THE EFFECT OF DEPTH OF PLACEMENT OF PHOSPHORUS FERTILISER ON THE GROWTH AND DEVELOPMENT OF FIELD PEAS

By

Mohammadali H. Derafshi

B.Sc. Agric. (Tehran, Iran)

M. Sc. Agric. Technology. (Texas A&I, U.S.A.)

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PREFACE

This thesis contains no material which has been submitted for the award of any other degree or diploma in any University, and contains no material previously published or written by another person, except where duly acknowledged in the text of the thesis.

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ABSTRACT

This thesis reports on the results of 3 glasshouse and 3 field experiments.

The glasshouse experiments measured the effects of depth of placement and level of phosphorus (P) on the growth of field peas (*Pisum sativum* L. cv. Alma). In one experiment, interactions between these treatments and variations in seed P content were also determined at an early stage of growth.

An alkaline, P deficient, virgin sandy loam soil was used in all glasshouse experiments. KH_2 PO_4 was used in multiple P levels and in different experiments was placed either at seed level or banded at 4, 7, 10 or 12 cm below the seed. Sequential measurements of plant growth, including shoots, nodules and roots at various depths were undertaken. P concentration and P content in shoots and roots were also measured.

Glasshouse experiment findings:

The results from the glasshouse experiments indicated that, although at early harvests (3 and 4 weeks after sowing) applying P fertiliser with the seed (WS) was better than placing P at 4 cm below the seed (B4), in later harvests (6 and 7 weeks after sowing) B4 appeared to be as effective as WS and in some cases (e.g., nodule fresh weight) was even better than WS.

Root growth was stimulated by the P applied in the zone of fertiliser placement. However, maximum root lengths were obtained at moderate levels of P and were reduced at high levels of P. The reduction of root growth at higher P levels may have been due to the levels being toxic for root growth. This hypothesis is supported by the plant (foliar) symptoms which were observed on some old leaves of the plants in higher P treatments. The alternative hypothesis is that, where the P concentration around the roots is sufficiently high to supply adequate P for plant growth, plants preferably utilise their potential for shoot growth rather than root growth; thus, root proliferation at higher P levels was less than root proliferation at lower P levels.

Nodulation in field peas was very sensitive to P deficiency and no active nodules were produced on plants without P fertiliser. Furthermore, the external P requirement for nodule fresh weight, at all harvests of these experiments, was higher than for shoot yield. These results are in contrast with the findings of Robson (1983) and Jakobsen (1985). The results presented here suggest that P supply affects nodulation in field peas dramatically and directly rather than indirectly by enhancement of plant growth, as concluded by previous workers.

Variations in the seed P content had a minor impact on growth and P uptake of pea seedlings even when grown under severely P deficient conditions. Where seed of high P content was sown and P fertiliser was placed deep (B12) a significant increase in shoot yield and nodulation occurred compared to where seed of low P content was sown.

The effectiveness of P applied at different soil depths was estimated from the slope of the relationship between the level of applied P and shoot dry matter within the zone of P deficiency. The data showed that the most effective method of P application was WS and B4 in Experiments 1 and 2, respectively and the effectiveness of applied P fertiliser was reduced where P was placed deeper than 7 cm below the seed.

Field experiment findings:

Two field experiments were conducted in 1994 and 1995 on an alkaline clay loam of moderately low soil P status located at Roseworthy, South Australia. Triple superphosphate was applied to field peas at different P levels (0, 5, 10, 20 and 40 kg ha^{-1}) and comparisons were made between applying the P with the seed, surface broadcasting P with and without incorporation and banding P 4, 7 and 10 cm below the seed. The field experiments were conducted under very dry conditions in 1994 (total rainfall 249 mm) and repeated in a season of moderate rainfall (382 mm) in 1995.

Samples of shoots and roots were taken at weeks 7, 12 and 17 in 1994 (Experiment 1) and at weeks 7 and 12 in 1995 (Experiment 2) and shoot and root dry matter (in both

experiments), nodule fresh weight and intact and sectioned root length (only in Experiment 2) were measured. Shoot P concentration and content were also determined at both harvests of Experiment 2.

In both experiments, response to the applied P fertiliser was highly significant. In the drought affected 1994 experiment, shoot and grain yield were unaffected by the methods of P placement. However, in the 1995 experiment, the B5 treatment produced a superior response in most of the parameters measured, but this occurred mostly at 12 weeks after sowing and only at near optimal P levels (40 kg P ha^{-1}). At sub-optimal P supply (<20 kg P ha^{-1}), differences between methods of P placement were not significant. This indicates that in a moderately P deficient soil considerable P is taken up from the local soil P in the near surface soil horizon.

Effectiveness of the P fertiliser at B5 was superior to WS and B10 (10 cm below the seed). The optimal level of P in the B5 treatment for 1.0 and 1.2 tonne per hectare of seed yield production was 10 and 24 kg P ha^{-1} respectively, whereas, in the WS and B10 treatments this appeared to be 10 kg P ha^{-1} for 1.0 tonne per hectare (not determined for 1.2 tonne per hectare) and 14 and 30 kg P ha^{-1} for 1.0 and 1.2 tonne per hectare of seed yield respectively.

The 1994 experiment was re-sown with wheat in 1995 to measure the residual effectiveness of P fertiliser treatments applied in 1994. No basal fertilisers were applied to the wheat. Shoot yield was measured at 10 and 20 weeks after sowing and seed yield was determined at grain maturity. Shoots from the second harvest were analysed for P concentration and content. P concentrations in the youngest emerged leaf blade ('YEB') collected 10 weeks from sowing were also measured. The results from this experiment indicated that, there was a strong residual response by the wheat to fertiliser P applied in 1994, but the response was independent of the method of P placement.

The results of all the field and glasshouse experiments suggest that placing P fertiliser 4-5 cm below the seed of field pea crops will be beneficial in terms of nodulation, P

uptake and grain yield and grain P concentration. An additional advantage of deeper P placement is the avoidance of possible P toxicity effects on young seedlings or rhizobia at higher P levels applied with the seed.

CHAPTER 1

GENERAL INTRODUCTION

Field peas (*Pisum sativum* L.)are one of the most important pulse (grain legume) crops grown in southern Australia. Different genotypes of this crop are used in intensive livestock rations and for human consumption. Field peas are a good source of protein (24%) and starch (48%) but are low in fat (1%).

The area sown to field peas in South Australia was 7,300 ha. in 1950 but in 1995 it exceeded 135,000 ha. Total production for Australia in 1993-94 was 523,000 tonnes, 34% of which was produced in South Australia. Two-thirds of the Australian field pea production in 1993-94, was exported. The gross value of production was Aus $128 million (Grain Statistics 1994).

The remarkable growth of the field pea industry, especially in South Australia, occurred because field peas are more adaptable than the other pulses to a wide range of soil types (from sandy loam to clay) and climatic conditions. They provide rotational benefits through disease control and maintenance of soil nitrogen fertility. However, peas do not grow well in acidic soils, low in calcium (Lie 1969) or in waterlogged conditions (Belford *et al.* 1980).

Field peas usually fit well into rotations with cereals, and are often grown after one or two cereal crops and prior to wheat (*Triticum aestivum* L.). This increases the yield of the following cereal crop by several means including; improving available soil nitrogen, decreasing cereal diseases and controlling grass weeds.

Phosphorus (P) is an important nutrient required for pea growth and nodule development (Canning and Kramer 1958). P has an essential role in nucleic acid synthesis in plant cells and provides energy for chemical reactions in cells (Boss 1964). It performs a vital function in the life cycle of the plant in the nucleic acid components of genes and chromosomes which carry the genetic material from cell to cell and seed to seed (Durrant 1974).

Most of the agricultural soils in the world do not provide sufficient P for commercially viable plant growth. Australian soils are even lower in total P by world standards and for unfertilised surface soil range widely from 1 to 5000 mg kg^{-1} but with an overall average of only 300 mg kg^{-1} (Wild 1958). Similarly, many South Australian soils are deficient in plant available P (see Table 2.2).

The main source of P fertilisers is from phosphate rocks (PR). Emigh (1972) estimated the world phosphate reserves at 1,298,000 million tonnes with an average P content about 4.4%. High-grade PR resources which have at least 12% P are more economical for P fertiliser manufacture. However, these sources of P which make up only about 11.9% of the total world PR production (US Bureau of Mines 1975) are rapidly declining and the use of lower grades of PR will increase the cost of P fertiliser manufacturing greatly in the near future.

On the other hand, P fertiliser utilisation efficiency by crops is very low and the absorbed P in the year of application seldom exceeds 40% (Williams 1957). P retention by soil constituents, especially Fe and Al in acidic soils or Ca in alkaline soils is the main factor responsible for this low efficiency. Common methods of applying P fertilisers such as broadcasting with incorporation or drilling with seed have low P fertiliser use efficiency and therefore, more research is needed to seek alternative methods which increase P use efficiency. Several experiments were conducted in Western Australia to compare deep placement of P fertiliser with broadcast or drilled with seed. These studies resulted in higher lupin yield and better P use efficiency. However, cereals did not respond to deep placement of P as much as lupins (Jarvis & Bolland 1991).

In this thesis, both field and glasshouse experiments were used to examine and compare different methods of applying P fertiliser with regard to early plant growth, nodule development and seed yield in field pea. The relative effectiveness and efficiency of applying P fertiliser with different methods were also reviewed and explanations for variations in plant response between methods of P application proposed.

CHAPTER 2
REVIEW OF LITERATURE

2.1. INTRODUCTION

This chapter reviews the literature and identifies gaps in knowledge relevant to the studies undertaken in this thesis. Firstly, a brief description is made on the forms of soil phosphorus (P) and how these sources interact and can be manipulated by farming practices to influence the P supplying capacity of soil for plant growth. Secondly, emphasis is given to reviewing how plant root systems of field peas (and other species) and their associated rhizospheres acquire P from the soil reserves. Thirdly, an assessment is also made of the role that plant and environmental factors have on P uptake and distribution within plants. Finally, knowledge is reviewed on how cultural and fertiliser practices can be used to affect the efficiency by which plants acquire and utilise fertiliser P for growth

2.2. DISTRIBUTION OF P WITH SOIL DEPTH

2.2.1 Forms of P in soils

Literature on the chemical nature and behaviour of soil P is extensive. In the context of this thesis, only a brief summary of this subject is made in relation to assessing how plant roots derive P from the soil reserves to meet their requirements for growth.

Soil P has been conventionally classified into four broad pools, viz: soil solution, inorganic, organic and microbial P (Figure 2.1). The majority of the soil P occurs as immobilised (non-labile) forms which include:

- primary phosphate minerals;
- insoluble phosphates of Ca, Fe and Al;
- phosphates occluded within colloidal oxides and silicate minerals; and

- P associated with or immobilised by the soil organic matter. This fraction can represent from 15 to 80% of the total soil P (Tisdale *et al.* 1993) at any given time.

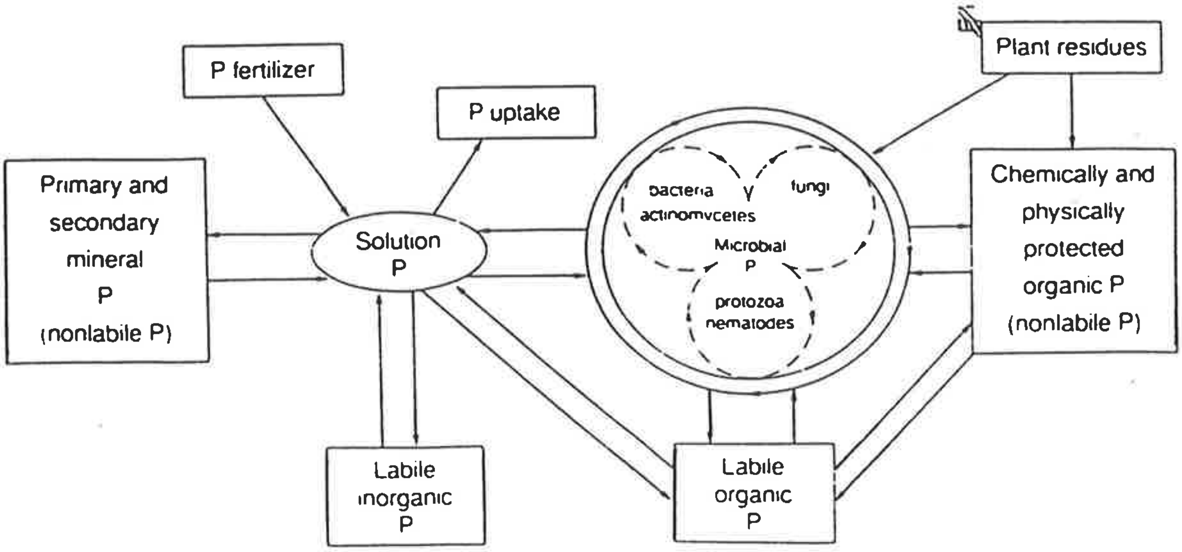


Figure 2.1. Schematic representation of the P cycle in soil (Chahan *et al.* in Tisdale *et al.* 1993).

In addition, from 1 to 10% of the total soil P can be immobilised by the soil microbial biomass as it decomposes soil organic matter. Thus, soil biota compete with plant roots for labile forms of P contained in the soil solution. According to Russell (1988) net mineralisation occurs when the organic C : organic P ratio is ≤ 200 : 1 and net immobilisation occurs at ratios ≥ 300 : 1. Importantly, P in the microbial biomass is recycled as microbial populations turn over and their tissue P is released by mineralisation processes. Phosphates are also adsorbed onto soil mineral surfaces and are released to the soil solution via desorption processes (Tisdale *et al.* 1993). A significant proportion of the P in the soil solution exists as organically bound P (Dalal 1977).

Processes leading to the transformation of P between these pools usually occur slowly in both directions. In simplified terms, P cycles within the soil matrix according to the following relationship:

Plant roots ⟵ Soil solution P ⟷ Labile P <------> Non-labile P

Ultimately, plant roots absorb $H_2PO_4^-$ and HPO_4^{2-} from the soil solution (Russell 1988); and the concentration of these ions in the soil solution is governed by the mineralisation and desorption of the labile P fractions present in the soil. As labile P concentrations are depleted, non-labile sources of P slowly replenish this pool, whilst labile P forms can be immobilised into the non-labile pool (Tisdale *et al.* 1993)

To a large extent, inherent soil properties (e.g., pH of the soil solution, soil mineral composition, activities of Ca, Fe and Al) and soil conditions (soil redox potential and temperature) govern the nature, rate and extent of chemical and microbial reactions between P, the soil solid and solution phases and the soil biota (Willett *et al.* 1978b). In a given soil, these reactions, in turn, determine the nature and size of each pool of soil P.

Land use also influences the size of each soil P pool. For example, McLaughlin *et al.* (1990) found that from 35 to 60% of the total soil P accumulated in Australian acidic pasture soils existed as organic P. Concentrations of microbial P, although in a dynamic state, are generally higher in permanent grassland and pasture soils than in cultivated soils (Richardson 1994). Environmental factors, such as soil temperature and water status, which govern microbial activity also determine the size of the microbial P pool.

P applied to the soil either as a fertiliser or as plant residues leads to net accumulation of P in the various soil pools. However, the immediate recovery of P from these sources by plants in most soils is usually quite low, and of the order of 1 to 25% for crops (Sharpley 1986). Thus, a major proportion of the P absorbed by plant roots derives from the previously accumulated (termed the "residual") soil P reserves.

This process has been demonstrated elegantly in the field by McLaughlin *et al.* (1988) for wheat grown on a solonized brown soil using a triple labelling technique. In this experiment, 13 and 10 kg P ha^{-1} were applied to the soil as ^{31}P and ^{32}P labelled medic residue and monocalcium phosphate respectively and wheat was grown in these treated soils for 95 days. Accumulation of P from soil P reserves was monitored by the natural P isotope. The accumulation of P from these three P sources by both wheat plants and soil P pools is described in Figure 2. 2.

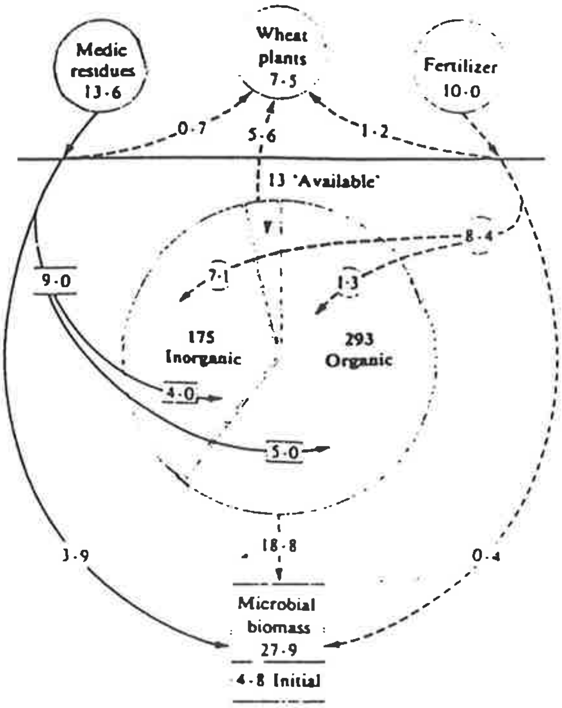


Figure 2.2. Distribution of P and amounts transferred (kg ha^{-1} to 100 mm depth) between various pools 95 days after sowing a wheat crop (McLaughlin *et al.* 1988)

Seventy five per cent of the P in the wheat plants (5.6 kg P ha^{-1}) was derived from the residual soil P reserves, whilst only 16% and 9% (1.2 kg ha^{-1} and 0.7 kg ha^{-1}) of that absorbed came from the applied fertiliser and medic residue sources respectively. Moreover, after 95 days, 71% of the fertiliser P had accumulated in the inorganic soil P pool. By contrast, 29%, 36% and 29% of the P applied as medic residues resided in the inorganic, organic and microbial biomass P pools respectively. During this experiment, the microbial P pool increased from 4.8 to 27.9 kg P ha^{-1}, a major portion of which derived from the residual soil P reserves (18.8 kg P ha^{-1})

2.2.2 Soil P tests

For many years a variety of soil P tests have been calibrated and used to assess the P fertility status of soils for plant growth (Olsen 1954, Colwell 1963, Rayment and Higginson 1992). Calibration criteria are derived by relating the soil test value to the degree of plant P stress, or proportional responsiveness of plants to current applications of P fertiliser (Reuter *et al.* 1995) The tests remain empirically based (Reuter and Hannam 1987), but attempt to estimate the P supplying capacity of a given soil under laboratory conditions by measuring the "intensity" (soil solution P) and "quantity" factors (P desorbable from soil surfaces and mineralised from labile organic P) which are associated with "plant available" P (Russell 1988). In essence, modern soil P tests attempt to estimate the labile forms of soil P.

In Australia, the soil P tests most commonly used commercially are the Colwell (Colwell 1963) and Olsen (Olsen *et al.* 1954) methods. In northern Australia, 0.005 M H_2SO_4 (Kerr and Von Stieglitz 1938) is used widely as an extractant for acidic soils growing sugar cane.

2.2.3 Distribution of total P in soil

By world standards, the total P content of undisturbed, Australian surface soils is reported to be of low to moderate status, averaging 300 mg P kg^{-1} (Wild 1958). This compares with estimates derived for American (Parker 1953) and British soils (Cooke 1958) of 500 and 650 mg P kg^{-1}. However, in all cases, wide spatial variations in total soil P content exist as a consequence of the nature of the soil forming parent materials, their degree of weathering and the extent of P leaching that has occurred over time (Stevenson 1986).

Recent information has now been published for 15 acidic pasture soil profiles of south-eastern Australia (McLaughlin *et al.* 1990). In these profiles, the total, inorganic and organic P concentrations generally decreased with soil depth (Table 2.1).

It is generally considered that for uncultivated grassland soils, the accumulation of P near the soil surface is a result of long-term deposition of litter P from vegetation. However, in cultivated soils, higher concentrations of total P (and other forms of P) in surface horizons are related to past applications of P fertilisers and, with the exception of sands, the strong retention of P within these horizons. For example, Cooke (1958) estimated that nearly one half of the P content in British surface soils originated from past fertiliser P applications.

Table 2.1 Variation with depth in total, inorganic and organic phosphorus in acidic topsoils estimated using the ignition/extraction procedure of Walker and Adams (1958), (McLaughlin *et al.* 1990)

Depth	Total P (mg kg^{-1})		Inorganic P (mg kg^{-1})		Organic P (mg kg^{-1})	
mm	Mean	Range	Mean	Range	Mean	Range
0- 20	441^a	192-821	105^a	38-243	336^a	143-579
20- 40	282^b	147-545	65^b	30-165	217^b	108-404
40- 60	213^c	83-381	51^c	20-124	162^c	63-278
60-100	167^d	48-278	38^d	7- 94	129^d	41-208

Values are the means and ranges for 15 sites. Means with the same superscript within each column are not significantly different ($P>0.05$)

2.2.4 Distribution of organic P in soil

The organic P content of soils varies considerably and depends on soil texture, composition of the parent material, organic matter content, drainage, soil pH and land use (Dalal 1977). For example, acidic pasture soils in Australia contain from 35 to 65% of their total P as organic P, part of which may exist in readily mineralisable forms (McLaughlin *et al.* 1990). Generally, the organic P content of the soil decreases with depth (Table 2.1), but exceptions to this generalisation do occur in some soils (Figure 2.3).

