaction effects. There are good physiological reasons for using some nutrient ratios, e.g. the use of the S/N ratio is based on the fixed requirements for S and N in proteins, but this does not apply to all nutrient ratios. The most sophisticated form of ratio analysis is the Diagnosis and Recommendation Integrated System (DRIS) (Walworth and Sumner, 1987). The DRIS procedure relies on the compilation of a databank of information on nutrient concentrations and yields over wide-ranging conditions. The system can rank nutrients in order of limiting importance for yield. It can identify if a particular nutrient is insufficient relative to other nutrients. It cannot identify absolute nutrient deficiencies.

Tissue and sap testing were developed because of the ease with which soluble unassimilated nutrient fractions (nitrate, phosphate, sulphate, potassium) can be extracted from plant organs and analysed. Sap testing also offers the prospect of *in-situ* analysis in the form of spot or quick tests. Physiologically, the concentration of soluble nutrient fractions in organs containing conducting vessels (stems and petioles) is thought to be the most sensitive plant indicator of soil nutrient supply. Concentrations in these tissues are liable to fluctuate however as nutrients are always in transit to leaves. These methods have been widely used on horticultural crops.

In the UK, little research has been done on plant testing in cereals. Foliar analysis may be used for diagnosing trace element deficiencies, but little or no use is made of plant analysis for diagnosing major element status. However, an increasing number of agencies and growers are showing interest in testing cereals and other arable crops for both major (N, P, K, S, Ca, Mg) and trace (Fe, Mn, Cu, Zn, B, Mo) nutrients. At present, interpretation of results is hampered by a lack of generally agreed critical values and a failure to recognise the

importance of growth stage and growing conditions. UK laboratories rely on world literature for critical plant PK values and for interpretation of plant test results.

3.6 Plant testing: New approaches

Three new approaches to plant testing were evaluated in this project to try to eliminate some of the problems associated with conventional plant analysis.

Firstly, leaves of a known physiological age were targeted. This should remove problems associated with plant ageing. Most workers have used the newest fully expanded leaf blade as it is easy to identify, and this leaf was targeted in the present work.

Secondly, nutrient concentrations were expressed on a tissue water basis. In theory, this should also remove effects due to plant ageing. The merits of the approach have been demonstrated by Leigh and Johnston (1983) for K, although it was less successful for P (Leigh and Johnston, 1986). Whole shoot tissue water concentrations (Kw) in spring barley declined less with plant age than dry matter concentrations. Equally importantly, Kw was affected only by K supply and not by N, P or water supply. Severely K-deficient barley shoots had mean Kw concentrations (during growth) of 70 mM, whilst abundantly-supplied shoots had mean Kw concentrations of 200 mM. Further work showed that other cereals abundantly supplied with K also accumulated K to 200 mM. However, it remains to be established if concentrations in cereals can fall below 200 mM without affecting growth and yield, i.e. what is the critical Kw concentration?

Thirdly, the use of Pi for assessing P status was evaluated. The rationale for this approach was not simply ease of measurement, but the physiological significance of Pi accumulation in plants. Plants abundantly supplied with macronutrients (N, P and S) accumulate any excess not immediately required for growth as simple inorganic ions (nitrate, phosphate and sulphate). Accumulation occurs in all organs: leaves, stems, petioles and roots. Conventional tissue testing uses stems and petioles which may be the best indicators of nutrient supply, but leaves should be the best indicator of crop demand. In theory, maintaining low concentrations of these ions in leaves at all times should ensure that supply and demand are always closely matched and should correspond to optimal nutrition (Barraclough, 1993). Critical Pi concentrations in different plant parts and how they are affected by tissue age and growing conditions remain to be established for most species.

These three approaches, essentially involving "foliar tissue testing", form the core of the present project. They have a better physiological basis than conventional plant analysis and, being based on concentrations of simple ions in tissue-water, also offer the prospect of *in-situ* spot testing.

3.7 Aims and general approach

The aim of this project was to investigate both conventional and new approaches to plant nutrient testing with a view to developing reliable plant tests for winter wheat. Specific objectives included: determination of critical P, Pi and K concentrations in shoots, stems and leaves for maximum growth and yield; assessment of the effects of growth stage, and sites (soil types) and seasons on critical concentrations; assessment of the merits of leaf vs. shoot, wet vs. dry and in the case of P, total P vs. Pi testing.

The approach involved a series of field experiments on winter wheat. Experiments were conducted at Rothamsted (P and K experiments), and at ADAS sites at Ropsley, Lincs. (P experiments), and selected sites in East Anglia (K experiments) in the period 1992-95. The Rothamsted experiments utilised fields having well established ranges of extractable (i.e. plant-available) soil P and K, whilst the ADAS experiments involved sites essentially deficient in soil P and K to which fresh fertiliser was added in the year the crop was grown. At Rothamsted, field experiments were complemented by hydroponic experiments in a controlled environment room.

4 METHODS

4.1 HYDROPONIC EXPERIMENTS

Winter wheat (*Triticum aestivum L*, cv. Mercia) was grown in hydroponics in a controlled environment room with 16 h daylength, 20/16°C day/night temperatures and a light intensity of 400 $\mu E/m^2/s$. A basal nutrient solution of the following composition was used: 3 mM N, 0.3 mM P, 3 mM K, 0.3 mM S, 1.5 mM Ca, 0.3 mM Mg, 100 μM Fe, 50 μM B, 10 μM Mn, 1 μM Zn, 1 μM Cu, and 0.5 μM Mo (supplied as calcium nitrate, monocalcium phosphate, potassium chloride, magnesium sulphate, ferric sodium EDTA, boric acid, manganese, zinc and copper sulphates and ammonium molybdate). Solutions were made up in demineralised water and adjusted to an initial pH of 5.5. Solutions were continuously aerated and changed every other day. Treatments consisted of wide ranges of external P or K concentrations with all other nutients being supplied in adequate amounts.

Seeds were germinated in moist sand and transplanted into one-litre pots after ten days. Nine plants were grown in each pot and there were six pots per treatment. Plants were harvested after three weeks when they were typically at the 6-leaf, 3-tiller stage (GS 23), i.e. before stem extension. Shoots were separated into individual components, fresh and dry weights determined, and P, Pi and K concentrations determined as in section 4.2.7.

4.2 FIELD EXPERIMENTS

4.2.1 Site details

Rothamsted (RES) (Hertfordshire. Grid Ref. TL122142): 128 m above sea level with largely flat fields. Mean annual rainfall 687 mm. A free-draining silty clay loam soil over clay with flints (Batcombe Series). Experiments were carried out on three fields: Exhaustion Land (P&K) in 1992, Sawyers(I) (P) and Sawyers(III) (K) in 1993,94,95.

Ropsley (ROP) (Lincolnshire. Grid Ref. SK976359): Mean annual rainfall 625 mm. Clay loam soil over clay (Beccles Association).

Fowlmere (FOW) (Cambridgeshire. Grid Ref. TL415461): Sandy loam soil over sandy loam (Swaffham Prior Association).

Ingham (ING) (Suffolk. Grid Ref. TL848735): Sandy loam soil over loamy sand (Newport Association).

Sedge Fen (FEN) (Suffolk. Grid Ref. TL667847): Silt loam soil over silt loam (Willingham Association).

4.2.2 The experiments

RES P: 1992 (Exhaustion Land - w. wheat - Mercia)
1993 (Sawyers(I) - s. oats - Keeper)
1994 (Sawyers(I) - w. wheat - Mercia)
1995 (Sawyers(I) - w. wheat - Mercia)

RES K: 1992 (Exhaustion Land - w. wheat - Mercia)
1993 (Sawyers(III) - w. wheat - Mercia)
1994 (Sawyers(III) - w. wheat - Mercia)
1995 (Sawyers(III) - w. wheat - Mercia)

ADAS P: 1992 (Ropsley - w. wheat - Mercia)
1993 (Ropsley - w. wheat - Mercia)
1994 (Ropsley - w. wheat - Mercia)
1995 (Ropsley - w. wheat - Mercia)

ADAS K: 1992 (Fowlmere - w. wheat - Haven)
1993 (Ingham - s. wheat - Cannon)
1994 (Fowlmere - w. wheat - Riband)
1995 (Sedge Fen - w. wheat - Soissons)

N.B. Years correspond to the year of harvest.

4.2.3 Experimental designs and treatments

RES - P and K(1992)

Each experiment consisted of 20 plots (6 m x 25.6 m) arranged in five strips of four plots. Plots had a range of unreplicated soil P or K. Soil P or K systematically increased along each strip.

RES - P(1994 and 95)

Six blocks of 12 plots (4.3 m x 15 m). Winter wheat was grown on two blocks. The 24 plots had a range of unreplicated soil P levels randomly arranged in the blocks (20 of the plots were sampled).

RES - K(1993-95)

Two blocks of 20 plots (9 m x 24 m) having a range of unreplicated soil K levels randomly arranged in each block. Winter wheat alternated with winter oats.

ADAS - P(1992-95)

Randomised block (11 treatments with 3 replicates) (7.6 m x 18.3 m). Fertiliser treatments were 0,17,31,44 kg P/ha on soils having differing P levels as a result of previous nil, low and high P fertiliser regimes in the period 1977-84.

ADAS - K(1992-95)

Randomised block (6 treatments with 3 replicates) (8 m x 24 m).
Fertiliser treatments were 0,25,50,75,125,175 kg K/ha.

4.2.4 Agronomic details

Details of previous crop, variety, sowing date, seed rate, harvest date, soil-N, -P, -K, -Mg, -pH, and rate and timing of NPK fertilisers are shown in appendices 2 and 3. All crops were precision drilled at 12 cm row spacing, given growth regulator and treated as necessary against weeds, pests and diseases.

4.2.5 Soil sampling

Soil sampling was undertaken twice a year at Rothamsted, in September prior to drilling (P and K) and in February (K only). Cores were taken to a depth of 23 cm using a 2 cm diameter auger. Twelve to sixteen cores were taken from each plot depending on the plot size. Cores were taken from two lengthwise transects of each plot and bulked into a composite sample.

Soil sampling was undertaken at Ropsley in September each year following ploughing but before drilling. Soil samples were taken at the potassium sites in September 1991 (Fowlmere I), January 1993 (Ingham), September 1993 (Fowlmere II) and February 1995 (Sedge Fen). Twenty five cores were taken from each plot (0-15 cm depth) and bulked to provide a

composite sample for analysis.

Field moist soil was air dried and milled to pass a 2 mm mesh. A subsample of dried soil was analysed for extractable-P (soil-P) and extractable- or exchangeable-K (Kext or Kex).

4.2.6 Plant sampling

At Rothamsted, a 3 m wide strip down the centre of each plot was reserved for combine harvesting. Plant samples (whole shoots) were taken at random from either side of this strip leaving a guard of at least 0.5 m between samples and at the edge of each plot. Each sample consisted of 4-8 x 0.5 m length of row (0.24-0.48m^2). Sampling dates are in APPENDIX 5.

In the ADAS procedure, a 3-4 m wide strip was reserved down the edge of each plot for combine harvesting. Plant samples were taken randomly from the remaining 2 m wide strip. Each sample consisted of a 0.48 m^2 quadrat. Leaf samples were taken from 30 plants at random and analysed as a composite sample. Sampling dates are in APPENDIX 5.

Sampling was carried out as quickly as possible to minimize tissue water loss and took place between 9 and 12 am. Sampling was not done on rainy days. Shoots were cut at ground level and dead or severely senesced leaves were discarded. Samples were kept in sealed plastic bags in a cool box.

In the laboratory, samples were stored in a cold room at 5°C until they could be processed, usually within two hours of cutting. (It was shown in a separate study, that fresh samples could be stored at 5°C in sealed plastic bags for up to 4 hours without affecting Piw concentrations). For each sample, total fresh weight was measured, and subsamples were dried overnight at 80°C in a conventional oven for P and K analysis or in a microwave oven for Pi analysis (section 4.2.7). At Rothamsted, shoot subsamples were separated into individual leaves and stems at some growth stages. Fresh and dry weights of all samples and subsamples were recorded. Dried samples were milled to pass a 1 mm mesh (Glen Creston or 8" Christy Norris mill).

Combine yields were taken from a 3-4 m strip on each plot. The width of cut from the combine was 2.3 m. Plot lengths harvested were in the range 12-20 m giving a harvest area of 27-46 m^2. The fresh weight of grain was measured, a subsample was weighed and dried in a conventional oven at 105°C. Yields were corrected to 85% DM and converted to t/ha.

4.2.7 Extraction and analysis of nutrients

Extractable soil P

The method used for determining extractable soil P was essentially that of Olsen *et al.* (1954). 5 g of air-dry soil (or 5 ml at ADAS) was shaken with 100 ml of 0.5 M sodium bicarbonate at pH 8.5 for 30 minutes at 20°C on a reciprocating shaker. The solution was filtered (Whatman No.42) and the first 5 ml discarded. ADAS used the method described in MAFF (1986). Extractable soil P was expressed as mg P/kg dry soil (RES) or mg P/l dry soil (ADAS). Soil P values expressed in these units will differ where the dry soil bulk density differs from 1 kg/l. Extracts were analysed immediately for Pi using the molybdate-blue colorimetric method (Murphy and Riley, 1962).

Extractable and exchangeable soil K

At ADAS, *extractable* soil K (Kext) was determined by shaking 5 ml of air-dried soil in 100 ml of 1 M ammonium nitrate for 30 minutes on a reciprocating shaker and filtering through a Whatman No.42 paper (MAFF, 1986). At RES, *exchangeable* soil K (Kex) was determined by leaching 5 g of air-dried soil with 100 ml of 1 M ammonium acetate for at least 4 hours. Soil K was expressed as mg K/l (ADAS) or mg K/kg (RES). Extractable K is always likely to be less than exchangeable K. Extracts were analysed for K using an inductively coupled plasma emission spectrometer (ICP) or a flame photometer.

Preparation of plant material for analysis

Plant material is normally prepared for analysis by oven drying fresh material at 80°C, and this method was used for %P and %K analysis. However, experiments showed that conventional oven drying caused significant increases in the amount of Pi in plant tissue compared with Pi in fresh plant sap. The increases were probably caused by the enzymic transformation of organic P compounds, such as phosphate-esters, into Pi during the early stages of conventional oven drying (Bieleski, 1973). It is a moot point as to whether the esters should also be included in the "P storage pool" as they are readily converted to Pi and presumably could also be considered a store for P. For the present study, it was decided to concentrate on inorganic Pi as its storage role was unequivocal. A method of drying plant material was needed which minimised the transformation of organic-P to Pi. This was achieved by microwaving plant material which rapidly raised the temperature and minimised organic P transformations.

Fresh plant material (30-40 g) was cut into small pieces (5-10 mm) and dried in a domestic

microwave oven on full power (750W). The samples were removed from the microwave when they were crisp and brittle to touch. To ensure the material was completely dry, the samples were dried in a conventional laboratory oven at 80°C for a further 4 hours. Drying times in the microwave oven varied with sample size and the plant tissue, but were usually in the range 2-5 minutes. Stems took longer to dry than leaves. To prevent charring of the samples and overheating of the microwave oven, a beaker of water was kept in the oven during drying.

Plant Pi

0.25-0.50 g of microwave-dried plant material was shaken with 25 ml of 2% (v/v) acetic acid for 30 minutes (Luckham MultiMix Major, oscillating, rolling bed shaker (setting 5) or other reciprocating shaker). There was no increase in the amount of Pi extracted when the samples were shaken for upto 4 hours. The extract was filtered through a Whatman No.6 or No.42 paper and the first 5 ml discarded. The filtrate could be stored overnight at 5°C before analysis for Pi. Pi was determined colorimetrically using the molybdate-blue method (Murphy and Riley, 1962).

Plant total-P

0.25-0.50 g of oven-dried, milled plant material was digested in a concentrated nitric/perchloric acid mixture and the residue dissolved in 10% (v/v) hydrochloric acid. Total-P was determined by ICP.

Plant K

0.25-0.50 g of oven dried, milled plant material was shaken with 25 ml cold distilled water for 30 minutes (Luckham MultiMix Major, oscillating, rolling bed shaker (setting 5) or other reciprocating shaker). The extract was filtered through a Whatman No.6 or No.42 paper discarding the first 5 ml. A 5 ml aliquot was mixed with an equal volume of 10% (v/v) hydrochloric acid and analysed for K by ICP or flame photometer. This water extraction method extracts at least 95% of the total-K extracted by strong acid digestion.

4.2.8 Statistical analysis

In the fertiliser response experiments conducted by ADAS, treatment effects on yield were assessed by analysis of variance and curve fitting techniques (Genstat 5, Release 3.1 and Minitab 8.2, Release 2). In the Rothamsted experiments, soil P and K levels were

unreplicated and results were assessed by curve fitting (Genstat 5, Release 3.1 and Fig.P, Version 6.0).

Curve Fitting

Successful plant testing depends on the determination of "critical" nutrient concentrations in plant tissue, i.e. concentrations below which growth or yield reductions occur. Conventionally, critical concentrations have been determined for 5-10% growth or yield reductions (Smith, 1986). In the present study, critical soil and plant values were estimated for 95% of maximum yield by fitting mathematical functions to the observed relationships. Several functions have been used by different workers and are discussed by Moorby and Besford (1983) and Colwell (1994).

A common function used in crop research is the exponential function developed by Mitscherlich in 1928 based on the Law of Diminishing Returns. The equation is:

$$y = a*\exp(-bx) + c$$

Where a, b and c are parameters. This function reaches a maximum asymptotically and is not suitable in situations where y declines at high values of x. There were no obvious cases of this in the Rothamsted data so the equation was considered appropriate and has been used on all Rothamsted data unless otherwise stated. In most cases very good fits were obtained. A linear function was also used where appropriate.

The ADAS data was fitted using linear, quadratic or linear plus exponential functions (Sylvester Bradley *et al.*, 1984) depending on the best fit. The equations are:

$y = ax + b$ (linear)

$y = ax + bx^2 + c$ (quadratic)

$y = a + br^x + cx$ (linear plus exponential)

where a,b and c are parameters and r is a pre-determined constant.

Mathematical derivation of critical plant concentrations

Maximum grain yield in each experiment was interpolated from a plot of "yield vs. soil concentration" at the highest soil value. For example, in the P experiment at Rothamsted in

1995, maximum grain yield at a soil P of 48 mg/kg, was 10.24 t/ha (Fig. 4.1a). 95% maximum yield was therefore 9.73 t/ha, which corresponds to a (critical) soil P value of 9.8 mg/kg.

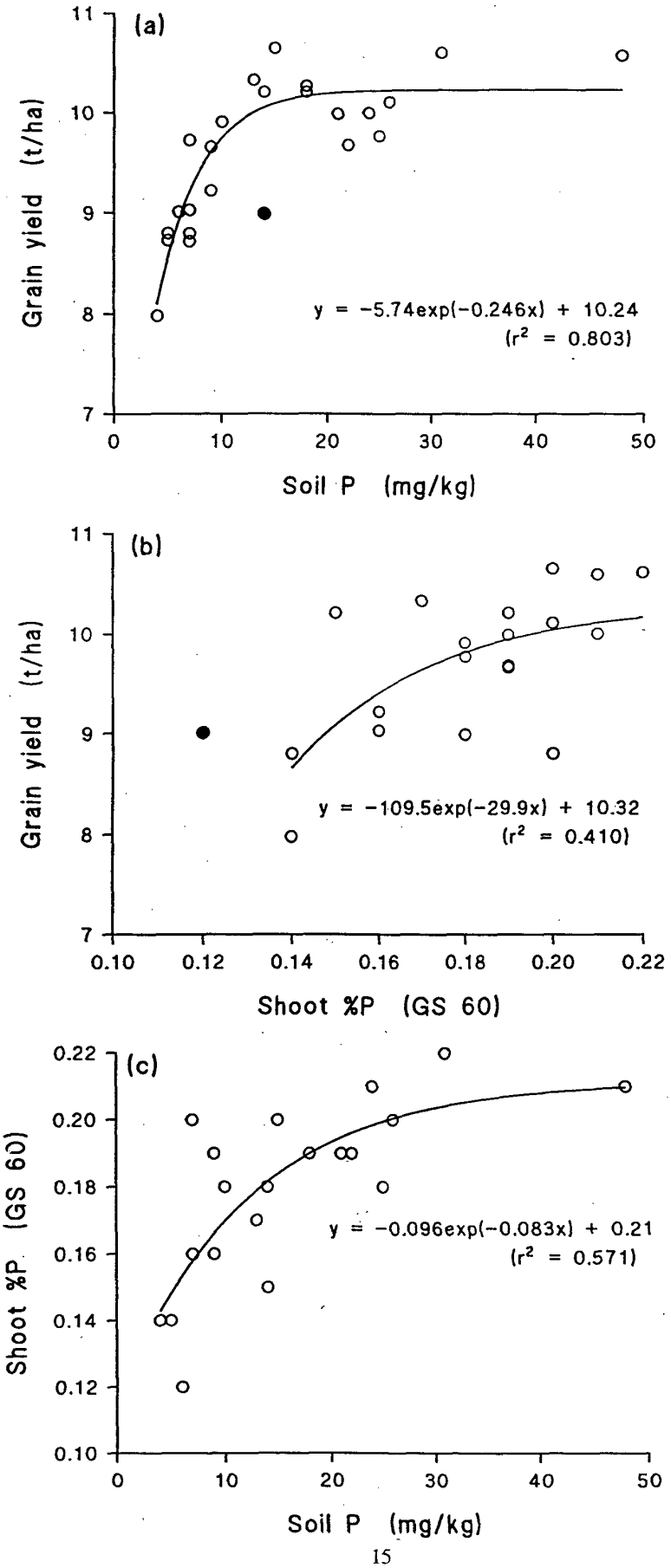
Critical plant concentration (CPC) in shoot, leaf or stem for 95% maximum yield should be derived from a plot of "yield vs. plant concentration". For example, in the P experiment at Rothamsted in 1995, yield is shown plotted against shoot %P measured at GS 60 in Fig. 4.1b. The relationship and fit were poor, but a (critical) shoot %P of 0.171% was derived for a 95% maximum yield of 9.66 t/ha.

"Yield/plant" relationships were invariably worse than "yield/soil" and "plant/soil" relationships in the present work. Consequently, CPCs were derived indirectly from "yield/soil" and "plant/soil" relationships. For example, in the P experiment at Rothamsted in 1995, shoot %P is shown plotted against soil P in Fig. 4.1c. A critical shoot %P of 0.167% was derived from this plot at a soil P of 9.8 mg/kg, which is the critical soil value for 95% maximum yield obtained from Fig. 4.1a.

4.2.9 Weather

Weather records are summarised in APPENDIX 4.

Figure 4.1 Derivation of critical plant concentrations



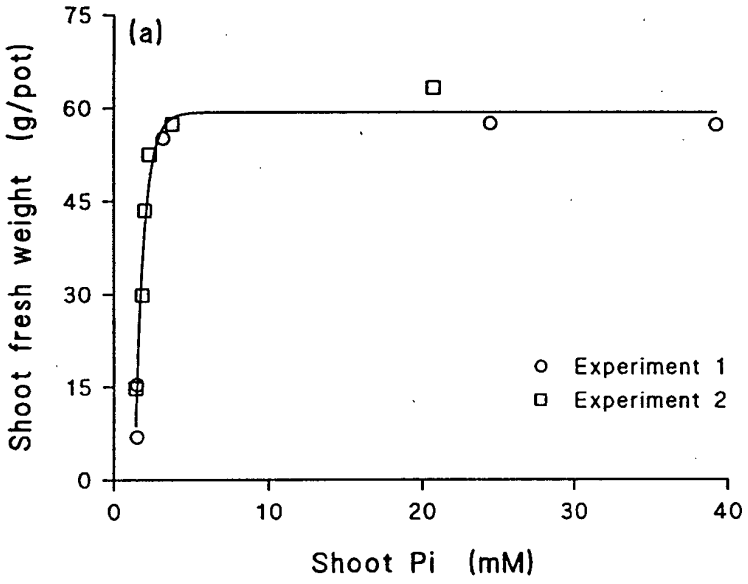
5 PHOSPHORUS: RESULTS AND DISCUSSION

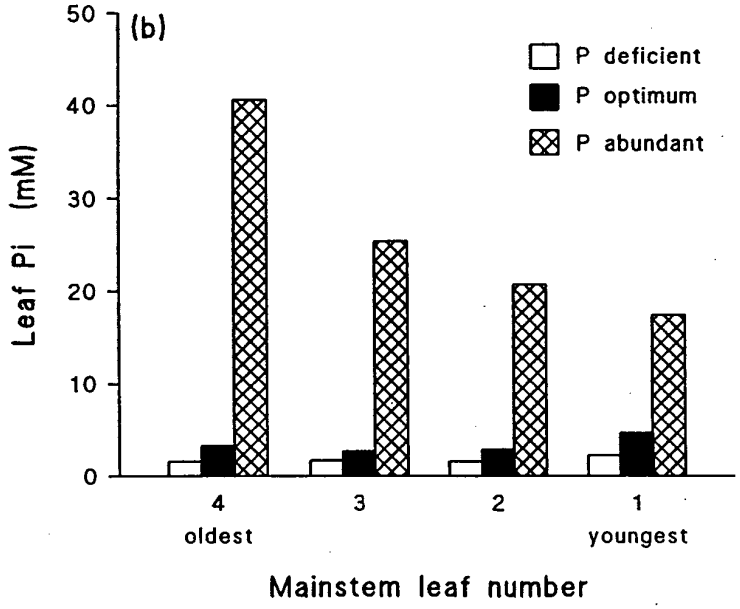
5.1 HYDROPONIC EXPERIMENTS

Inorganic phosphate concentrations in tissue water (Piw) in young whole shoots ranged from 1.5 to 40 mM depending on P supply. Critical shoot Piw for 95% of maximum shoot growth was 3 mM (Fig. 5.1a). Increased shoot growth with P supply was due mainly to increases in the number and weight of tillers. P supply had little effect on the weight of individual mainstem leaves. In P-deficient plants, Piw in all individual mainstem leaves was in the range 1.3-1.8 mM (Fig. 5.1b). In P-optimum plants, Piw was around 3 mM in individual mature (not senescing) leaves and 5 mM in the youngest (still unfolding) leaf (Fig. 5.1b). In P-abundant plants, Piw was greatest in oldest leaves and least in youngest. No data is reported in the literature on Piw in hydroponically-grown wheat, although Hylton *et al.* (1965) reported a critical concentration of 6 mM in leaf(1) for ryegrass. These authors had oven-dried the plants however, which is likely to lead to higher Pi values than microwave-drying.