2.2.5 Distribution of extractable soil P in soil

As a consequence of past P fertiliser applications and soil properties, extractable concentrations of P in surface (0-10 cm) soils are typically quite diverse and variable. Table 2.2 provides data from a survey conducted in South Australia during 1992 and 1994.

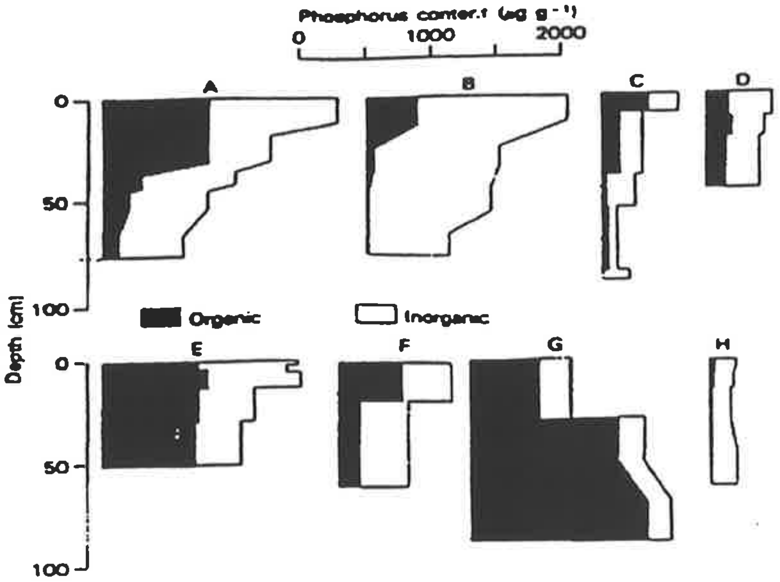


Figure 2.3. Distribution of phosphorus in various soil profiles.

A & B. Freely and poorly drained cultivated clay loam of the Insch Association, Scotland (Williams and Saunders 1956).

C. Uncultivated Koputaroa soil developed on windblown sand, New Zealand (Syers and Walker 1969).

D Uncultivated Dawes silt loam, Nebraska (Allaway and Rhoades 1951).

E. Uncultivated Pima calcareous clay loam, Arizona (Fuller and McGeorge 1951).

F. Cultivated Orthic Deep Black, Melfort, Saskatchewan (McKercher 1966).

G. Uncultivated *Carex globularis* pine bog, northern Finland (Kaila 1956b).

H. Leached forest soil, Ibadan, Nigeria (Nye and Bertheux 1957).

Table 2.2. Bicarbonate extractable (Colwell 1963) P (mg kg^{-1}) at 0-10 cm depth for several locations in South Australia (Jeffery and Hughes 1994).

Location	Extractable soil P	Location	Extractable soil P	Location	Extracable soil P.	Location	Extracable soil P.
Booleroo Cent.	31	Nantawarra	14	Huddleston	20	Langhorne Creek	49
Melrose	62	Brinkworth	22	Burra	25	Eden Valley	30
Warner-town	30	Wokurna	30	Mt. Bryan	12	Wharminda	17
Laura	58	Kybunga	51	Leasingham	61	Kimba	11
Manoora	47	Bowillia	36	Woodside	25	Cleve	40
Hanson	21	Mintaro	21	Wistow	15	Cooper	37

Note: Each sample bulked from 20 cores (0-10 cm) taken around a pit.

As with total P, extractable P levels usually decrease appreciably with increasing soil depth, and in most cases to very low levels (Figure 2.4). Essentially, similar observations were made by McLaughlin *et al.* (1990) for acidic pasture soils of south-eastern Australia using P extracted by either resins or 0.5 M NaH CO_3 .

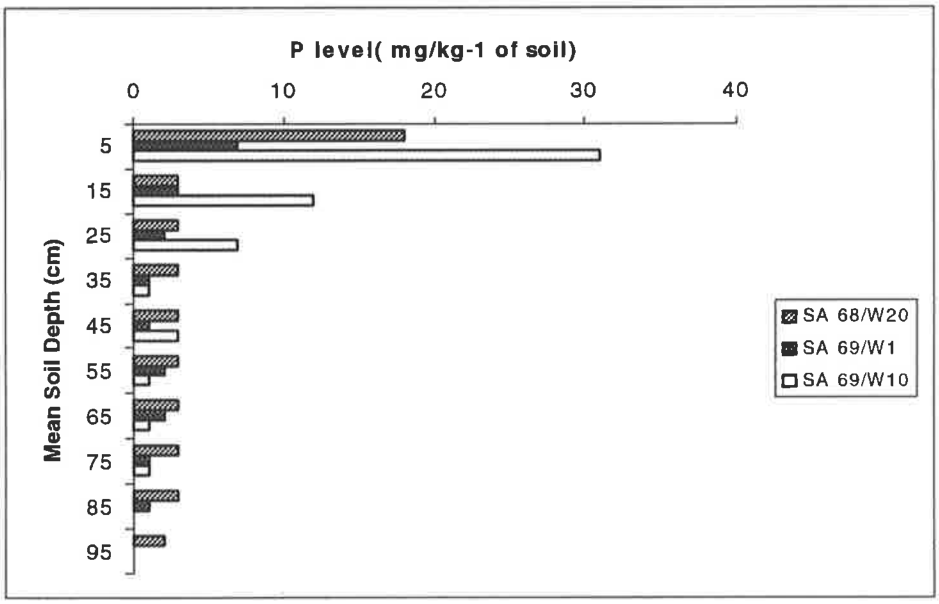


Figure 2.4. Distribution of extractable P in the soil profile at the site of three South Australian wheat experiments (Colwell 1977).

2.2.6 Conclusion

The available evidence indicates that the P content of most Australian agricultural soils is concentrated largely in the surface horizon. The P status of the subsoil is at best modest or low. Indeed, in the cultivated soils of SA (Colwell 1977) very low levels of extractable P exists at depths below 15 cm. Moreover, except for sandy soils, the mobility of fertiliser P in soil is considered low. Such data imply that deeper plant roots could have restricted access to sources of soil P as they explore the soil volume beyond the P-enriched surface horizon.

2.3. GROWTH OF THE PEA ROOT SYSTEM

2.3.1 Root function

The primary functions of roots are to anchor the plant in the soil matrix and to absorb soil water and nutrients necessary for plant growth. Root growth can be limited by a diverse range of edaphic (e.g., nutrient deficiencies, soil compaction, root diseases, salinity) and environmental (e.g., soil moisture stress and low soil temperature) factors, which in turn, restrict nutrient and water uptake and thereby limit plant yield. Roots also exude protons (Churchill *et al.* 1983, Romheld and Kramer 1983) and phosphatases (Bieleski 1973, McLachlan 1982, Tarafdar and Jungk 1987) into the root rhizosphere which can enhance the availability of soil P reserves for root uptake.

2.3.2 Description of root growth in field peas.

Pea plants establish their early root growth, which includes production of the primary axis and main framework of laterals, using cotyledonary reserves of nutrients. The growth rate of roots maximises at about the time of initiation of flower primordia and then declines abruptly, before flowering starts. A minor resurgence of root growth may occur at flower initiation and when pod development begins. Root growth ceases completely at pod maturity (Salter and Dew 1965).

In solution culture studies, the pattern of root elongation in pea plants was shown to proceed at alternate high and low rates. At the end of each period of low growth rate, higher order roots emerged (Yorke and Sagar 1970). Elongation rate of primary roots was zero from 5-8 days and increased to a maximum on days 10-11 and then decreased and subsequently ceased. Secondary roots tended to occur in clumps. Secondary roots with greatest growth potential occurred along the primary rootand also, but less markedly, at the positions of clumps. Tertiary roots appeared on day 16 and elongated rapidly up to day 20 (when the experiment was terminated) (Yorke and Safar 1970).

A very early study (Jean 1928) indicates that root length in field peas is under genetic control and there is a close correlation between the second generation and their parental plants. There is also a good correlation between plant height and root length. The author suggested that this might be due to a response to the transpirational demands of the plants, the taller shoots requiring the longer roots. However, field peas produce much less roots than cereal crops. Hamblin and Tennant (1987) found that root lengths of cereals were consistently 5 to 10 times greater than those of grain legumes (lupin (*Lupinus angustifolius*) and pea).

Soil conditions such as soil compaction, soil moisture content and soil nutrient level affect pea root growth in different ways. For example, the pea plant increases its root length in P deficient conditions to maximise the P uptake (Srihuttagum and Sivasithamparam 1991). Root growth reaction to soil water is not consistent and varies in different genotypes. However, this variation was much lower compared with that of other plant species (Table 2.3). Field peas like most of the grain legumes, have a less finely branched root system than either grasses or pasture legumes and their diameter increases as the water stress of the soil increases.

Table 2.3. Total root length in Xeric Psamments per ground area (La) (cm cm^{-2}), average root density (Lv) (cm cm^{-3}) and root diameter (d) (mm) for wet and medium rainfall sites (428 and 298 mm in the growing season)(Hamblin and Hamblin 1985).

Species ^{A}	Wet site			Medium site		
	L_a	L_v	d	L_a	L_v	d
Lupin	9	0.05	0.37-0.72	9	0.04	0.37-0.80
Sub clover	92	1.10	0.22-0.31	56	0.91	0.22-0.40
Medic	57	0.60	0.23-0.40	80	0.86	0,28-0.40
Wheat	40	0.17	0.25-0.34	25	0.17	0.20-0.22
Field Peas:						
cv. Buckley	10	0.16	0.26	13	0.16	0.33
cv. Dun	16	0.25	0.28	9	0.18	0.31

^{A} The values are the average among different genotypes within each species.

2.3.3 Root distribution with soil depth

The distribution of roots within the soil profile is likely to have important consequences on the acquisition of soil nutrients and water by crop plants. Thus, while the proliferation of roots in the nutrient-enriched surface horizon may benefit the nutritional status of crops, it may also render crops more susceptible to water stress, particularly during seasons with low rainfall and high evaporation.

Field pea roots are generally regarded as having relatively shallow and less extensive root systems (see Table 2.3) compared to wheat, lupins and chickpeas when grown on the same soil type (Hamblin and Tennant 1987, Anderson *et al.* 1991). For example, lupins and wheat had less than 50% of their total root length in the top 20 cm, whereas field pea had over 70% of roots in that layer. Further more, rooting depth was also less in field pea (65 cm), compared with lupin or wheat which were 190 and 113 cm, respectively (Hamblin and Hamblin 1985). Rooting depth of field peas was closely correlated to the water loss from the soil profile during the growth period, but the total root length was less affected (Hamblin and Tennant 1987).

Studies on root distribution of different genotypes of field pea in a water limited environment (Wongan Hills, Western Australia) showed that despite low rainfall and consequently, a relatively dry surface soil horizon, from 80-97% of the root biomass for all genotypes measured at peak vegetative growth was located within 20 cm of the soil surface (Table 2.4). However, roots of cv. Wirrega extended deeper and extracted soil water from 2 m, which was 40 cm below the extraction depth measured for the other genotypes.

Table 2.4. Distribution of root biomass (g DM m^{-2}) at different soil depths for 6 different field pea genotypes harvested at peak biomass, (Armstrong *et al.* 1994).

Genotype	Soil Depth (cm)								
	0-20	20-40	40-60	60-80	80-100	100-120	120-140	140-160	Total
Dundale	49	2	0.8	0.35	0.17	0.05	0.01	0	52.4
Wirrega	49	4	3.5	1.4	0.8	0.7	0.17	0.05	59.6
Protrega	55	6	5.2	2.5	1.4	0.5	0.12	0	70.7
Dinkum	46	1	0.5	0.23	0.3	0.12	0.03	0	48.2
L-82	47	3	1.75	0.5	0.15	0.12	0.03	0.01	52.5
L-80	44	1.5	0.5	0.23	0	0.02	0.01	0	46

The temporal pattern of shoot and root growth for different pea genotypes, grown under field conditions (Wongan Hills), also appears to be sigmoidal (Figure 2.5).

As a result, their shoot : root dry weight ratios increase progressively from values of around 1 during early growth to between 8 and 10 at maturity (Armstrong and Pate 1994).

Cultivar Wirrega, and to a lesser extent, Protrega genotype produced shoot and root biomass greater than that of other genotypes tested. This is based largely, on exceptionally high rates of crop growth (rate of dry matter accumulation per unit ground area) and green area duration (time integral of green area) late into the season.

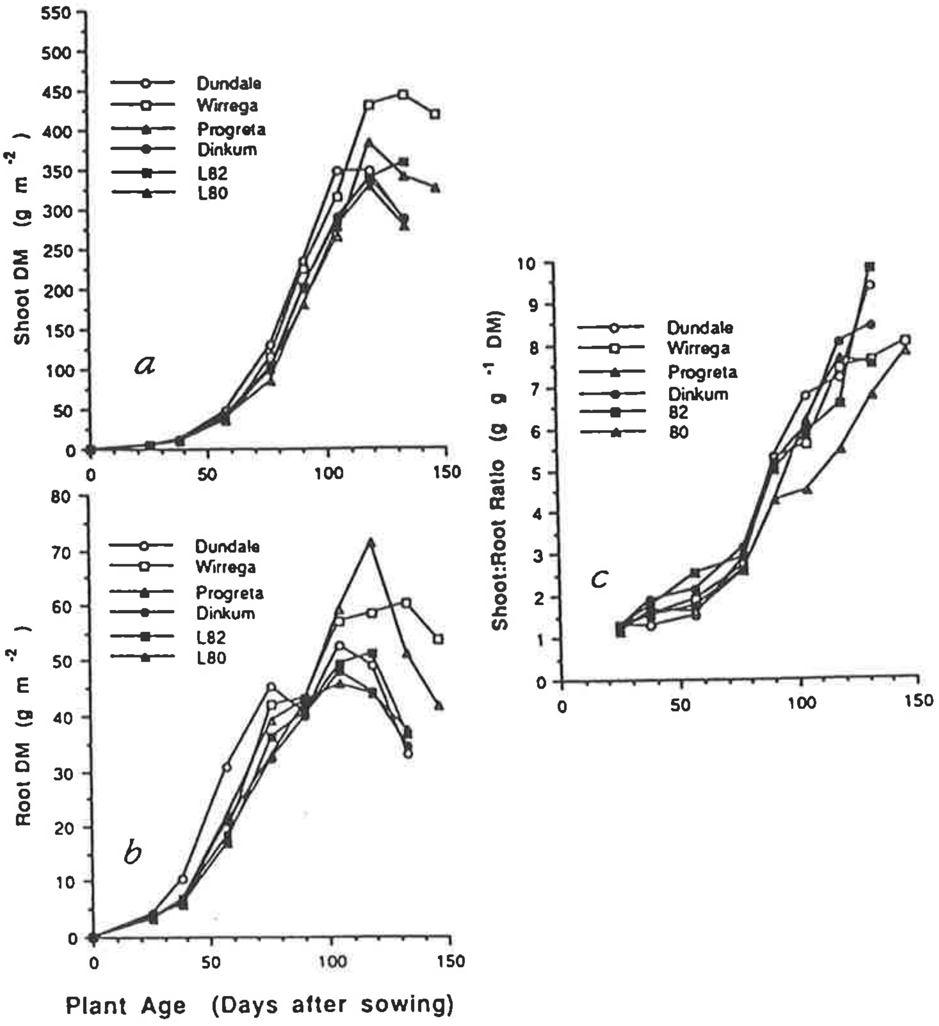


Figure 2.5. Seasonal changes in shoot biomass (a), root biomass (b) and shoot/root dry weight ratio (c) of field pea genotypes (Armstrong and Pate 1994)

These features were in turn related to continued production of root biomass some 2-4 weeks beyond that measured for the other field pea genotypes. While cereals are noted for their higher investment of carbon into roots under deteriorating environmental conditions such responses could well be used to advantage in an indeterminate crop such as peas where root density is inherently low and active root and leaf growth continues well beyond anthesis (Armstrong and Pate 1994)

2.3.4 Sites of P uptake in the developing root system

The ability to absorb P varies between different parts of a plant root system and is an important factor in studies of "effective" volume of soil around roots. Thus, the P status of the volume of soil in the vicinity of roots with high absorption sites may well govern the rate of P acquisition by plant roots. For example, Bowen and Rovira (1966) developed a scanning technique for recording the extent of uptake of ^{32}P from different parts of the developing root system. Their data for wheat indicate that maximum P uptake occurred within a 3 cm region of the root apex and in the basal portion of the root system. Lower uptake was recorded in the central portion of the root. High P uptake was also recorded in basal portions of unbranched roots where lateral root primordia emerged within the following 1 or 2 days. Similar measurements on 4- day old tomato (Lycopersicon asculentum L.) plant roots recorded maximum uptake 1-2 cm behind the apex (Bowen and Rovira 1967). However, both the rate of root growth and P status affected P uptake patterns. Thus it is unwise to transpose detailed patterns of uptake of roots grown in one culture to another set of cultures and conditions. For example, uptake pattern for 14 day old soil-grown wheat roots showed a peak uptake in the apical 4 cm, and a gradual decline in uptake along the root to approximately a quarter of that in the apical region up to the lateral root zone. However, uptake of P by lateral roots far exceeded that of the main root (Rovira and Bowen 1968).

Pea species also exhibit similar patterns to those cited above. For example, more P was accumulated in the region 1-2 mm behind the apex of pea roots than in the region 10 mm behind the apex (Figure 2.6).

Similarly the uptake of N in the form of ammonium or nitrate differed between zones examined over the 13.5 cm length of the pea; uptake of both N forms was greatest in the apical 1.0 cm. and least in the 1.0-4.5 cm zone (Grasmanis & Barley 1969). The amount of nitrate and ammonium nitrogen absorbed in 30 min by each zone are shown in Table 2.5.

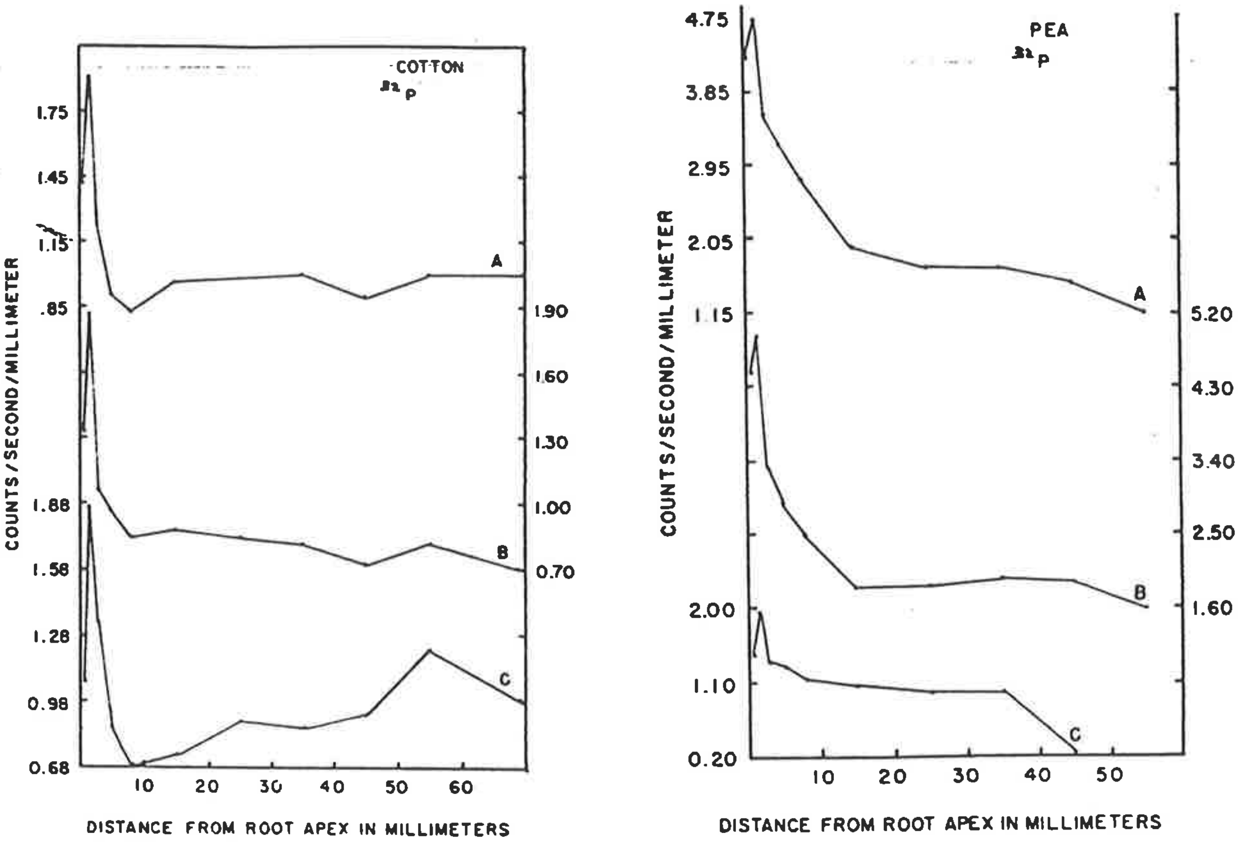


Figure 2.6. The amount of ^{32}P accumulated by various regions of pea roots, expressed as counts per second per mm. A is the average of 15 roots with an average length of 60 mm., B is the average of 18 roots with an average length of 57 mm, and C is the average of 5 roots with an average length of 46 mm. (Canning and Paul 1958).