Pi is a major storage form of P, but a certain concentration of Pi is obligatory for metabolism and growth before storage begins. In expanding wheat leaves this appeared to be about 5 mM, whilst in mature leaves and whole shoots it was about 3 mM. Above these concentrations, storage begins and Pi accumulated to concentrations of 40 mM without affecting growth. Concentrations in young expanding leaves were more regulated against fluctuations in P supply than those in mature leaves. Leaf(1) Pi tracked shoot Pi very closely.

Figure 5.1 Shoot and leaf Pi concentrations in hydroponic experiments





5.2 FIELD EXPERIMENTS

5.2.1 Grain yield/Soil-P/Fertiliser-P relationships

Yield ranges for all sites and seasons are shown in Table 5.1. Rothamsted values were interpolated from fitted curves at the maximum and minimum soil P values (Fig. 5.2a). Soil P at Rothamsted, measured before sowing, ranged from 1-51, 4-39 and 4-48 mg/kg in 1992,94,95, respectively, i.e. bottom of ADAS Index 0 (very deficient) to bottom of Index 4 (abundant) (see APPENDIX 1).

Ropsley values represent the lowest and highest fitted treatment yields, and are the combined response to both fresh fertiliser P and residual soil P. Soil P at Ropsley, measured after harvest, ranged from 7-24, 11-28, 11-22, 9-21 and 11-24 mg/l in 1991-95, respectively, i.e. top of Index 0 (deficient) to top of Index 2 (sufficient).

Table 5.1 Grain yields (85% DM)

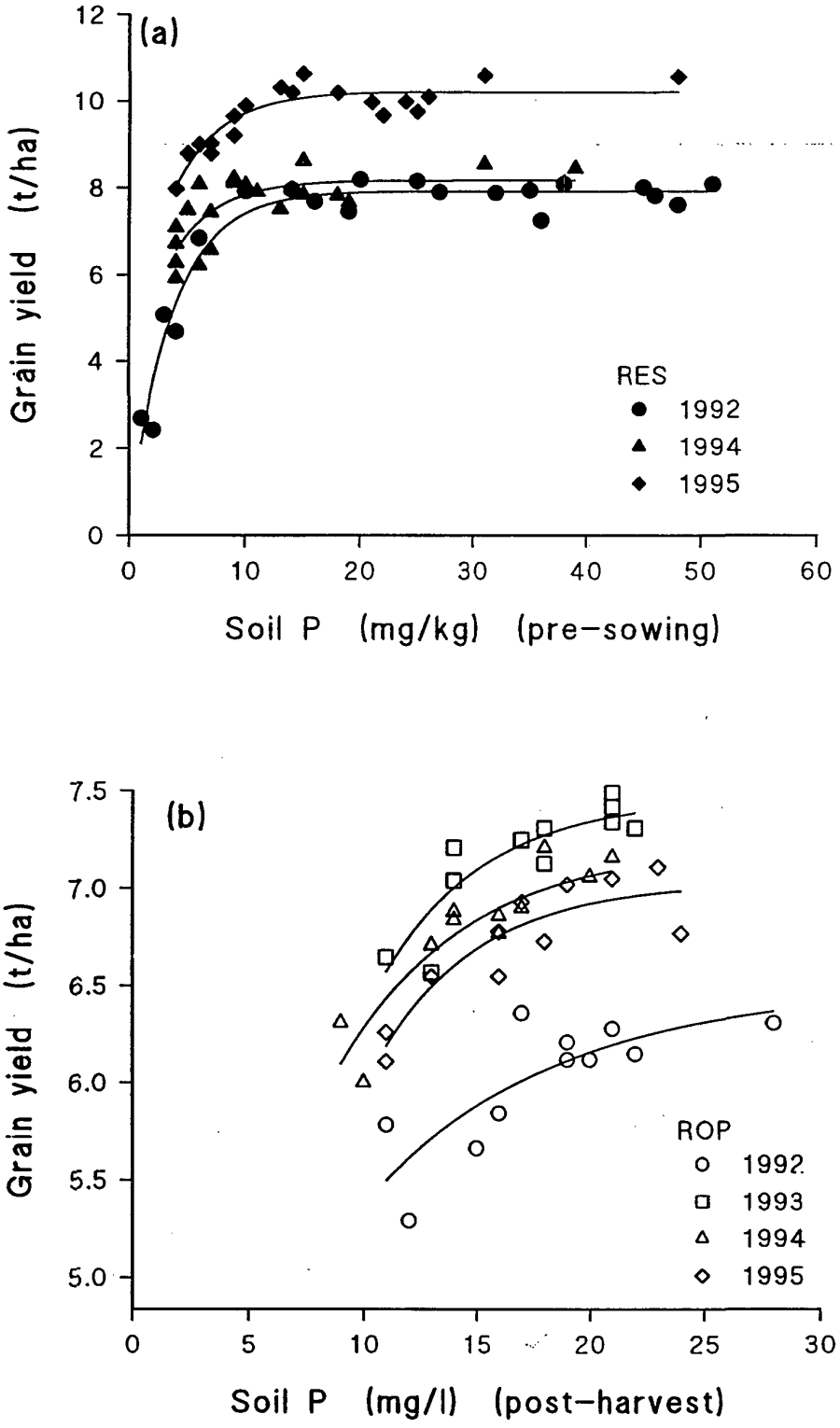
SITE	1992	1993	1994	1995
ROTHAMSTED	2.09-7.93	N/A	6.57-8.19	8.09-10.24
ROPSLEY	5.29-6.32	6.57-7.37	6.00-7.15	6.11-7.02

Maximum yield at Rothamsted was 7.93, 8.19 and 10.24 t/ha in 1992,94,95, respectively. It is possible that yields in 1992 and 1994 were depressed by take-all and N supply, respectively. In 1994, 150 kg/ha of fertiliser N was applied compared with 192 kg in 1992 and 200 kg in 1995). The drought in 1995 appears not to have affected yield unduly.

There were good relationships between yield and soil P at Rothamsted (Fig. 5.2a). Critical soil P for 95% maximum yield was 11, 9 and 10 mg/kg in 1992,94,95, respectively. Yield response was 5.84, 1.62 and 2.15 t/ha in 1992,94,95, respectively. The exceptionally low yield of 2.09 t/ha at low soil P in 1992 was probably due to the very low soil P availability, just 1 mg/kg, although take-all is known to have a greater effect at low soil P and may also have contributed to the very low yield.

At Ropsley, maximum fitted yields were 6.32, 7.37, 7.15 and 7.02 t/ha in 1992-95, respectively.

Figure 5.2 Grain yield and soil P (Rothamsted and Ropsley)



Yield responses were 1.03, 0.80, 1.15 and 0.91 t/ha. As the responses at Ropsley were due to a combination of residual soil P and freshly applied fertiliser P, it is difficult to assign critical soil P levels with certainty. Approximate critical values were derived by relating yield to the soil P determined in the autumn after harvest (Fig. 5.2b). On this basis, critical soil P for 95% maximum yield was 17, 15, 15 and 15 mg/l in 1992,93,94,95, respectively.

Critical soil P changed little between years at a given site. At Rothamsted, it averaged about 10 mg/kg, whilst at Ropsley, estimated critical soil P averaged about 16 mg/l. Very little information is available in the literature on critical soil P for winter wheat. Johnston *et al.* (1986), working on a heavy chalky boulder clay soil, found critical soil P for winter wheat was 20 mg/kg, and for spring barley it was 25 mg/kg at low N and 33 mg/kg at high N. Critical soil P clearly depends on soil type. Holford and Mattingly (1976) found that critical soil P increased with increasing soil buffer power, i.e. the heavier the soil the greater the critical value. It also seems to depend on N supply and possibly on soil water, although evidence on this is scant.

5.2.2 Shoot growth, P uptake, tissue water content

Shoot growth and P uptake for P-sufficient crops are shown in Fig. 5.3. At Rothamsted, growth was very similar in all years. Growth was less in 1994 than the other two years, probably as a result of later sowing and slightly less N being applied. By anthesis, dry matter production in 1994 was less by about 300 g/m^2. Differences in growth were reflected in differences in P uptake (Fig. 5.3b). Greatest uptake was in 1992 with 35 kg P/ha at anthesis compared with 20 kg P/ha in 1994 and 95. The maximum P uptake by 10 t/ha wheat crops grown previously at Rothamsted was of the order of 40 kg P/ha (Barraclough, 1986).

At Ropsley, growth curves were very similar in 1992 and 1993 but different in the other two years. Growth and P uptake were greatest in 1992, paradoxically the lowest-yielding year. The poor early growth and uptake in 1994 were surprising as this crop was sown the earliest (in September). Most uptake occurred in April-May and was complete by anthesis (Fig. 5.3d). Maximum uptake was in the range 15-35 kg P/ha. Holford and Doyle (1993) reported that P uptake by wheat was greatest in wet years and least in dry years.

Shoot and leaf(1) water contents in relation to growth stage are shown for all sites and seasons in Fig. 5.4. Water contents at Rothamsted bore little relation to monthly rainfall, either in the three months prior to sampling (Jan-Mar) or in the two main sampling months of April and May (see Appendix 4).

Figure 5.3 Shoot growth and P uptake in P-sufficient crops

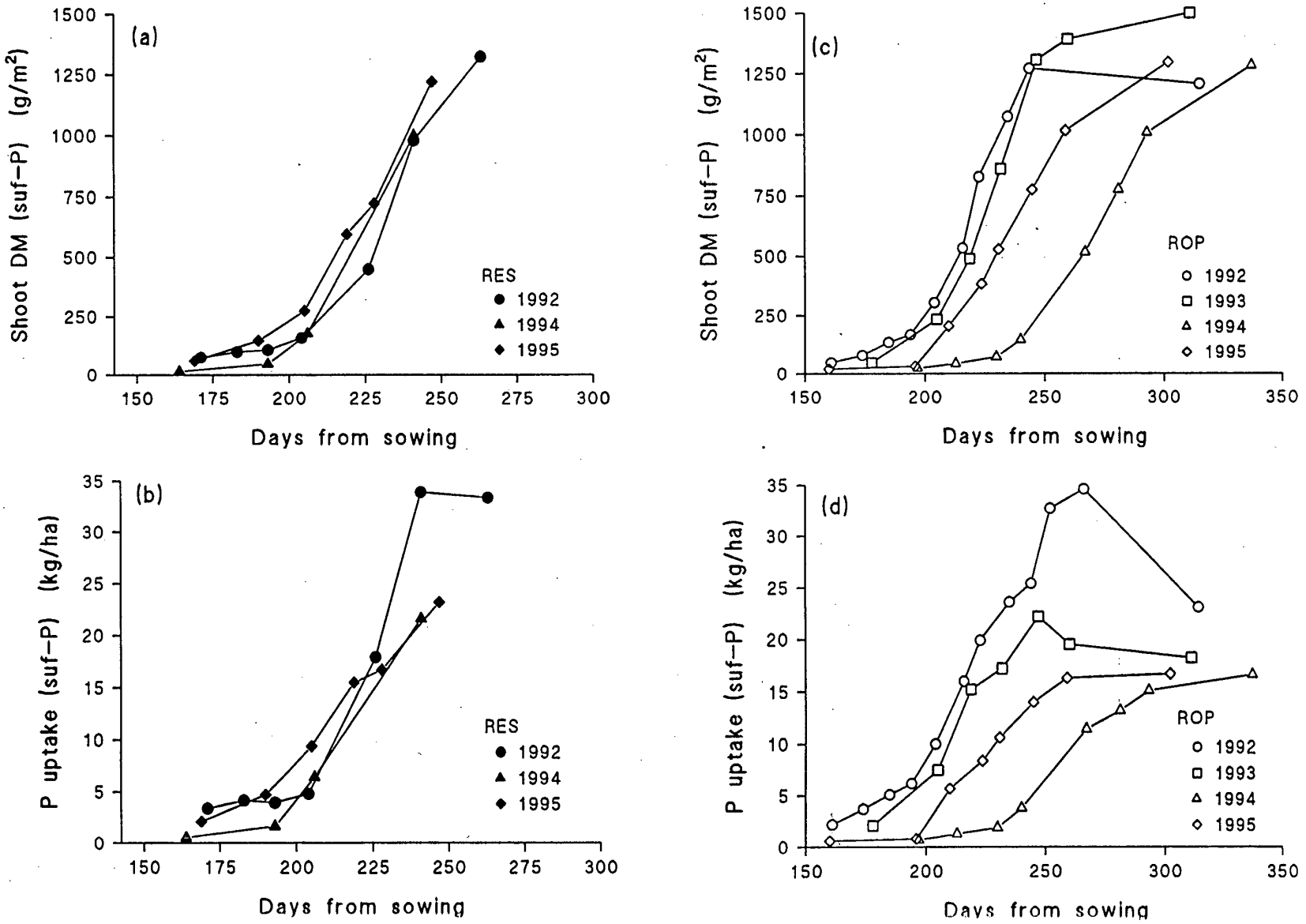
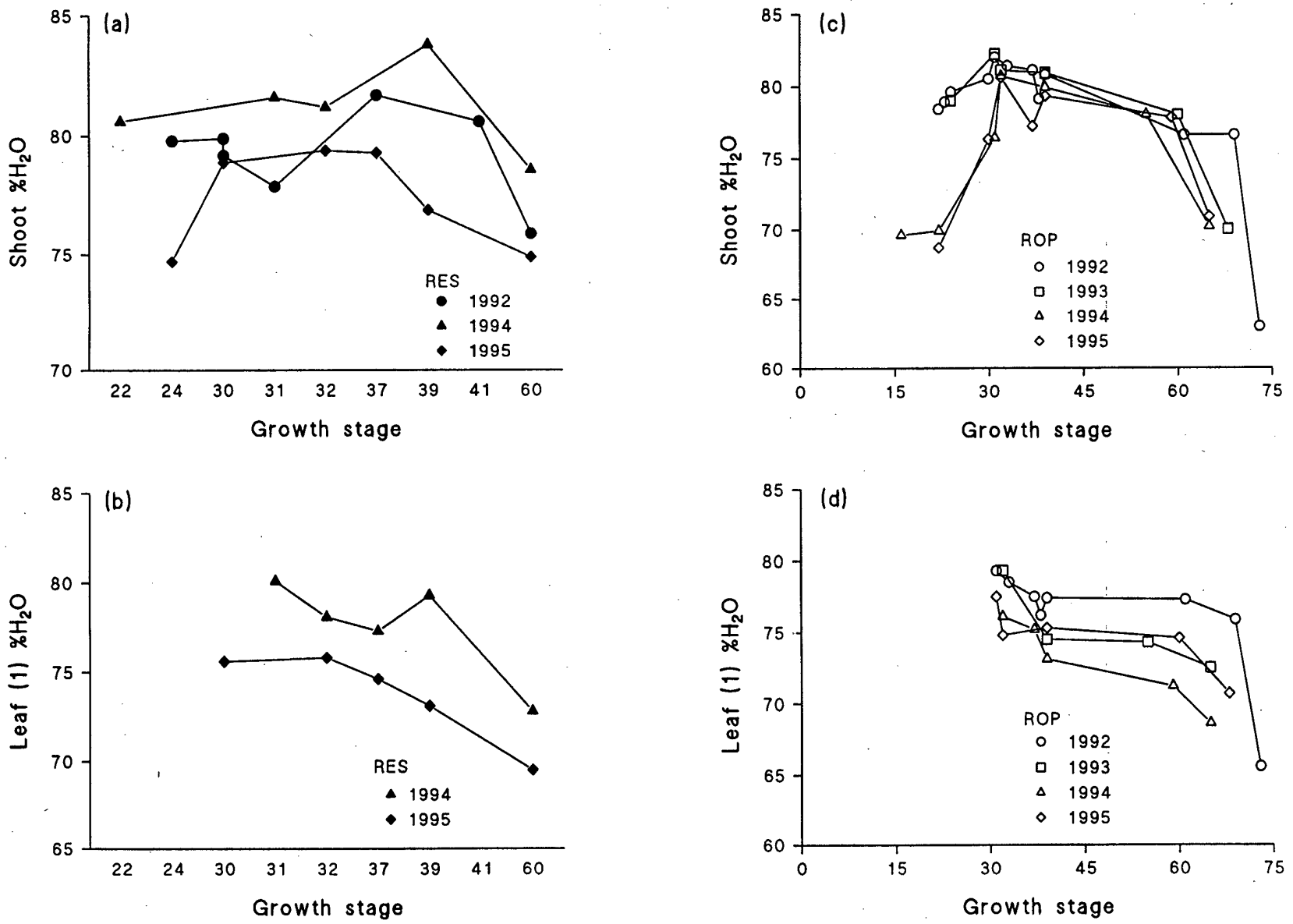


Figure 5.4 Shoot and leaf(1) tissue water contents



5.2.3 Shoots: P and Pi concentrations

Shoot concentrations and soil P

Mean shoot %P (between GS 24-60) in relation to soil P is shown for Rothamsted in Fig. 5.5a. Data for 1992 and 1994 were reasonably described by a single relationship, whereas that in 1995 was different with generally lower shoot %P. This was most likely due to the dry conditions in 1995. Overall, shoot %P increased with soil P from 0.20% to 0.35%. Shoot Pw was less affected than %P by soil P, and less variable between years; the effect of the dry season in 1995 was eliminated. Overall, shoot Pw increased with soil P from 18 to 28 mM (Fig. 5.5b).

The relative increase in shoot Pi with soil P was much greater than that in shoot P (Figs. 5.5c,d). At high soil P, Pi was typically about a third of P. As in the case of P concentrations, expressing Pi concentrations on a tissue water basis eliminated differences due to the dry conditions in 1995. The large change in Pi with soil P is advantageous for diagnostic testing, but the range was not as great as in solution culture. In the field, shoot Piw reached a maximum of no more than 10 mM at a soil P of 50 mg/kg compared with 40 mM in solution culture when P supply was abundant. This is due to soil solids buffering P concentrations in soil solution.

Shoot concentrations and time

Changes in shoot %P with time (days from sowing, DFS) for P-sufficient crops are shown in Fig. 5.6a. In general, shoot %P for different sites and seasons agreed reasonably well. All crops showed the characteristic decline in %P during growth, which is largely due to increased structural material (cellulose) relative to metabolic material during stem elongation.

Differences in %P between sites and seasons were most pronounced in the early stages of growth, although the crop at Rothamsted in 1992 deviated later in the season. Differences between sites in the same year could be due to differences in growing conditions (temperature, water, N) or to differences in soil P. Thus Rothamsted had greater soil P levels than Ropsley, and shoot %P was generally greater at Rothamsted than at Ropsley. Differences between years at the same site could be due to differences in growing conditions and factors affecting P availability (e.g. soil water).

Figure 5.5 Shoot P and Pi concentrations and soil P (Rothamsted)

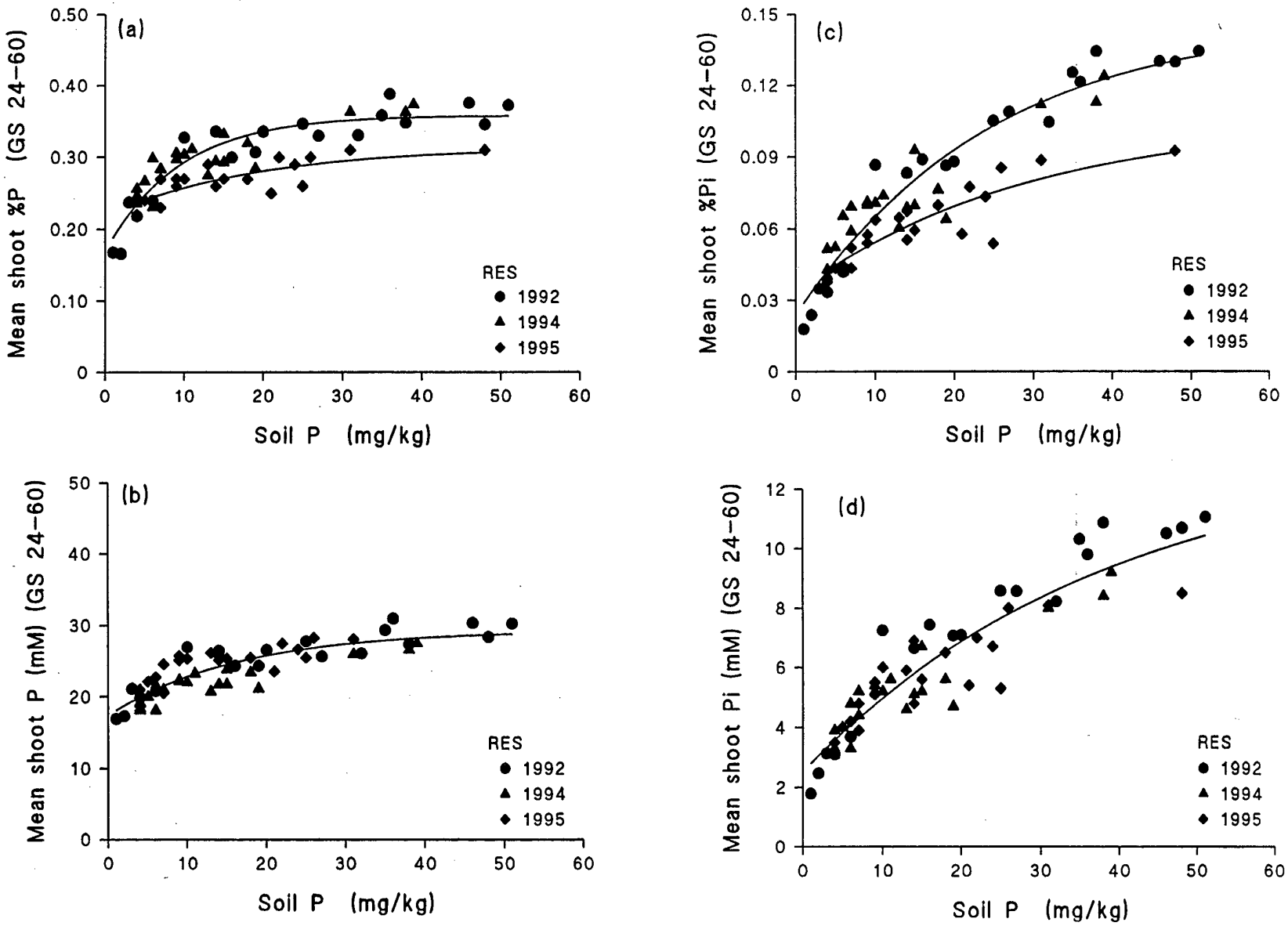
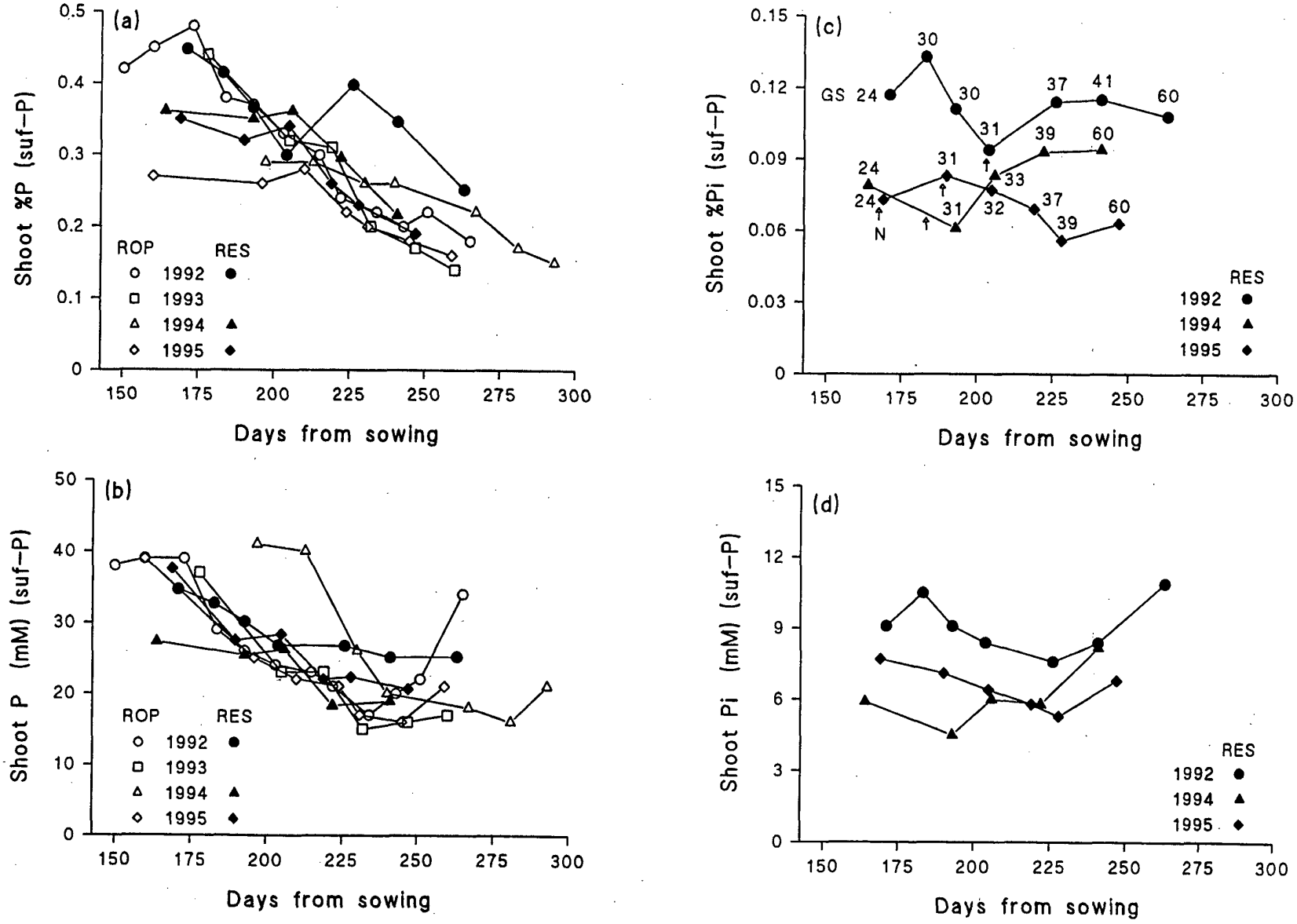


Figure 5.6 Shoot P and Pi in P-sufficient crops over time



At Ropsley, the large early differences in %P between 1992 and 1995 were probably due to differences in soil water content. Dry topsoil is known to reduce the availability of soil P (Leigh and Johnston, 1986). In field experiments studying the effects of water availability on spring barley, Day (1981) found that shoot %P was reduced, typically by 0.1%, by drought. Soil water was not measured in the present study, but shoot tissue water which reflects water availability was measured. Shoot tissue water levels were much lower at Ropsley in 1995 than in 1992 (Fig. 5.4c). This could also account for the early differences in %P at Rothamsted in 1992 and 1995, but not for the low %P in 1994. At the first sampling, shoot %P was much lower in 1994 than in 1992, despite a higher tissue water content in the 1994 crop (Fig. 5.4a).