Table 2.5. Uptake of nitrate and of ammonium into successive zones of the pea radicle. Absolute values given in parentheses for the 0-1 cm zone are expressed as n-equiv/30 min (Grasmanis and Barley 1969).

Uptake Measured	Distance from Apex (cm)				Distance from Apex (cm)			
	0-1	1-4.5	4.5-9	9-13.5	0-1	1-4.5	4.5-9	9-13.5
	Nitrate uptake				Ammonium uptake			
Per centimetre	100 (2.8)	31	41	41	100 (17.4)	25	48	54
Per square centimetre	100 (10.2)	28	35	29	100 (78.7)	23	38	38
Per mg dry weight	100 (4.6)	63	54	35	100 (35.6)	54	63	46
Per mg fresh weight	100 (0.6)	29	26	19	100 (4.2)	24	30	25
Per mg nitrogen	100 (64.8)	90	91	70	100 (497.1)	78	106	90

2.3.5 Conclusions

Compared to other crops, there exists only limited information on the dynamics of root growth in field peas. The evidence assembled above indicates that:

- roots are primarily restricted to the surface 20 cm of soil;
- root growth follows a sigmoidal pattern of development and maximises near the initiation of flower primordia;
- genotypic differences between field pea genotypes occur particularly in the vicinity immediately behind root meristerms.

These observations imply that the placement of P fertiliser in relation to the developing root system could have important implications on the efficiency by which field peas acquire and utilise P during growth. This is particularly so given that P supply may also indirectly influence di-nitrogen fixation and hence the N status of plants

2.4. FACTORS AFFECTING UPTAKE OF P BY ROOTS

2.4.1 Soil P concentration

Inorganic P concentrations in the soil solution are very low, and even in fertile soils are seldom higher than 10 µM (Fried and Shapiro 1961). However, plant roots are able to absorb P from solution concentrations well below 0.01 µM (Barber *et al.* 1968). P concentration at the root surface influences P absorption by plant roots. The relation between ion influx into a root and its concentration at the root surface is described by Michaelis-Menten kinetics through the following equation.

$$I = \frac{I_{\max} \times C_l}{K_m + C_l}$$

where, I is ion influx into the root cell, I_{max} is the maximum ion influx, C is ion concentration at the root surface, and K_m is the concentration when the influx rate is equal to 1/2 I_{max}.

The rate of nutrient uptake by plant roots growing in soil is governed by soil and plant factors. Mechanistic models have been developed to predict nutrient uptake rates by plant roots growing in soil (Nyle *et al.* 1975, Claassen and Barber 1976, Chushman 1979, Silberbush and Barber 1983, Barber and Silberbush 1984). These models describe nutrient influx by either diffusion or mass flow through the soil to the plant roots and their absorption by the root according to the nutrient gradient within the rhizosphere.

Claassen and Barber (1976), in developing their model, considered ten parameters (Table 2.6). Three were soil parameters, nutrient concentration in soil solution before any root growth, soil buffering capacity and effective diffusion coefficient.

Table 2.6. Soil and plant root parameters used in the Claassen and Barber model (1976) to describe nutrient influx through the soil to the plant roots.

	Parameters	Symbol
Soil	• Nutrient concentration in soil solution (before root growth)	C_{li}
	• Soil buffering capacity	b
	• Effective diffusion coefficient	D_e
Plant	• Maximum nutrient influx at high concentrations at the root surface	I_{max}
	• Maximum nutrient concentration at the root surface	$C_{l\circ}$
	• Minimum nutrient concentration (where no influx occurs)	C_{min}
	• Mean root radius	$r_{\circ}$
	• Root growth rate	K
	• Initial root length	$L_{\circ}$
	• Water influx	$V_{\circ}$

The remaining seven were plant parameters; three of which described the relationship between nutrient concentration at the root surface and ion influx into the roots. Michaelis-Menten kinetics used to describe this relation were determined in separate solution culture experiments using the procedure of Claassen and Barber (1974) as amended by Nielsen and Barber (1978), and the equation:

$$I_n = I_{\max}(C_{l_o} - C_{\min}) / (K_m + C_{l_o} - C_{\min})$$

where I_n is net influx; I_{max} is maximum influx for high concentrations at the root surface (C_{l_O}); C_{min} is the minimum nutrient concentration where no influx occurs; K_m is equal to C_{l_O}-C_{min}; and $I_n = 1/2\ I_{max}$. Of the remaining seven plant parameters, three are related to temporal changes in root growth. These are mean root radius, root growth rate, and initial root length. The final parameter in the model is water influx which is calculated from water use and root surface area measurements.

The Cushman model (Cushman 1979) has one additional parameter which describes half the distance between root axes. This parameter was calculated from root length data and soil volume and was included to cover competition between different parts of the root system for nutrient access. Although use of the Claassen-Barber model involves complicated calculations (Claassen and Barber 1976), a computer program has been developed to calculate total nutrient uptake with time. In their experiment with K Claassen and Barber (1976) found that the model over-predicted K uptake in corn (*Zea mays* L.) by 56%. This was probably because they assumed competition for K uptake by the roots did not occur. Root competition is more likely for K than for P because K has a larger diffusion coefficient which results in a greater extension of the K depletion gradient from the root (Silberbush and Barber 1983).

The Claassen-Barber and Cushman models must be used with certain reservations. For instance, there are factors which were not considered in their models. These include root hairs, mycorrhiza development (Abbott and Robson 1982) and temperature (McKell *et.al.* 1962), all of which affect the P uptake by plant roots. Silberbush and Barber (1983), in their model for predicting P and K uptake rates by soybean (*Glycine max* (L) Merr.), did not consider the effects of root hairs and mycorrhizae on P and K uptake. In their experiments, high P concentration in the soil solution and the young roots were used (most roots were <15 days old). Root hairs do not affect P uptake in soil solutions with high P concentration (Powell 1974)and mycorrhizae either develop slowly on roots or are suppressed at high levels of P supply (Jensen 1983, Jakobsen 1986).

The contribution of root hairs to P uptake has been evaluated by Bouldin (1961) using a model root that is characteristic of corn and P diffusion characteristics consistent with levels normally found in soil. This study indicated that in soils with low a P level and a high buffer capacity, the effective diffusion coefficient was very low ($D_e = 5x10^{-11}$ cm^2 s^{-1}). Consequently the diffusion distance in these soils within 4 days was of the order of 0.006 cm, which was less than the average distance between root hairs in their model. Hence, root hairs contribute substantially to P uptake by the root. The study also showed that, for soils of high P status and with a D_e of $1x10^{-8}$ cm^2 s^{-1}, the average diffusion distance in 4 days was 0.08 cm, which is almost three times the root hair length and more than 10 times the distance between root hairs. Hence, almost all of the P in the soil within the root hair cylinder could reach the root within 1 hour. Since the average diffusion distance is much greater than the length of the root hair, the main effect of root hairs would be to enhance absorption of P in the root hair zone and increase in the effective radius of the roots.

2.4.2 Soil moisture status

P uptake by plant roots takes place where P ions are at the root surface. Contact between P ions and the root surface results from either diffusion of soil P through soil to roots or by the extension of roots towards the P source. However, both mechanisms function only in the presence of an adequate soil moisture content. For example, a significant reduction in P uptake by sorghum (*Sorghum bicolor*(L) Moench) (Eck and Fanning 1961), by perrenial ryegrass (*Lolium perenne* L.)(Cornish *et al.* 1984) and by corn (Munõz and Arscott 1991) was reported where soil moisture tension was increased. The suppression of P uptake under moisture stress conditions could be attributed to either a decrease in the diffusion of soil P or to restricted root growth or both (Barber *et al.* 1963, Barber 1978). Water stress may also increase mechanical impedance to root extension (Barley 1963). Furthermore, in conditions of higher soil moisture content, the dissolution of sparingly soluble forms of soil P will be greater, enhancing the concentration of P in the soil solution. For example, at 8.66% soil moisture content, uptake by grain sorghum increased as the depth of P fertiliser placement increased. But under soil moisture stress (2.63%) the effect of fertiliser P placement was not observed (Eck and Fanning 1961).

Factors such as thickness of moisture films, diffusion path length, degree of hydration and some physiological attributes like root elongation, turgidity and numbers of root hairs appear to be important factors also controlling P uptake in relation to soil moisture tension (Olsen *et al.* 1960). For example, at low soil P levels an increase in available water to 1/3 -bar tension raised P uptake by corn plants from 1.4 to 3.4 $\mu g\ g^{-1}$ of soil, but at high P levels P uptake increased from 8 to 23 $\mu g\ g^{-1}$ of soil as soil water content was increased (Olsen *et al.* 1960). This suggests that for plants subjected to alternate wet and dry periods, a high soil P level could supply the P requirements of plants, but at low P supply, P acquisition by plants is rendered more difficult. Soil drying reduces root length, but this effect is negligible in soil with low bulk density (1.0 g cm^{-3}) compared with 97% reduction in soil with high bulk density (1.4 g cm^{-3}) (Table 2.7). While the effect of soil bulk density on diffusion of P to the surface of the root is small, mechanical resistance due to the increased soil strength should be the main factor limiting root length in more compacted soil which is linearly related to P uptake (Cornish *et al.* 1984). This study (Table 2.7) indicates that drying the soil reduced P uptake per unit of length of root, but, in compacted soil, this effect was small compared with the effect of drying on root extension. The authors concluded that when this soil type is compacted (not cultivated), moisture stress will reduce P uptake mainly because mechanical resistance reduces root extension and root extension ceases well within the available water range in intact soil cores.

Further glasshouse experiments have been conducted by Bolland (1992) to study the effect of moisture stress on P uptake and shoot yield in wheat and some pasture plants including subterranean clover (*Trifolium subterraneum* L.) and annual medics (*Medicago* spp.). The results of these studies showed that, compared to adequate water, water stress consistently reduced shoots dry weight and the maximum yield plateau, for the relationship between yield and the level of P applied, by up to 25 to 60%. The relationship between yield and P concentration or content (internal efficiency of P use) also differed for low and high soil moisture status, so that the same P concentration or content in tissue was related to different yields.

2.4.3 Soil temperature

Root growth and consequently P uptake and plant growth are often limited by low and high soil temperatures (Figure 2.7). For example, results of a study on legume species (McKell *et al.* 1962) indicated that supraoptimal or suboptimal soil temperatures depressed total P uptake by the plant, especially when grown at a lower P supply (Table 2.8).

Table 2.7. Effects of soil water regimen, bulk density (g cm^{-3}) and NaHCO$_3$-extractable soil P level (µg g^{-1}) (Colwell 1963) on P uptake and growth of ryegrass (Cornish *et al.* 1984)

	Watered daily (-0.02 MPa)				Drying ^{A}			
Bulk density:	1.0		1.4		1.0		1.4	
Soil P	10	36	10	36	10	36	10	36
Root length (cm pot^{-1})	872^{c}	162^{d}	619^{b}	595^{b}	690^{b}	668^{b}	15^{a}	20^{a}
Shoot DM (mg pot^{-1})	66.8^{e}	113.0^{a}	50.4^{d}	91.8^{f}	15.9^{b}	38.6	5.0^{a}	8.6^{a}
Root DM (mg pot^{-1})	122.7^{c}	115.6^{c}	62.2^{b}	59.7^{b}	55.7^{b}	38.5^{b}	6.0^{a}	9.4^{a}
Shoot P concentration (%)	0.46^{a}	0.85^{b}	0.38^{a}	0.88^{b}	0.36^{a}	0.80^{b}	0.36^{a}	0.47^{a}
Root P concentration (%)	0.15^{a}	0.24^{bc}	0.17^{a}	0.22^{bc}	0.15^{a}	0.27^{c}	0.20^{ab}	0.20^{a}
P uptake (µg cm^{-1})	0.57^{b}	0.77^{c}	0.48^{b}	1.58^{d}	0.21^{a}	0.64^{bc}	1.68^{d}	2.40^{e}
P uptake (mg pot^{-1})	0.49^{e}	1.23^{g}	0.29^{c}	0.95^{f}	0.13^{b}	0.41^{d}	0.02^{a}	0.05^{a}

^{A} Watered twice daily but no water after emergence. Means within rows followed by the same superscript are not significantly different ($P \geq 0.05$).

Obviously, the availability of soil P is less at low than at high soil temperatures (Sutton 1969). Low temperatures may restrict the mineralisation of organic P and in addition may reduce one or more of the primary factors that regulate the uptake of inorganic P by plants. In particular, it is possible that low temperature inhibits the rate of release of available P and/or decreases the rate of diffusion of P from the soil to the root.

In potato (*Solanum tuberosum* L.) early responses to supraoptimum root zone temperatures are inhibition of cell divison in the root apical meristem and less geotropic response (Sattelmacher *et al. 1991c)*, or in surghum a decrease in epidermal cell length suggesting acelerated maturation of the epidermal cells (Pardales *et al.* 1992).

Typically, at low soil temperatures root growth is retarded, the roots become shorter and thicker, and particularly lateral root formation is depressed (Gregory 1983). For example, the total root length measured in wheat at its optimum temperature (25 °C) was 275 (m plant^{-1}); the total root length at 20 and 30 °C, was decreased to 98 and 138m plant^{-1} ,respectively (Huang *et al.* 1991a,b).

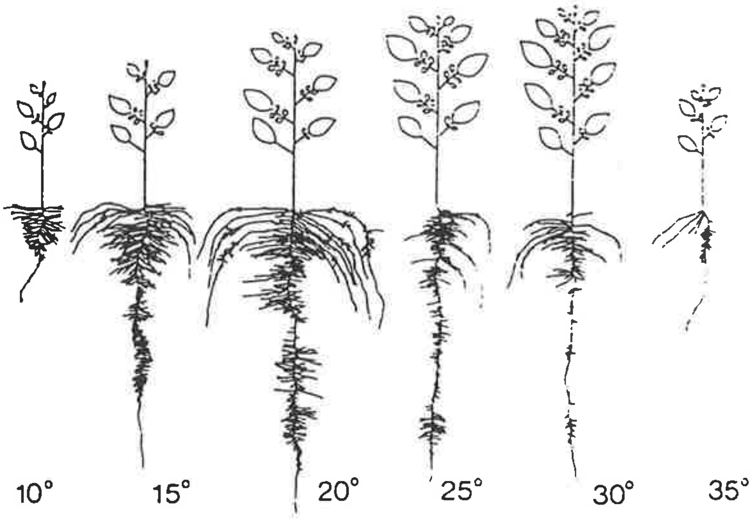


Figure 2.7. Influence of root zone temperature on root morphology and shoot growth of potato seedlings, (Sattelmacher *et al.* 1990c)

Table 2.8. Total P concentration of legume species as affected by the interaction of temperature and P-fertility level (Mckell *et al.* 1962).

Temperature ^{0}C	Applied P level kg/ha	Total P concentration (%)	Significance ^{A}
10	0	0.24	a
	49	0.27	b
	194	0.46	e
15	0	0.34	c
	49	0.40	d
	194	0.46	e
20	0	0.31	b
	49	0.41	d
	194	0.51	f

^{A} Values followed by the same letter are not-significantly different ($P>0.05$).

2.4.4 Vesicular Arbuscular Mycorrhizae

The majority of microorganisms in the rhizosphere are free living fungi or bacteria. Only a very limited number of species form symbiotic associations with plant roots. Two major groups of mycorrhizal fungi which form such associations are the ectomycorrhizae and endomycorrhizae c(Tinker 1980). Ectomycorrhizae are more often associated with temperate trees, whereas endomycorrhizae are found on the majority of the world's vegetation. The main group of endomycorrhizae are the vesicular-arbuscular mycorrhizae (VAM).

VAM improve nutrient absorption by host plants and thus increase plant growth (Jasper *et.al.* 1979, Harley and Smith 1983, Hayman 1983, Abbott and Robson 1984, Jakobsen 1987). The effect of VAM on P nutrition has received more attention than other nutrients because plant P requirement is high and P supply in soil is normally low. On low P soils, VAM infected plants usually have a low root : shoot ratio and a high shoot fresh-weight : dry-weight ratio which indicates greater water uptake by mycorrhizal plants and thus better plant growth than uninfected plants. Improvement of P uptake by various mycorrhizal plants has also been noted by several researchers. These plants include field peas (Jakobsen 1987, Staun *et al.* 1987), cowpeas (*Vigna unguiculata* (L.) Walp.) (Ikombo *et al.* 1991), ryegrass

(Jasper *et al.* 1979), tomatoes (Cress *et al.* 1979) and subterranean clover (Abbott and Robson 1977).

VAM infect host roots, grow into the soil between roots, absorb soil P which is then transported through the root to the shoots via the xylem. One mechanism underlying the increased rate of P uptake is the efficiency by which mycorrhizal roots exploit the soil profile, with hyphae extending beyond the zone of depletion surrounding the growing root and its root hairs (Tinker 1975, Nye and Tinker 1977, Owusu-Bennoah and Wild 1979,). It seems likely that VAM infection increases nutrient uptake primarily by shortening the distance that nutrients must diffuse through soil to the roots. For example, Hattingh *et al.* (1973) found that VAM hyphae could intercept labelled P (^{32}P) placed 27 mm from a mycorrhizal onion (*Allium cepa* L.) root, whereas it remained unavailable to non-mycorrhizal roots. The effect of VAM in stimulating P uptake by plants varies in diverse conditions. Soil P status, plant genotype, even plant age can influence the abundance and distribution of VAM and also the infection of roots by VAM fungi (Barber and Rovira 1975, Estaun *et al.* 1987). Addition of P fertiliser has been shown to either have no effect (Porter *et al.* 1978, Anderson *et al* 1987) or decrease (Hayman *et al.* 1975, Jensen and Jakobsen 1980, Jensen 1983, Jakobsen 1986) the level of mycorrhizal infection in a range of agricultural crops.

2.4.5 Acid Phosphatases

Acid phosphatases are ubiquitous and usually highly active enzymes in plants and they are thought to play a role in P metabolism. Leaf phosphatases are plant enzymes which act under P deficient conditions and split off P within plant cells and thereby mobilise P for new growth centres. Root acid phosphatases are adaptive enzymes which are secreted or released by plant roots into the rhizosphere where they split phosphate from organic P sources and provide a greater supply of inorganic P within the rhizosphere for root uptake (Ridge and Rovira 1971, Martin 1973). It is thought that increased phosphatase activity is due to de novo protein synthesis. The repression and derepression of protein synthesis are controlled by the concentration of some internal P compounds, possibly orthophosphate (Bouling *et al.* 1981).

Moreover, P deficiency in soil could cause a considerable increase in phosphatase activity in the rhizosphere (Tarafdar and Jungk 1987). Bieleski and Johnson (1972) observed that phosphatase activity of the roots of *Spirodela oligorrhiza* increased by 4-5 times under P deficiency conditions. It has also been postulated that the greater uptake of P in P deficient soils by plants in association with ectomycorrhiza (Harley 1969) and endomycorrhiza (*Endogone sp.*) (Daft and Nicolson 1969) may be due at least in part to the greater phosphatase activity of the mycorrhizal plants, in addition to the increase in root surface area and increased volume of soil exploited by radiating hyphae (Harley 1969).

P uptake and total dry matter yield is negatively related to phosphatase activity in plants. Thus, root phosphatase activity has been promoted as a good indicator of plant P status and a possible supplement to nutrient analysis ((Bestford 1979, McLachlan 1980, 1982). Romer *et al.* (1995) studied effects of both genetic variability and P supply on phosphatase activity in 9 wheat and 23 barley (*Hordeum vulgare* L.) cultivars in pot experiments. The results of this study indicated that variability of phosphatase activity caused by cultivars was higher than that caused by P supply. It is, therefore, concluded that the acid phosphatase activity is not suitable as a generally applicable tool for diagnosing P supply. In comparison, total P concentration of the plants was influenced, to a higher degree, by P supply than by cultivars. Total P is, therefore, more suitable as a criterion for diagnosing P status of plants than phosphatase activity.

2.4.6 Root disease

Root pathogens affect root growth in various ways. For example, the take-all fungus (*Gaeumannomyces graminis* var. *tritici*) is a relatively slow-growing pathogen, which grows along the root sending hyphae into the stele where it proliferates inside the phloem and xylem, thus decreasing uptake and transfer of ions (Clarkson *et al.* 1975). By contrast, *Rhizoctonia solani* is a root rot fungus which markedly decreases root length, water and nutrient uptake by plants (Rovira 1990).

Both cyst nematode (*Heterodera goettingiana*) in North America and common root rot (*Aphanomyces euteriches*) which is found world wide, seriously reduce yield in field peas. However, field peas in South Australia have not been seriously affected by these root diseases (J. Davidson pers. comm.). In a study on wheat in South Australia Simon and Rovira (1985) showed that *Heterodera avenae* reduced the length of seminal root axes per plant by 33% in soil containing 1.1 eggs per gram of soil and by 74% in soil containing 5.8 eggs per gram of soil. Plants severely infected with *H. avenae* (5.8 eggs per gram) were less able to utilise P distributed through the soil. For example, plant response to applied P at high and low initial population of *H. avenae* was 97% and 48%, respectively.