At Rothamsted in 1992, the decline in %P with growth was interrupted by a sharp increase at GS 37 (226 DFS). This was immediately following a large application of fertiliser N. The N was given as a single dose, to what was probably an N-deficient crop, and was the first and only N application to the crop. Similarly at Ropsley in 1992, an increase in %P was noted following the application of N in early March. Increases in shoot %P following the addition of N fertiliser (against a general decline during stem extension) are well documented for cereals (Gregory *et al.*, 1979; Barraclough, 1986; Leigh and Johnston, 1986).

Expressing P concentrations on a tissue water basis reduced the variation between sites and seasons, at least prior anthesis. It did not bring the anomalous Rothamsted 1992 crop completely into line however (Fig. 5.6b). Shoot Pw declined with time in a similar way to shoot %P. Between tillering and anthesis, Pw declined from 40 to 20 mM overall compared with 0.40 to 0.20% for %P. The sharp increases in %P following the application of N to the crops at Rothamsted and Ropsley in 1992 were eliminated. Leigh and Johnston (1986) also reported that expressing concentrations on a tissue water basis reduced differences in shoot %P due to differences in N supply, and completely eliminated those due to differences in water supply.

Shoot Pi concentrations for Rothamsted are shown in Figs. 5.6c,d. Pi concentrations, unlike P concentrations, did not consistently decline during stem extension, but they were variable. Shoot %Pi, but not Piw, appeared to increase in response to N, matching the situation with P concentrations, i.e. "dry" concentrations responded to N whilst "wet" concentrations did not. The major feature of the Rothamsted Pi data is the marked difference in Pi between 1992 and the other two years on ostensibly the same soil. Shoot %Pi and Piw were consistently higher in 1992 than in the other two years and the reasons for this are unknown. All

Rothamsted crops were grown on the same soil series, but the 1992 crop was grown on a different field with a different cropping and fertilising history which may have affected P availability, despite similar Olsen-P values.

Changes in P and Pi concentrations with time on individual plots at Rothamsted in 1992 (i.e. for different soil P levels) are shown in Fig. 5.7. Critical concentrations are also shown for comparison. Critical P concentrations tracked P concentrations in P-sufficient crops very closely (Fig. 5.7a). Shoot %Pi in P-sufficient crops changed erratically with time depending on soil P (Fig. 5.7c). High soil P plots showed a marked increase in %Pi following the N application, whilst lower soil P plots showed no increase. The net effect was an increase in %Pi in P-sufficient crops, but a slight reduction in critical %Pi. Clearly critical %Pi did not track %Pi exactly at all times. Critical Pi concentrations were more stable during growth than critical P concentrations.

5.2.4 Shoots: Critical P and Pi

Examples of relationships between yield and shoot P and Pi concentrations for Rothamsted in 1992 are shown in Fig. 5.8. The relationships between yield and shoot %P or Pw (Figs. 5.8a,b) shifted with growth stage, but a single relationship was adequate for all growth stages in the case of yield and %Pi or Piw (Figs. 5.8c,d). The overall critical %Pi concentration in 1992 was about 0.05%, and the overall critical Piw concentration was about 5 mM. Relationships between yield and plant concentrations were not as good in other years.

Critical shoot P and Pi concentrations for all sites and seasons are shown in Fig. 5.9. There were large differences in critical %P between sites and seasons particularly in the early stages of growth. Critical values at late tillering were in the range 0.25-0.45%, declining to about 0.20% at anthesis. At anthesis, %P at all levels of soil P had generally converged (see Fig. 5.6a) and critical shoot %P was therefore reasonably constant between sites and seasons at that time.

When shoot P concentrations were expressed on a tissue water basis, critical values still declined with growth from about 40 mM at tillering to 20 mM at anthesis, but the early site/season variation was reduced indicating that this was largely a tissue water effect (Fig. 5.9b).

Figure 5.7 Changes in shoot P and Pi with time for different soil P (Rothamsted 1992)

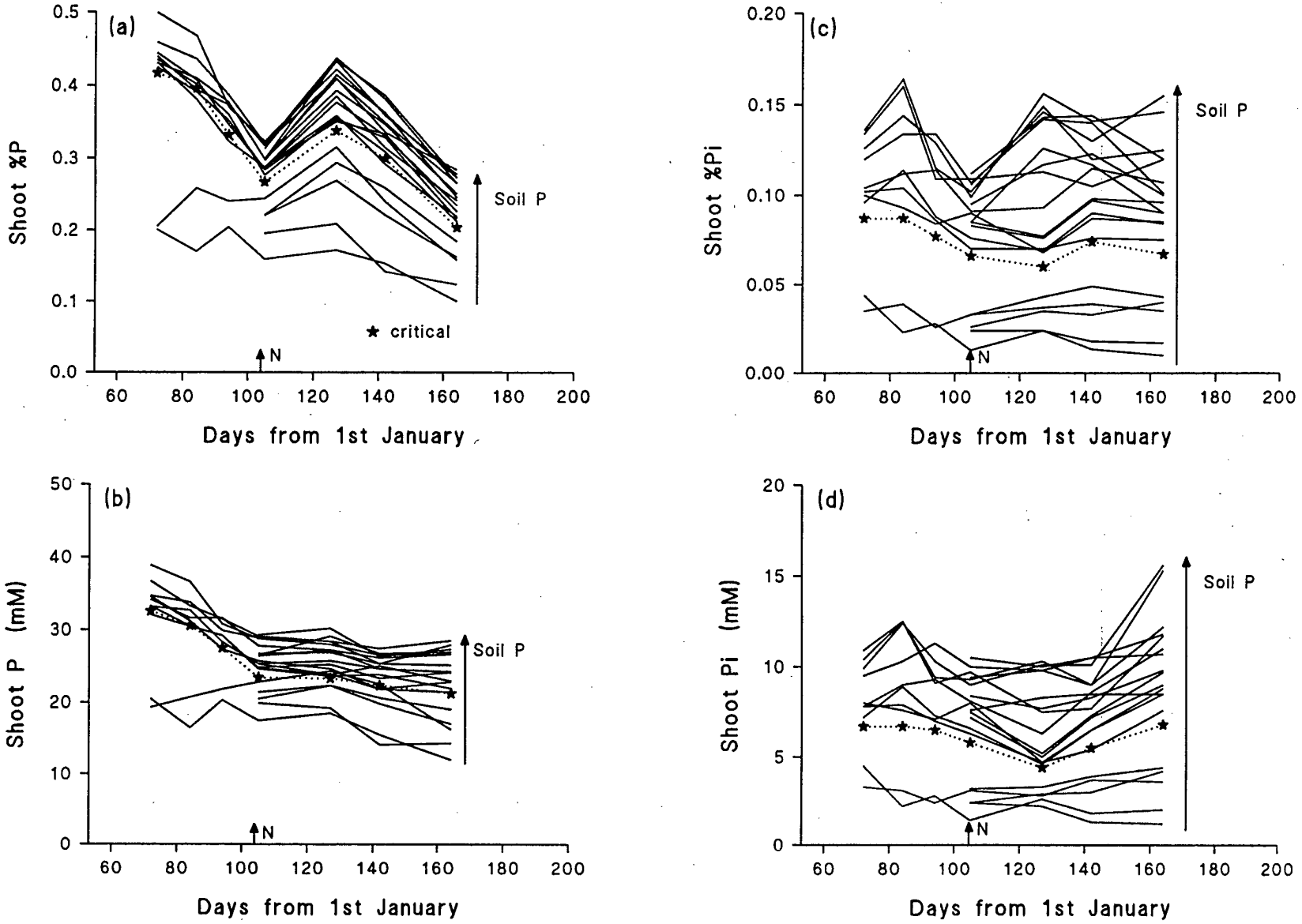


Figure 5.8 Grain yield and shoot P and Pi at Rothamsted in 1992

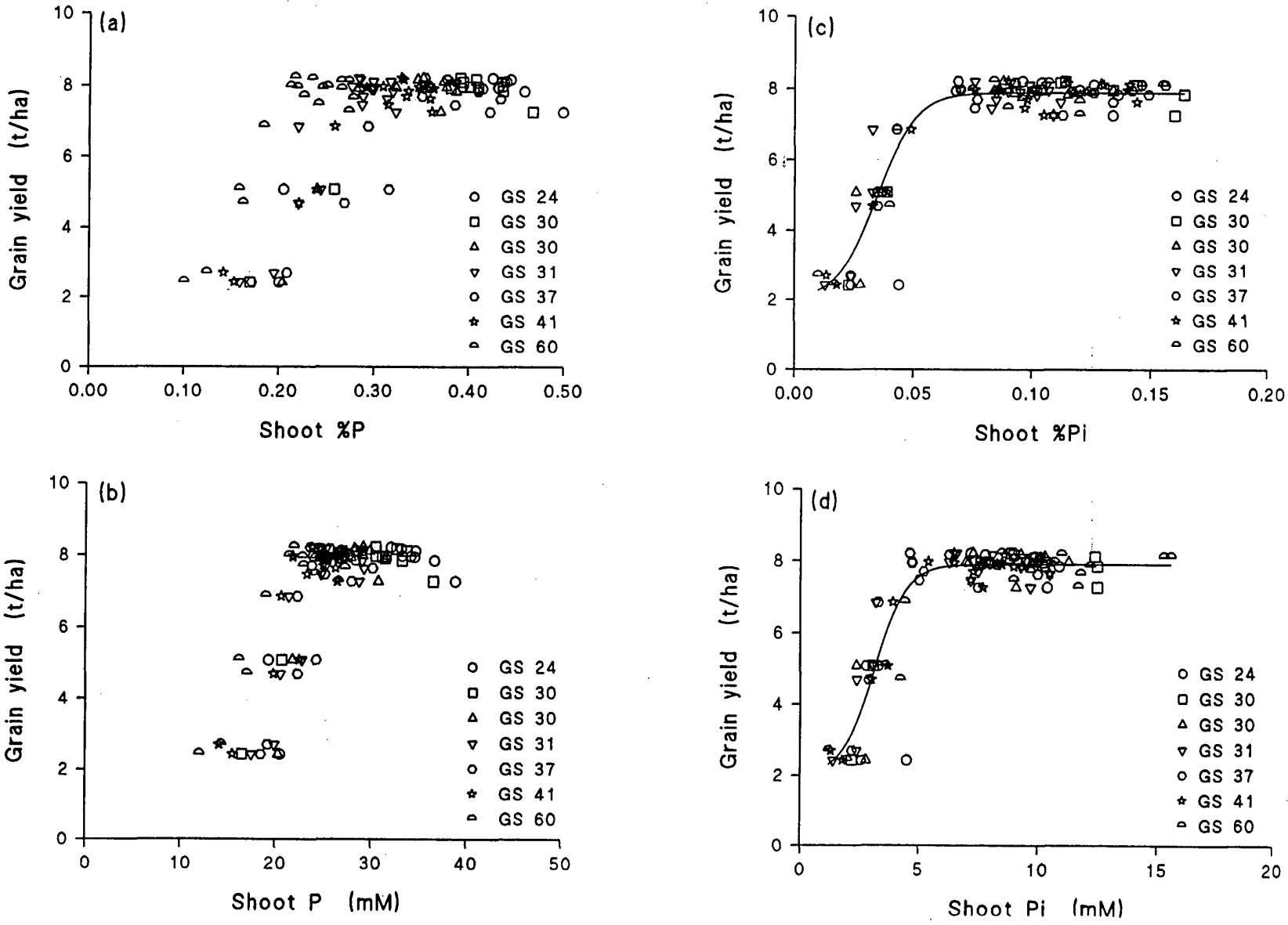
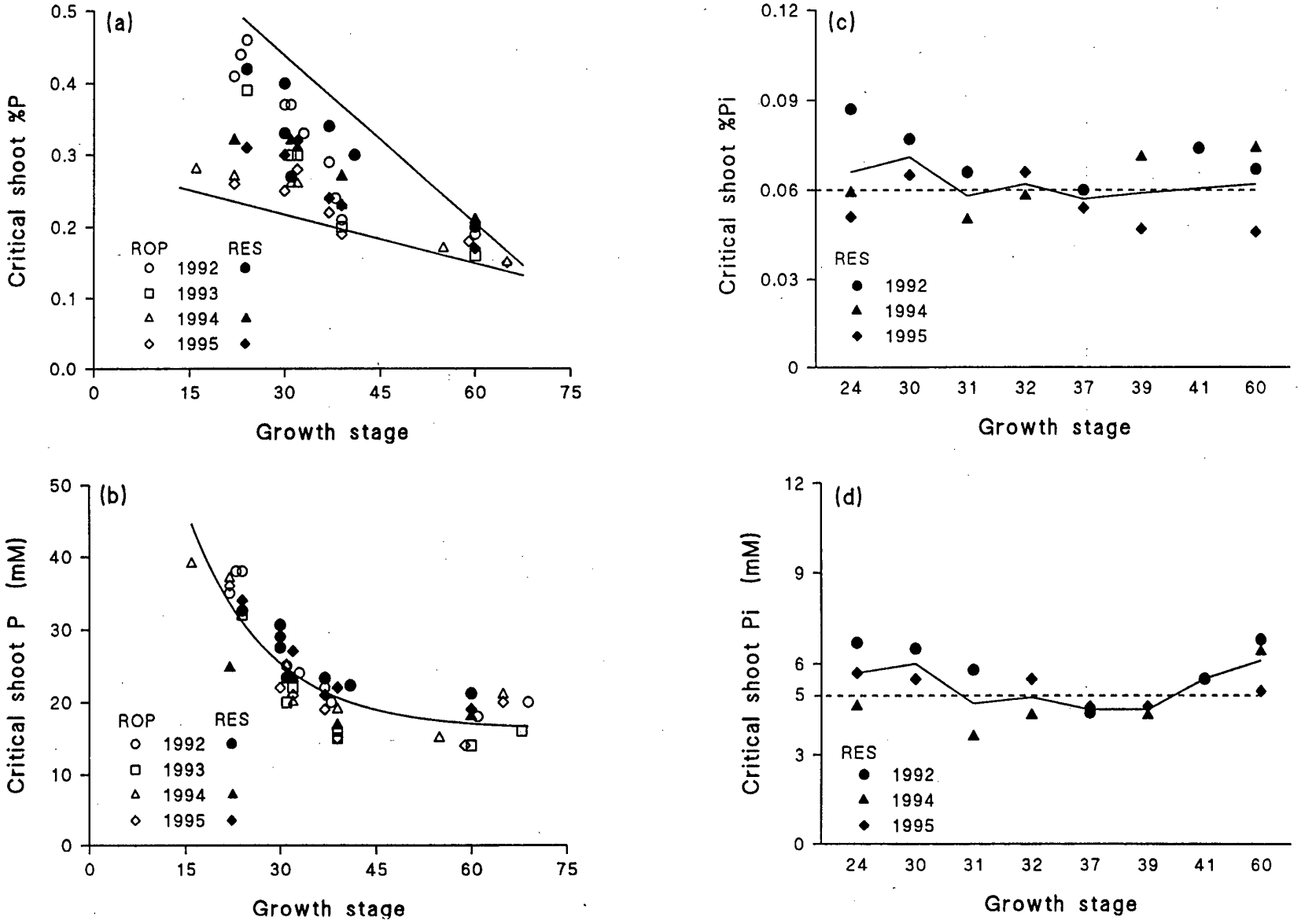


Figure 5.9 Critical shoot P and Pi values at different growth stages



Critical shoot %Pi concentrations for Rothamsted are shown in Fig. 5.9c. No consistent trend with time was apparent, but critical %Pi changed during growth and varied between seasons. Variation was greatest early and late in the season and least during stem elongation. The differences were probably the result of differing P availability between seasons as discussed above. Mean critical shoot %Pi during stem elongation (GS 31-39) was 0.059% in a range of 0.047-0.071%.

Critical shoot Piw (Fig. 5.9d) followed a similar pattern to critical %Pi in that there was no consistent trend with time, although there is the suggestion of a hypobolic relationship. Variation between seasons was less than in %Pi, and critical shoot Piw was most stable during stem elongation (GS 31-39) with a mean value of 4.7 mM in a range of 3.6-5.8 mM. Critical values increased during booting and inflorescence in all seasons due to declining tissue water contents.

Over all sites, seasons and growth stages, Piw was the least variable critical shoot concentration parameter with a coefficient of variation (CV) of 18.2%. This was closely followed by shoot %Pi with a CV of 19.5%. The decline with growth stage in critical shoot %P and Pw had a large effect on variation with CVs of 28.4% and 29.3%, respectively. On this basis, shoot Pi is a better indicator of crop P status than shoot total P.

It is not obvious why critical Pi concentrations should change with growing conditions. In theory, accumulation of Pi should indicate optimal P supply irrespective of other limiting factors. If P was abundant but N was limiting for example, Pi should still accumulate to indicate that P supply was more than adequate for requirements under the N-limited conditions.

5.2.5 Shoots: Literature on critical P and Pi

There is no UK literature on critical shoot %P in winter wheat. Data from other countries are given in Table 5.2. There is no literature, for the UK or elsewhere, on critical shoot Pw, %Pi or Piw in wheat.

There are large differences in literature values for critical %P between sites and seasons at the same growth stage. This is especially evident in the early growth stages (GS 22-31) with a range of 0.20-0.62%. A similarly wide range, 0.25-0.50%, was found in the present work. Bolland and Paynter's data also show very large site/season variations in relation to DFS.

Table 5.2 Critical shoot %P for winter wheat crops

LOCATION	GS	CRITICAL	REFERENCE
NZ	51-59	0.20%	Cornforth & Sinclair, 1984
AUS	24	0.20%	Reuter & Robinson, 1986
AUS	21	0.62%	Reuter & Robinson, 1986
	24	0.56%	
	30	0.35%	
	30-31	0.23%	
	61	0.12%	
AUS	00-40[a]	0.52-1.49%[a]	Bolland & Paynter, 1994
	41-60[a]	0.38-0.61%[a]	
	61-90[a]	0.34-0.53%[a]	
	>90[a]	0.18-0.45%[a]	
USA	45	0.30%	Reuter & Robinson, 1986
USA	30	0.30%	Westfall *et al.*, 1990
	31	0.32-0.40%[b]	
	39	0.15-0.20%[b]	
USA	24-30	0.40%	Westfall *et al.*, 1990
	31-49	0.20%	
USA	51-59	0.20%	Westfall *et al.*, 1990

[a] Range is for different sites and seasons
Values shown under "GS" are actually "days from sowing"

[b] Critical Nutrient Range (CNR) is shown - above CNR the crop is likely to be well-supplied, below CNR the crop is likely to be deficient.

5.2.6 Leaf(1): P and Pi concentrations

Concentrations of P and Pi were measured in the newest fully expanded leaf (leaf(1)), i.e. the newest leaf with a visible collar. As mainstems cannot be unambiguously identified in the field at all growth stages, samples consisted of a mixture of leaves from mainstems and primary tillers in unknown proportions.

Leaf(1) concentrations and soil P

Mean P and Pi concentrations in leaf(1) in relation to soil P at Rothamsted are shown in Fig. 5.10. Concentrations are averages for the period GS 30-60. Leaf P concentrations changed relatively little with soil P (Figs. 5.10a,b); the change in Pi was greater (Figs. 5.10c,d). %P and %Pi concentrations at high soil P were lower in 1995 than in 1994 due to the drought affecting P availability. This difference was eliminated by expressing concentrations on a tissue water basis. At high soil P, Pi concentrations were about a third of P concentrations in leaf(1), the same proportion as in shoots.

Leaf(1) concentrations and time

The overall trend with time in leaf(1) %P was a decline (Fig. 5.11a), but much less than the decline observed for shoots (Fig. 5.6a). Leaf(1) %P was reasonably consistent between sites and seasons. On a tissue water basis, leaf Pw showed no discernible trend with time, but fluctuations both during the season and between sites and seasons were greater than in %P (Fig. 5.11b).

leaf(1) %Pi data in P-sufficient crops are shown in Fig. 5.11c. A common feature was a peak in concentration during stem extension. This may have been a delayed response to earlier N applications, or may be due to the remobilisation of Pi in preparation for grain filling. Leaf(1) %Pi was greater at Rothamsted than at Ropsley, presumably due to the greater maximum level of soil P at Rothamsted. The highest soil P level at Rothamsted was 50 mg/kg compared with 25 mg/l at Ropsley. Leaf(1) Piw gradually increased during the season (Fig. 5.11d) due to declining tissue water contents (Figs. 5.4b,d).

Changes in P and Pi concentrations with time on individual plots (i.e. for different soil P levels) at Rothamsted in 1994 are shown in Fig. 5.12. Critical concentrations are also shown for comparison. Critical concentrations tracked actual concentrations very closely in all cases.