In North America, Fusarium root rot (*Fusarium solani)* is one of the most important yield constraints of field peas causing yield reductions from 10 to 50%. This fungus primarily infects the cotyledons, cotyledonary attachment area, epicotyl and hypocotyl of pea seedlings and depresses P uptake seriously (Kraft and Berry 1972, Kraft and Giles 1979). Infected pea roots are unable to penetrate readily into soil, and especially into soils compacted by tractor wheels or tillage implements. The infected roots are usually severely rotted, reduced in length and are unable to grow towards sources of soil water and nutrients necessary for optimum yields (Kraft *et al.* 1981).

2.4.7 Nutrient stress

It is widely acknowledged that severe, and in some cases, moderate, deficiencies of most essential plant nutrients reduce root growth and may even alter the geometry of the developing root system (see Table 2.9). Usually these effects exert a more pronounced impact on shoot growth than on root growth, This latter observation for P may occur through a number of possible mechanisms which are discussed in more detail under section 2.6. Nevertheless, edaphic factors which restrict root growth or alter the pattern of root geometry inevitably reduce yield, nutrient uptake and the efficiency of fertiliser use.

Similarly, toxicity of elements such as aluminium(Al) (Robson and Pitman 1983) and boron (Paull *et al.* 1992) also depress root development and thereby restrict the capacity of the plant to acquire nutrients such as P which is relatively immobile in the soil. Al reduces the utilisation of P by plants in two ways; root growth is limited by toxic monomeric Al species present in the soil solution of many acid soils, while P may be adsorbed onto the surfaces of Al oxides or even precipitated as Al phosphate thereby reducing its availability (Russell 1973).

Furthermore, the stress of some nutrients in soil can reduce the utilisation of P by plants indirectly. For example, Fe deficiency in lupins (Tang *et al.* 1990) or Cu deficiency in subterranean clover (Reuter 1980) depress N_2 fixation and plant growth which then reduces plant P utilisation

2.4.8 Impact of fertiliser practices

Localising P fertiliser in the soil or mixing it thoroughly within the soil changes the soil P concentration, and thus the uptake of P by crops. Barber and his colleagues (Anghinoni and Barber 1980, Borkert and Barber 1985, Kovar and Barber 1989) studied the effect of soil P concentration on P uptake by corn and soybean in different soil types. Their results indicated that as the same total amount of applied P was mixed with increasing proportions of soil, P uptake by plants increased to a maximum and then decreased (Figure 2.8).

Table 2.9. Selected examples of the impact of single nutrient deficiencies on root growth.

Limiting nutrient	Plant species	Effect on root growth	Reference
N	Tobacco	Lower shoot :root DW, elevated carbohydrates level	1
P	*Stylosanthes hamata*	Lower shoot : root DW, rapid P transport from shoot to root and from older roots to meristerm	2
K	Cotton	Decreased root length density and root area,	3
S	Wheat and lupin	Increased root DW, root length, root hair ,root length and area, and decreased root diameter and root S concentration	4
Ca	Most dicotyledons	Impaired root function or root growth.	5
Mg	Sorghum	Red and stunted.	6
Cu	Subterranean clover	Protein synthesis is inhibited, decreased root DW	7
Zn	Subterranean clover	Impaired root function, decreased root DW	8
Mn	Lupins	Root growth decreased	9
B	Sunflower	Impaired root function or root growth.	10
Al	Soybean	Roots stunted with many root laterals, root tips are brown.	11

References: 1 = Rufty *et al.* (1990), 2 = Smith *et al.* (1990), 3 = Brouder and Cassman (1990), 4 = Gilbert and Robson 1983), 5 = Loneragan *et al.* (1968), 6 = Clark (1984), 7 and 8 = Reuter (1980). 9 = Nable and Loneragan (1984), 10 = Husa and McIlrath (1965), 11 = Sartain and Kamprath (1975).

Although root length was stimulated increasingly in the fertilised soil increasingly, more of the added P reacted with the soil constituents and was rendered less available for uptake by plants. Thus, the processes of soil P immobilisation begin to exert a greater effect than root growth stimulation (Kovar and Barber 1987, 1989).

Given the above, the importance of soil properties on the bioavailability of applied P to plants must be emphasised. For example, on a P fixing calcareous silt loam, increasing the probability that root-fertiliser contact occurred was more important in terms of the efficiency of P fertiliser use than reducing soil-fertiliser contact (Sleight *et al.*1984). This may be true even though increasing soil-fertiliser contact may result in greater fixation of the applied P than would be expected where the P is applied in a concentrated zone within the soil.

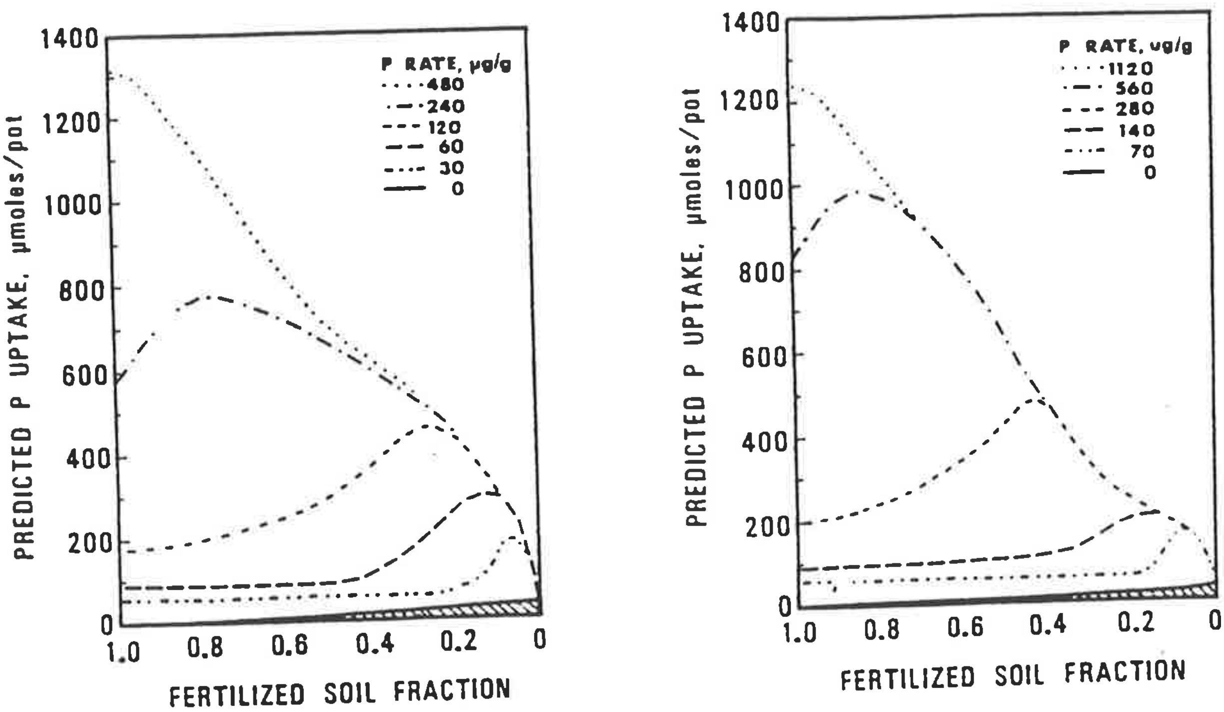


Figure 2.8. Predicted P uptake by corn as a function of P levels per pot and placement in a fine-silty, mixed, mesic Aquic Argiudoll (left) and a fine-silty, mixed, mesic Ultic Hapludalf (right), (Anghinoni and Barber 1980).

Indeed, on a fine loamy soil with high pH (7.8) deep banding of P resulted in higher uptake in winter wheat than where the fertiliser was broadcast or broadcast and then incorporated into the surface soil (Halvorson and Havlin 1992). However, on a well drained, silt loam with a neutral soil pH, placement treatments did not affect the yield or the uptake of P by soybean plants (Ham and Caldwell 1978). Soil acidity is a major factor limiting P uptake by grain legumes. P applied to acid soils reacts strongly with soil constituents such as Fe, restricting its mobility with consequent reductions in availability to plants. Higher Al concentration in these soils would also restrict the efficiency of P uptake. Two reactions possibly occur between Al and P, one at the cell surface in soil solution which results in fixation of P by an adsorption precipitation reaction (Clarkson 1966) and consequent reduction in P concentration of soil solution; the other reaction occurs within the cell, possibly within mitochondria which reduces P concentration in plant tops (Munns 1965). Andrew and Jones (1978) suggested that the use of the ratio of Ca to Al in the soil solution could constitute a valuable means of diagnosis for acid soil problems. For example, in several acid soils, this ratio was approximately 1 : 1, whereas in fertile productive soils the ratio was in the vicinity of 40 : trace.

2.4.9 Seed P content

During seed germination and early vegetative growth, the nutrient supply to the plant is derived in part from seed reserves and in part from soil. For example, subterranean clover seedlings deplete their small P reserves within 14 days and thereafter must rely totally on external P sources for growth (Krigel 1967).

Several field and glasshouse experiments have indicated that plants respond to changes in seed P content. Variations in seed P content on growth in annual pasture legumes have been demonstrated in burr medic (*Medicago denticulata* Wild.), yellow serradella (*Ornithopus* spp.), subterranean clover and balansa clover (Trifolium balansae) in Australia (Bolland and Baker 1988, 1989, 1990, Bolland and Paynter 1990, Bolland 1991). The general conclusion from these experiments is that superior seedling growth and P uptake in shoots occurred where seeds of high P content were sown on P deficient soils compared to where seeds of low P content were sown. This early response diminished with advancing plant age, and as the level of P fertiliser was raised. Studies in Europe and North America have shown similar results. For example, Austin (1966b) reported decreased plant growth from sowing low P seed when no P fertiliser was applied. When P fertiliser was applied there were no differences in plant growth. However, this response has not been an invariable observation since, others have shown responses to seed P when P fertiliser has been applied (Roberts 1948).

Almost all of the above studies have concentrated on the effect of seed P content on early plant growth. However, recent work in Western Australia (Paynter 1992) has studied effects of P content on grain yield of lupin and wheat in soils of different P status. In 29 wheat experiments, under both field and glasshouse conditions, only 4 cases showed decreased grain yield where seed of low P status was sown. In 20 lupin experiments conducted both in the field and in glasshouses, only 2 experiments showed a significant reduction in grain yield when low seed P content was sown. Nevertheless, the positive effects observed in the minority of these experiments indicate seed P content can be important factor in P efficiency.

Positive relationships between seed P content and yield of wheat and lupin could also be due to variations in the other nutrient contents in the seed, particularly N and/or K (Paynter 1992)

Two different methods are used to provide seeds with low and high P levels; increasing seed P content by soaking them in various solutions containing P (Roberts 1948) or by altering the external supply of P to the plants producing seed (most of the experiments used seed produced in this way). Neither of these methods assures a similar content of other nutrients in the seed which may affect the interpretation of the results of these experiments.

2.4.10 Conclusions

This section has described a variety of environmental and plant factors which influence the efficacy by which soil and fertiliser P is acquired by crop root systems. Some of these factors which reduce P uptake (e.g., other nutrient deficiencies; soil-borne root disease; maintenance of optimal soil P reserves) can be calculated through site-specific restrictions to root growth and thereby improve the efficacy of P absorption by roots. Other root environmental factors, such as soil moisture stress and low soil temperature, may affect the chemical form in the soil, its ability to diffuse to plant root, or the ability of roots to grow torwards soil P sources.

The efficacy of P absorption by roots will be enhanced where P fertiliser is placed within the zone of root proliferation and, indeed, in the zone of P placement, root growth is often observed to be stimulated. However, mixing the applied P within the soil can lead to reactions between the fertiliser P and the reactive soil constituents which may reduce its effectiveness and the efficiency of P fertiliser use.

2.5. IMPACT OF P DEFICIENCY ON P CIRCULATION WITHIN THE PLANT

Some plant genotypes show more tolerance than others and have more adaptive responses to P deficient conditions. These responses include an increased P uptake capacity (Cartwright 1972, Lefebvre 1982), an increase in the proportion of the whole plant mass present as roots (Chapin and Bieleski 1982), an increase in the proportion of total plant P present in the root system (Barrow 1975, Temple-Smith and Menary 1977) and changes in the morphology of the root system (Foehse and Jungk 1983, de Jager 1984). To improve the effectiveness of P fertiliser, study of the mechanisms which are responsible for adaptation of plants to growth on low P soils is essential.

The range of nutrient concentrations in plants is classified as deficient, marginal, critical value, adequate, high and toxic or excessive (Reuter and Robinson 1986). Plants with deficient concentrations exhibit visible deficiency symptoms and growth is severely reduced. In some cases this range has been defined in experiments, in others, it has been developed from analytical data collected during problem diagnosis. Where values in the deficient range are found, corrective measures should be taken.

The range of P concentrations associated with P deficiency varies among plant species; in a species, this range of concentrations varies with the plant parts selected and the plant growth stage. For example, the deficient P concentration in the shoot of field peas , 36 and 81 days after sowing, was < 0.6% and < 0.4%, respectively (Faferia 1977), whereas the critical range of P at the youngest open leaves in pre-flowering was reported to be 0.25-0.3% (Lamb and Poddar 1987) (any nutrient level below the critical range is considered deficient).

Gilbert *et al.* (1989a, 1989b) imposed P stress to 3 different varieties of perennial *Stylosanthes* species (Seca, Schofield and CPI 34904) and found that Seca tolerated P deficiency (4 mg/kg of loamy sand soil) more than the others by allocating more of its dry matter to stem and through producing more fine roots.

2.5.1 Effect of P deficiency on root and shoot growth

Generally, as the level of P supply increases the root to shoot ratio decreases (White 1972, Christie and Moorby 1975) and P deficiency enhances the relative responsiveness of root growth and depresses shoot growth (Greenway and Gunn 1966, Smith *et al.* 1990). However, more usually, P deficiency depresses both root and shoot growth, but shoots are depressed more than roots so that the root : shoot weight ratio increases. In severe P deficiencies, this ratio can more than double (Asher and Loneragan 1967). The transfer of *Stylosanthes hamata* plants from a.previously P-sufficient nutrient solution to a P free solution caused a rapid and a substantial increase in root weight percentage to occur (Smith *et al.* 1990). The rapid and substantial changes in allocation of plant biomass that occur during the development of P stress are likely to be an important adaptive mechanism for maximising P uptake by plant. Relatively longer roots and greater root surface area resulting from this response are key factors in maximising P uptake by plants growing in P–deficient soils (Barber and Silberbush 1984).

2.5.2 Effect of P deficiency on N_2 fixation

Increase in external P supply to a P deficient soil enhances nodulation and N_2 fixation in leguminous species dramatically. This beneficial effect of P can be seen both in increased nitrogen (N) concentrations in shoots and earlier nodulation development (subterranean clover: McLachlan and Norman 1961, Robson *et al.* 1981; *Stylosanthes humilis:* Shaw *et al.* 1966, Gates *et al.* 1966, Gates and Wilson 1974; field peas: Jakobsen 1987; soybean: Singleton *et al.* 1985, Israel 1987). However, a greater external requirement for symbiotic N_2 fixation than for growth of the host legume shoots when supplied with adequate inorganic N has frequently been claimed (Israel 1987). An alternative view is that increased P supply increases nodulation and N_2 fixation by increasing host legume growth (Robson 1983, Jakobsen 1985). There are three reasons for our interest in the involvement of P in symbiotic N_2 fixation:

- comparison of the external and internal requirements for P between legumes supplied with mineral N with those reliant on symbiotic N_2

- effect of P supply on nodule weight and number and,
- the effect of P supply on shoot N_2 concentrations.

Increasing P supply, which increases the growth of shoots, generally, increases both nodule number and weight (Robson 1983, 1988). Indeed, nodule weight is closely correlated with shoot weight (Graham and Rosas 1979, Cassman *et al* 1981b, Robson *et al.* 1981, Israel 1987) over a wide range of P supply, providing little support for the frequent comment that adding P increases nodule weight more than shoot weight. This comment is based largely on effects of applied P increasing the ratio of nodule weight to shoot weight, which occurs only because there must be a certain shoot weight before nodules are formed.

On the other hand, Graham and Rosas (1979) found that nodules on beans (*Phaseolus vulgaris* L.) were an extremely strong sink for P. Thus, when P supply was increased from 0 to 138 kg P ha^{-1}, leaf weight increased 4.3-fold, nodule weight increased 9-fold and N_2 fixation rate of those nodules increased 19-fold. These data indicate that P supply had direct effects on nodulation and N_2 fixation over and above the indirect effects mediated through increased shoot growth.

The importance of P for N_2 fixation in white clover (*Trifolium repens*) has been demonstrated by Hart (1990). In this study which was conducted in solution culture, P concentration was higher in nodules than in roots or shoots and the acetylene reducing activity was closely related to nodule P. Addition of N to this solution strongly inhibited the nodule activity and reduced the P concentration in the nodules. The author suggested that, where plants received N they were relieved of the necessity to maintain high concentrations of P in the nodules and there was a change in the relative strength of sinks for P, although where the external supply of P was stopped, redistribution of P was insufficient to compensate for the shortfall in supply (Hart 1990).

2.5.3 Preferential retention of P in roots

The effect of P deficiency in enhancing the root : shoot weight ratio appears to result from the ability of deficient root tissues to use absorbed P for preferential growth of the root system rather than translocating it to the shoots (Williams 1948).

It thus appears that P–deficient tissue has first call on any P available to it. This could account for the ability of root systems to proliferate in the immediate vicinity of bands of fertiliser P in soils (Duncan and Ohlrogge 1958, Alston 1976)

There is also evidence that the mechanisms for the preferential use of recently acquired P by roots may involve not only retention and transport to root meristems, but also the translocation of P and assimilates from the shoots to the roots, possibly triggered by root signals to stimulate root growth. For example, Smith *et al.* (1990) found that roots of *Stylosanthes hamata* contained the minimum proportion of the plant's P content when root P concentrations were 8-10 μmol P g^{-1} root, and shoot P concentrations were 16-20 μmol P g^{-1} shoot. When tissue concentrations were less than these values, plants suffered from P stress and P was either preferentially retained by the roots or rapidly transferred from shoots to roots, reducing the growth rates of shoot, but permitting root growth to continue. Upon reducing the external P supply to plants whose root P concentrations exceeded 8 to 10 μ mol P g^{-1} root, excess P was rapidly transferred from the root to the shoot to maintain shoot growth rates.

2.5.4 Remobilisation of P within the plant

As mentioned before, another adaptive response which most plants show under P stress is an increase in the proportion of total plant P present in the root system. In higher plants, the activity of P transport in roots increases well in advance of any significant effect of P deficiency on plant growth (Bowen 1970). For example,Clarkson and Scattergood (1982) reported that transfer of barley and tomato plants to a culture containing no P caused a sharp reduction in shoot and root P content in both species. However, the reduction in roots seemed better regulated than in shoots because of internal P translocation from shoots to roots.

In addition to external P supply, movement of sucrose in plants and the nature and metabolic activities of plant cells and organs are important factors which govern the content and distribution of P in plants. Young developing leaves have a high P content regardless of the levels of P supply. These leaves continue to increase in P content while they are importing sucrose and the external P supply is maintained. But once leaves stop importing and start exporting sucrose, they also commence to export P (Greenway and Gunn 1966, Hill *et al.* 1978). Indeed, while leaves are exporting P in the phloem, they may be also importing P in the xylem. Thus, there exists either a net gain or net loss of P in individual leaves. The adequacy of external P supply now becomes important because it largely determines the amount of P in the xylem sap.

P is a mobile nutrient in most plant tissues and readily moves from old to young tissues, irrespective of plant P status. Remobilisation of P during plant development or nutrient stress usually results in P content being lower in old leaves than in younger leaves and, as a consequence, leaf P concentrations are higher in younger tissues than in mature or older tissues.

2.5.5 Conclusion

Plant genotypes tolerate P deficiency to differing degrees and possibly through different mechanisms. The high internal mobility of P within the plants occurring through phloem transport provides a high degree of internal redistribution of P. This involves redistribution of P and assimilates from the shoots to roots of P deficient plants, mobilisation of P from older leaves to actively growing leaves and the preferential transport of P to the meristems of both shoots and roots. Phosphatase enzymes are involved in these processes.

Importantly, the level of external P supply impacts strongly on the extent and rate of plant P remobilisation, being necessarily higher under P deficient conditions. In legumes, P deficiency also has a marked effect on the efficiency of the symbiotic N_2 fixation process.

There exists little published information on the influence of P deficiency on P mobilisation in field peas.

2.6. IMPACT OF P FERTILISER PRACTICES ON P USE EFFICIENCY

2.6.1 Comparative effectiveness of P fertiliser types

The original source of P in most manufactured P fertilisers is rock phosphate (RP) with a general formula of $Ca_{10} (Po_4)_6 (X)_2$, where X is either F^-, OH^- or Cl^-. These minerals are called apatites. The common term used to describe the P content in P fertiliser is "water soluble P" or "available P" which plants are able to absorb.

Available P is used as a criterion to classify the common P fertilisers used in agriculture (Table 2.10).

The P content of RP has only limited value for plants. For maximum effectiveness, RPs should be finely ground and mixed thoroughly within acidic soils at application rates from 3-5 times the level of P normally provided in conventional water-soluble fertilisers (Khasawneh and Doll 1987). The main factor limiting its utilisation by plants is that the P dissolves too slowly to meet crop demands (Terman and Allen 1967, Palmer and Jessop 1982). However, plant species respond to RP differently. For example, in the investigations by Bryan and Andrew (1971), *Lotus bainesii, S. guianensis, Centrosema pubescens, Indigofera spicata* and *Medicago sativa* gave medium to good responses to RP, whereas *Desmodium uncinatum* and *Macroptilium lathyroides* only gave a very small response. In the field experiment reported in this paper, the response of *L. bainesii* to rock phosphate was almost equal to that from superphosphate (SSP). The above experiments were accomplished without any detailed recognition of the possibility of the symbiotic effects of mycorrhiza and other rhizosphere organisms (Andrew and Jones 1978).