Figure 5.10 Leaf (1) P and Pi and soil P (Rothamsted)

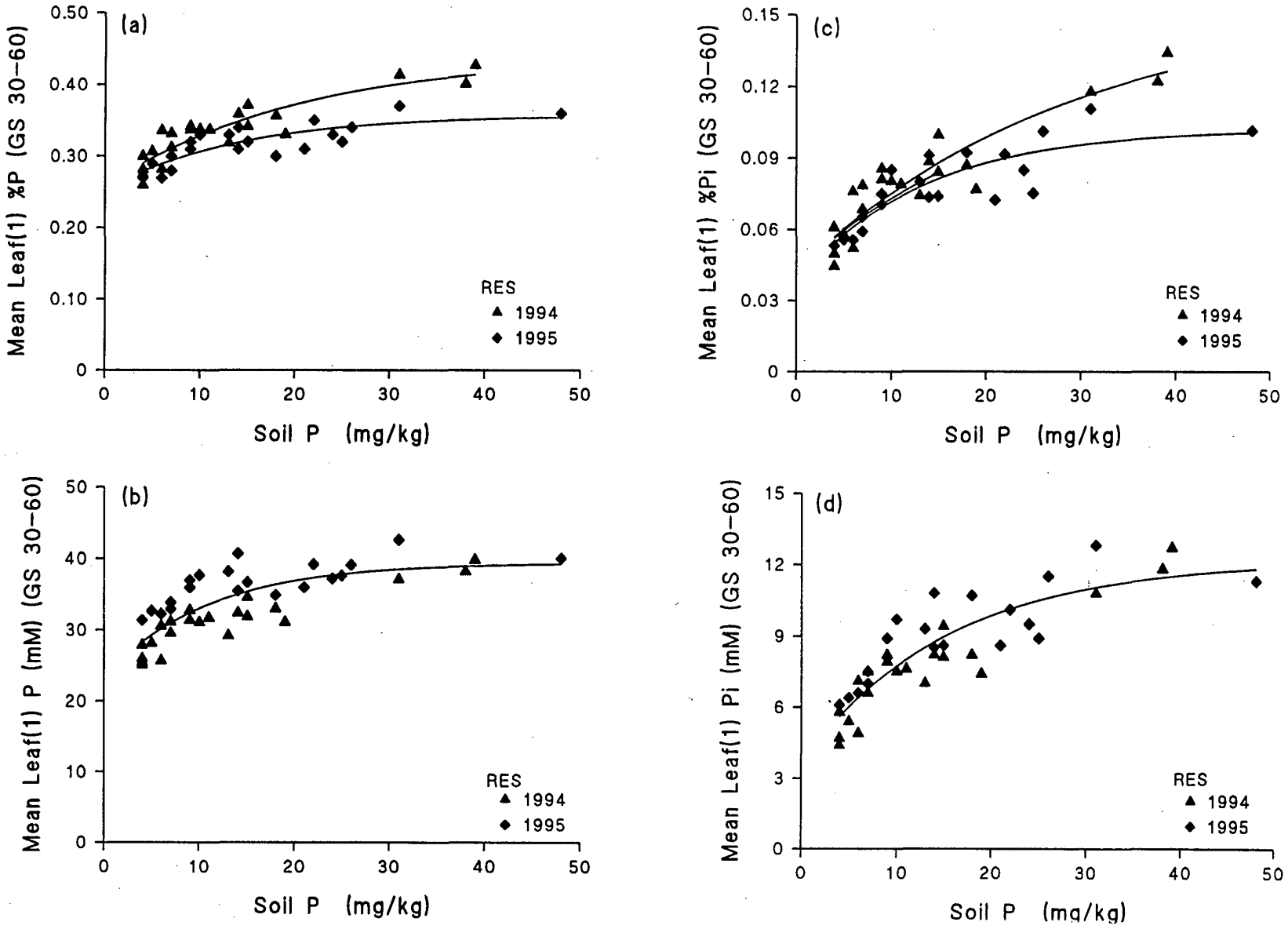


Figure 5.11 P and Pi in leaf (1) of P-sufficient crops with time

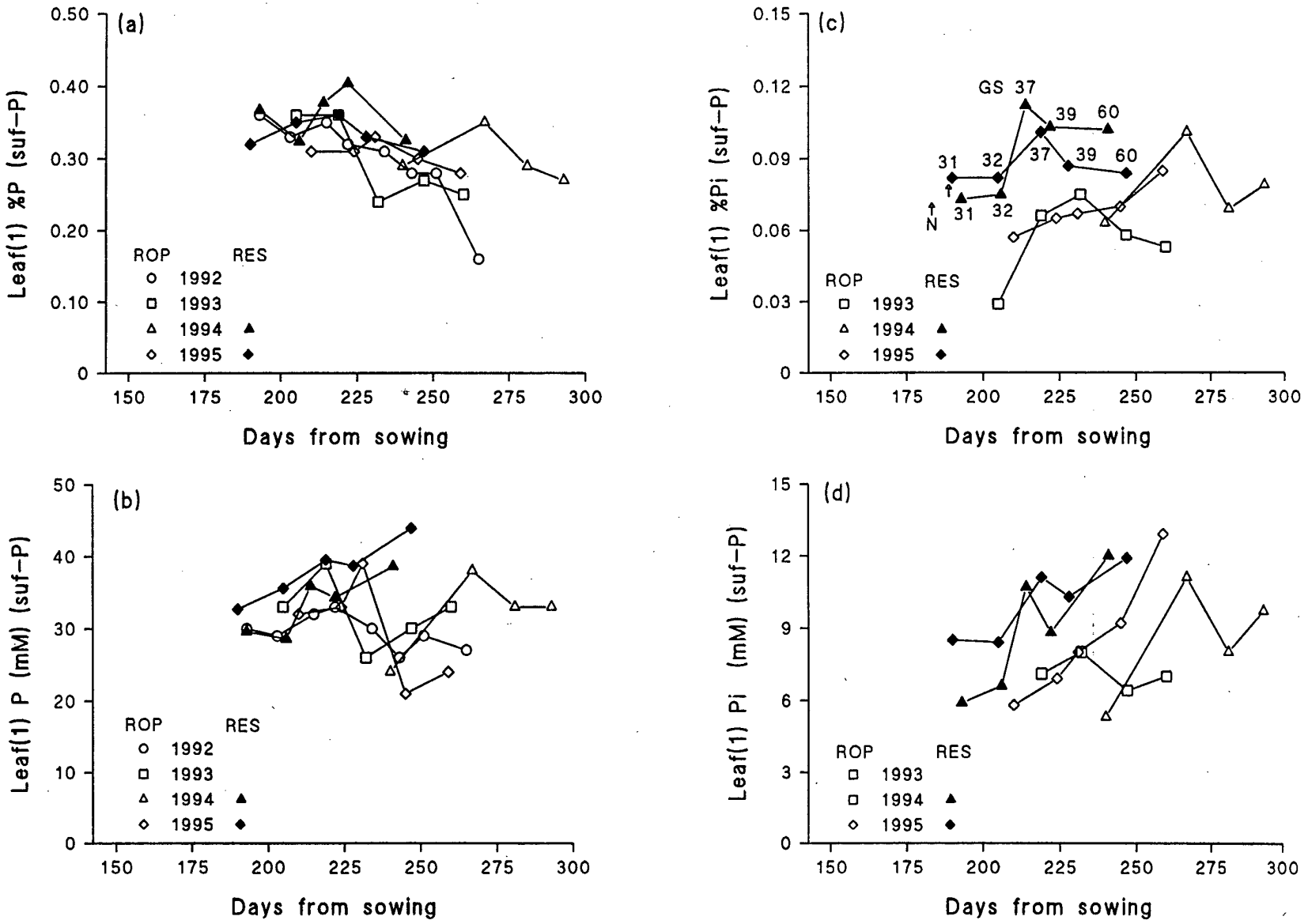
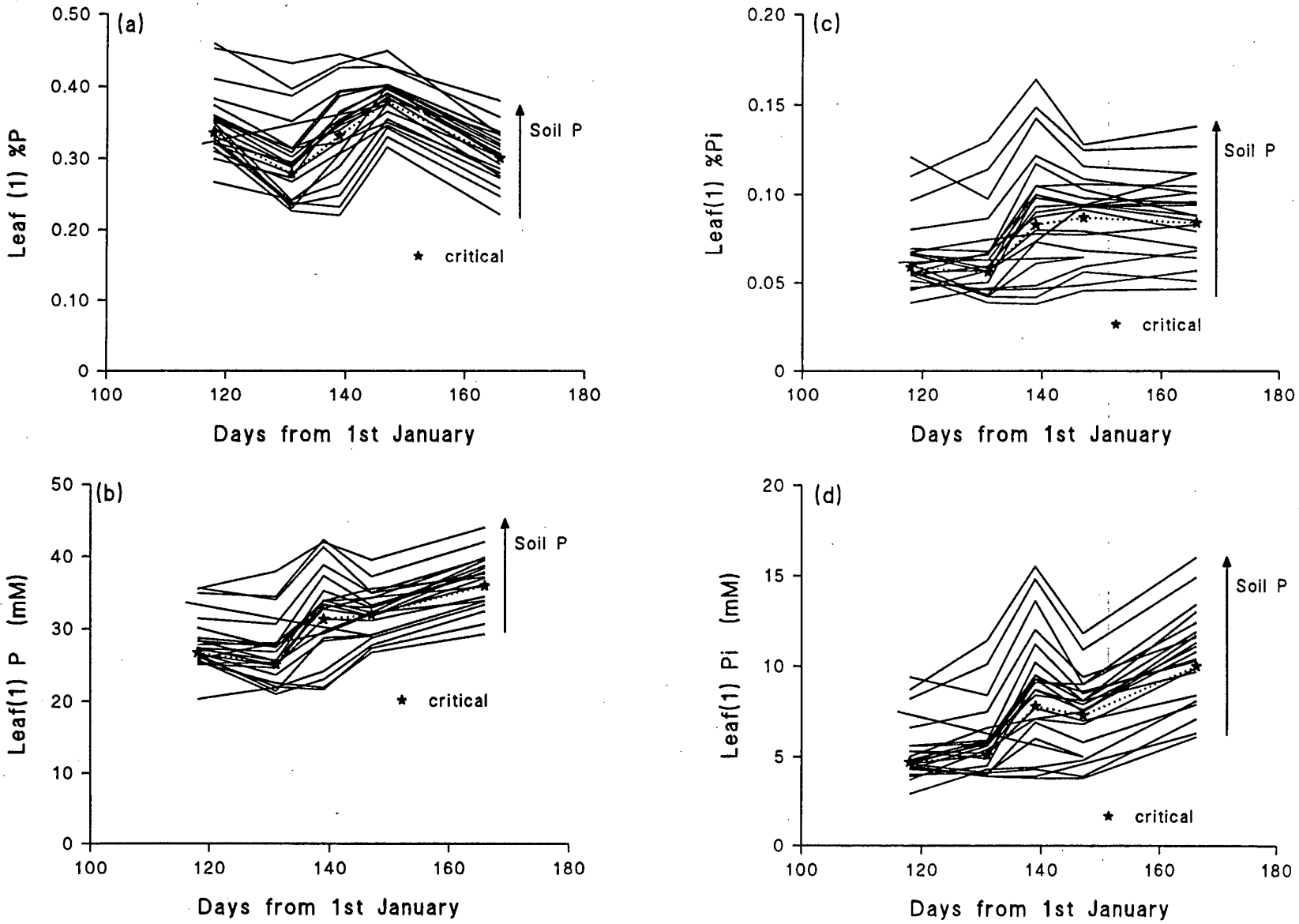


Figure 5.12 Leaf (1) P and Pi with time for different soil P (Rothamsted 1994)



Concentrations in different plant parts

In general, concentrations in leaf(1) were equal or greater than those in whole shoots (compare Fig. 5.5 with 5.10 and Fig. 5.6 with 5.11). A detailed comparison of leaf and shoot concentrations at Rothamsted in 1994 is shown in Fig. 5.13. Leaf(1) concentrations were always equal or greater than shoot concentrations. Differences between shoots and leaves were generally more marked on a tissue water basis than on a dry matter basis. There was an increase in leaf(1) concentration, but not in shoots, at 140 DFS (GS 37). Gregory *et al.* (1979) found that %P was greater in leaf sheaths than in blades before stem extension, but greater in leaves (that is all leaves combined) than in stems thereafter. They found that %P declined in (all) leaves and stems with growth, but much more in stems during stem elongation.

P and Pi concentrations in different leaves at Ropsley are shown in Table 5.3. Concentrations were measured at GS 39 and are averages over all P treatments. Concentrations were greatest in the flag leaf (leaf(1)) and declined the older the leaf.

Figure 5.13 P and Pi in shoots and leaf (1) of P-sufficient crops at Rothamsted in 1994

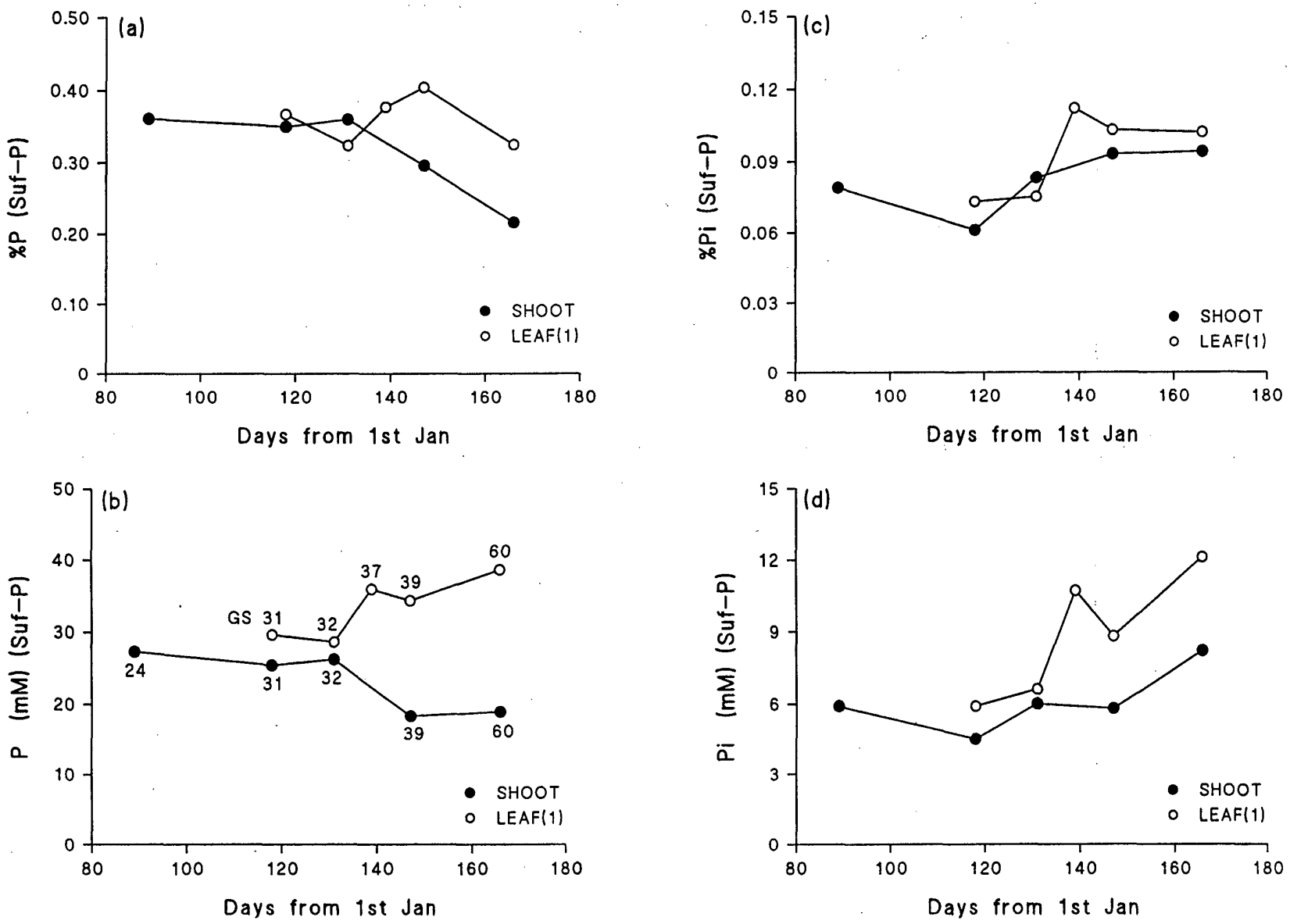


Table 5.3 Percent P and Pi concentrations in different leaves at GS 39 (Ropsley 1992-95)

Leaf	1992		1993		1994		1995	
	%P	%Pi	%P	%Pi	%P	%Pi	%P	%Pi
1	0.31	0.079	0.24	0.074	0.35	0.103	0.32	0.064
2	0.29	0.071	0.26	0.056	0.29	0.058	0.25	0.048
3	0.23	0.056	0.20	0.039	0.24	0.043	0.22	0.036
4	-	-	0.15	0.031	0.20	0.038	0.18	0.028
Stem	-	-	0.08	0.012	0.21	0.043	0.17	0.029

5.2.7 Leaf(1): Critical P and Pi

Examples of relationships between grain yield and leaf(1) P and Pi concentrations for Rothamsted in 1994 are shown in Fig. 5.14. The relationships are much poorer than those for shoots in 1992, and there is no clear universal relationship for leaf Pi as was the case for shoot Pi in 1992 (Fig. 5.8).

Critical leaf(1) %P showed no consistent trend with time but fluctuated and varied between sites and seasons (Fig. 5.15a). The variation was less than for shoots. The mean critical value between GS 31-39 was 0.32% in a range of 0.28-0.38%. The mean value declined to 0.28% (range 0.26-0.30%) at anthesis. Critical leaf(1) Pw was more variable than %P, particularly at anthesis. Mean critical leaf(1) Piw increased slightly during crop growth from about 30 mM at GS 31 to 35 mM at GS 60 (Fig. 5.15b).

Critical leaf(1) %Pi showed no consistent trend with time, but fluctuated and varied with site and season to a greater extent than %P. Most values were in the range 0.06-0.08% (Fig. 5.15c). At Ropsley, critical values were very close to 0.06% in all years. At Rothamsted, critical %Pi increased at GS 37 in both years, matching observed increases in %Pi.

Expressing leaf(1) Pi concentrations on a tissue water basis made little difference to the site/season variation, and resulted in a distinct increase in critical values with growth stage (Fig. 5.15d), due to declining tissue water contents (Fig. 5.4). Values increased from around 5 mM at GS 31 to 9 mM at GS 60. Critical values at Rothamsted were always greater in 1995 than those in 1994 due largely to lower tissue water contents (Fig. 5.4b).

Over all sites, seasons and growth stages, %P was the least variable critical leaf(1) concentration parameter with a coefficient of variation (CV) of 11.2%. CVs for leaf(1) Pw, %Pi and Piw were 17.5%, 17.5% and 24.0%, respectively. On this basis, leaf(1) %P is the best overall indicator of crop P status.

5.2.8 Leaf(1): Literature on critical P and Pi

There is no UK data in the literature on critical leaf P and Pi concentrations in winter wheat; very little worldwide data on leaf %Pi, and no data at all on critical leaf Pw and Piw concentrations. Data on critical leaf(1) %P in wheat from other countries are given in Table 5.4.

Figure 5.14 Grain yield and leaf(1) P and Pi concentrations (Rothamsted 1994)

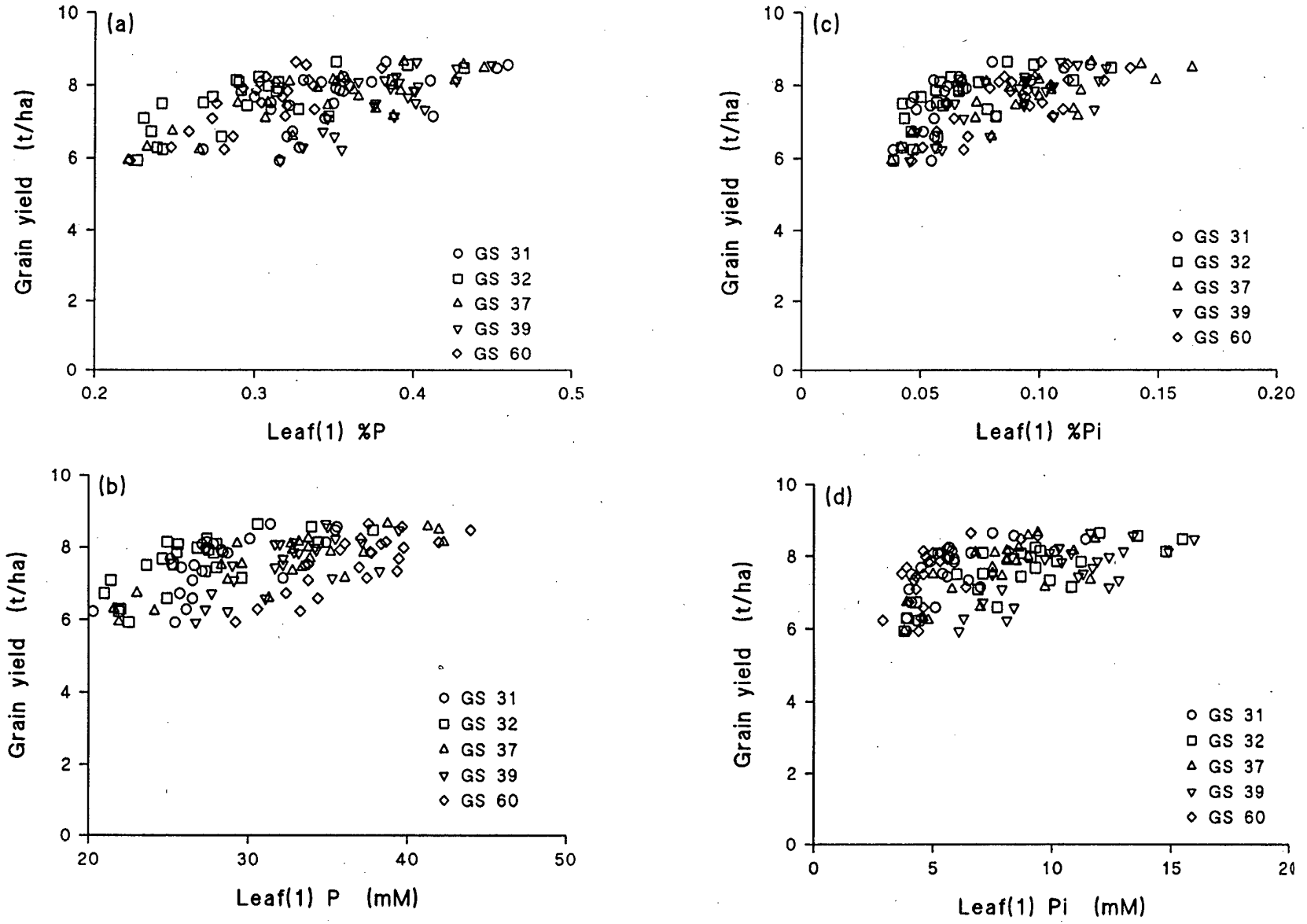


Figure 5.15 Critical leaf(1) P and Pi concentrations with growth stage

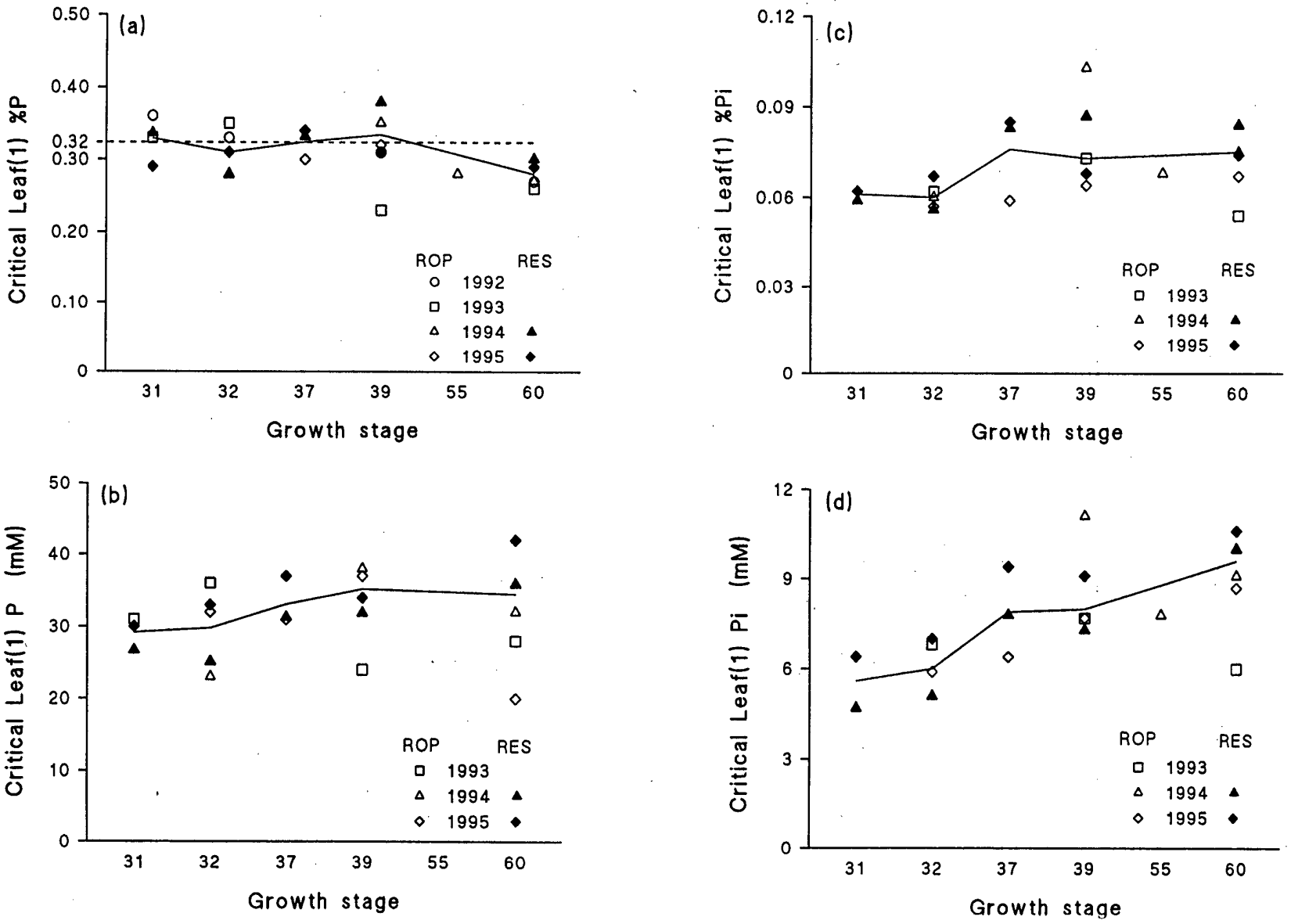


Table 5.4 Critical leaf(1) %P for winter wheat crops

LOCATION	LEAF	GS	CRITICAL	REFERENCE
AUS	Leaf(1)	21	0.55-0.60%	Reuter & Robinson, 1986
		24	0.40-0.44%	
		30	0.30-0.37%	
		30-31	0.27-0.30%	
	Leaf(2)	21	0.40-0.45%	
		24	0.39%	
		30	0.23-0.30%	
		30-31	0.23-0.27%	
	Leaf(3)	21	0.41-0.44%	
		24	0.33%	
		30	0.23-0.27%	
		30-31	0.22%	
AUS	Leaf(1)	13	0.30%	Reuter & Robinson, 1986
USA	Leaf(1)	49	0.20%	Reuter & Robinson, 1986
USA	Leaf(1)	41-49	0.30%	Westfall *et al.*, 1990
USA	Leaf(1+2)	49	0.21%	Benton Jones *et al.*, 1991
USSR	Leaf(1)	21-24	0.35%	Reuter & Robinson, 1986
		30-39	0.32%	
		60-69	0.25%	
FRA	Leaf(2+3)	60-69	0.31%	Loue, 1987

The most comprehensive set of critical leaf %Pvalues for wheat are those given by Reuter and Robinson (1986) for Australian crops. Critical values declined substantially during tillering, but critical ranges were quite narrow for a given leaf at a given growth stage. The Australian values for leaf(1) at GS 30-31 (0.27-0.37%) are in good agreement with the present work (ca. 0.32%). The present results are also in good agreement with the Russian, French and American results cited by Westfall *et al.* (1990).

There is very little data in the literature on leaf(1) %Pi concentrations. Reuter and Robinson (1986) reported critical values of 0.013% and 0.007-0.009% at GS 24 and 30, respectively, much lower than the present values. According to Saarela (1990), critical %Pi in leaves(1+2) for wheat grown in Finland was less than 0.036%, again lower than the present values. A value of 0.18% was reported by Raun and Westerman (1991) for wheat grown in the USA, although the leaves had been oven-dried. When comparing Pi concentrations from different studies it is important to take account of the extraction and analytical methods that were employed, as this can affect Pi concentrations as a result of phosphate ester transformations.

5.3 CONCLUSIONS FOR P

YIELD RESPONSE TO SOIL P

At Rothamsted, maximum grain yield response to soil P was nearly 6 t/ha on soil with an extractable P value of 1 mg/kg. This was an extremely deficient soil corresponding to the bottom of ADAS P Index 0. On soil with an extractable P of 4 mg/kg (middle of Index 0), the response averaged nearly 2 t/ha. At Ropsley in Lincolnshire, yield response to soil and fertiliser P on a soil at 10 mg/l (bottom of Index 1) averaged 1 t/ha.

CRITICAL SOIL P

Critical soil P (for 95% maximum grain yield) differed little between years on a given soil, but depended on soil type. At Rothamsted, critical soil P was 10 mg/kg (bottom of Index 1), and at Ropsley it was 16 mg/l (bottom of Index 2). [Critical soil P according to current ADAS recommendations is 15 mg/l (top of ADAS P Index 1).]

TOTAL-P: WHOLE SHOOTS

P in dry matter

Critical %P in whole shoot dry matter (for 95% maximum grain yield) declined during growth and varied between sites and seasons. Variation was greatest during tillering. The

average critical value declined from 0.35% at late tillering to 0.20% at anthesis. The decline in critical shoot %P during growth is due mainly to dilution of P with structural dry matter. Site and season differences were most likely caused by differences in growing conditions, particularly the availability of N and water.

P in tissue water

Critical whole shoot P concentrations expressed on a tissue water basis (Pw) also declined during growth, but the early site/season variation evident in critical %P was reduced. Average critical shoot Pw declined from 35 mM at late tillering to 20 mM at anthesis.

TOTAL-P: LEAF(1)

P in dry matter

Critical %P in the newest fully expanded leaf blade (leaf(1)) was the most stable P concentration parameter. It averaged 0.32% during stem elongation (GS 31-39), in a range of 0.28-0.38%, but declined at anthesis.

P in tissue water

Expressed on a tissue water basis, critical leaf(1) Pw was more variable than %P and increased during plant growth. Mean critical leaf(1) Pw increased from 30 mM at GS 31 to 35 mM at GS 60.

INORGANIC-Pi: WHOLE SHOOTS

Pi in dry matter

Critical %Pi in shoot dry matter, unlike shoot %P, did not consistently decline during plant growth, but varied between seasons. Mean critical shoot %Pi during stem elongation (GS 31-39) was 0.059% in a range of 0.047-0.071%.

Pi in tissue water

Winter wheat abundantly supplied with P accumulated inorganic phosphate (Pi). In hydroponics, young shoots accumulated Pi to 40 mM without adversely affecting growth, whilst a Pi concentration of 3-5 mM appeared obligatory for metabolism and growth with storage beginning above this. In the field, shoots accumulated Pi to levels of 12 mM, about a third of total P. In the field, seasonal differences in critical %Pi were reduced by expressing Pi concentrations on a tissue water basis. Mean critical shoot Piw during stem elongation (GS 31-39) was 4.7 mM in a range of 3.6-5.8 mM.

INORGANIC-Pi: LEAF(1)

Pi in dry matter

Critical %Pi in the newest fully expanded leaf blade (leaf(1)) was more variable than critical leaf(1) %P. Over all sites and seasons, most critical %Pi values were in the range 0.06-0.08%. There was no consistent trend in critical leaf(1) %Pi with time.

Pi in tissue water

Expressing leaf concentrations on a tissue water basis increased variability in critical leaf(1) Piw and caused values to increase with crop growth from about 5 mM at GS 31 to 9 mM at GS 60. Some of the increase was due to declining tissue water content in the leaves.

WHOLE SHOOTS vs LEAF(1)

Leaf(1) testing was generally superior to whole shoot testing in the case of total-P, with no consistent decline in critical values during growth and the lowest site/season variation. In the case of inorganic-P, shoot testing was superior to leaf(1) testing.

DRY MATTER vs TISSUE WATER

Expressing concentrations on a tissue water basis reduced site/season variation in critical shoot concentrations, but increased variation in critical leaf(1) concentrations. It altered the time course of critical leaf(1) concentrations but not that of critical shoot concentrations.

TOTAL-P vs INORGANIC-Pi

Pi testing was superior to P testing in the case of whole shoots but not in the case of leaf(1). There was no consistent decline in critical shoot Pi during growth and less site/season variation than in P.

5.4 RECOMMENDED TESTS FOR P

The recommended test for diagnosing the P status of winter wheat, based on the stability of critical concentrations during growth and between sites and seasons, is leaf(1) %P. Mean critical leaf(1) %P was 0.32% during stem elongation (GS 31-39) in a range of 0.28-0.38%.

Whole shoot %Pi and Piw were also reasonably stable during stem elongation (GS 31-39), with mean critical values of 0.06% (range 0.05-0.07%) and 5 mM (range 4-6 mM), respectively. Sampling whole shoots may present greater problems than sampling leaf(1) however.

6 POTASSIUM: RESULTS AND DISCUSSION

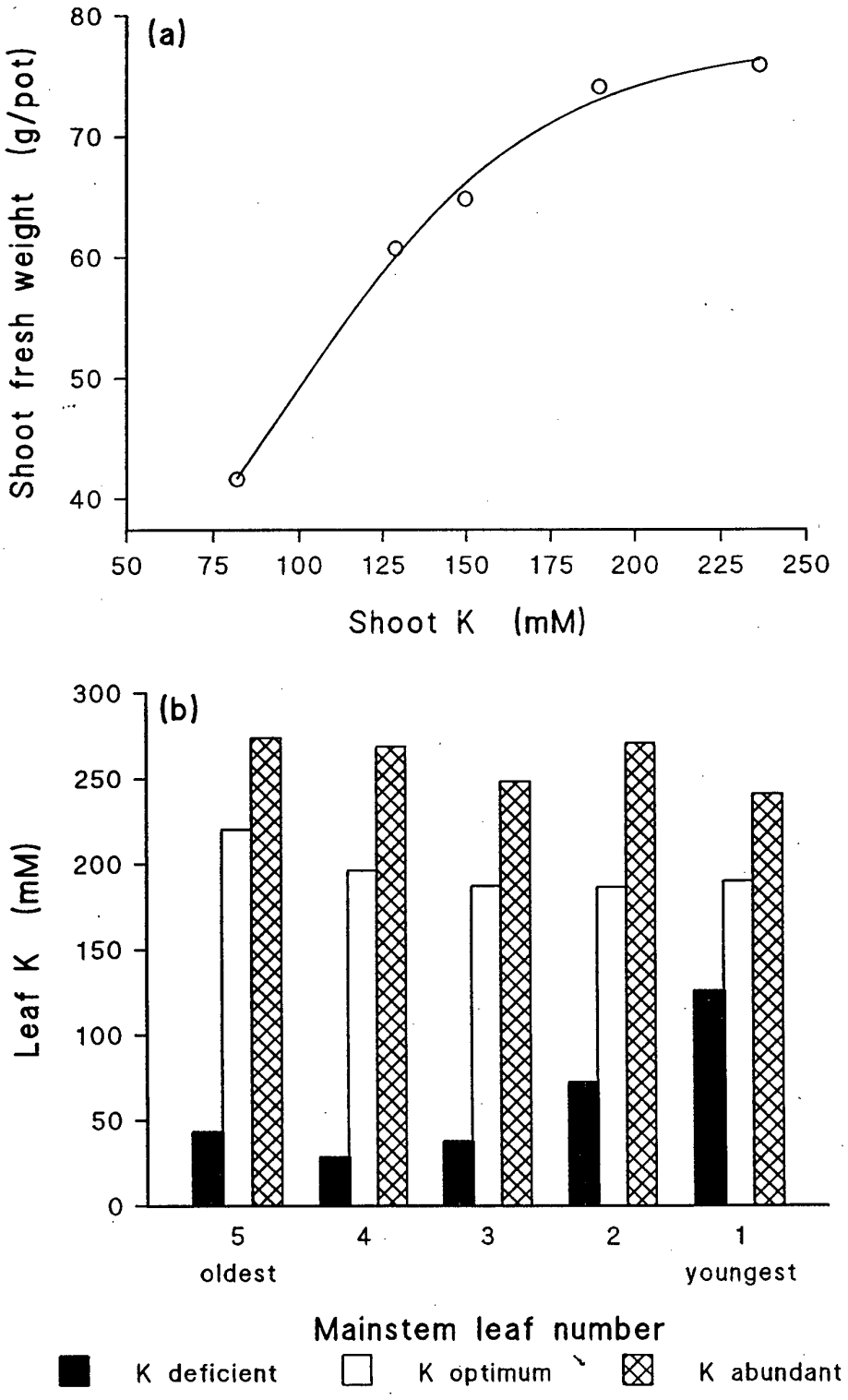
6.1 HYDROPONIC EXPERIMENTS

Potassium concentrations in the tissue water of young whole shoots ranged from 80 to 250 mM depending on K supply, with a near two-fold effect on growth (Fig. 6.1a). Critical shoot Kw for 95% of maximum shoot fresh weight was 190 mM. This was in good agreement with the results of Jensen (1982) who reported a critical shoot Kw of 180 mM for wheat. Increases in shoot growth with K supply were due mainly to increases in the number and weight of tillers rather than to the weight of the mainstem. Potassium concentrations were very similar in all mainstem leaves when K supply was adequate to abundant (Fig. 6.1b); at abundant supply, Kw attained a ceiling of about 250 mM, whilst at adequate (critical) supply, Kw was about 190 mM. Only when K supply was deficient did Kw differ markedly between leaves; the youngest leaf, which was still expanding, had a concentration of 130 mM, compared with concentrations of 50 mM or less in older leaves. Clearly, under deficiency conditions, concentrations in leaves that were still expanding were protected at the expense of older leaves. Concentration differences between plants deficiently- and adequately-supplied with K were greater the older the leaf.

A concentration of 250 mM is probably the "osmotic ceiling" for potassium accumulation in optimally growing wheat. Similar ceiling concentrations were attained under field conditions. The existence of an osmotic ceiling means that tissue water concentrations are likely to be less useful than dry matter concentrations for indicating when K supply is abundant.

It is well known that Na can substitute for K in biophysical roles in some species, so the availability of Na would be expected to lower critical K concentrations. The present experiments were performed with Na-free solutions. Calcium and magnesium are also able to substitute for K to a limited extent, so critical K concentrations will also be affected by the availability of these ions.

Figure 6.1 Leaf and shoot K concentrations in hydroponic experiments



6.2 FIELD EXPERIMENTS

6.2.1 Grain yield/Soil K/Fertiliser K relationships

Yield ranges for all sites and seasons are shown in Table 6.1. Yield ranges for Rothamsted were derived from fitted curves at the maximum and minimum soil Kex values determined in early spring (Fig. 6.2a). Topsoil Kex ranged from 59-167, 40-177 and 59-186 mg/kg in 1993, 94 and 95, respectively, i.e. top of ADAS Index 0 (deficient) to mid Index 2 (sufficient) (see Appendix 1).

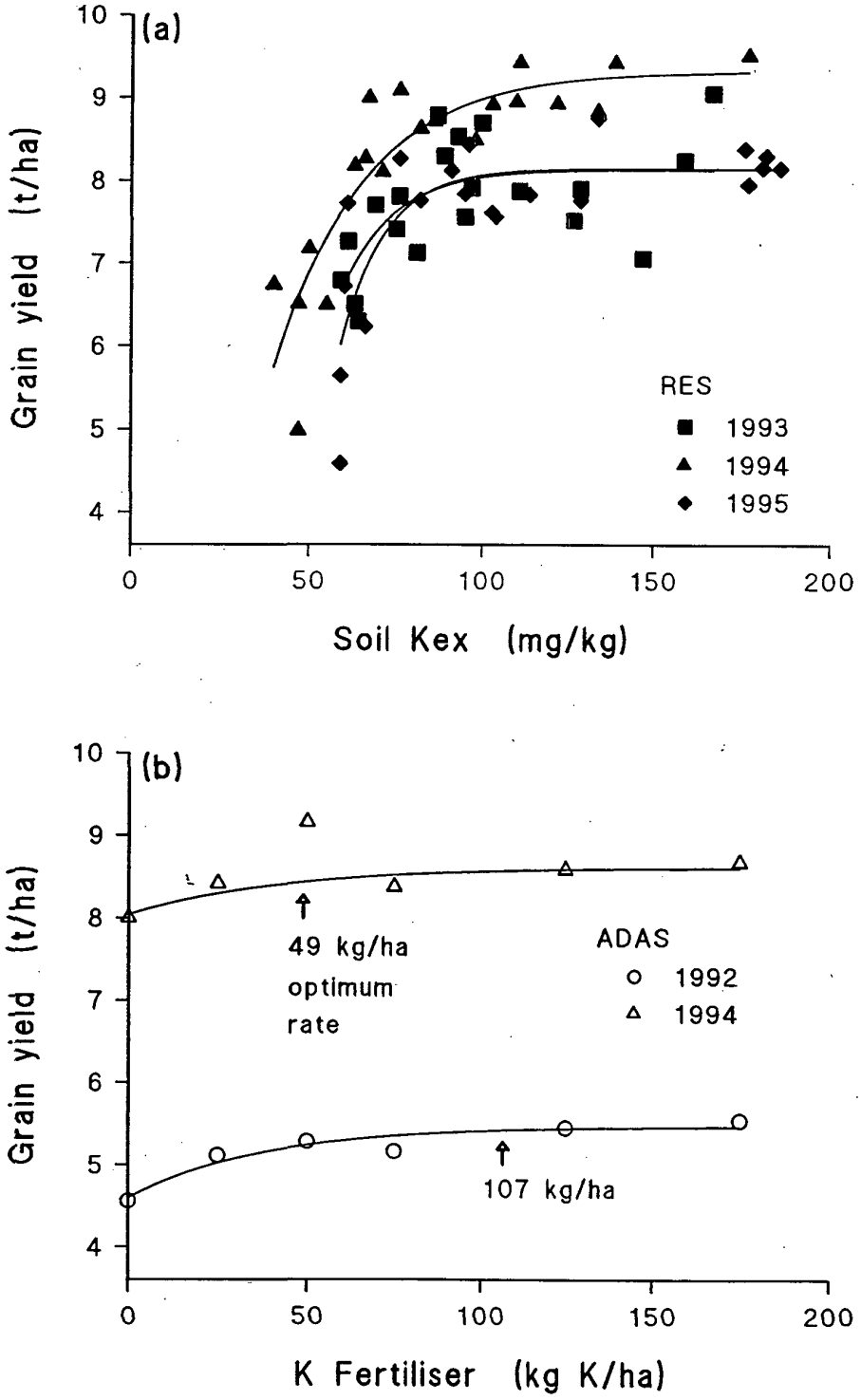
Fowlmere yield ranges represent the lowest and highest fitted treatment yields, and are the combined response to both residual and fresh fertiliser K (Fig. 6.2b). Topsoil Kext at Fowlmere, measured after harvest of the previous crop, was 32 and 50 mg/l in autumn 1991 and 1993, respectively. At Ingham in 1993, the spring wheat crop did not respond to K fertiliser (topsoil Kext 79 mg/l), nor did the winter wheat crop respond at Sedge Fen in 1995 (topsoil Kext 48 mg/l). All sites would have been expected to respond to K fertiliser on the basis of their soil Kext values.

Table 6.1 Grain yields (85% DM)

SITE	1992	1993	1994	1995
ROTHAMSTED		6.68-8.15	5.78-9.32	6.00-8.15
FOWLMERE	4.57-5.51		8.00-8.80	
INGHAM		7.37		
SEDGE FEN				7.60

Maximum yield (85% DM) at Rothamsted was 8.15, 9.32 and 8.15 t/ha in 1993, 94 and 95, respectively. It is possible that yield was limited by N supply in 1993 (115 kg N/ha was applied compared with 200 kg/ha in 1994 and 1995), and by drought in 1995. Yield in relation to Kex is shown in Fig. 6.2a. Critical Kex for 95% of maximum yield was 78, 92 and 80 mg/kg in 1993, 94 and 95, respectively. Yield responses to soil Kex were 1.47, 3.54 and 2.15 t/ha (mean 2.39 t/ha), i.e. the greatest response was not in the driest year.

Figure 6.2 Grain yield and soil Kex or fertiliser rate



At Fowlmere, maximum yields were 5.51 and 8.80 t/ha in 1992 and 1994, respectively. The cause of the low yield in 1992 is unknown, but the crops were not grown on the same field. Yield response was 0.94 t/ha in 1992 with an economic optimum fertiliser rate of 107 kg K/ha (128 kg K_2O/ha) (Fig.6.2b). In 1994, the response was 0.80 t/ha with an optimum fertiliser rate of 49 kg K/ha (59 kg K_2O/ha).

There is no information in the literature on critical soil K levels for maximum yield of winter wheat under UK conditions. At Rothamsted, critical Kex for spring barley was less than 80 mg/kg, whilst for potatoes, beans and sugar beet it was more than 200 mg/kg (Johnston and Goulding, 1990). In a summary of ADAS work on spring barley, Edwards (1988) reported that the crop did not respond to fertiliser K when Kext was above about 120 mg/l (ADAS Index 2). The maximum yield response at Index 1 to 40 kg K/ha (50 kg K_2O/ha) of fertiliser was about 0.5 t/ha.

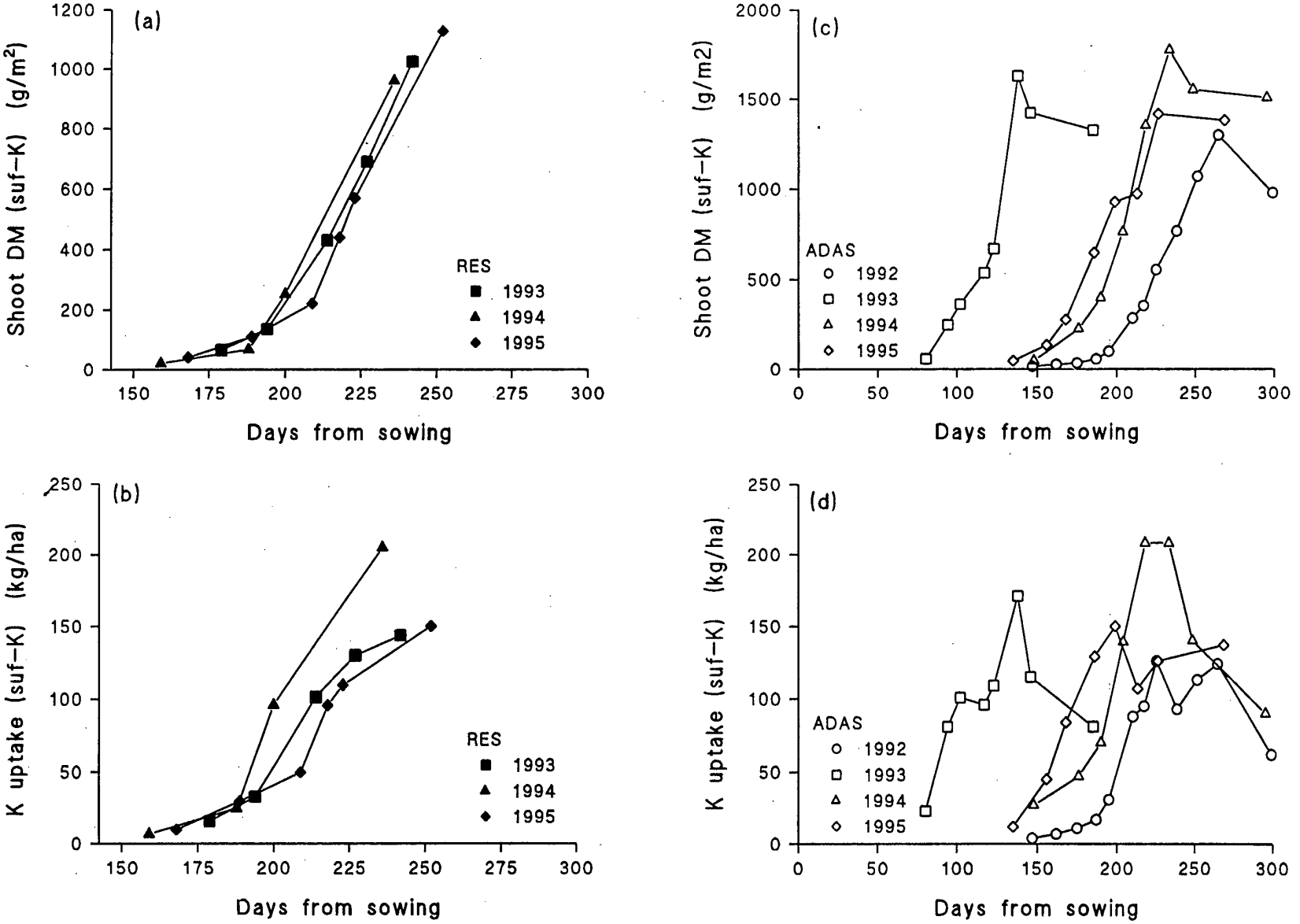
Topsoil Kex or Kext are widely used as indicators of K availability to crops. However, they are by no means perfect as they take no account of non-exchangeable K (Knex), which can become available during the growing season (Johnston and Goulding, 1988), or of subsoil K reserves. Kuhlmann (1990) found that subsoil K contributed, on average, 34% of the total K uptake by spring wheat. Topsoil Kex usually accounts for no more than 30% of the variance in yield response to K fertilisers even for K sensitive crops (Cooke, 1982).

6.2.2 Shoot growth, K uptake, tissue water content

Shoot dry matter production and K uptake for K sufficient crops are shown in Fig. 6.3. At Rothamsted, growth was similar in all three years. Dry matter production at anthesis was less in 1994 probably because of a later sowing date, but despite this the 1994 crop had the largest K uptake and grain yield.

Growth and K uptake at the ADAS sites are shown in Figs. 6.3c,d. The highest and lowest yielding crops, at Fowlmere in 1994 and 1992 respectively, were matched by the highest and lowest shoot growth and K uptake. The 9 t/ha crop at Rothamsted and near 9 t/ha crop at Fowlmere in 1994 were associated with K uptakes of the order of 200 kg/ha. All other crops had maximum uptakes of about 150 kg/ha. Maximum uptakes of the order of 250 kg/ha were previously observed at Rothamsted for 10 t/ha wheat crops (Barraclough, 1986). The well known post-anthesis loss of K (Gregory *et al.*, 1979; Barraclough, 1986) occurred in the present crops.

Figure 6.3 Shoot growth and K uptake by K-sufficient crops



Water contents of shoot and leaf(1) in K sufficient crops are shown for all sites and seasons in Fig. 6.4. At Rothamsted, water contents were greatest in 1994, the year of maximum K uptake and yield. Despite this, plant water contents bore little relation to monthly rainfall, either in the three months prior to sampling (Jan-Mar) or in the two main sampling months of April and May (see Appendix 4).

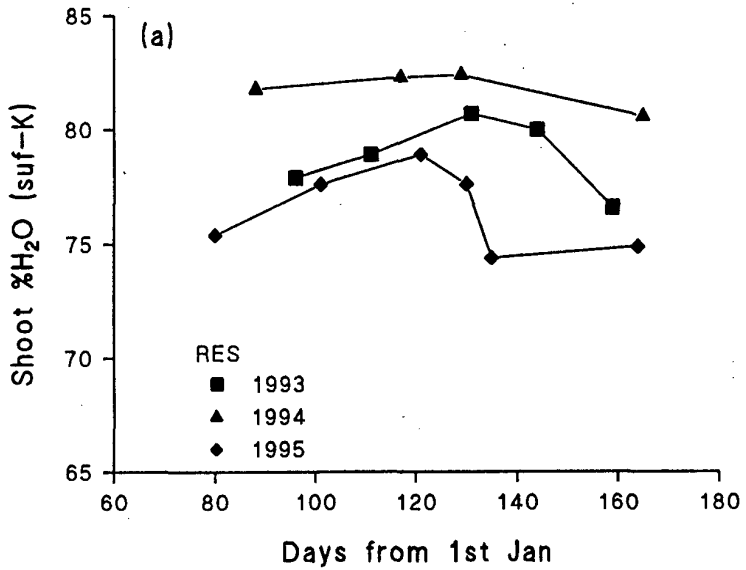
6.2.3 Shoots and leaf(1): K concentrations

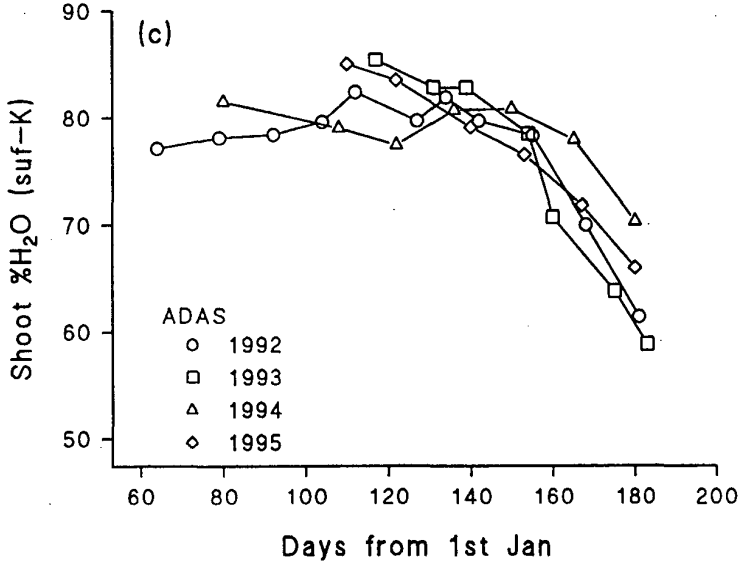
Concentrations and soil K

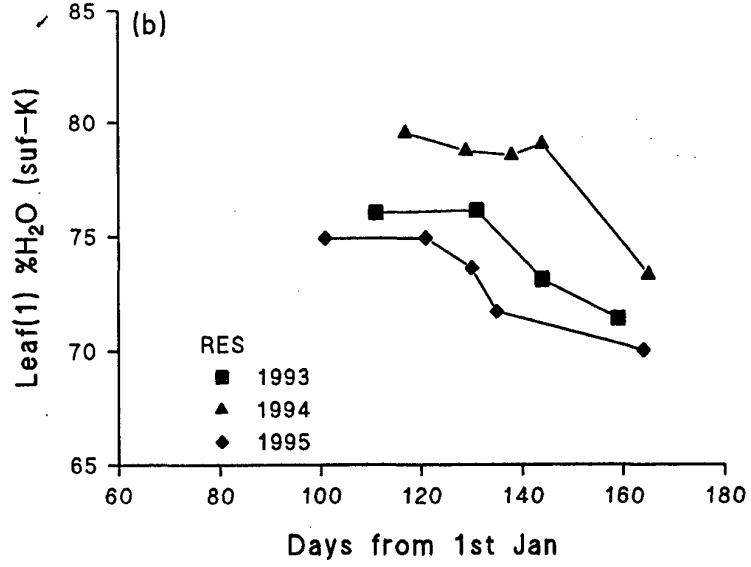
Mean shoot and leaf(1) %K (averaged over the period GS 24-60) in relation to soil Kex are shown in Fig. 6.5a for Rothamsted. At a given soil Kex, mean shoot %K was greater in 1994 than in the other two years. Although a Kex value of 200 mg/kg cannot be considered abundant, mean shoot concentrations attained plateau values of about 2% with this supply in 1993 and 1995, and 3% in 1994. Soil Kex at which 95% of the plateau value was reached were 121, 105 and 125 mg/kg in 1993, 94 and 95, respectively (cf. values of 78-92 mg/kg at which 95% of maximum yield was obtained). Similar patterns were evident in leaf(1) %K (Fig 6.5c).