Table 2.10. Common commercially available P fertilisers (Tisdate *et al.* 1993)

Material	*Abbreviations*	*Analysis (%)*				*Form of P*	*Available P as (%) total P*
		N	*P*	*K*	*S*		
Rock phosphate	RP	-	11-17	-	-	Orthophosphate	14-65
Single superphosphate	SSP	-	7-10	-	11-12	Orthophosphate	97-100
Wet process phosphoric acid		-	21-23	-	-	Orthophosphate	100
Triple superphosphate	TSP or CSP	-	19-23	-	1-1.5	Orthophosphate	97-100
Monoammonium phosphate	MAP	11-13	21-27	-	0-2	Orthophosphate	100
Diammonium phosphate	DAP	18-21	20-23	-	0-2	Orthophosphate	100
Ammonium polyphosphate	APP	10-15	15-27	-	-	Mixture of ortho & polyphosphates	100
Urea-ammonium phosphate	UAP or UAPP	21-34	7-18	-	-	Mixture of ortho & Polyphosphates	100
Nitric phosphates	NP	14-29	6-12	0-8	-	Orthophosphate	80-100
Ammoniated normal superphosphate	-	2-5	6-9		9-11	Orthophosphate	97-100
Ammoniated TSP	-	4-6	19-23		0-1	Orthophosphate	96-100
Monopotassium phosphate	-	-	22	14.5	-	Orthophosphate	100
Dipotassium phosphate	-	-	18	22	-	Orthophosphate	100
Potassium polyphosphate	-	-	22	17	-	Polyphosphate & Orthophosphate	100

Bolland *et al.* (1988), in their review of the results from 164 Australian pot and field experiments on the basis of the substitution value of RP for superphosphates, concluded that RP fertilisers cannot be regarded as economic substitutes for fertilisers containing water soluble P for most crops grown in Australia. Freshly applied superphosphate, was agronomically more effective than RP in the year of application and RP effectiveness remained low in subsequent years. Very high levels of application of RP were required to match the effectiveness of low application levels of water soluble P fertilisers.

Partially acidulated rock phosphate (PARP) produced by treating RP with H_3PO_4 or H_2SO_4 (Tisdate *et al.* 1993), increases the water-soluble P content compared to RP and improves short-term plant responses to these products. However, often their effectiveness is inferior to water soluble P fertilisers for annual crops. In other cases yields produced from PARP are comparable to those from water soluble P sources such as SSP. In these cases the performance of PARP may be aided by favourable soil conditions (e.g., McLean 1970).

Superphosphates, such as single and triple superphosphate, have a negligible effect on soil pH. Single superphosphate (SSP), containing 7-9.5% P and 11-12% sulpfur(S) is an excellent source of these nutrients and can be applied to soils with a wide range of pH values. Triple superphosphate (TSP) is manufactured by treating PR with phosphoric acid and has little sulphur content, but has a higher P content than single superphosphate (17-23% P). The contained P in superphosphates is about 90% water soluble. TSP, like SSP, is an agronomically effective P fertiliser and its high P content is attractive because of reduced transport, storage and handling costs.

Ammonium phosphates are produced by reacting wet process H_3PO_4 with NH_3. The most common compositions of monoammonium phosphate (MAP; $NH_4H_2PO_4$) and diammonium phosphate (DAP; $(NH_4)_2 HPO_4$) are 11-22-0 and 18-24-0, respectively. Both MAP and DAP are granular fertilisers and are completely water-soluble. They can be used as starter fertilisers, but care must be taken with row or seed placement of DAP since free NH_3 can cause seedling injury and inhibit root growth, particularly in calcareous or high pH soils (Tisdale *et al.* 1993).

Granule size

Results from several studies indicate that early crop responses to applied P increase with increase in granule size of water-soluble P fertilisers applied to acid soils low in available P (Engelstad and Terman 1980).

For water-soluble P fertiliser granules up to 6 mm in diameter, effectiveness is related to the amount of water-soluble P per granule, which in turn determines the volume of soil affected by P (Taylor and Terman 1964). For example, Sample and Taylor (1964) found that the P in 6 mm fertiliser granules having 14 and 70% P water solubility diffused into 4.2 and 20.6 cm^3 volumes of soil, respectively. Crop response to larger granules depends on the probability of roots finding the very few diffusion zones (or a fertiliser band) at a given rate of P application (Moreno

1959, van Burg 1963). A normal field application of granular water-soluble P fertiliser affects 2% or less of the soil in the root zone.

In contrast to results with water-soluble P fertilisers, AOAC water-insoluble P fertilisers should usually be of smaller particle size (<20 mesh or <1 mm) and be mixed well within acid or alkaline soils (Engelstad and Terman 1980). Agronomic effectiveness of water-insoluble P compounds is a function of granule surface area. Very little agronomic evidence has been obtained to show that hardness of water-insoluble P granules has appreciable or long lasting effects. More porous granules, however, have a greater granule surface area per unit of applied P. The same is true for granulation of other salts or even inert materials with the P source (Bouldin *et al.* 1960). However, granulating NH_4 NO_3 with water-insoluble P may increase P solubility and the volume of the P diffusion zone. The presence of ammonium salts has also been found by many investigators to increase P uptake by crops (Terman 1971).

In general, granule-size P solubility effects tend to be obscured in soils of higher P status. In these situations, yield response is unlikely with any types of P fertiliser but early growth responses may still occur, especially with short -season vegetable crops (Engelstad and Terman 1980).

2.6.2 Soil P reserves and residual P value

Available sources of soil P which are absorbed by plant roots may come from fertiliser which is applied that season, from organic crop residues or from native soil P, which includes P from previously applied fertilisers (Figure 2.1). Generally, an annual crop absorbs up to 5 to 25 per cent of the P supplied by a single application of a water soluble P fertiliser. The proportion of applied P accumulated by the current crop appears to depend on the soil P status. For example, on a soil of low P status, the recovery of P by wheat approached 34% ((Holford and Doyle 1993), but on another soil of moderate P status, the recovery was only 16% (McLaughlin *et al.* 1988). For example, Sharpley (1986) compared the residual value of P fertiliser with freshly applied P and observed that the recovery of fertiliser P by winter wheat was inversely related to the residual Bray-1 P status of the soil.

Importantly, the P that is not used for current crop use, progressively accumulates in the soil, and as a consequence the P status of the soil, (or the effectiveness of the residual P fraction) improves with successive annual applications of P (Jackson 1966). This occurs in most soils, even though the residual value of each application diminishes with time of soil contact (Arndt and McIntyre 1963, Barrow and Carter 1978, Bolland *et al.* 1984, Trumble and Donald 1988, Bolland 1986; 1992). Eventually, the soil P status reaches a level where "maintenance" P applications are required to replace the P exported in farm products (Younge and_Plucknett 1966) and lost by leaching or immobilisation (Ozanne and Shaw_1961).

Indeed, on soils where P is immobilised by reaction with soil constituents (eg.; in iron and aluminium rich soils or calcareous soils) or where P is leached (sandy soils), the contribution of P from previously applied phosphatic fertiliser to current crop uptake is likely to be substantially smaller. As a result, on these soils, the recovery of P by crops from current applications of P is correspondingly higher (Fitter 1974).

Different methods of P application also change the residual effectiveness of P fertiliser for subsequent crops (Sander *et al.* 1990). For example, relative to drilling P with lupin seed at 3 cm, placement 5-9 cm below the seed in the year before, improved the future effectiveness of applied P for early lupin dry matter production (Jarvis and Bolland 1990). In this experiment, lupins senesced 3 weeks earlier in the treatments where the P was placed at 3 cm depth in the soil in the previous year or was drilled with lupin seed in the next year. By contrast, where P was placed deeper in the previous year, lupins remained green and continued to produce pods and grain until they senesced about 3 weeks later. Both increased depth of placement and increased P level in the first year, delayed senescence. However, the effect of method of application on residual value of P is not always similar. Initial band applications of P to wheat increased fertiliser effectiveness and grain yield of a subsequent grain sorghum crop more than broadcasting or drilling P with sorghum seed. Alternatively, deep banding of P fertiliser to wheat in a wheat-fallow-wheat crop system did not affect the residual value of applied P, although wheat grain yield, P uptake and head numbers were increased as the original P application rates increased (Sander *et al.* 1990)

2.6.3 Root stimulation in zone of P placement

Root growth is usually enhanced at sites of high nutrient supply. When only part of the root system of a plant is exposed to a higher external concentration of a deficient nutrient, that portion of the root system makes more growth: the area of absorbing surface per unit volume of soil is greater in the portion of the soil enriched with placed fertiliser than in soil receiving the same level of broadcast fertiliser. For example, root length measured on wheat plants, where concentrated superphosphate was either broadcast and worked into the surface of the calcareous soil or drilled with the seed, showed that, root proliferation in the banded layer of the soil was 2.5 times higher than in wheat which received a broadcast application (Marta and Brown 1989).

This effect of increased root growth can also be demonstrated in split-root experiments by placing fertiliser in soils or by localising nutrient supply to only one zone along the root axis. For example, De Miranda *et al.* (1989) divided the roots of individual sorghum plants between equal volumes of soil in a growth chamber experiment in which only one of the volumes received P fertiliser. The minus-P roots did not produce as much dry weight or length as the plus-P roots. In another study on supply of P to only one root zone of barley with the remainder of the root system maintained in a P-free nutrient solution, Drew and Saker (1978) showed that the total length of laterals increased 15-fold over that of control roots grown with a uniform supply of P (Table 2.11). The corresponding increase in dry weight (by a factor of 10) occurred partially at the expense of both the basal and apical root zones, where dry weight actually decreased when P supply was localised to the middle zone Table 2.11).

P supply also influences the length and density of root hairs per unit root length. For example, exposing rape (*Brassica napus*), spinach (*Spinacia oleracea*) and tomato roots to ahigh P concentration (>100 µM) in a nutrient solution, decreased root hairs markedly, whereas exposure to low concentration of P (<10 µM) increased the length of root hairs of these plants (Fohse and Jungk 1983). However, in maize plants, lower soil P availability had no effect on root hair length, but distinctly increased the density of root hairs per unit root length (Marschner *et al.* 1987).

Table 2.11. Effect of localising the P supply to a middle 4cm segment of a single seminal root axis of barley on lateral root length and the dry weight, measured after 21 days (Drew and Saker 1978).

Root zone	Uniform supply		Localised supply ^{A}	
	Length of lateral roots (cm)	Dry weight (mg)	Length of lateral roots (cm)	Dry weight (mg)
A (basal)	40.0	8.9	14.3	3.5
B (middle)	27.2	3.7	332.0	37.8
C (apical)	17.5	10.2	10.2	4.9

^{A} P was supplied to a 4-cm segment (middle, or B zone) of a single seminal root axis.

In addition, root density is increased in the zone of P placement and thus modifies the distribution of roots in the soil profile. In annual species, rooting density rapidly increased several fold in zones of higher P concentration. Deeper placement of P fertiliser, therefore, enhanced plant growth under drought stress conditions when the water potential of the topsoil decreased to wilting point but ample water was available in the subsoil (Garwood and Williams 1967).

2.6.4 Comparative effectiveness achieved by different P placement methods

To maximise the efficiency of P fertiliser use, applied P must be positionally and chemically accessible to crop roots.

Fertiliser placement options generally involve surface or subsurface applications before, at, or after planting (Figure 2.9) and the effectiveness of these strategies can be affected by subsequent tillage practices. These are now discussed in turn and compared.

Broadcast applications

One method of applying fertiliser has been to broadcast it onto the soil surface without further incorporation (e.g., no-till cropping systems). Applied P in this practice is positionally less accessible to plant roots. Thus, fertiliser use efficiency is low on all but sandy soils, where P can leach down to the root zone during the growing season.

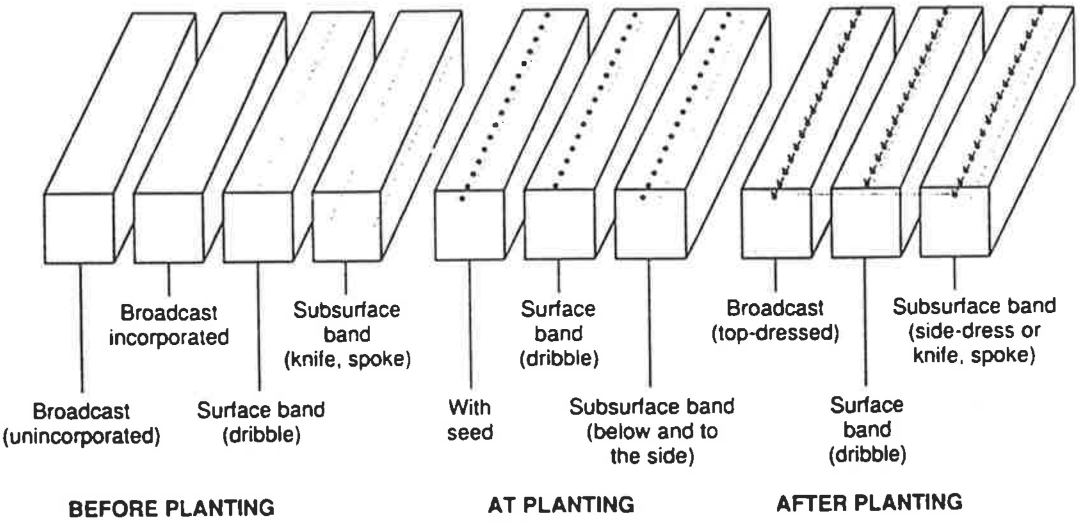


Figure 2.9. Cross section of soil profile showing fertiliser placement (Tisdale *et al.* 1993).

However, surface applications can also be efficient where solid or liquid P fertilisers are applied to forage and sod crops. Here, some of the applied P is absorbed by crowns of the plants and by the shallow roots (Jones *et al.* 1969, Blevins *et al.* 1971). In this strategy, less soil-fertiliser P contact occurs compared to where the applied P is disked in, and thus there is less opportunity for P immobilisation.

Broadcasting and Incorporation:

A common method of applying fertiliser has been broadcasting it on the soil surface and then incorporating it into the soil. Depending on the level of incorporation, the fertiliser P is, more or less, uniformly mixed with the surface soil. With this system, applied P is more accessible to developing root systems, but the amount of surface contact between fertiliser and soil has increased and consequently more P reacts with and is retained by reactive soil components. This is most obvious in acidic, calcareous and fine-textured soils where strong adsorption reactions occur (Williams and Simpson 1965).

A second disadvantage in the broadcasting and the broadcasting/incorporation of P fertiliser is that the P is located in the surface horizon of the soil, which can remain dry during periods of the growing season, restricting root access to applied P (Jarvis and Bolland 1991). In low rainfall areas and on sandy soils, this problem is exacerbated because the surface layers of the soil can remain dry for relatively long periods (Scott 1973, Jarvis and Bolland 1990, 1991).

Several studies have compared broadcast and broadcast/incorporation methods of P fertiliser application with applying fertiliser P with the seed or placing the fertiliser below the planted seed. Generally, for the above mentioned reasons, fertiliser use efficiency (P uptake) and effectiveness of application of P (plant yield) were significantly lower where P was mixed in the topsoil (Sander *et al.* 1990, Jarvis and Bolland 1990, 1991, Sanchez *et al.* 1991, Halvorson and Havlin 1992).

Banded applications:

A more common practice is to band the P fertiliser with the planted seed. The fertiliser is placed adjacent to sown seeds and is immediately accessible for absorption by plant roots, providing the soil remains relatively moist. In addition, banding fertilisers reduces the extent of chemical reactions occurring between the applied P and the soil, and thus leads to enhanced P use efficiency (Sleight *et al.* 1984, Barber and Kovar 1985). Although this placement method results in early stimulation of plant growth, it is not widely used for N-P fertilisers, particularly at high fertiliser levels, due to problems associated with impaired seedling emergence, and decreased stands (Mortvedt 1976). Most of the crop damage comes from the high salt injury caused by the N component of the fertiliser. However, applying high rates of superphosphate with seed especially on sandy soils, can increase risks of seedling toxicity and salt injury. (Bhatti and Loneragan 1970, Miller and Ohlrogge 1977,Bowden and Smith 1984). Soil moisture of the seed zone at the time of planting has a substantial influence on the amount of seedling damage caused with these fertilisers. Dry conditions increase the potential for damage.

Split application

Where a major portion of the P fertiliser is broadcast before planting, a return to a low rate of fertiliser in the seed row seems to be beneficial for the stimulation of early growth (Lang 1966, Burson 1968, Miller and Ohlrogge 1977). This "starter placement" in combination with ploughed-in fertiliser was known as "pop-up" fertilisation and provides several benefits: a "starter P" level is available for early crop growth without the risk of P toxicity occurring at higher levels and it also allows for active root growth to occur in the moister subsurface soil below the seed.

The question of band versus broadcast application is very important. When all of the P is either banded or broadcast, the relative efficiency is related to both the P status of the soil and the level of P application. As the P level increases, broadcast applications can be equal or superior to banding (Welch *et al.* 1966). When the application is split between band and broadcast, at no point will band application alone achieve the maximum yield, thus the advantage of building up the general soil P level. In general, differences between seed-placed and broadcast P decline with increasing levels of available soil P (Peterson *et al.* 1981).

Highest yields were obtained with a combination of banded and broadcast P. This agrees with the findings of Ham *et al.* (1973) for soybean and of Barber (1958) for corn that banding alone on low P soils is inadequate and that supplementary broadcast P is needed to achieve optimal yields. Banded P at lower levels tends to maximise return on the investment in fertiliser P, while broadcast P usually gives the highest return per hectare.

The placement of P fertiliser with the sown seed to supplement pre-plant, deep-band applications is also reported to increase early dry matter production (Cabrera *et al.* 1986), but further research is needed to determine whether this seed-placed fertiliser will result in additional yield benefits in situations where yield responses to pre-plant bands occur.

Table 2.12. Summary of examples of deep band application of P fertiliser in different conditions. The results are compared with a control treatment in which P fertilzer was broadcast and/or drilled with the seed.

Plant species	Soil texture	Banding depth from surface (cm)	Experiment site	Result	Reference[A]	Location
Corn	Unknown	10 cm below and side	Field	higher yield	1	USA
Barrel medic	Red loam	5-10 cm from soil surface	Field	higher yield and efficiency	2	NSW
Wheat	Sandy red brown	25 cm from soil surface	Glasshouse	higher yield	3	S.A.
Soybean	Silt loam	8 cm below the seed	Field	n.s.	4	USA
Wheat (5 sites)	Unknown	drilled with seed	Field	higher yield	5	USA
Winter wheat	Unknown	5-15 cm from soil surface	Field	n.s.	6	USA
Field Peas	Sandy	5 cm below the seed	Field	higher yield	7	W.A.
Wheat	Sandy	5-9 cm from soil surface	Field	n.s.	8	W.A.
Lupin	Sandy	8-16 cm from soil surface	Field	higher yield and efficiency	9	W.A.
Winter wheat	silt loam	5 cm side, 4 below	Field	higher yield and efficiency	10	USA
Winter wheat	silt loam	3 cm side, 8 cm below	Field	n.s.	11	USA
Wheat	Loam and loamy sand	5 cm from soil surface	Field	higher yield	12	S.A.

[A] 1 = Welch *et al.* (1966). 2 = Scott (1973). 3 = Alston (1976)Peterson *et. al.* (1981). 6 = McConnell *et al.* (1986). 7 = Jarvis, R. Pers. Comm. Jarvis and Bolland (1990). 9 = Jarvis and Bolland (1991). 10 = Sanders *et al.* (1990) 11 = Halvorson and Havlin (1992). 12 = Rainbow *et al.* (1994).

Deeper Placement:

In subsurface band applications or deep placement, fertiliser is applied directly below the seed or to the side and below the seed. In these methods, the P fertiliser is banded in a small volume of soil. As a consequence, roots will contact soil with a higher content of fertiliser. Examples of deep placement of P fertilisers in different soil types and species are shown in Table 2.12 and have resulted in a variety of consequences.

Soil moisture content, plant species, soil type and soil P status appear to be the most important factors involved in effectiveness of deep placement of P fertilisers and to the variation in the results of these studies.

Definitions of P efficiency and P effectiveness

P efficiency in plant species is usually expressed either as efficiency in acquisition by the roots or efficiency in utilisation by plants (P use efficiency). Efficiency in acquisition is defined in terms of total uptake per plant or specific uptake rate per unit root length. Efficiency in utilisation is expressed as dry matter production per unit P in the dry matter (Marschner 1995). As a rule the acquisition of nutrients by the roots plays the most important role in nutrient efficiency (Gutschick 1993). For example, Ozanne *et al.*(1969) examined P efficiency in 3 pasture species and showed that, although each species produced similar dry weight at the highest level of P supply, the growth response of the three species to a given level of P supply increased from *Trifolium cherleri* to subterranean clover and annual ryegrass. Moreover, there was a close correlation between P utilisation efficiency and root dry weight.