When K concentrations were expressed on a tissue water basis, the variation between years was reduced, especially in leaf(1) (Figs. 6.5b,d). The higher %K values in 1994 were modulated by higher tissue water contents in that year (Fig. 6.4a,b). On the other hand, shoot Kw was higher in 1995, the drought year, due to the lower tissue water contents in that year. In the case of leaf(1), mean concentrations were very similar in all three years with a common plateau concentration of around 200 mM. This is in agreement with the findings of Leigh (1989) who reported that several monocotyledenous crop species accumulated K to a mean ceiling concentration of 200 mM.

Figure 6.4 Shoot and leaf(1) tissue water contents







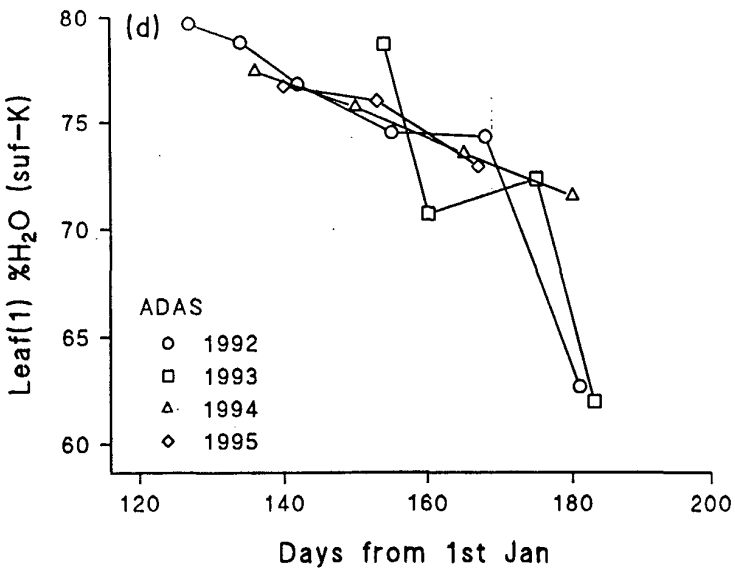
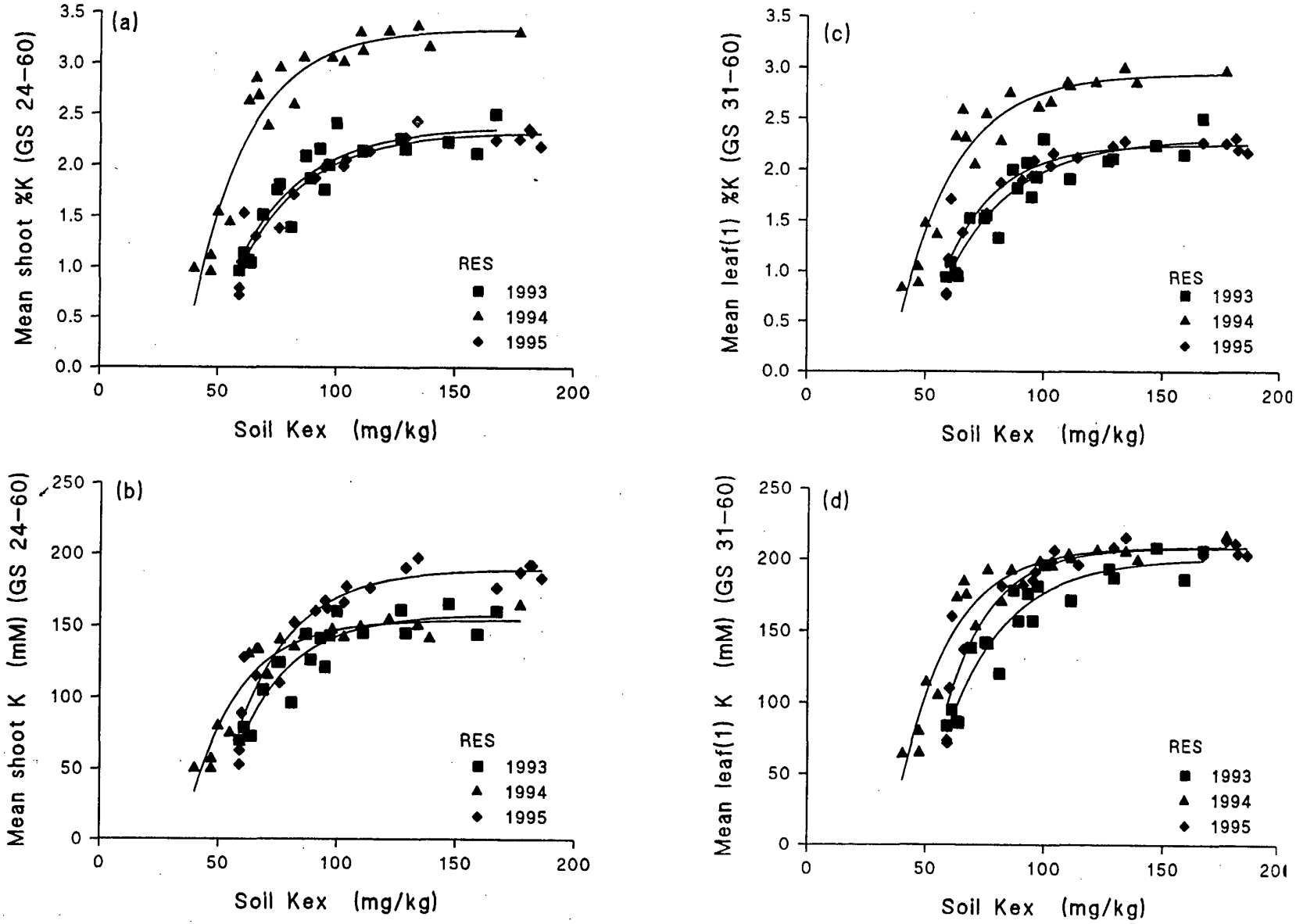


Figure 6.5 Shoot K concentrations and soil Kex at Rothamsted



Concentrations and time

Potassium concentrations in shoot and leaf(1) in relation to time for crops well supplied with K are shown in Fig. 6.6 for Rothamsted and Fig. 6.7 for the ADAS sites.

At Rothamsted, shoot %K increased initially, following application of N fertiliser, and then declined during stem extension (Fig 6.6a). The decline during stem extension is largely due to increasing stem/leaf weight ratios and decreasing stem K/DM ratios (see Fig. 6.8).

Shoot %K was similar in 1993 and 1995 at Rothamsted, but was substantially greater in 1994, the highest-yielding year. The most likely explanation is that K availability was enhanced by favourable water supply in 1994, as evidenced by greater tissue water contents in that year (Fig. 6.4a).

Shoot Kw values followed a similar time course to shoot %K (Fig. 6.6b), with concentrations declining during growth from 200 to 100 mM. Differences between years were substantially reduced by the modulating effect of tissue water content (see Fig. 6.4a).

Leaf(1) %K largely followed shoot %K with time, i.e. an initial increase, possibly in response to N fertiliser application, followed by a decline (Fig. 6.6c). There was a marked peak in concentration at GS 37 in 1995, not matched in the shoots, which was possibly caused by a delayed response to N following rain. Differences in leaf(1) %K between years were most marked during the early stages of growth.

Leaf(1) Kw behaved similarly to %K (Fig. 6.6d), but the marked concentration peak in 1995 was enhanced by a lower tissue water content (Fig. 6.4b). Leaf(1) Kw in K-sufficient crops varied in a range of 150-250 mM.

At the ADAS sites, shoot %K and Kw in winter wheat generally followed the Rothamsted pattern, i.e. an initial increase, possibly due to application of fertiliser N, followed by a decline (Figs. 6.7a,b). Paradoxically, shoot K at Fowlmere was lowest in the highest-yielding year (1994) (but much lower than at Rothamsted in that year), and highest in the lowest-yielding year (1992).

Figure 6.6 Shoot and leaf(1) K concentrations of K sufficient crops over time (Rothamsted)

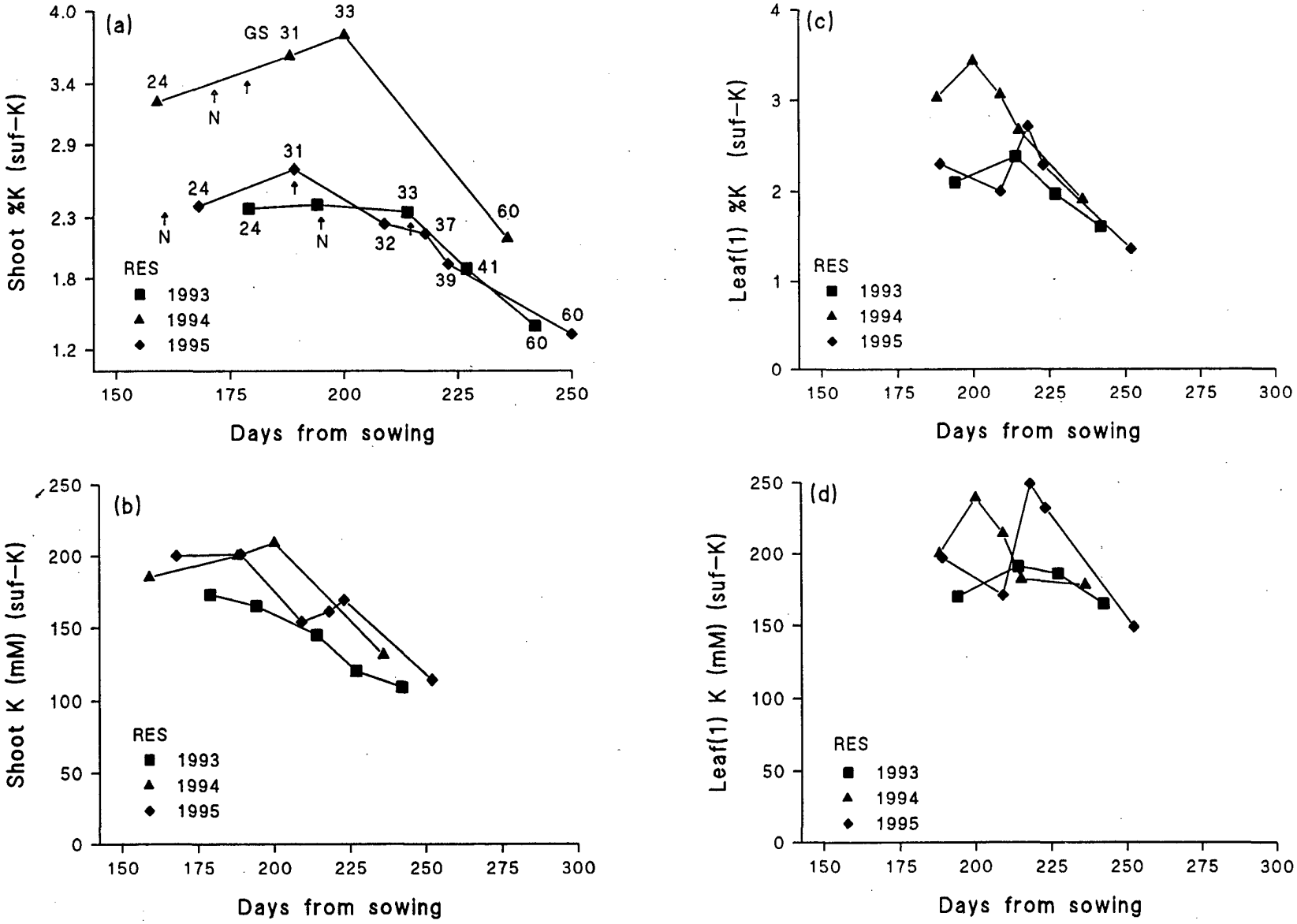
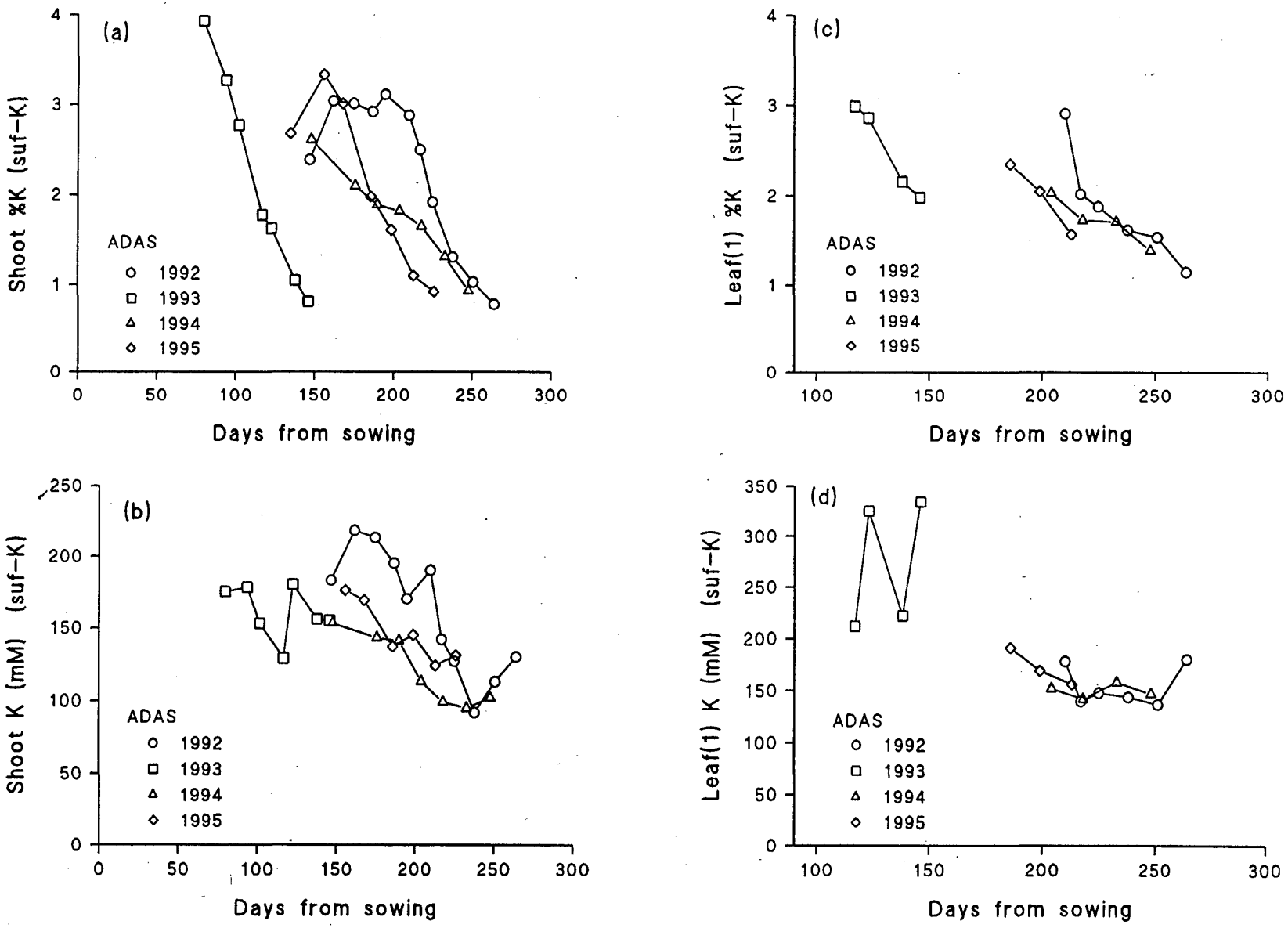


Figure 6.7 Shoot and leaf (1) K concentrations of K sufficient crops over time (ADAS)



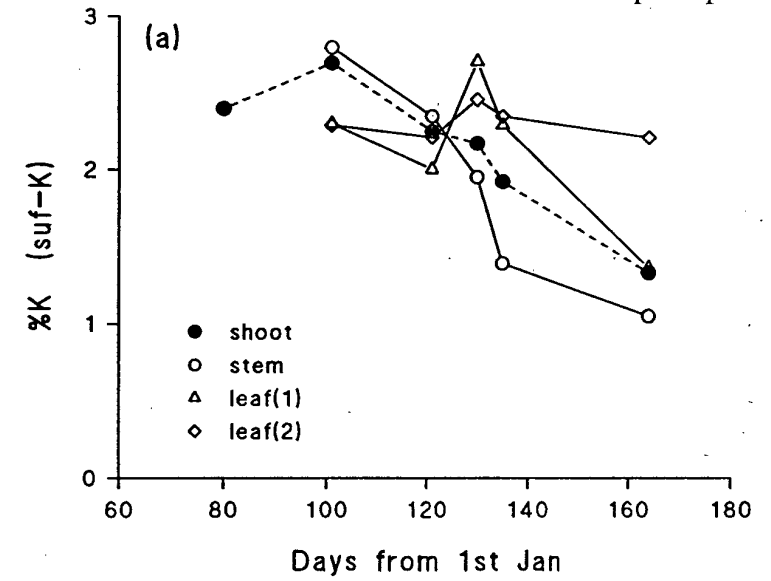
Leaf(1) %K at Fowlmere was remarkably similar in both years (Fig. 6.7c), declining steadily and without the peaks observed at Rothamsted. The decline was matched by a similar decline in tissue water (Fig. 6.4d) resulting in nearly constant leaf(1) Kw values of about 150 mM. Potassium concentrations in winter wheat at Sedge Fen in 1995, where there was no yield response to K, were similar to those at Fowlmere. Potassium concentrations in the spring wheat crop at Ingham in 1993 always exceeded those in the three winter wheat crops.

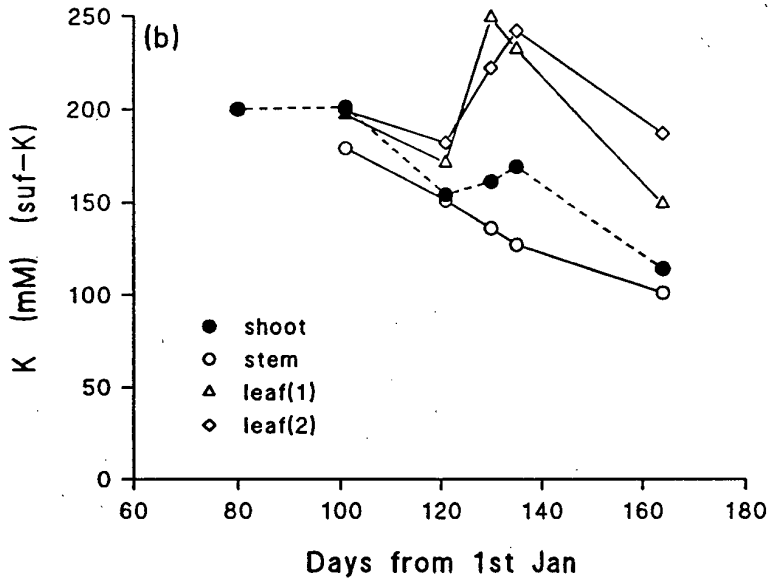
The availability of N and water appear to have had a big impact on plant K concentrations, and by implication critical K concentrations. Increases in shoot %K as a result of adding N fertiliser (followed by a decline during stem extension) are well documented in the literature for cereals (Gregory *et al.*, 1979; Leigh and Johnston, 1983; Barraclough, 1986; Withers, 1991). Changes in leaf %K with N supply have been studied in France (Loue, 1987). The responses were complex and depended on crop K status and leaf position. With leaf(1), %K increased with N at all K rates, whilst for leaf(2) %K decreased with N at low K, was constant at intermediate K, and increased at high K. The apparent effect of N on leaf(1) Kw in the present work was unexpected in view of the findings of Leigh and Johnston (1983) that there was no effect of N supply on shoot Kw concentrations in spring barley. Clearly more work is needed to establish the extent and under what conditions Kw is affected by N supply.

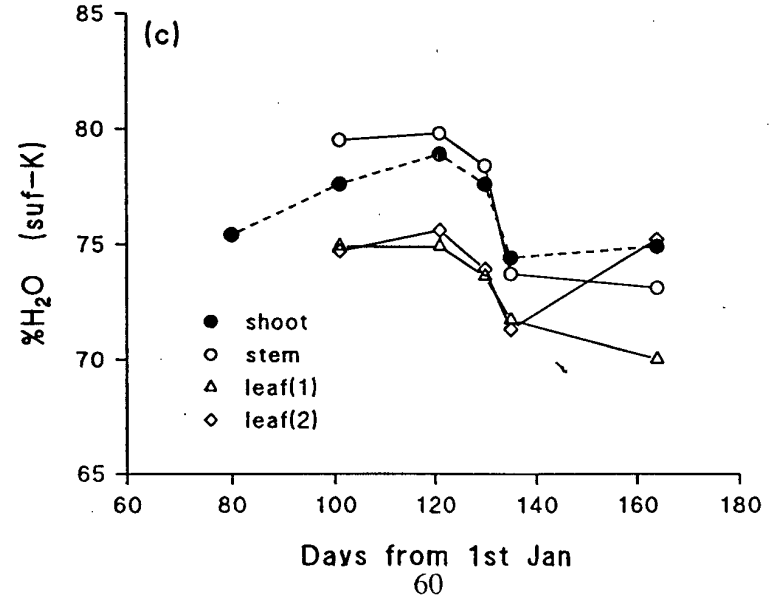
Concentrations in different plant parts

Potassium concentrations in different parts of the wheat plant are shown in Fig. 6.8. The data are for plants well supplied with K at Rothamsted in 1995. Percent K in dry matter was greater in stems than in leaves upto GS 32 (day 120) (Fig. 6.8a), but greater in leaves thereafter. This was also shown by Gregory *et al.* (1979). Kw concentrations were always lower in stems than in leaves (Fig. 6.8b). The decline in whole shoot %K, Kw and $\%H_2O$ during stem extension was matched by similar declines in stems (Figs. 6.8a,b,c). As stems make up an increasing proportion of shoot weight during stem extension it is not unexpected that shoot concentrations should follow those of stems during this phase of growth. Percent K concentrations in leaf(1) were more erratic than those in stems, showing sharp peaks (at GS 37 as discussed previously) before declining at anthesis. The peak was exacerbated in leaf(1) Kw by a declining tissue water content. Leaf(2) %K was much more stable than leaf(1) %K at just over 2% throughout the season (Fig. 6.8a). Leaf Kw concentrations fluctuated in the range 150-250 mM during the season, whilst shoot and stem Kw declined steadily from 200-100 mM.

Figure 6.8 K concentrations and tissue water in different plant parts







Percent K was measured in different leaves at Fowlmere in 1992. At GS 51, %K in deficient plants was 1.00, 0.96 and 0.74% in leaves (1), (2) and (3), respectively, i.e a decrease with leaf age. Leaf(1) was the flag leaf. Comparable values for sufficient plants were 1.30, 1.39 and 1.49%, i.e. an increase with leaf age. Similar results were reported by Loue (1987) for wheat at anthesis. At deficient K, leaf %K decreased in the order (1) > (2) > (3), whilst at sufficient K the order was (1) < (2) = (3).

6.2.4 Shoots and leaf(1): Critical K

Examples of relationships between grain yield and shoot and leaf(1) K concentrations are shown in Fig. 6.9 for Rothamsted in 1995. Changes in the relationships for shoots are due to the consistent decline in shoot concentrations during growth, whilst variation in the relationships for leaf(1) are due to fluctuations during growth.

Critical concentrations are shown in relation to measured concentrations on individual plots (i.e. for different soil Kex values) for Rothamsted in 1995 in Fig. 6.10. Critical concentrations generally tracked actual concentrations but were more attenuated.