The slope of the relationship between applied P levels and shoot or seed yield can be used to estimate the effectiveness of different methods of P application (Barrow and Campbell 1972, Scott 1984, Jarvis and Bolland 1991).

Efficiency in utilisation of P could also be estimated by considering the relationship between yield and P content of shoots or between final yield and P content in a crop. For example, Jarvis and Bolland (1990, 1991) found that, despite a 10-90% increase in relative effectiveness from deep banding, compared to drilling with seed, internal P use efficiency by lupin did not change with different methods of placement. This suggests that once P had been taken up by the plant, the same P content produced the same yield regardless of the method of application.

Soil moisture

Low soil moisture conditions are major factors limiting the effectiveness of broadcast P fertiliser. By contrast, P placed deep below the seed remains in moist soil for a longer period during the growing season and permits roots to absorb the P over longer periods (Stanford and Pierre, 1953; Russell, 1961). For example, compared with broadcast applications, band placement of NPK increased the yield of wheat by 48% and 288% under irrigated and non-irrigated conditions, respectively (Chaudhary and Prihar 1974). The broadcast fertiliser remains positionally less accessible near the soil surface due to the lack of actively feeding roots in that zone. Moreover, there will be a positive correlation between the soil moisture content and plant P uptake which occurs where P fertiliser is placed in a moist zone of soil. For example, Simpson and Lipsett (1973) reported that the growth of lucerne was better where fertiliser was placed deep in a wet subsoil than where it was applied in dry topsoil: the beneficial effects of deep placement were not observed when the top soil was wet. In an another experiment conducted with barrel medic (*Medicago truncatula* Gaertn.) Scott (1973) showed that where superphosphate was topdressed or placed at 5 and 10 cm depths, maximum dry matter yield and P uptake occurred in the 10 cm depth treatment and the lowest uptake occurred when plants were grown in the topdressed treatment. In this study, average soil moisture measurements 14 days after 18 mm rain, were 3, 8 and 9.8% for the 0-2, 4-6 and 8-12 cm soil depths respectively.

The issue of lower P uptake in dry soils becomes more critical in coarse textured soils where the moisture holding capacity consequently is low. For example, in a sandy-textured soil in a low rainfall area of south-western Australia, Jarvis and Bolland (1991) found that, relative to drilling with the seed, the effectiveness of superphosphate was increased by 10-90% by banding it below lupin seed and decreased by 30-60% when it was topdressed.

The distribution of moisture in the soil profile fluctuates widely during the growing season which may influence P use efficiency by plants. These effects can occur at any time during the growing season, but will be most important when plant demand for P is high. Variations in seasonal rainfall at different sites may well explain the season to season and site to site variations in crop response to the depth of placement of P fertilisers

Plant species

Plant species vary in their responses to deep placement of P fertiliser. This may be because the pattern of demand for P during growth varies among plants. Species differences involve such parameters as rate of growth, length of growth period and degree of root proliferation. Generally, longer season crops such as corn outgrow early growth responses to applied P, with little effect on final yield. Root development of such crops usually provides uptake of soil P adequate for later growth.

For short-season crops, such as certain vegetables, growth responses to added P tend to persist until harvest because root development is often inadequate for P uptake during the short growing period (Engelstad and Terman 1980).

Lupin is a less determinant crop than wheat; it tends to keep producing both vegetative and reproductive tissue until its growth is truncated by moisture stress at the end of the season (Bowden *et al.* 1994). On the other hand, wheat grows negligible vegetative tissue after anthesis. The demand for P by lupins not only exceeds that of the wheat crop, but much of this demand continues late into the growing season when P supply becomes increasingly dependent on the moisture conditions in the soil at the location of the applied P. This difference in the shape of the demand curves of the two crops is illustrated in Figure 2.10.

Fertiliser placement of P for small grains has attracted much more attention because these crops often respond better to banded than to broadcast applications (MacLeod *et al.* 1976, Richards 1977, Harapiak and Beaton 1986, , Randall and Hoeft 1986). This is especially true on soils of low P status with a high P fixation capacity. Also contributing to this response to banding may be the limited root systems and the shorter growing seasons, cooler temperatures and drier conditions under which many of these crops are grown.

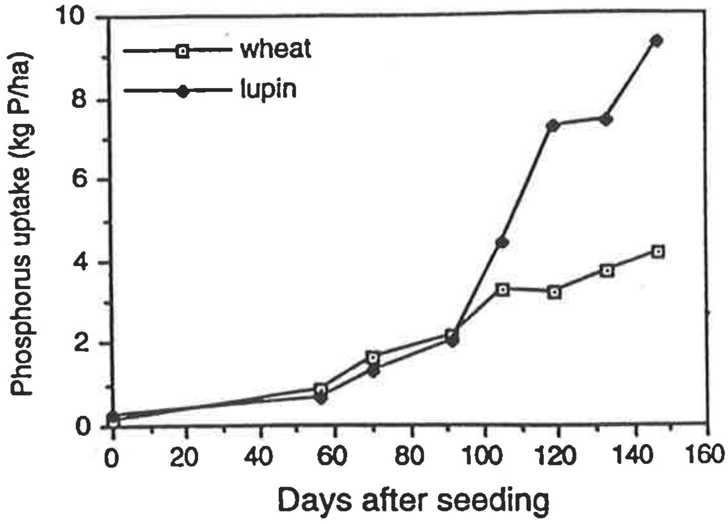


Figure 2.10. P uptake patterns for lupins and wheat as measured for P banded 7 cm below the seed level (Bowden *et al.* 1994)

Soil P status

Soil P status has also been shown to have a marked effect on the crop response to different placement methods (Engelstad and Terman 1980, Welch and Flannery 1985, Young *et al.* 1985, Rehm 1986a). With low levels of available soil P, placement in the effective rooting zone generally results in greater efficiency of P use. However, banding alone on low P soils has also been shown to be inadequate and supplementary broadcast P is sometimes needed to reach top yields (Barber 1958). For example, Welch *et al.* (1966) compared banded and broadcast P on three Illinois soils and found that banded P resulted in much greater P efficiency when subsoil P was low. On soils with higher subsoil P levels, broadcast placement of P was as effective as banding. On soils of medium to high soil P status, the method of application was less important. The exceptions might include soils quite low in temperature at planting and also short-season vegetable crops.

Soil pH

Soil pH affects the availability of applied P by influencing the nature of ensuing P reactions, and the reaction products formed. Generally, soil P availability is greatest in the soil pH range of 5.5 to 7.0 (Engelstad and Terman 1980). With broadcasting and thorough mixing, fertiliser P comes into intimate contact with a large amount of soil. This results in high P fixation where the soil pH is very high or very low, and especially in fine textured soils (Sleight *et al.* 1984, Barber and Kovar 1985). Under these conditions, band-applied P should be more efficient at delivering P for plant growth than broadcast P applications.

Rate of P immobilisation

The rates of chemical reactions between P and soil adsorption sites for P can determine the effectiveness of P application strategies. In some soils with a high fixing capacity, the period of P adsorption and precipitation reactions may be short, whereas with other soils it may last for months or even years. This time period will determine whether the fertiliser P should be applied once in the rotation or split into smaller, more frequent applications. Adsorption of fertiliser P is greater in fine-textured soils because the amount of reactive mineral surface is greater than in coarse-textured soils. If fertiliser P is broadcast and incorporated, the P is exposed to a greater amount of surface; hence, more fixation takes place than if the same amount of fertiliser had been band applied. Band placement reduces the contact between the soil and fertiliser, with a subsequent reduction in P adsorption (Peterson *et al.* 1981). Although this is not the only factor to consider in P fertiliser placement, it is very important for crops grown on low-P soils with a high P adsorption capacity. Thus, band placement generally increases the plant utilisation of the water-soluble P fertilizers such as the superphosphates and ammonium phosphates (Tisdale *et al.* 1993).

Soil texture

Soil texture may also influence the effectiveness of P applied by various methods. Since the greater part of the P in applied P fertilises is in the form of the water-soluble monocalcium phosphate, it might be expected that, especially in coarse textured soils, the portion not quickly assimilated by plants would be removed by leaching (Hingston 1959, Paton and Loneragan 1960, Russell 1960b, Ozanne, *et al.* 1961). However, in soils of medium and fine texture, the great amount of applied P remains in the topsoil. For example, William (1950b), found that nearly all the P applied over a period of years was retained in the surface 15 cm of soil under sown pasture. In another study, on loamy sand, liquid N-P fertiliser applied either in a 10 x 10 cm band or dribbled directly above the seed produced yields significantly higher than when broadcast, whereas on sandy loam soils, corn yield responses to banded and broadcast placement methods were similar (Walker *et al.* 1984). However, these results contrast with the results from Western Australia where banded applications of superphosphate on sandy loam soils are more effective than broadcast applications (Jarvis and Bolland 1990, 1991). It seems that, in coarse textured soils where the seasonal rainfall is high, methods of placement become less important because of the leaching of applied P downward in the soil profile

2.6.5 Interactions between tillage practices and methods of P application

Different tillage practices can change the availability of P to plants in several ways. Tillage changes the physical micro-environment of the soil including, aeration, bulk density and moisture content, and thus can affect the amount and distribution of roots within soils (Drew and Saker 1978).

Tillage also affects the distribution of P in soil by physically mixing the applied and residual P contained in the soil. Mixing may increase the availability of P to a plant by increasing the amount of contact between roots and the P-enriched soil. However, mixing may also decrease the availability of P by increasing the extent of reactions between applied P and inorganic constituents of soil. Apart from these effects associated with mixing, tillage can also influence reactions involving the mineralisation and immobilisation of organic P sources (Robson and Taylor 1987). Tillage can also affect P uptake by plants through influencing the formation of VAM on plant roots, but it seems that different tillage methods have smaller effects on the number of VAM spores than on the distribution of spores with depth (Kruckelmann 1975 , Smith 1978a).

Without tillage, the level of extractable P is higher in the surface 7.5 cm layer and lower in deeper layers than the concentration of P after ploughing. Ploughing distributes soil P more uniformly within the ploughed depth (Shear and Moschler 1969). However, nutrient concentrations and contents are frequently similar in crop grown with or without tillage (Shear and Maschler 1969, Triplett and Van Doren 1969). Robson and Taylor (1987) have set four reasons for this. First, the effect of tillage on distribution of roots with depth appears to closely match the effects on distribution of nutrients (Drew and Saker 1980). Second, most comparisons have been made in moist environments where drying out of the surface layers for long periods is unlikely to occur (Cannell and Graham, 1979). Third, many of the comparisons have involved nutrients which are readily retranslocated within the plant from old leaves to new growth and from vegetative growth to grain. Thus, for nutrients (such as P and K), short periods of soil surface dryness may not have marked effects on nutrient uptake or plant growth. Finally, many of these comparisons have been conducted at high levels of nutrient supply (for example Estes, 1972). At high levels of nutrient supply, changes in the availability of nutrients to plants may not be reflected in marked effects on nutrient uptake.

2.6.6 Conclusion

Deep placement of P fertiliser could enhance P uptake, and hence P fertiliser effectiveness, in two main ways. First, plant roots can grow efficiently and absorb P more easily from moist soil. Second, P uptake by plants increases due to the increased P concentration in the soil surrounding roots.

Banding P a few cm below the seed permits higher rates of P to be used without the risk of toxic effects of P on plant germination, and in legumes, deleterious effects of high P fertiliser levels on nodulation may be circumvented.

However, it would also appear that deep placement of P is not beneficial for all crops or in all soil conditions. For example, when P is applied to row crops grown in coarse-textured soils of low P status, the results are usually favourable. However, where small grains such as wheat or barley are grown in fine-textured soils at high P levels the effects of deeper placement may not be so obvious. This suggests that more research work needs to be conducted in this area.

2.7. SUMMARY

The available evidence indicates that many agricultural soils in southern Australia are moderately low in P and the distribution of P in these soils is uneven, being usually concentrated in the surface horizons.

Studies on the distribution of pea roots reveal that most pea genotypes have more than 80% of their roots concentrated in the surface 20 cm of soil. Thus, the traditional practices of applying P fertiliser with the seed (e.g., at 5 cm depth) or partially mixed within the top soil before sowing, may not necessarily achieve maximum P use efficiency.

Furthermore, soil moisture conditions in dryland Mediterranean environments are largely independent of management, but adjusting fertiliser application methods may maximise benefits gained from applying fertiliser in deeper soil layers with higher soil moisture contents. In such environments, deeper placement of P fertiliser in the moist soil layer below the seed may improve the efficiency of P absorption by plant roots during growth because both soil P supply and soil moisture conditions within the rooting zone are enhanced.

P deficiency causes P to be mobilised within the plant. In general, previously accumulated P is redistributed from older tissues to active growing centres in both the shoots and roots. Redistribution from the shoots to the roots also occurs under P deficient conditions. Symbiotic N_2 fixation in legumes is also markedly reduced by P deficiency, but little published information exists for field peas.

The efficacy of various placement methods of fertiliser P appears to depend on soil P status, soil type, plant species, tillage system and climatic conditions. Evidence is emerging which suggests that for some crops deep placement of P fertiliser within the soil may enhance P use efficiency. Such work has not included field peas which is grown extensively in southern Australia, and requires optimal P supply both for yield and N_2 fixation.

This thesis compares the relative effectiveness and efficiency of applying P fertiliser at different soil depths and assesses reasons for variations in plant response between methods of P application in field pea.

CHAPTER 3

INTERACTIVE EFFECTS OF SEED P CONTENT AND DEPTH OF P PLACEMENT AND RATE OF APPLIED P ON YIELD, NODULATION AND EFFICIENCY OF P ACCUMULATION DURING EARLY VEGETATIVE GROWTH OF FIELD PEAS.

3.1. SUMMARY

Interactive effects of seed phosphorus (P) content (0.75 or 0.53 mg P seed^{-1}), depth of fertiliser placement (placed at seed level, 2.5cm below the soil surface, or 12 cm below the seed) at six levels of P (0, 15, 45, 90, 135 and 180 mg per pot) were examined during early vegetative development of field peas (cv. Alma) grown under glasshouse conditions in a soil deficient in both P and N. Plants were harvested, at 4 weeks after sowing and shoot and root dry matter yield and their P concentrations and contents were measured. Root length and nodule fresh weight were also determined.

There was a strong response to increasing levels of P supply and P applied with the seed was superior in its effects on plant growth and P status. Nodulation was very sensitive to P deficiency and responded to P fertiliser relatively more than plant dry matter yields. The main effects of seed P content on all parameters measured were not-significant at this early vegetative growth stage, although interactive effects of seed P content and P placement were observed where P was applied 12 cm below the seed.

3.2. INTRODUCTION

Traditionally, P fertilisers are either broadcast onto the soil surface and then partially incorporated during sowing operations or applied with the seed in drill rows.

Recent studies have indicated that the efficiency of P acquisition by plants (legumes and cereals) can be improved by placing the applied P fertiliser below the sown seed (Anghinoni and Barber 1980, Borkert and Barber 1985, Jarvis and Bolland 1990, 1991). With legumes, nodulation could also be improved if the seed and fertiliser were separated because concentrated zones of fertiliser P may decrease nodule occupancy by some nodule forming bacteria (Hicks and Loynachan 1987)).

Variation in seed P content may also influence growth and P efficiency especially during early vegetative growth (Austin 1966b, Bolland and Baker 1988, Bolland 1991). The general conclusion reached from these latter studies was that seed with high P content can improve plant growth during early stages of growth where plants are grown on P deficient soils. On the other hand, deep placement of P fertiliser below the seed may also deprive seedlings from an external P supply during seedling growth and make them more dependent on their own P reserves. A higher concentration of P in seed could therefore provide advantages where applied P is sown below the seed, especially on soils of low P status.

Experimental data are limited on the effect of deep placement of P fertiliser applied to crops grown from seeds with high or low P content. Thus, interactions were examined between seed P content, depth of P placement at 6 levels of applied P on the yield, nodulation and efficiency of P accumulation in field peas grown under glasshouse conditions in a soil deficient in both P and N.

3.3. METHODS AND MATERIALS

3.3.1 Soil and location

The experiment was conducted in August 1994, in a glasshouse using the surface horizon (0-20 cm) of a P deficient virgin sandy soil (type Uc1.11; Northcote 1979), collected at Avon, 70 km north of Adelaide. The properties of the soil are listed in Table 3.1.

3.3.2 Experimental design

A factorial, completely randomised block experiment was designed to evaluate interactions between the three treatment variables. Each treatment was replicated three times. The treatments comprised 6 levels of applied P (0, 15, 45, 90, 135 and 180 mg pot^{-1} designated hereafter as P_0, P_{15}, P_{45}, P_{90}, P_{135} and P_{180}), two levels of fertiliser placement (placed 2.5cm below the soil surface at seed level (WS) or placed 12 cm below the seed (B12)) and two seed P contents of field peas cv. Alma (0.75 and 0.53 mg P/seed) designated hereafter as high and low, respectively. The 100 seed weight for high and low P seed types averaged 21.5 and 21.2 grams, respectively.

Table 3.1. Selected properties of the soil used in the 1994 glasshouse experiment (before basal nutrients were applied).

pH (water)	8.3
pH (0.01M $CaCl_2$)	7.7
Extractable P ^{A}	6 mg/kg
Extractable K ^{B}	239 mg/kg
Extractable S ^{C}	9.1 mg/kg
Organic Carbon ^{D}	0.68%
Total N	0.05%
Electivity conductivity (1 : 5)	0.19 dS/m

^{A} Colwell, 1963. ^{B} Sodium Bicarbonate Extract. ^{C} Potassium chloride extract. ^{D} Walkley and Black (1934).

Basal nutrients (Table 3.2) were applied as solutions to 3 kg portions of sieved soil, allowed to dry for 2 days and then thoroughly mixed. The soil was then placed in pots 30 cm deep and 10 cm in diameter. P treatments were added as KH_2 PO_4 solution at either of two depths (seed level and 12 cm below the seed level) as the respective pots were progressively filled. 5 pea seeds inoculated with group E inoculum (*Rhizobium leguminosarum*) were planted in each pot and five days later, two of the emerged plants were removed. The sealed pots were placed at random in a water bath controlled at 12 °C and were re-randomised twice during the course of the experiment. The average minimum and maximum glasshouse temperature during the 4-week experimental period ranged from 11.5 °C to 22.5 °C, respectively.

Pots were watered to field capacity (12% w/w) with deionised water at regular intervals.

3.3.3 Experimental procedures and measurements

Four weeks after sowing (5-6 nodes per stem), shoots of 3 plants in each pot were cut at soil level, weighed and then dried at 70 °C in a forced draught oven for 72 hours to determine shoot dry weight.

Table 3.2. Levels of macro and micro nutrients applied as basal nutrients to the soil.

Macro nutrients solutions:	mL per pot (3 kg of soil)
$CaCl_2.2H_2O$ (73.51 g/litre)	1
K_2SO_4 (87.14 g/litre)	5
$FeSO_4.7H_2O$ (75 g/litre),	1
NH_4NO_3 (80 g/litre),	2
Micro nutrients solution:	
$Na_2MoO_4\,2H_2O$ (0.12 g/litre)	5
H_3BO_3 (0.50 g/litre)	
$CuSO_4.5H_2O$ (0.80 g/litre)	
$Co(NO_3)_2.6H_2O$ (0.25 g/litre)	
$MgSO_4.7H_2O$ (13.4 g/litre)	
$MnSO_4.4H_2O$ (8.85 g/litre)	
$ZnSO_4.7H_2O$ (1.41 g/litre)	

The three intact root systems were then separated from the soil and washed with a spray of water over a 2 mm sieve. One of the root systems from each pot was preserved in 30% ethanol, stored at 4 °C and prepared for root length measurement (Pederson *et al.* 1994). The other two roots were dried at 70 °C in a forced draught oven for 72 hours to determine root dry weight. After the root length measurement was recorded, the first root sample was also oven dried and its weight added to the other two root samples to obtain root weight per three plants. Nodules on these roots were cut with a scalpel blade and weighed to obtain nodule fresh weight per pot.

Shoot and root samples were ground <1 mm, digested with nitric acid and analysed for P by inductively coupled plasma spectrometry (Zarcinas *et al.* 1987).

3.3.4 Statistical analyses

Experimental data were analysed using Genstat 5 (release 1993).

The relationships between shoot dry matter and applied P level were fitted by the Mitscherlich equation (Campbell and Keay 1970):

$$Y = A\ (1\text{-}B\ e^{-CP})$$

where Y is shoot yield (g per 3 plants); A is the maximum yield achieved; P is the level of P applied (mg per 3 plants); B is responsiveness to applied P and C is the curvature coefficient for the relationship. Higher C values mean a steeper response to applied P.

From the relationship between shoot yield and P concentration in the shoots, the internal P requirement was estimated at 90 percent maximum yield. Maximum yield was derived from the Mitscherlich function describing the relationship between shoot yield and the level of applied P.

Apparent recovery of applied P by the 4 weeks old pea plants was estimated by the following equation for all P levels and for the two depths of P placement:

$$\%\text{Apparent P Recovery} = (P_f - P_0/P)\ X\ 100$$

where P_f and P_0 are total P uptake by the pea plants from the fertilised and from the corresponding P_0 treatments, respectively, and P is the quantity of P applied.

3.4. RESULTS

Variance ratios for all measured variables are shown in Table 3.3 and the complete statistical analyses are presented in Appendices 3.1 to 3.10.

3.4.1 Symptoms and phasic development

P_0 plants were stunted and their average height was about one half that achieved by plants grown at higher levels of P supply. Light yellow spots developed on the margins of the leaf blades of these plants were similar to the symptoms of P deficiency in field pea reported by Snowball and Robson (1991). Severe P deficiency also delayed phenological development slightly: at harvest, P_0 plants had 4 to 5 nodes per plant compared to 5 to 6 in other P treatments. Other than reduced growth, plants grown at lower levels of P supply, other than P_0, did not exhibit any distinctive symptoms.

Table 3.3. Statistical significance of the main effects of the experimental variables and their interactions on measured plant parameters (1994 glasshouse experiment)

Variables	P level	P placement	Seed P content	P level X P placement	P level X Seed P	P placement X Seed P	P level X P placement X Seed P
Shoot DW	***	***	n.s.	**	n.s.	$P = 0.06$	n.s.
Root DW	***	*	n.s.	n.s.	n.s.	*	n.s.
Plant DW	***	***	n.s.	**	n.s.	***	n.s.
Nodule FW	***	***	n.s.	***	n.s.	$P = 0.06$	*
Root length	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Root:Plant DW ratio	***	***	n.s.	n.s.	n.s.	n.s.	n.s.
Root:Plant P content ratio	***	n.s.	n.s.	**	n.s.	n.s.	$P = 0.06$
Shoot P content	***	***	n.s.	***	n.s.	n.s.	n.s.
Root P content	***	***	n.s.	***	n.s.	*	$P = 0.10$
Plant P content	***	***	n.s.	***	n.s.	n.s.	n.s.
Shoot P concentration	***	***	n.s.	**	n.s.	n.s.	n.s.
Root P concentration	***	***	n.s.	***	n.s.	n.s.	n.s.

The probability of F statistic at * is $P = 0.05$, at ** is $0.05>P\geq0.002$ and at *** is $P\leq0.001$. n.s = not-significant

3.4.2 Shoot and plant yield

The growth and accumulation of P by the pea seedlings clearly responded positively to applied P (Tables 3.3, 3.4 and 3.5).

Increased levels of P supply and depth of P placement exerted a significant response on the shoot dry matter yield ($P<0.001$), (Appendix 3.1). At a specific level of P supply, applying P at the seed level (WS) markedly improved shoot and plant yield compared to the equivalent B12 treatment (Table 3.4 and Figure 3.1 A and C).

However, seed P content and the interaction between seed P content and P level did not affect shoot or plant yield significantly.

Where P fertiliser was applied at seed level, shoot dry weight was unaffected by seed P content, but where it was applied deeper (B12) sowing seeds with a higher P content resulted in higher shoot yields, but the yields achieved over all levels of P supply were inferior to those achieved where the P fertiliser was applied with the seed (Table 3.4 and Figure 3.1, A). Similar effects were observed for plant yield (Table 3.4; Figure 3.1 C).

3.4.3 Root yield and root length

Both root mass and root length of P_0 plants were higher than those produced by other P treatments (Figure 3.1 B and E). As P supply increased, root yields decreased to a relatively constant value (Table 3.4; Appendices 3.2 and 3.3). Although the main effect of P placement on root yield was significant ($P<0.05$), with one exception (P placement X seed P content interaction), treatment interactions were not significant (Tables 3.3, 3.4). The significant interaction between depth of P placement and seed P content suggested that seed with a high P content produced more root mass than seed of a low P content, but only where the P fertiliser was applied 12 cm below the seed (Table 3.4, Appendix 3.2, Figure 3.1 B).

Treatment interactions on root length were not significant (Appendix 3.3, Figure 3.1 E).

3.4.4 Nodule fresh weight

Nodulation was very sensitive to severe P deficiency with no functional nodules being produced on P_0 plants. The main effects of P level, P placement and their interaction on nodule fresh weight were highly significant (Table 3.3, Appendix 3.4), and the interaction between all 3 treatment variables was also significant ($P = 0.05$). Collectively, these interactions indicated that nodule fresh weight increased markedly at higher levels of P supply but only where the P fertiliser was applied with the seed (Tables 3.3, 3.4, Figure 3.1 D). In addition, nodule fresh weight was unaffected by variations in seed P content in the B12 treatments. However, in the WS series, plants derived from seed of lower P content produced a greater nodule weight than plants derived from seed of higher P content when grown at the higher levels of P supply (Table 3.4; Appendix 3.4).

Table 3.4. Effect of P application level, placement and seed P content on mean shoot, root and plant dry matter yield, nodule fresh weight, root:plant dry weight and P content ratio of field peas measured 4 weeks from sowing (1994 glasshouse experiment).

P placement	Seed P	P level	Shoot DW (g)	Root DW (g)	Plant DW (g)	Nodule FW (mg)	Root:plant DW ratio (%)	Root:plant P content ratio (%)
WS	High	0	0.76	0.37	1.13	10	33.1	44
	Low	0	0.81	0.37	1.18	10	31.4	43
	High	15	1.04	0.33	1.37	40	24.2	27
	Low	15	0.94	0.32	1.26	50	25.4	30
	High	45	1.05	0.27	1.33	60	20.7	24
	Low	45	1.16	0.30	1.46	37	20.5	28
	High	90	1.14	0.29	1.43	70	20.3	26
	Low	90	1.16	0.30	1.66	67	20.0	20
	High	135	1.20	0.31	1.51	77	20.3	27
	Low	135	1.21	0.31	1.52	107	20.5	34
	High	180	1.17	0.28	1.45	83	19.3	27
	Low	180	1.29	0.32	1.61	127	19.8	36
	Mean P placement (WS)		1.08	0.31	1.41	63	23	31
	Means of seed P content in WS		H = 1.06 L = 1.10	H = 0.31 L = 0.32	H = 1.37 L = 1.45	H = 57 L = 69	H = 23 L = 23	H = 29 L = 32
B12	High	0	0.77	0.45	1.22	10	36.8	38
	Low	0	0.72	0.36	1.08	10	33.7	39
	High	15	0.84	0.36	1.20	10	30.2	38
	Low	15	0.75	0.35	1.10	13	32.0	38
	High	45	1.04	0.35	1.39	10	25.0	31
	Low	45	0.74	0.31	1.05	13	29.5	36
	High	90	0.98	0.34	1.32	20	26.1	25
	Low	90	0.89	0.31	1.20	17	25.8	30
	High	135	0.94	0.34	1.27	30	26.0	27
	Low	135	0.88	0.30	1.18	17	25.3	19
	High	180	0.93	0.33	1.26	20	26.4	28
	Low	180	0.91	0.28	1.19	13	23.5	21
	Mean P placement (B12)		0.86	0.34	1.21	15	28.4	31
	l.s.d. ($P = 0.05$) for P placement means		*(0.04)*	*(0.02)*	*(0.05)*	*(8)*	*(1.3)*	*(n.s.)*
	Means of seed P content in B12		H = 0.92 L = 0.81	H = 0.36 L = 0.32	H = 1.28 L = 1.13	H = 17 L = 14	H = 28.4 L = 28.3	H = 31 L = 31
	l.s.d. ($P = 0.05$) for seed P means		*(0.06)*	*(0.03)*	*(0.07)*	*(n.s.)*	*(n.s.)*	*(n.s.)*

n.s. = not-significant ($P > 0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg P/seed (High) and 0.53 mg P/seed (Low). Note: Nodule fresh weights have been transformed by the addition of 10g ie. base= data+10g/3plants.

Table 3.5. Effect of P application level, placement and seed P content on mean shoot, root and plant P content and P concentration of shoots and roots of field peas measured 4 weeks from sowing (1994 glasshouse experiment).

P placement	Seed P	P level	Shoot P content (mg/3 plants)	Root P content (mg/3 plants)	Plant P content (mg/3 plants)	Shoot P concentration (%)	Root P concentration (%)
WS	High	0	1.20	0.92	2.12	0.16	0.25
	Low	0	1.20	0.85	2.05	0.14	0.23
	High	15	3.60	1.32	4.92	0.35	0.40
	Low	15	3.20	1.38	4.58	0.34	0.43
	High	45	5.60	1.84	7.44	0.53	0.67
	Low	45	5.90	2.34	8.27	0.51	0.79
	High	90	7.30	2.51	9.82	0.64	0.86
	Low	90	7.20	1.77	8.97	0.63	0.70
	High	135	7.50	2.53	10.03	0.63	0.83
	Low	135	6.10	2.86	8.96	0.50	0.92
	High	180	8.67	3.12	11.79	0.74	1.15
	Low	180	6.20	3.53	9.73	0.48	1.21
	Mean P placement (WS)		5.3	0.31	7.40	0.47	0.70
	Means of seed P content in WS		H = 5.6 L = 5.0	H = 2.04 L = 2.12	H = 7.64 L = 7.12	H = 0.51 L = 0.44	H = 0.69 L = 0.71
B12	High	0	1.3	0.97	2.27	0.17	0.22
	Low	0	1.2	0.76	1.96	0.17	0.21
	High	15	1.5	0.89	2.39	0.18	0.25
	Low	15	1.4	0.84	2.24	0.18	0.24
	High	45	2.5	1.09	3.59	0.24	0.32
	Low	45	1.5	0.82	2.32	0.20	0.27
	High	90	3.6	1.36	5.96	0.37	0.40
	Low	90	2.9	1.11	4.01	0.32	0.36
	High	135	3.1	1.29	4.39	0.33	0.54
	Low	135	4.1	1.02	5.12	0.46	0.36
	High	180	3.7	1.11	4.81	0.40	0.33
	Low	180	3.9	0.91	4.81	0.44	0.34
	Mean P placement (B12)		2.6	1.01	3.61	0.29	0.32
	l.s.d. (P = 0.05) for P placement means		*(0.5)*	*(0.13)*	*(0.57)*	*(0.05)*	*(0.06)*
	Means of seed P content in B12		H = 2.6 L = 2.5	H = 1.12 L = 0.91	H = 3.72 L = 3.41	H = 0.28 L = 0.29	H =0 .34 L = 0.30
	l.s.d. (P = 0.05) for seed P means		*(n.s.)*	*(0.19)*	*(n.s.)*	*(n.s.)*	*(n.s.)*

n.s. = not-significant (*P*>0.05). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg P/seed (High) and 0.53 mg P/seed (Low)

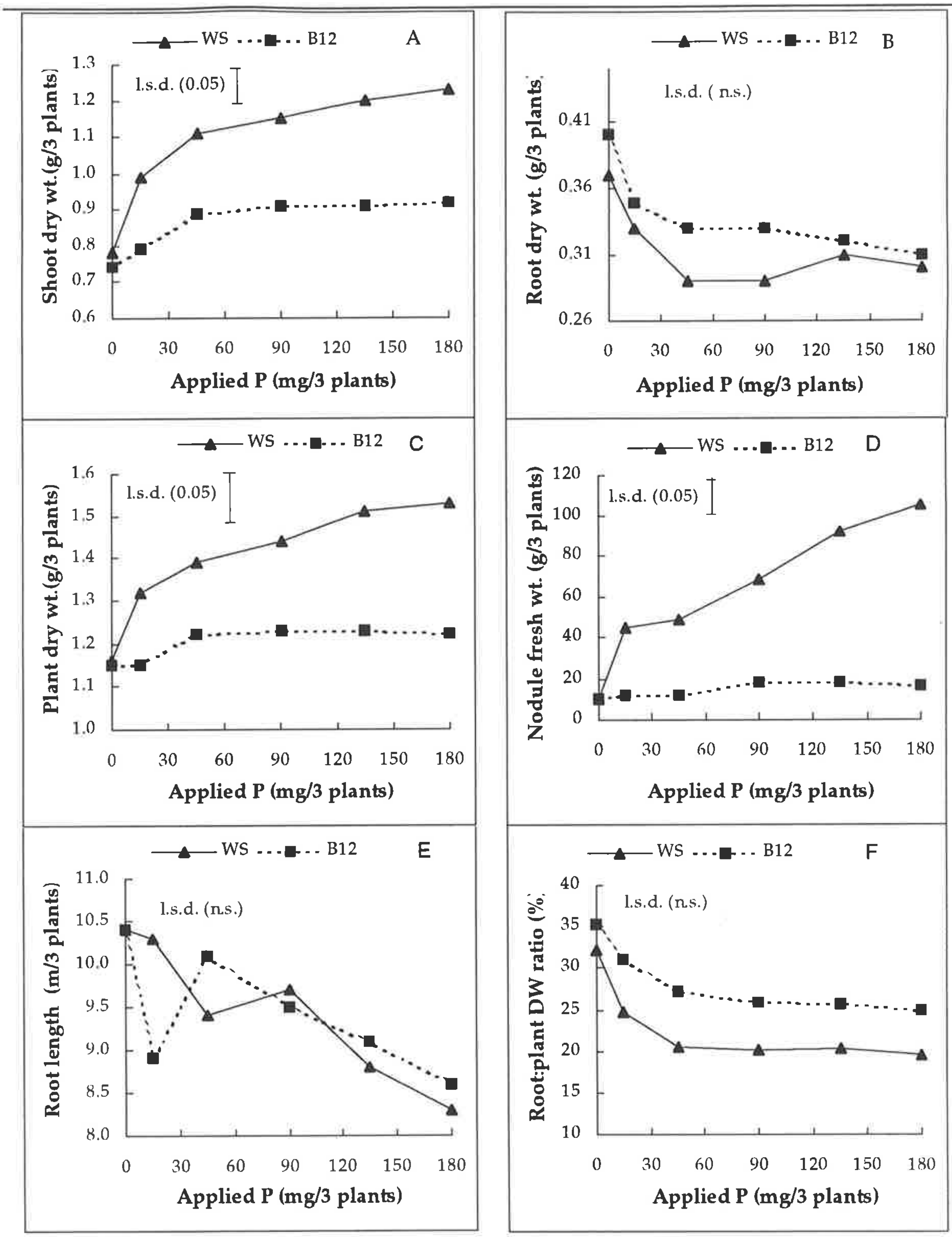
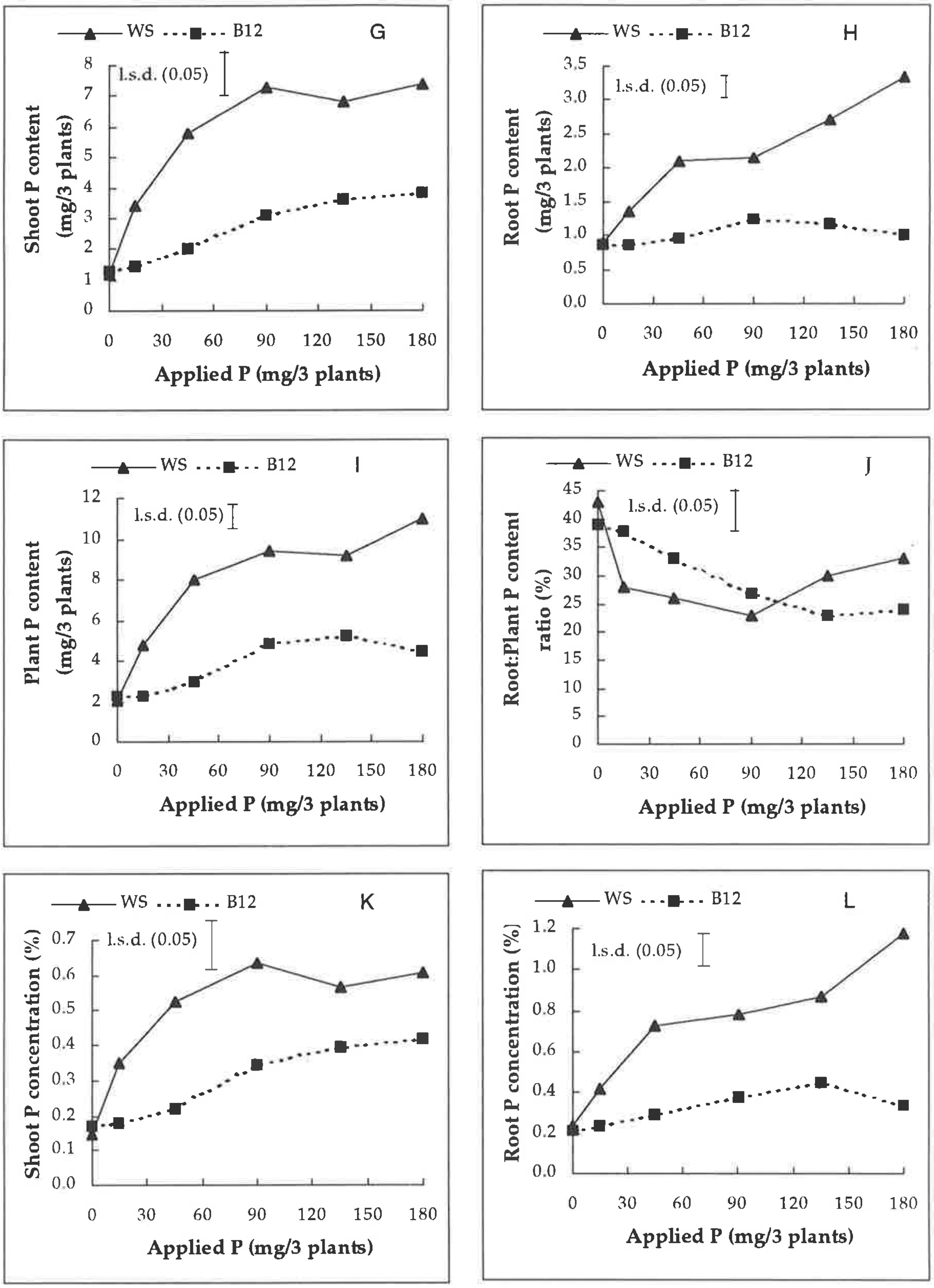


Figure 3.1. Interactive effects of level of P supply and depth of P placement on dry matter yields of shoots, roots and plants, nodule fresh weight, root length and root : plant dry weight ratio P concentration and P content of shoots and roots, plant P content and root : plant P content ratio of field peas harvested 4 weeks after sowing. LSD (*P* = 0.05) are for the P level x P placement interactions. ns = not significant(1994 glasshouse experiment). *Note: Nodule fresh weights in D have been transformed by the addition of 10g ie. base=data+10g/3 plants.

Figure 3.1 continued



3.4.5 Root : plant dry weight and P content ratio

No treatment interactions were observed for the root : plant dry weight ratio (Tables 3.3, 3.4; Appendix 3.5). Generally, the ratio decreased from above 30% for P_0 plants to between 20-25% for plants of higher P status (Table 3.4; Figure 3.1 F; Appendix 3.5). Also, the ratio was higher for plants of the B12 series than for plants of the WS series (Figure 3.1 F) which can be associated with treatment effects on shoot and root yield (Figures 3.1 A, B).

Similar, but less consistent treatment trends were observed for the root : plant P content ratio. Thus, in severely P deficient plants (P_0), proportionally more of the plant P accumulated in the roots compared to plants of higher P status (Table 3.4; Appendix 3.6). Also, at P_{15} the ratio was higher in B12 plants than in WS plants, reflecting the greater effectiveness of P applied at sowing depth (Figure 3.1 J). Variations in seed P content did not affect this ratio (Table 3.4).

3.4.6 P accumulation and concentration in shoots and roots

The accumulation of P in shoots, roots and the plant was affected markedly by the level of P supply and by the depth of P placement (Table 3.5; Appendices 3.8, 3.10 and 3.11). Strong interactions occurred between both these experimental variables ($P<0.001$). The effects of seed P content were mainly not significant, (except that root P content of B12 plants was higher where seeds of higher P content were sown).

At each level of applied P, the quantities of P accumulated by the shoots, roots and plant were substantially greater in WS plants than in B_{12} plants (Figures 3.1 G, H, I). In WS plants, P accumulation in shoots and roots reached a maximum at P_{90} and P_{180}, respectively. By contrast, maximum P uptake in both the roots and shoots of B12 plants appeared to be reached at P_{90}. At this level of applied P, (P_{90}), the total quantity of P accumulated by WS plants was nearly double that taken up by plants of the equivalent B12 treatment (Table 3.5).

In general, the above treatment interaction between level of P supply and depth of P placement essentially reflected similar trends in the measured P concentrations in shoots and roots (Figures 3.1 K, L).

3.4.7 External P requirements

Mitscherlich functions were fitted to the relationships between mean shoot dry weight and level of P supply for both P placement treatments (WS and B12). The derived coefficients were:

Depth of Placement	Mitscherlich Coefficient			
	A	B	C	R^2
WS	1.2	0.34	0.04	0.96
B12	0.97	0.20	0.03	0.97

which clearly demonstrate the superiority of the WS treatment (on shoot yield) compared to B12 for correcting P deficiency in young pea plants. Maximum yield achieved (A) and the yield response to applied P (B) were substantially higher for plants in the WS series. The rate of curvature (C) in the Mitscherlich equation was also marginally steeper for WS than for B12 plants. From both relationships, the external P requirement for 90 per cent maximum shoot yield was calculated to be 45 (WS) and 32 (B12). This difference reflects both the higher yields achieved and the greater fertiliser effectiveness of plants grown under the WS regime than of those grown in the B12 treatment (Figure 3.2).