Critical K concentrations in whole shoots and leaf(1) for all sites and seasons are shown in Fig. 6.11. Critical shoot %K declined during growth and, with the exception of the Rothamsted 1994 crop, was reasonably constant over sites and seasons (Fig. 6.11a). Critical values were most variable at late tillering (GS 24). The mean critical value, excluding Rothamsted 1994, declined from 2.20% at GS 31 to 1.14% at GS 61. Equivalent values for the Rothamsted 1994 crop were 3.44% and 1.97%, respectively.

Expressing shoot concentrations on a tissue water basis removed some of the site/season variation, but critical concentrations still declined during growth (Fig. 6.11b). Mean critical shoot Kw, excluding Rothamsted 1994, declined from 174 mM at GS 24 to 89 mM at GS 61. Corresponding values for the Rothamsted 1994 crop were 190 and 122 mM, respectively.

Critical leaf(1) %K was less variable than shoot %K over sites and seasons and there was no consistent decline up to GS 39 (Fig. 6.11c). Mean critical leaf(1) %K for all sites and seasons, excluding Rothamsted 1994, was reasonably constant during stem elongation (GS 31-39) with a value of 1.92% (range 1.61-2.49%). Mean critical concentration declined to 1.39% (range 1.17-1.73%) at GS 61. Corresponding values for the Rothamsted 1994 crop were 2.88% (range 2.48-3.21%) between GS 31-39, and 1.84% at GS 61.

Figure 6.9 Grain yield and shoot and leaf (1) K (Rothamsted 1995)

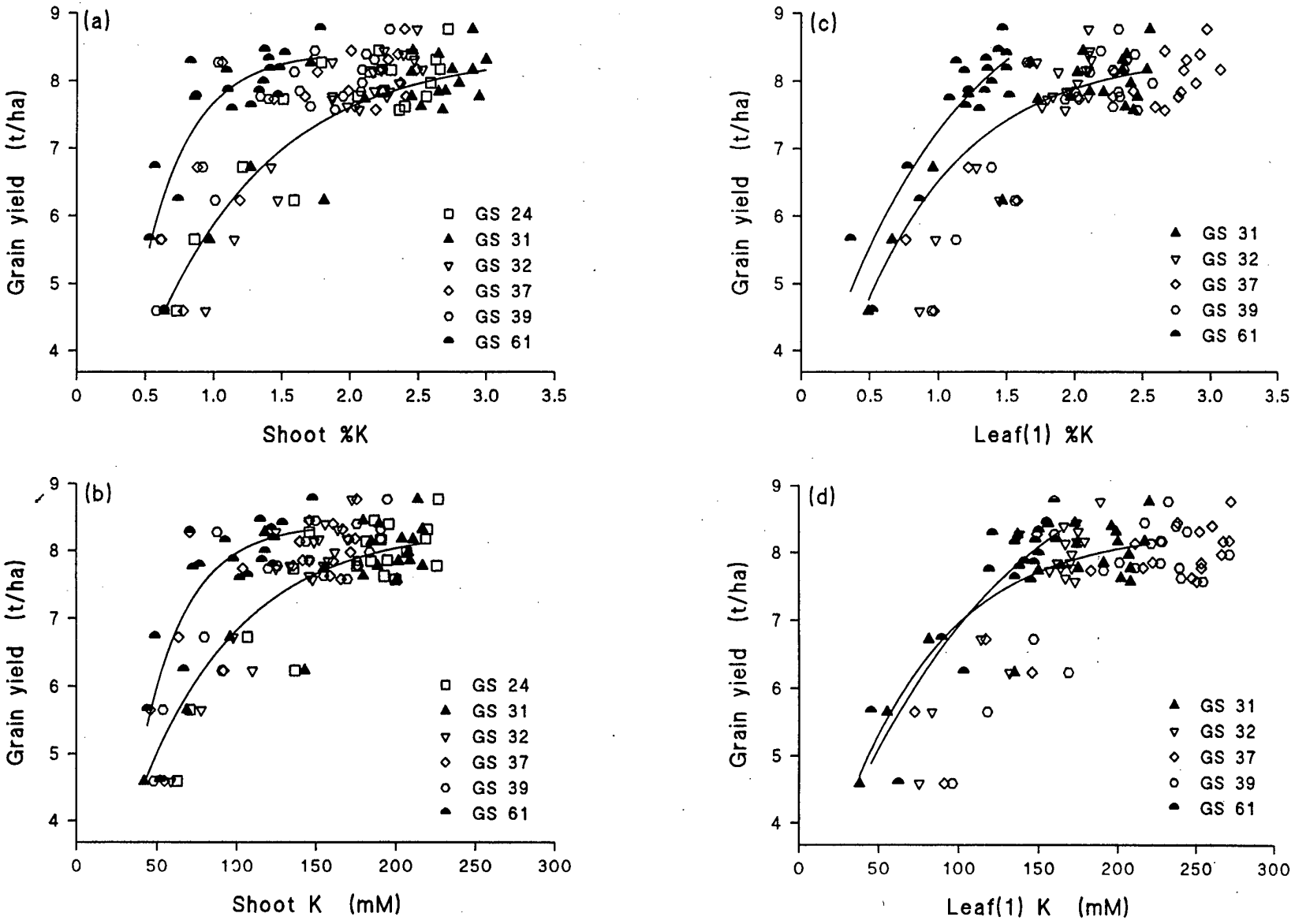


Figure 6.10 Shoot and leaf(1) K concentrations over time for different soil Kex (RES 1995)

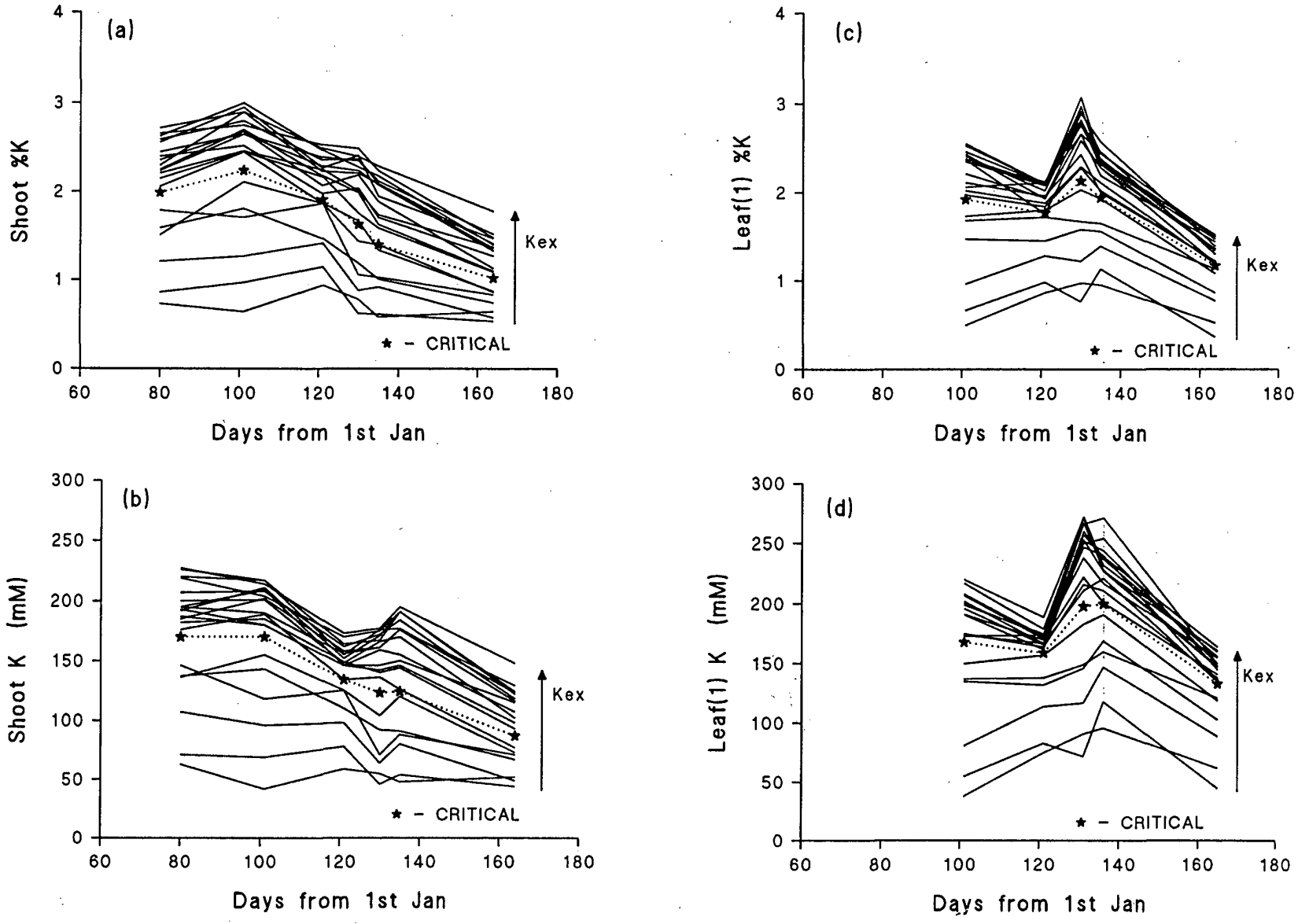
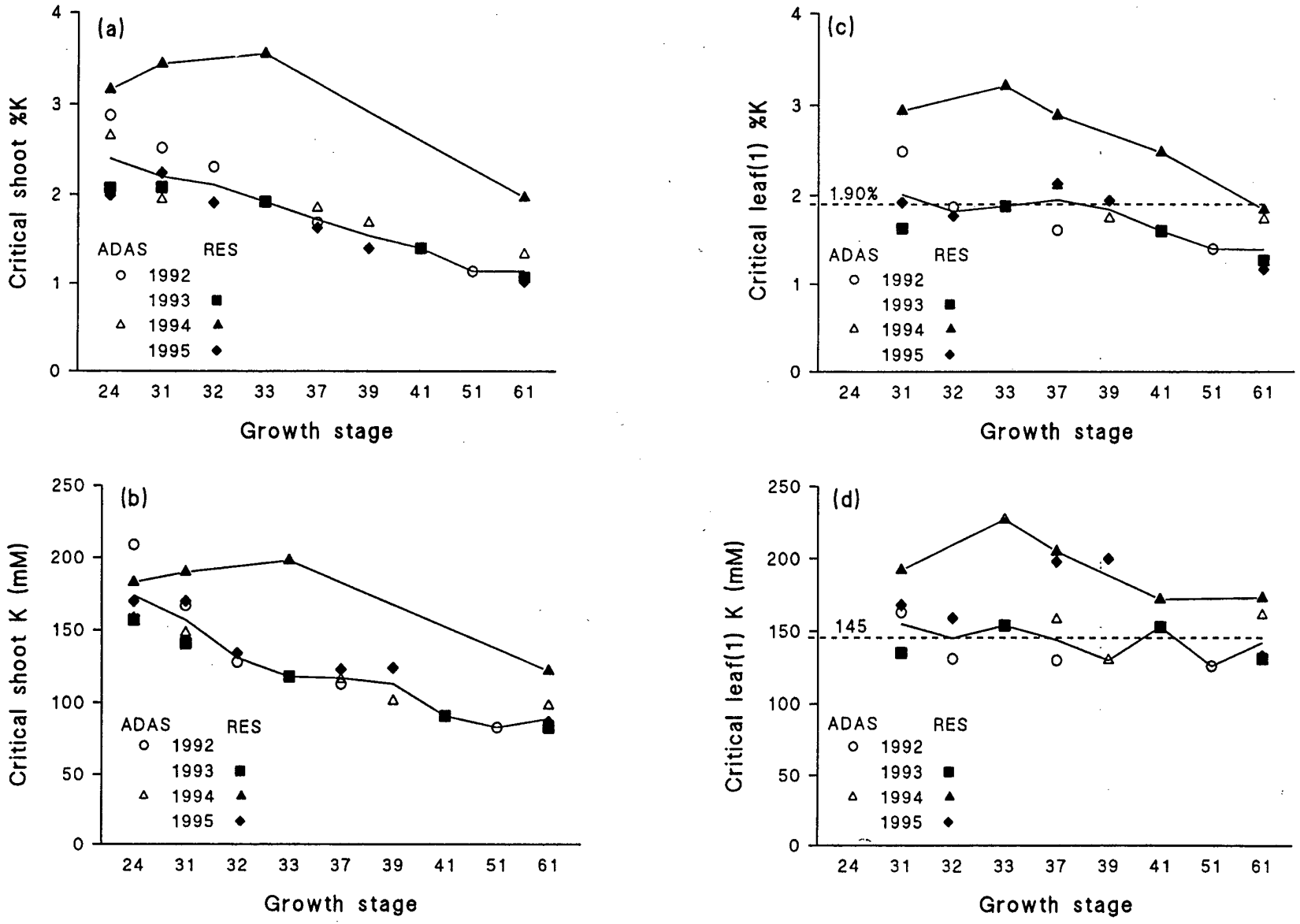


Figure 6.11 Critical shoot and leaf (1) K concentrations at different growth stages



Critical tissue water concentration in leaf(1) was the least variable concentration parameter over time and between sites and seasons (Fig. 6.11d). Mean critical leaf(1) Kw over all sites and seasons, excluding Rothamsted 1994 and those values affected by drought in 1995, was 145 mM (range 126-168 mM) between GS 31-61. Corresponding value for the Rothamsted 1994 crop was 194 mM (range 172-227 mM).

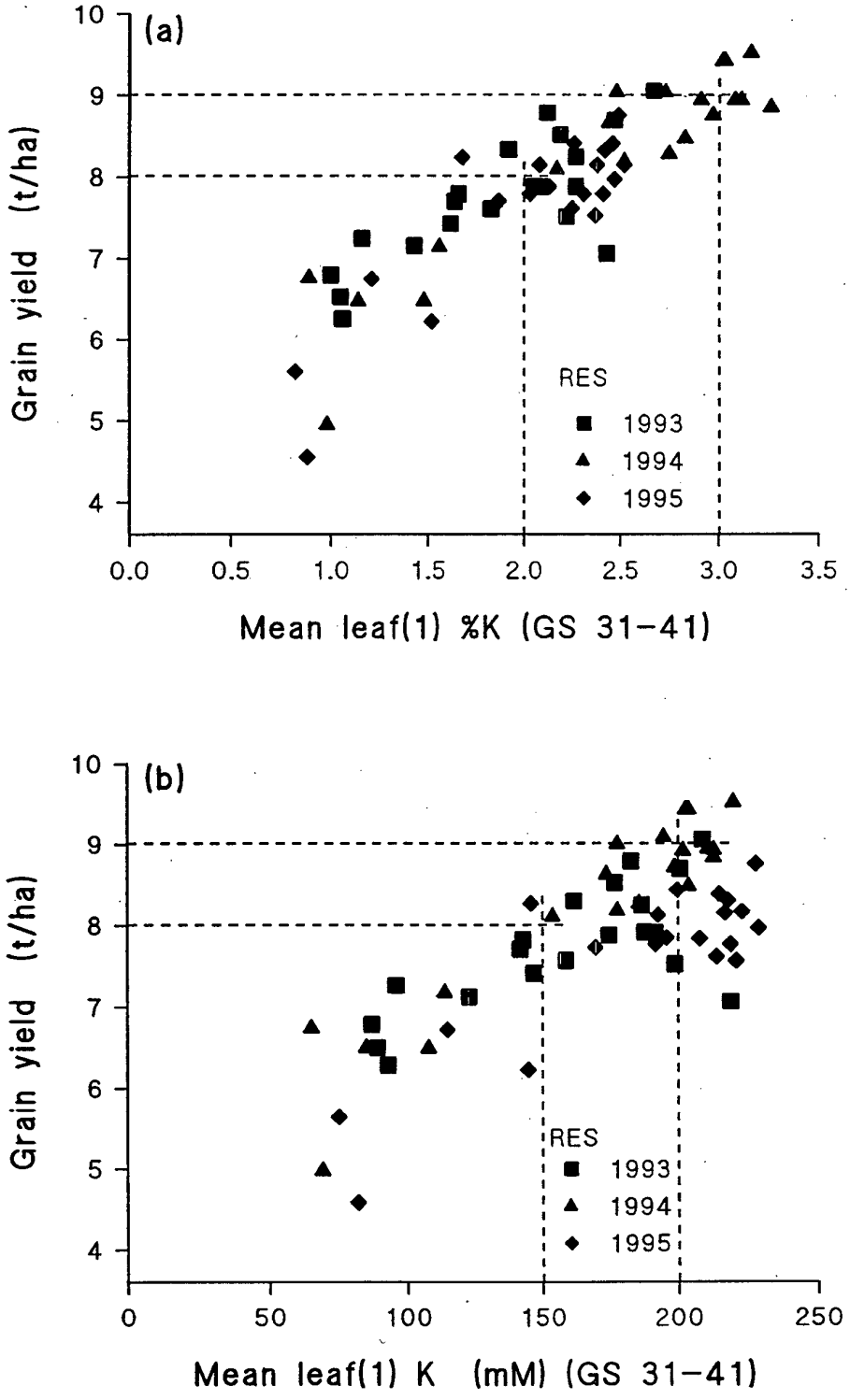
Over all sites, seasons and growth stages, leaf(1) Kw was the least variable critical concentration parameter with a coefficient of variation (CV) of 18.0%. CVs for leaf(1) %K, shoot Kw and shoot %K were 27.5, 27.3 and 34.2%, respectively. On this basis, leaf K is a better indicator of crop K status than shoot K.

Potassium concentrations in the crop at Rothamsted in 1994 were different from all other crops in this study. The Rothamsted 1994 crop was grown without any obvious limitations and the maximum yield was 9.32 t/ha. The crops at Rothamsted in 1993 and 1995 may have been limited by N and drought, respectively. The 1994 crop had much higher actual and critical K concentrations and this crop probably best represents the K status required for high-yielding winter wheat.

Average critical leaf(1) K concentrations during stem elongation (GS 31-41) for a given site and season were ranked in the same order as grain yields (with the exception of Rothamsted 1995 which had anomalously high mid-season critical values due to the drought conditions). Relationships between mean leaf(1) K during stem elongation and grain yield for Rothamsted are shown in Fig. 6.12. From this, a yield of 8 t/ha was associated with a mean leaf concentration of about 2% in DM or 150 mM, whilst a yield of 9 t/ha was associated with mean concentrations of the order of 3% in DM or 200 mM. However, at a mean leaf concentration of 200 mM, individual plot yields varied in the range 7.5-9.5 t/ha showing that factors other than K supply were affecting plot yields (Fig. 6.12b).

Critical K concentrations were also determined in leaf(2), the second newest fully expanded leaf blade, at Rothamsted in 1995. Leaf(2) %K was more stable than leaf(1) %K during growth (see Fig. 6.8), and critical leaf(2) %K was remarkably constant during stem elongation in the range 1.72-1.81%. Critical leaf(2) Kw varied in the range 150-185 mM. Critical K in leaf(2) was also measured at Rothamsted in 1993, values were 1.72% and 150 mM at GS 41, in good agreement with those in 1995.

Figure 6.12 Grain yield and leaf(1) K at Rothamsted



6.2.5 Shoots and leaf(1): Literature on critical K

There is no literature on critical shoot %K for UK winter wheat crops. Data from other countries is given in Table 6.2. The present data, with the exception of Rothamsted 1994, agree reasonably well with the literature values. All data clearly show the decline in critical shoot concentration with growth stage. There is no data in the literature on critical shoot Kw.

Table 6.2 Critical shoot %K for winter wheat crops

LOCATION	GS	CRITICAL	REFERENCE
	24	3.2%	
	32	2.0%	
	51-59	1.5%	
	71-91	0.9%	
AUS	51-59	1.5%	Reuter & Robinson, 1986
USA	41-49	1.8%	Reuter & Robinson, 1986
USA	51-59	1.5%	Reuter & Robinson, 1986
USA	31	2.0-2.5%(CNR)	Westfall *et al.*, 1990
	39	1.5-2.0%(CNR)	
USA	24	3.2%	Westfall *et al.*, 1990
	30-37	2.0%	
	39-49	1.8%	
USA	51-59	1.5%	Westfall *et al.*, 1990
USA	41-49	1.8%	Melsted *et al.*, 1969
NZ	51-59	1.5%	Cornforth & Sinclair, 1984

CNR - Critical Nutrient Range - above CNR the crop is likely to be well-supplied, below CNR the crop is likely to be deficient.

There is no literature on critical leaf %K for UK winter wheat crops. Data from other countries are given in Table 6.3.

Table 6.3 Critical leaf %K for winter wheat crops

LOCATION	LEAF	GS	CRITICAL	REFERENCE
USA	Leaf(1)	41-49	2.0%	Westfall *et al.*, 1990
USA	Leaf(1)	49	1.5%	Reuter & Robinson, 1986
USA	Leaf(1+2)	49	1.5%	Benton Jones *et al.*, 1991
USSR	Leaf(1)	21-24	3.4%	Reuter & Robinson, 1986
		30-39	3.1%	
		60-69	2.3%	
FRA	Leaf(2+3)	60-69	2.6%	Loue, 1987

Most critical %K values for leaves reported in the literature relate to the top two or three leaves. Critical values are in the range 2.4-3.4% (during tillering); 3.1% (during stem elongation); 1.5-2.0% (during booting); and 2.3-2.6% (during flowering). These values are somewhat greater than the overall mean of 1.92% found for most crops in the present work, but in good agreement with the critical values for the Rothamsted 1994 crop. There is no data in the literature on critical leaf Kw.

6.3 CONCLUSIONS FOR K

YIELD RESPONSE TO SOIL K

At Rothamsted, maximum grain yield response to soil K was 3.5 t/ha. This was for a soil Kex of 40 mg/kg (middle of ADAS K Index 0). For a soil Kex of 60 mg/kg (top of Index 0), the response was 1.5-2.2 t/ha. On a light sandy loam soil at Fowlmere (K Index 0) yield response to fresh fertiliser K was about 0.9 t/ha. On a second Index 0 site in Suffolk, there was no response to fresh K fertiliser.

CRITICAL SOIL K

Critical soil Kex (for 95% maximum grain yield) differed little between years at Rothamsted and was in the range 78-92 mg/kg. Topsoil K was not a reliable guide to the likelihood of grain yield response to fresh fertiliser K. [Critical soil Kext according to current ADAS recommendations is 120 mg/l (top of ADAS K Index 1)].

WHOLE SHOOTS

K in dry matter

Critical shoot K concentrations (for 95% maximum grain yield) depended on yield. Crops yielding up to about 8.5 t/ha in the present study had similar critical K values, but a crop grown at Rothamsted in 1994, which yielded 9.3 t/ha, had significantly greater critical K concentrations. For crops yielding up to 8.5 t/ha, the mean critical shoot %K declined from 2.20% at GS 31 to 1.14% at GS 61. Corresponding values for the Rothamsted 1994 crop were 3.44% and 1.97%, respectively. The reason for these differences is not clear, but was most likely caused by interaction with soil water and N supply which affect soil K availability and crop K requirements.

K in tissue water

Critical whole shoot K concentrations expressed on a tissue water basis (Kw) also declined during growth, but site/season differences were reduced. For crops yielding up to 8.5 t/ha, mean critical shoot Kw declined from 157 mM at GS 31 to 89 mM at GS 61. Corresponding values for the Rothamsted 1994 crop were 190 mM and 122 mM, respectively.

LEAF(1)

K in dry matter

Critical leaf(1) %K was less variable than shoot %K over sites and seasons and there was no consistent decline or other trend with time up to GS 39. Mean critical leaf(1) %K for crops

up to 8.5 t/ha was reasonably constant during stem elongation (GS 31-39) with a value of 1.92% (range 1.61-2.49%). The mean critical value for the Rothamsted 1994 crop over the same period was 2.88% (range 2.48-3.21%).

K in tissue water

Expressed on a tissue water basis, critical leaf(1) Kw was the least variable concentration parameter between sites and seasons. For individual crops, critical leaf(1) Kw fluctuated with time but there was no overall trend. For all crops, critical leaf(1) Kw was in the range 130-230 mM. For crops up to 8.5 t/ha, critical leaf(1) Kw averaged 145 mM (range 126-168 mM) between GS 31-61. The mean critical value for the Rothamsted 1994 crop between GS 31-61 was 194 mM (range 172-227 mM).

WHOLE SHOOTS vs LEAF(1)

Leaf(1) testing was generally superior to whole shoot testing because there was no consistent decline in critical values during stem elongation and there was less site/season variation.

DRY MATTER vs TISSUE WATER

Expressing concentrations on a tissue water basis reduced site/season variation but made no difference to the time course of either critical shoot or leaf(1) concentrations.

6.4 RECOMMENDED TESTS FOR K

The recommended tests for diagnosing the K status of winter wheat, based on the stability of critical concentrations during growth and between sites and seasons, are leaf(1) %K or leaf(1) Kw. For crops yielding up to 8.5 t/ha, mean critical leaf(1) %K during stem elongation (GS 31-39) was 1.9% (range 1.6-2.5%), and mean critical leaf(1) Kw (GS 31-61) was 150 mM (range 130-170 mM). Corresponding values for a 9.3 t/ha crop were 2.9% (range 2.5-3.2%) and 200 mM (range 170-230 mM), respectively.

7 GENERAL DISCUSSION

Law of the minimum

Plant analysis is only capable of detecting the deficiency of one nutrient at a time. Analysis of a plant deficient in N may show that it has adequate K, but this gives no indication as to whether K would be limiting should N supply be increased (Bates, 1971). The determination of critical nutrient concentrations in plants for maximum yield requires that the nutrient in question is the only limiting factor. This can be hard to achieve in the field where other factors, particularly N supply or water availability, may inadvertently become limiting at some stage. This will affect concentrations and hence critical concentrations derived from them where the crop is being used for calibration purposes. This is probably why critical concentrations determined under field conditions, even where "best practice" is adopted, vary so widely.

Derivation of critical concentrations

Relationships between yield and nutrient concentration in a given plant part at a given time often showed condsiderable scatter, indicating the importance of "other factors" in determining yield. Relationships between plant concentration and soil concentration, on the other hand, tended to be better and critical plant concentrations were indirectly derived from these. A further complication in deriving critical values from such relationships was the choice of mathematical function. This can have a big effect on critical values obtained by interpolation. Colwell (1994) recommended that the choice of function should not only be based on standard statistical tests of significance or goodness of fit, but also on how well the function was observed to fit the data and how realistic interpolated values appeared to be.

Prognosis vs Diagnosis

The approach taken in this study was essentially prognostic as opposed to diagnostic, in that grain yield was related to plant concentrations determined at an earlier, vegetative stage of growth (soil testing is also prognostic). Prognosis is making a prediction about future nutrient supply and the liklihood that plant concentrations will be maintained at levels necessary for maximum yield. The earlier this can be done the more useful the test, but the greater the risk of other factors upsetting the prediction. Diagnosis, on the other hand, indicates if nutrient supply has been adequate for maximum growth up to the time of testing. It says nothing about future supply so is safer than prognosis. Maximum vegetative growth at all times may or may not be a determinant of maximum grain yield however. A crop could show early nutrient

deficiency and reduced growth yet still produce maximum grain yield.

Best time to test plants

From the growers point of view, the sooner plants can be tested the better, as this allows time for remedial fertiliser dressings to be applied should they be required. Unfortunately, variations in critical concentrations between sites and seasons were greatest early in the season, i.e. during tillering.

Crop nutritionists have long favoured anthesis as the ideal testing time. Most nutrient uptake is complete by anthesis and in theory this is the time for assessing the overall nutrient supplying capability of a soil. However, nutrients are being remobilised for grain filling at this stage and tissue water contents are also declining and these factors can complicate the interpretation of results. Consequently, the best time to test the nutrient status of field-grown cereals is considered to be during stem elongation, GS 31-39.

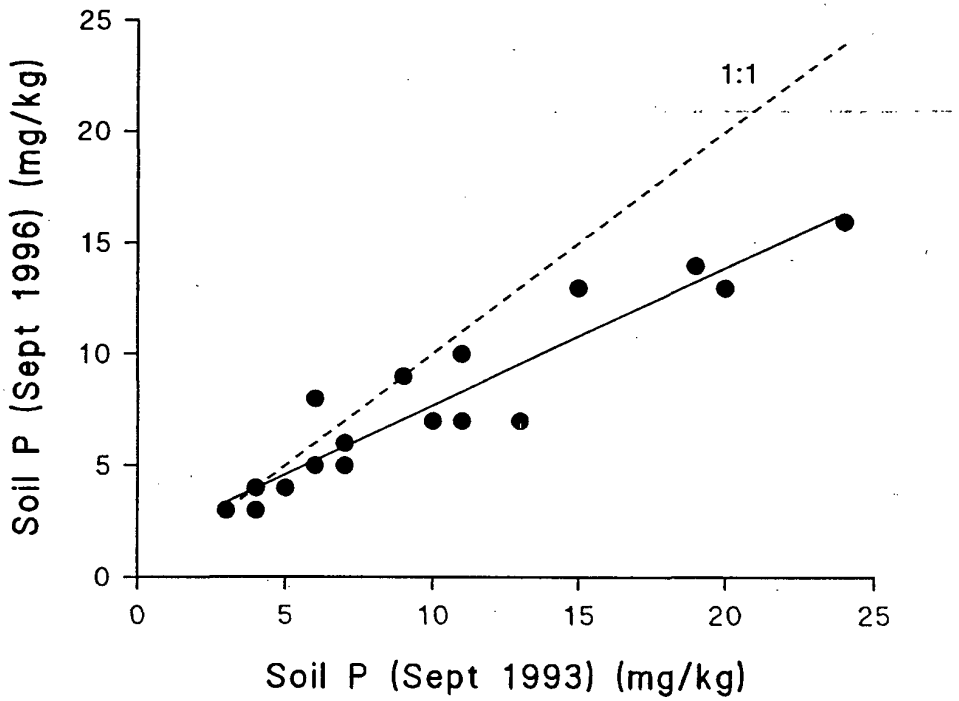
Fertiliser strategy and crop rotation

The most appropriate fertiliser strategy to adopt will depend on crop rotation. Root crops like potatoes and vegetables generally have higher soil P and K requirements than cereals and other small grain crops (e.g. rape) because of less well developed root systems. With a high proportion of vegetable and potato crops in the rotation, ADAS advice is therefore to maintain soil P and K levels at a higher status (Index 3) than for rotations comprising small grains and forage crops (Index 2). A balanced PK fertiliser policy should aim to build-up soil reserves to satisfactory levels for the cropping rotation. Reserves of soil PK can have advantages over fresh dressings of fertiliser as they are well incorporated into the rooting zone (Johnston and Goulding, 1988). However, it should be borne in mind that "satisfactory" soil levels for most crops, whether they be cereals or potatoes, are not actually known for a given field (soil type), as ADAS recommendations necessarily relate to the "average" crop, site and season.

Rate of decline of soil reserves

If dressings of P and K fertiliser are witheld whilst cropping continues, at what rate will levels of soil extractable P and K decline? This is essentially determined by cropping and soil type, i.e. the amounts of P- and K-bearing minerals in the soil.

Figure 7.1 Decline in soil P levels between 1993 and 1996 at Rothamsted



The decline in soil P at Rothamsted in the three year period 1993-96 is shown in Fig. 7.1. Decline was greater the higher the soil P. For this silty clay loam at Index 2 (16-25 mg/kg), the decline was of the order of 10% a year. On the clay loam soil at Ropsley, extractable soil P declined by about 40% over a nine year period.

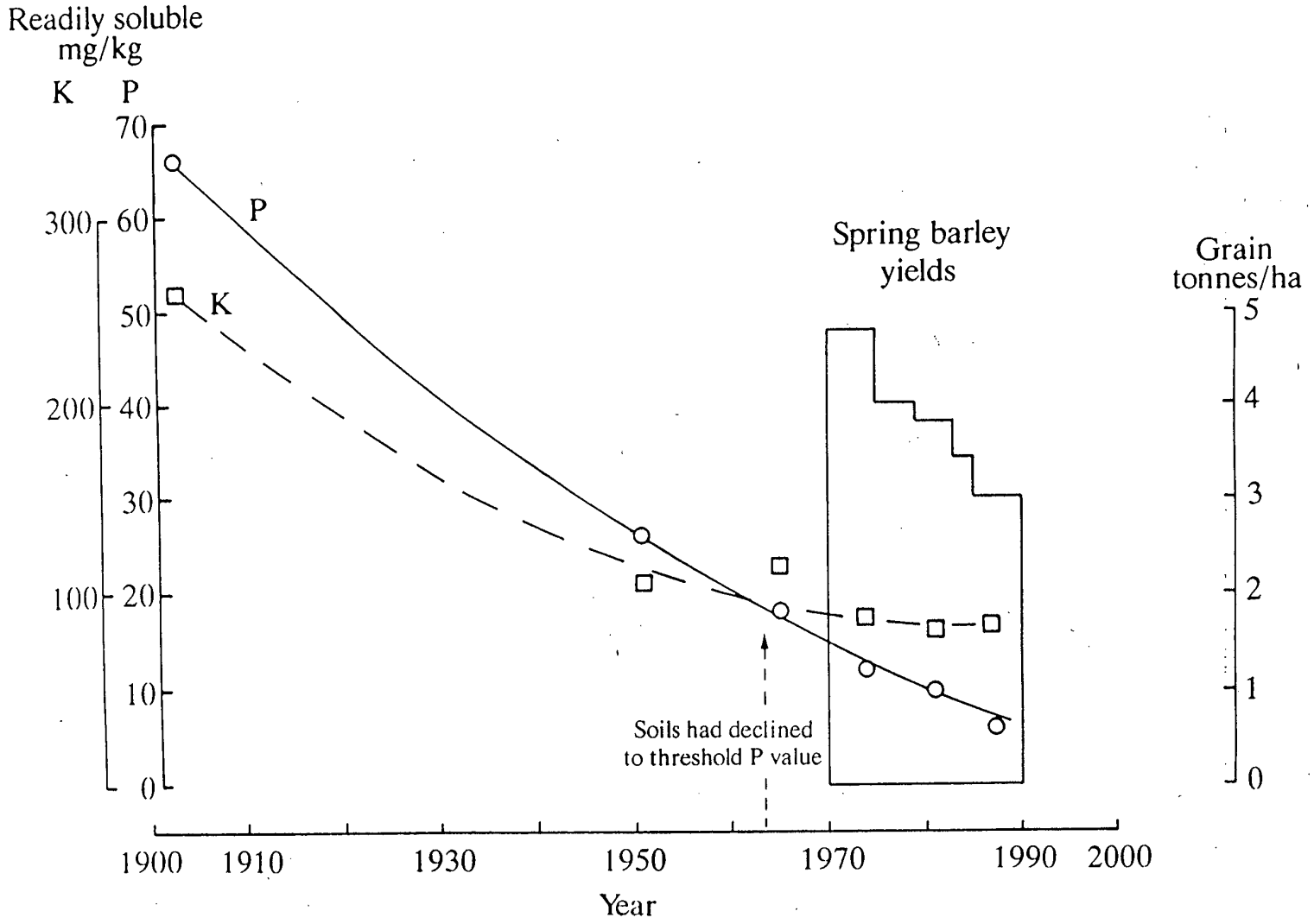
The long-term decline in soil P and K has been monitored at Rothamsted on the "Exhaustion Land" experiment over a 90 year period (Johnston, unpublished). This site was continuously cropped with spring barley between 1900 and 1990. On plots given no P or K since 1900, soil P declined almost linearly at a rate of 0.7 mg/kg over the 90 year period (Fig. 7.2). On the same site, Kex declined by 145 mg/kg in the first 50 years and by a further 30 mg/kg in the next 40 years (Fig. 7.2). The slower decline in Kex over the later years is consistent with the release of non-exchangeable K. On a sandy clay loam soil in Suffolk, Johnston and Poulton (1992) reported a P half life of nine years.

Medium term studies (8-12 years) were conducted by ADAS on two calcareous soils, a shallow silty clay loam over chalk in Wiltshire and a shallow clay loam over limestone in Gloucestshire (Withers *et al.*, 1994). The chalk site was in a grass/cereals rotation and P and K inputs occurred in years when animals were grazing. Initial soil P and K values (to 15 cm depth) were 18 and 239 mg/l, respectively, well above ADAS threshold levels. Soil P and K levels started to decline after three years at average rates of 0.8 and 11 mg/l per year, respectively. Cereal yield was reduced after six years in response to declining P when soil P had dropped below the ADAS critical P threshold (9 mg/l), but only after eleven years in response to declining soil K, when soil Kext had dropped near to the ADAS critical threshold of 120 mg/l.

The limestone site was in continuous cereals. Initial soil P and K values were 49 and 363 mg/l, respectively, again well above ADAS threshold levels. Soil P and K levels started to decline immediately and over the experimental period the average rate of decline was 3.4 and 23 mg/l per year, respectively. Cereal yield was reduced after three years in response to declining P when soil P was 37 mg/l, well above the ADAS P threshold. Soil Kext never dropped below 200 mg/l and there were no yield reductions due to declining soil K.

These experiments also showed that on calcareous soils, available P and K levels could not be maintained by matching application to offtake. The experiments confirmed the long term K supplying ability of soils with appreciable clay contents, the dependence of critical soil P on soil type, and shortcomings of soil analysis as a reliable guide to fertiliser need.

Figure 7.2 Decline in soil P and K on "Exhaustion Land" at Rothamsted



8 FURTHER WORK

More detailed work is needed on the dynamics and distribution of nutrient pools in plants in relation to nutrient supply, growing conditions and growth before we can explain why critical plant concentrations vary during the season and between sites (soil types) and seasons. Plant concentrations change because supply changes, or because dry matter or tissue water contents change, or because nutrients remobilise during plant development.

The supply of N and water are major variables in the field and it is important to know how they affect P, Pi and K concentrations. Other factors contributing to variation in the field are plant-based, namely that mainstems cannot be unequivocally identified at all growth stages, and leaf age is not known precisely. Field samples invariably consist of a mixture of mainstem and tiller leaves of varying ages, and more information is needed on the effects of leaf age, to identify the width of the measuring window, and on differences between leaves of the same age on different tillers. More work is needed on leaves to identify the best leaf to sample. Limited measurements made on leaf(2) showed that K concentrations were more stable in this leaf than in leaf(1).

All work in the present study was carried out on a single variety and critical concentrations could depend on variety. However, there are good physiological reasons for supposing that any varietal effect is likely to be small, especially in the case of Pi and K concentrations.

Expressing concentrations on a tissue water basis undoubtedly provides more insight into the regulation of nutrient concentrations in plants, but it also provides the opportunity of carrying out *in-situ* tests. More work is needed on methods of extracting sap quickly and easily from cereal leaves, and the new generation of in-field sap testing devices, such as reflectometers and miniaturised specific ion electrodes, need testing under field conditions.

9 ACKNOWLEDGEMENTS

ROTHAMSTED: We would like to thank Ian Pearman and John Haynes for help with the experimental work. Johnny Johnston provided Fig. 7.2 and made valuable comments on the manuscript. IACR receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC).

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APPENDIX 1

Soil Indices

ADAS SOIL INDICES			
INDEX	PHOSPHORUS	POTASSIUM	MAGNESIUM
0	0-9 mg/l	0-60 mg/l	0-25 mg/l
1	10-15	61-120	26-50
2	16-25	121-240	51-100
3	26-45	241-400	101-175
4	46-70	401-600	176-250
5	71-100	601-900	251-350
6	101-140	901-1500	351-600
7	141-200	1501-2400	601-1000
8	201-280	2401-3600	1001-1500
9	>280	>3600	>1500

APPENDIX 2

Agronomy

ROTHAMSTED P SITES (AGRONOMY)						
Harvest Year	Site	Sow date	Seed rate (kg/ha)	Variety	Previous crop	Harvest date
1992	Exhaustion	23/09/91	161	Mercia	s.barley	31/07/92
1994	Sawyers I	17/10/93	170	Mercia	s.oats	16/08/94
1995	Sawyers I	04/10/94	173	Mercia	w.lupins w.beans	03/08/95

ADAS P SITE - ROPSLEY (AGRONOMY)					
Harvest year	Sow date	Seed rate (kg/ha)	Variety	Previous crop	Harvest date
1992	10/10/91	174	Mercia	w.wheat	21/08/92
1993	12/10/92	174	Mercia	w.wheat	19/08/93
1994	07/09/93	174	Mercia	w.wheat	10/08/94
1995	06/10/94	190	Mercia	w.wheat	04/08/95

ROTHAMSTED K SITE - SAWYERS III (AGRONOMY)					
Harvest year	Sow date	Seed rate (kg/ha)	Variety	Previous crop	Harvest date
1993	09/10/92	190	Mercia	Fallow	16/08/93
1994	21/10/93	170	Mercia	W.oats	15/08/94
1995	04/10/94	173	Mercia	W.oats	03/08/95

ADAS K SITES (AGRONOMY)						
Harvest year	Site	Sow date	Seed rate (kg/ha)	Variety	Previous crop	Harvest date
1992	Fowlmere	09/10/91	170	Haven	w.wheat	08/08/92
1993	Ingham	06/02/93	185	Cannon (s.wheat)	carrots	10/08/93
1994	Fowlmere	24/10/93	170	Riband	w.rape	15/08/94
1995	Sedge Fen	15/11/94	190	Soissons	potatoes	10/08/95

APPENDIX 3

Nutrition

ROTHAMSTED P SITES (NUTRITION)								
Harvest Year	Site	Soil analysis (mg/kg)				Fertiliser (kg/ha)		
		P	K	Mg	pH	N	P	K
1992	Exhaustion	1-51				192 (14 Apr)	0-132	NONE
1994	Sawyers I	4-39				150 (18 Apr)	NONE	100
1995	Sawyers I	4-48				40 (21 Mar) 160 (11 Apr)	NONE	100

ADAS P SITE - ROPSLEY (NUTRITION)							
Harvest Year	Soil analysis (mg/l)				Fertiliser (kg/ha)		
	P	K	Mg	pH	N	P	K
1992	7-24	159	59	6.6	40 (6 Mar) 160 (21 Apr)	0-44	83
1993	11-28	175	66	6.7	40 (6 Mar) 160 (21 Apr)	0-44	83
1994	11-22	176	71	7.1	40 (8 Mar) 160 (28 Apr)	0-44	83
1995	9-21	158	66	6.8	45 (15 Mar) 155 (19 Apr)	0-44	83

ROTHAMSTED K SITE - SAWYERS III (NUTRITION)							
Harvest year	Soil analysis (mg/kg)				Fertiliser (kg/ha)		
	P	K	Mg	pH	N	P	K
1993	34	59-167	78	6.7	75 (22 Apr) 40 (13 May)	NONE	SP
1994	22	40-177	91	6.6	155 (11 Apr) 45 (18 Apr)	52	SP
1995	21	59-186	99	6.8	40 (14 Mar) 160 (11 Apr)	35	SP

ADAS K SITES (NUTRITION)								
Harvest year	Site	Soil analysis (mg/l)				Fertiliser (kg/ha)		
		P	K	Mg	pH	N	P	K
1992	Fowlmere	13	32	17	7.9	234	66	0-175
1993	Ingham	31	79	42	8.0	170	18	0-175
1994	Fowlmere	9	50	35	8.3	210	35	0-175
1995	Sedge Fen	32	48	41	8.3	180	26	0-175

APPENDIX 4
Weather

ROTHAMSTED RAINFALL (mm)					
MONTH	1992	1993	1994	1995	MEAN
JAN	25	90	103	128	65
FEB	21	8	54	84	48
MAR	57	23	55	55	57
APR	64	90	65	11	53
MAY	103	45	69	28	53
JUN	36	131	18	28	57
JUL	62	59	23	19	47
AUG	114	39	54	2	53
SEP	128	115	65	108	55
OCT	71	124	88	31	66
NOV	114	56	41	50	64
DEC	50	110	91	93	69
YEAR	844	888	726	636	687

30-Year mean is shown

ROTHAMSTED MAXIMUM AIR TEMPERATURE °C					
MONTH	1992	1993	1994	1995	MEAN
JAN	5.9	8.8	7.8	7.4	5.8
FEB	8.3	5.8	6.0	9.1	6.1
MAR	10.3	10.3	10.9	9.5	8.9
APR	12.4	12.8	11.7	13.2	11.8
MAY	18.9	16.1	14.4	16.8	15.6
JUN	20.4	19.9	19.5	18.2	18.8
JUL	20.5	19.6	24.4	24.6	21.8
AUG	20.1	19.7	21.0	25.0	20.8
SEP	17.4	15.9	16.3	17.2	17.9
OCT	10.8	11.7	13.7	16.6	14.0
NOV	10.3	7.3	12.1	10.4	9.0
DEC	6.0	7.9	9.3	3.9	6.7
YEAR	13.4	13.0	13.9	14.3	13.0

30-year mean is shown

ROPSLEY RAINFALL (mm)				
MONTH	1992	1993	1994	1995
JAN	6	51	65	80
FEB	13	12	51	52
MAR	59	14	53	39
APR	34	76	52	14
MAY	50	58	42	38
JUN	35	45	10	21
JUL	75	69	76	7
AUG	40	49	47	7
SEP	19	124	110	59
OCT	89	62	54	21
NOV	78	69	49	62
DEC	53	80	68	75
YEAR	551	709	677	475

30-year mean 625 mm

ROPSLEY MAXIMUM AIR TEMPERATURE °C					
MONTH	1992	1993	1994	1995	MEAN
JAN	5.7	8.5	7.3	7.1	5.8
FEB	8.8	6.9	5.4	9.2	6.1
MAR	10.6	10.3	11.1	9.2	9.0
APR	12.8	12.8	12.2	12.8	11.6
MAY	18.6	15.6	13.8	16.5	15.4
JUN	20.8	19.5	19.7	18.1	18.7
JUL	20.9	20.1	24.5	25.1	20.5
AUG	20.5	17.4	20.8	24.4	20.3
SEP	17.3	15.7	16.3	17.7	17.8
OCT	10.6	11.4	13.0	16.7	14
NOV	10.2	6.7	12.0	10.2	8.9
DEC	5.6	7.5	8.7	3.8	6.6
YEAR	13.5	12.7	13.7	14.2	12.9

30-year mean is shown

ADAS K SITES RAINFALL (mm)				
MONTH	FOWLMERE 1991/92	INGHAM 1992/93	FOWLMERE 1993/94	SEDGE FEN 1994/95
SEPT	47	83	74	74
OCT	18	61	108	74
NOV	85	89	39	23
DEC	11	37	72	36
JAN	42	49	66	84
FEB	11	23	36	73
MAR	44	18	31	39
APR	35	58	61	14
MAY	52	62	57	18
JUN	22	40	16	21
JUL	76	73	11	17
AUG	76	57	44	8
YEAR	519	650	615	481
MEAN	534	574	534	574

30-year mean is shown

ADAS K SITES MAXIMUM AIR TEMPERATURE °C				
MONTH	FOWLMERE 1991/92	INGHAM 1992/93	FOWLMERE 1993/94	SEDGE FEN 1994/95
SEP	20.5	18.0	16.7	17.2
OCT	14.1	11.3	12.1	14.5
NOV	9.8	10.5	7.4	13.0
DEC	7.3	6.6	8.5	10.1
JAN	6.4	9.0	8.4	0.1
FEB	9.2	6.1	6.7	10.0
MAR	11.0	10.3	11.7	10.2
APR	13.1	13.5	12.4	14.0
MAY	19.8	16.7	15.1	18.0
JUN	21.7	20.0	20.3	18.5
JUL	21.8	20.5	25.8	25.6
AUG	21.2	19.7	22.1	25.4
YEAR	14.7	13.5	13.9	14.7

APPENDIX 5
Sampling dates

ROTHAMSTED P SITES (SAMPLING DATES)												
GS	1992 (EXHAUSTION)				1994 (SAWYERS I)				1995 (SAWYERS I)			
	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE
24	1	171	72	12.03.92	1	164	89	30.03.94	1	169	81	22.03.95
30	2 3	183 193	84 94	24.03.92 03.04.92					2	190	102	12.04.95
31	4	204	105	14.04.92	2	193	118	28.04.94				
32					3	206	131	11.05.94	3	205	117	27.04.95
37	5	226	127	06.05.92	4	214	139	19.05.94	4	219	131	11.05.95
39					5	222	147	27.05.94	5	228	140	20.05.95
41	6	241	142	21.05.92								
60	7	263	164	12.06.92	6	241	166	15.06.94	6	247	159	08.06.95

ADAS P SITE (ROPSLEY) - SAMPLING DATES

GS	1992				1993				1994				1995			
	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE
16									1	197	82	23.03				
22	1	146	64	04.03					2	213	98	08.04	1	160	74	15.03
23	2	161	79	19.03												
24	3	174	92	01.04	1	178	98	08.04								
30	4	185	103	12.04									2	196	110	20.04
31	5	194	112	21.04	2	205	125	05.05	3	230	115	25.04				
32					3	219	139	19.05	4	240	125	05.05	3	210	124	04.05
33	6	204	122	01.05												
37	7	216	134	13.05									4	224	138	18.05
38	8	223	141	20.05												
39	9	235	153	01.06	4	232	152	01.06	5	267	152	01.06	5	231	145	25.05
55									6	281	166	15.06				
59													6	245	159	08.06
60					5	247	167	16.06								
61	10	244	162	10.06												
65	11	252	170	18.06					7	293	178	27.06	7	259	173	22.06
68					6	260	180	29.06								
73	12	266	184	02.07												

ROTHAMSTED K SITE - SAWYERS III (SAMPLING DATES)												
GS	1993				1994				1995			
	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE
24	1	179	96	06.04.93	1	159	88	29.03.94	1	168	80	21.03.95
31	2	194	111	21.04.93	2	188	117	27.04.94	2	189	101	11.04.95
32					3	200	129	09.05.94	3	209	121	01.05.95
33	3	214	131	11.05.93								
37					4	209	138	18.05.94	4	218	130	10.05.95
39									5	223	135	15.05.95
41	4	227	144	24.05.93	5	215	144	24.05.94				
60					6	236	165	14.06.94	6	252	164	13.06.95
65	5	242	159	08.06.93								

ADAS K SITES (SAMPLING DATES)																
GS	1992 (FOWLMERE)				1993 (INGHAM)				1994 (FOWLMERE)				1995 (SEDGE FEN)			
	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE	CUT	DFS	JD	DATE
13	1	147	64	04.03												
21																
23	2	162	79	19.03	1	80	117	27.04	1	148	80	21.03	1	135	89	30.03
30	3	175	92	01.04					2	176	108	18.04	2	156	110	20.04
30	4	187	104	13.04												
31	5	195	112	21.04	2	94	131	11.05	3	190	122	02.05	3	168	122	02.05
31	6	210	127	06.05												
32	7	217	134	13.05	3	102	139	19.05								
37	8	225	142	21.05	4	117	154	03.06	4	204	136	16.05	4	186	140	20.05
39									5	218	150	30.05	5	199	153	02.06
51	9	238	155	03.06												
52					5	123	160	09.06								
59					6	138	175	24.06								
61									6	233	165	14.06	6	213	167	16.06
71	10	251	168	16.06					7	248	180	29.06	7/8	226	180	29.06
77	11	264	181	29.06	7	146	183	02.07								