As indicated earlier, the fresh weight of nodular tissue appeared to be especially sensitive to P deficiency at this early stage of plant growth (Table 3.4; Figure 3.1 D). Indeed, with WS plants, nodule weight appeared to increase progressively as P supply increased, but in B12 plants the response was *decidedly* more shallow and appeared to maximise near P_{90}. Mean data presented in Figure 3.2 shows that, for WS plants, the external P requirement for 90% maximum functional nodulation (fresh weight basis) was more than three times higher than the estimated external P requirement for 90% maximum shoot yield (i.e., 45 mg P/3 plants and 135 mg P/3 plants, respectively). Comparable estimates for B12 plants are 30 and 60 mg P/3 plants, respectively.

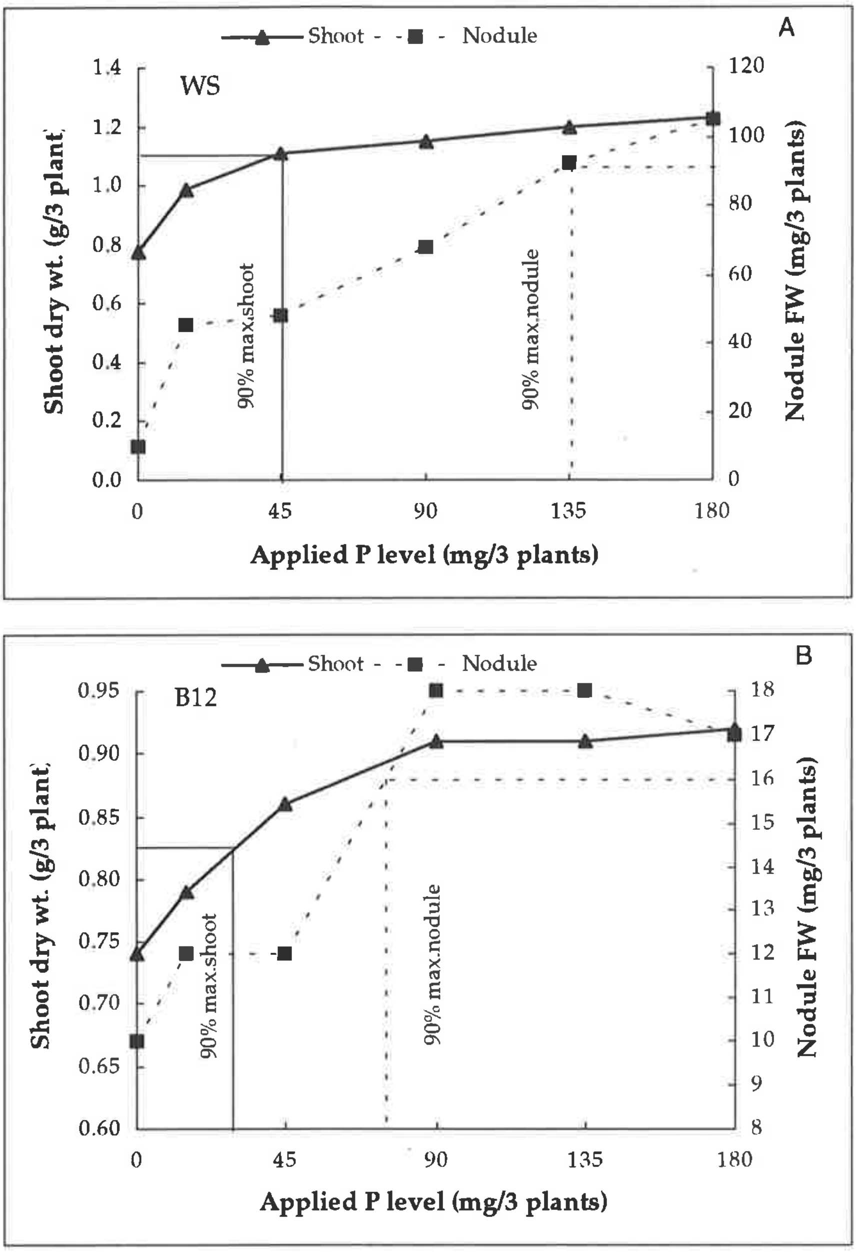


Figure 3.2. External P requirement of field peas for maximum nodulation and shoot dry matter (1994 glasshouse experiment).

3.4.8 Internal P requirement

From the relationship between shoot dry weight and shoot P concentration for the WS treatment (Figure 3.3) it is estimated that for this stage of growth a concentration of at least 0.34% P in field pea shoots is required to produce 90 per cent maximum yield.

3.4.9 Apparent P recovery and P effectiveness

Apparent recovery of P by plants was maximised at 18% in P_{15} (WS) and progressively declined at higher levels of P supply. The apparent recovery of P in plants of B12 treatments was much lower than comparable WS treatments and reached a maximum of 2.3% at P_{90} (Figure 3.4)

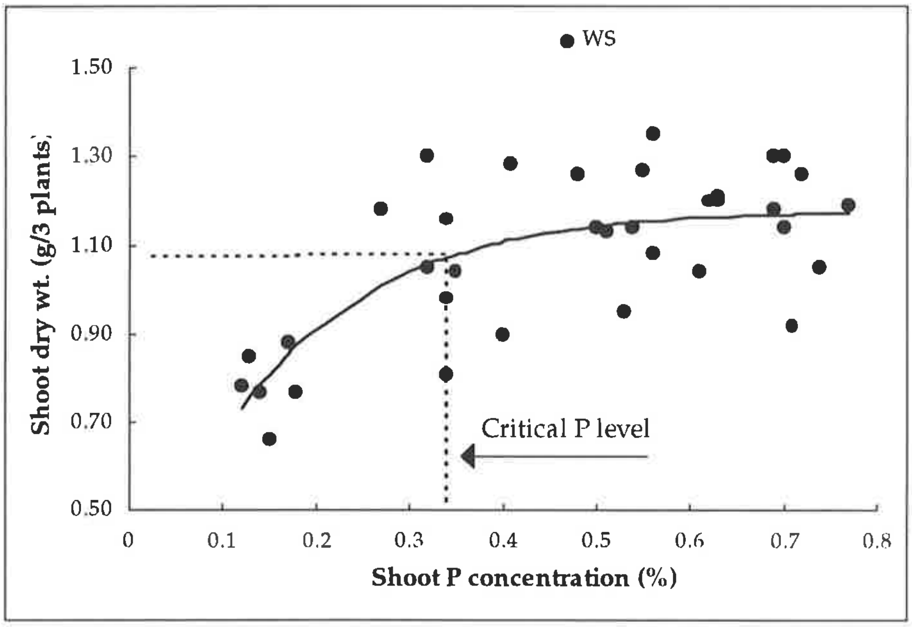


Figure 3.3. Relationship between shoot dry matter yield and P concentration in whole shoots for the WS series (1994 glasshouse experiment).

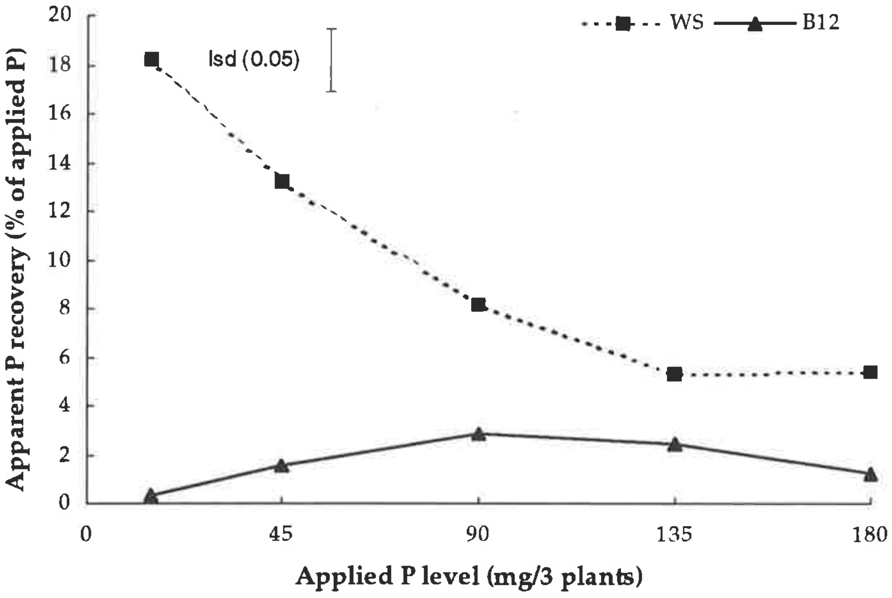


Figure 3.4. Apparent recovery of P by field peas at different levels of P applied at either seed level or 12 cm below the seed level (1994 glasshouse experiment).

3.5. DISCUSSION

Severe P deficiency, as exhibited in P_0 plants in this experiment, depressed shoot yield, effective nodulation and P uptake by plants and delayed phenological development during the early vegetative stages of growth. The disorder increased root yield and the root : plant yield ratio. Essentially similar observations have been made in other studies with other plant species (e.g., Greenway and Gunn 1966, White 1972, Christie and Moorby 1975, (Srihuttagum and Sivasithamparam 1991). Applications of P fertiliser, particularly when applied at seed level reversed these effects.

Depth of fertiliser P placement

Based on yield and P uptake data, this experiment demonstrated that for early vegetative growth, fertiliser P placed with the seed (WS) was markedly more effective than applying P 12 cm below the seed (B12). The shallow response to increasing levels of applied P, which occurred in plants of the B12 series, suggested that plant roots did eventually reach the deeper P-enriched soil layer but the P was positionally inaccessible to allow the developing root system to exert a full response to the applied P during the formative seedling stage of growth. On the other hand, it could be argued that having reached the zone of deep-placed P, plants could then respond positively to deeper placed P fertiliser at later stages of growth. This hypothesis is examined in subsequent experiments (Chapter 4). These later experiments also investigated plant responses to P being placed at shallower depth (viz., 4, 7 and 10 cm below the sown seed.

Variation in seed P content

Variations in the seed P content had at best only a minor impact on growth and P uptake of pea seedlings even when grown under severely P deficient conditions. Sowing seeds of higher P content resulted in a small positive effect on shoot and root yields and root P content ($P<0.05$), but only where the P was applied 12 cm below the seed. Effects of seed P content on nodule yield were marginally significant ($P = 0.06$). These data suggest that utilisation of P reserves located in the sown seed may stimulate root growth of young pea seedlings grown on soils of low P status in the root zone. The scale of these findings is different to other studies using different plant species where seeds of higher P content increased early growth substantially at low levels of external P supply (Austin 1966b, Bolland and Baker 1990, Bolland and Paynter 1990, Bolland 1991). The reason for these contrasts is not entirely clear. The explanation may lie simply in the relatively small difference in P content between the low and high seed treatments (0.53 and 0.75 mg P/seed respectively). Such a difference may not have been sufficiently large to produce a strong positive response during early seedling development. However, the difference in seed P content between both seed types (0.22 mg P/seed) comprised approximately 55% and 31% of the total P accumulated by the shoot and plant respectively in 4 week old P_0 plants.

Alternatively, it could be argued that a stronger effect might have occurred if the harvests had been performed at a later stage of growth. For example, Bolland and Baker (1988) reported that growth responses to variations in the P content of wheat seed were greater 35 days from sowing compared to an earlier harvest, 15 days from sowing.

Nodulation

In this experiment, nodulation in young pea plants was shown to be very sensitive to P deficiency, with no functional nodules being produced on P_0 plants. Indeed, the external P requirement for 90% maximum nodule weight was 3 times higher than the external P requirement for 90% maximum shoot yield (Figure 3.2). This indicates that nodulation processes in young field peas (and presumably symbiotic N_2 fixation) have a greater requirement for P than the host plant has for growth. It also suggests that P may affect the effectiveness or efficiency of the nodulation process directly. This finding agrees with the results of Israel (1987) but contrasts with the findings of Gates (1974), Robson (1983) and Jakobsen (1985). Gates and Wilson (1974) working with *Stylosanthes humilis* and Robson *et.al.* (1981) with subterranean clover found a positive interaction between P and combined N (i.e. increasing P supply increases N_2 fixation by stimulating growth of the legume host plant rather than by affecting rhizobia growth, their survival or nodule formation and function). However, in this experiment, only nodule fresh weight was measured and only a low level of N was applied as a basal fertiliser (Table 3.2).

The results of this experiment also demonstrated clearly that deep placement of P fertiliser depressed nodulation during early vegetative stages of growth. Sowing seeds with higher P content did not compensate for this effect on nodulation (Table 3.4; Appendix 3.4). These preliminary data suggest that in a soil of very low P status P applied P 12 cm below the seed was too deep to allow its efficient utilisation for the effective nodulation of pea plants.

The three-way interaction between the P level, P placement and seed P content also indicated that where higher levels of P ($\geq P_{135}$) were applied to the seed with higher P content, nodule fresh weight was decreased compared to where these P levels were applied to seeds of lower P content (Appendix 3.4). This suggests that concentrating higher levels of P supply with inoculated seed can depress nodulation (nodule fresh weight).

3.6. APPENDICES

Appendix 3.1. Effect of P application level, placement and seed P content on mean shoot dry weight measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	Overall mean
		Mean shoot dry weight (g/3 plants)						
WS	High	0.76	1.04	1.05	1.14	1.20	1.17	1.06
	Low	0.81	0.94	1.16	1.16	1.21	1.29	1.10
B12	High	0.77	0.84	1.04	0.98	0.94	0.93	0.92
	Low	0.72	0.75	0.74	0.89	0.88	0.91	0.81
Overall mean:								
P level		0.77	0.89	1.00	1.04	1.06	1.07	
P placement:								
WS		0.78	0.99	1.11	1.15	1.20	1.23	1.08
B12		0.74	0.79	0.89	0.91	0.91	0.92	0.86
Seed P:								
High		0.77	0.94	1.05	1.06	1.07	1.05	0.99
Low		0.76	0.85	0.95	1.03	1.04	1.1	0.95

Statistics:	LSD ($P = 0.05$)	Probability
P level	0.08	$P<0.001$
P placement	0.04	$P<0.001$
Seed P	n.s.	$P = 0.2$
P level x P placement	0.1	$P = 0.01$
P level x Seed P	n.s.	$P = 0.35$
P placement x Seed P	0.06	$P = 0.006$
P level x P placement x Seed P	n.s.	$P = 0.13$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.2. Effect of P application level, placement and seed P content on mean root dry weight measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	Overall mean
		Mean root dry weight (g/3 plants)						
WS	High	0.37	0.33	0.27	0.29	0.31	0.28	0.31
	Low	0.37	0.32	0.30	0.30	0.31	0.32	0.32
B12	High	0.45	0.36	0.35	0.34	0.34	0.33	0.36
	Low	0.36	0.35	0.31	0.31	0.30	0.28	0.32
Overall mean:								
P level		0.39	0.34	0.30	0.31	0.31	0.30	
P placement:								
WS		0.37	0.33	0.29	0.29	0.31	0.30	0.31
B12		0.40	0.35	0.33	0.33	0.32	0.31	0.34
Seed P:								
High		0.41	0.35	0.31	0.32	0.33	0.31	0.34
Low		0.37	0.34	0.31	0.31	0.31	0.30	0.32

Statistics:	LSD (P = 0.05)	Probability
P level	0.04	$P = 0.001$
P placement	0.02	$P = 0.03$
Seed P	n.s.	$P = 0.17$
P level x P placement	n.s.	$P = 0.94$
P level x Seed P	n.s.	$P = 0.94$
P placement x Seed P	0.03	$P = 0.03$
P level x P placement x Seed P	n.s.	$P = 0.87$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.3. Effect of P application level, placement and seed P content on mean root length measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean root length (m/3 plants)						
WS	High	9.9	10.2	8.6	9.6	9.5	8.3	**9.3**
	Low	11.0	10.4	10.1	9.8	8.1	8.3	**9.6**
B12	High	10.5	8.4	11.0	9.5	9.5	9.0	**9.7**
	Low	10.2	9.3	9.2	9.5	8.7	8.1	**9.2**
Overall mean:								
P level		10.4	9.6	9.8	9.6	8.9	8.5	
P placement:								
WS		10.4	10.3	9.4	9.7	8.8	8.3	**9.5**
B12		10.4	8.9	10.1	9.5	9.1	8.6	**9.4**
Seed P:								
High		10.2	9.3	9.8	9.5	9.5	8.7	**9.5**
Low		10.6	9.9	9.7	9.7	8.4	8.2	**9.4**

Statistics:	LSD (*P* = 0.05)	Probability
P level	1.14	*P* = 0.03
P placement	n.s.	*P* = 0.85
Seed P	n.s.	*P* = 0.75
P level x P placement	n.s.	*P* = 0.52
P level x Seed P	n.s.	*P* = 0.69
P placement x Seed P	n.s.	*P* = 0.25
P level x P placement x Seed P	n.s.	*P* = 0.55

n.s. = not-significant (*P*>0.05). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.4. Effect of P application level, placement and seed P content on mean nodule fresh weight measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean nodule fresh weight (mg/3 plants) ^{A}						
WS	High	10	40	60	70	77	83	**57**
	Low	10	50	37	67	107	127	**66**
B12	High	10	10	10	20	30	20	**15**
	Low	10	13	13	17	17	13	**14**
Overall mean:								
P level		10	28	30	43	55	61	
P placement:								
WS		10	45	48	68	92	105	**61**
B12		10	12	12	18	18	17	**14**
Seed P:								
High		10	25	35	45	48	52	**36**
Low		10	32	25	42	62	70	**40**

Statistics:	LSD (P = 0.05)	Probability
P level	14	$P<0.001$
P placement	8	$P<0.001$
Seed P	n.s.	$P = 0.25$
P level x P placement	19	$P<0.001$
P level x Seed P	n.s.	$P = 0.22$
P placement x Seed P	n.s.	$P = 0.15$
P level x P placement x Seed P	27	$P = 0.05$

[A] In order to eliminate nil values, which frequently occurred in control plants, a base of 10 is used and added to the observed values. n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P content were 0.75 mg/seed (high) and 0.53 mg/seed (Low)

Appendix 3.5. Effect of P application level, placement and seed P content on mean root:plant dry weight ratio measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean root:plant dry weight ratio (%)						
WS	High	33.1	24.2	20.7	20.3	20.3	19.3	**23.0**
	Low	31.4	25.4	20.5	20.0	20.5	19.8	**22.9**
B12	High	36.8	30.2	25.0	26.1	26.0	26.4	**28.4**
	Low	33.7	32.0	29.5	25.8	25.3	23.5	**28.3**
Overall mean:								
P level		33.7	27.9	23.9	23.0	23.0	22.2	
P placement:								
WS		32.2	24.8	20.6	20.1	20.4	19.5	**23.0**
B12		35.3	31.1	27.3	25.9	25.6	25.0	**28.4**
Seed P:								
High		35.0	27.2	22.8	23.2	23.2	22.9	**25.7**
Low		32.5	28.7	25.0	22.9	22.9	21.6	**25.6**

Statistics:	LSD ($P = 0.05$)	Probability
P level	2.2	$P<0.001$
P placement	1.3	$P<0.001$
Seed P	n.s.	$P = 0.89$
P level x P placement	n.s.	$P = 0.65$
P level x Seed P	n.s.	$P = 0.33$
P placement x Seed P	n.s.	$P = 0.96$
P level x P placement x Seed P	n.s.	$P = 0.59$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.6. Effect of P application level, placement and seed P content on mean root:plant P content ratio measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean root:plant P content ratio(%)						
WS	High	44	27	24	26	27	27	**29**
	Low	43	30	28	20	34	36	**32**
B12	High	38	38	31	25	27	28	**31**
	Low	39	38	36	30	19	21	**31**
Overall mean:								
P level		41	33	30	25	27	29	
P placement:								
WS		43	28	26	23	30	33	**31**
B12		39	38	33	27	23	24	**31**
Seed P:								
High		41	32	27	25	27	27	**30**
Low		41	34	32	25	27	30	**31**

Statistics:	LSD (P = 0.05)	Probability
P level	5	P<0.001
P placement	n.s.	P = 0.97
Seed P	n.s.	P = 0.36
P level x P placement	8	P = 0.002
P level x Seed P	n.s.	P = 0.90
P placement x Seed P	n.s.	P = 0.25
P level x P placement x Seed P	n.s.	P = 0.06 (marginal)

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.7. Effect of P application level, placement and seed P content on mean shoot P concentration measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean shoot P concentration (%)						
WS	High	0.16	0.35	0.53	0.64	0.63	0.74	**0.51**
	Low	0.14	0.34	0.51	0.63	0.50	0.48	**0.44**
B12	High	0.17	0.18	0.24	0.37	0.33	0.40	**0.28**
	Low	0.17	0.18	0.20	0.32	0.46	0.44	**0.29**
Overall mean:								
P level		0.16	0.26	0.37	0.49	0.48	0.52	
P placement:								
WS		0.15	0.35	0.52	0.64	0.57	0.61	**0.47**
B12		0.17	0.18	0.22	0.34	0.40	0.42	**0.29**
Seed P:								
High		0.16	0.27	0.39	0.51	0.48	0.57	**0.40**
Low		0.15	0.26	0.36	0.48	0.48	0.46	**0.36**

Statistics:	LSD (P = 0.05)	Probability
P level	0.08	$P<0.001$
P placement	0.05	$P<0.001$
Seed P	n.s.	$P = 0.16$
P level x P placement	0.14	$P = 0.002$
P level x Seed P	n.s.	$P = 0.67$
P placement x Seed P	n.s.	$P = 0.07$
P level x P placement x Seed P	n.s.	$P = 0.11$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.8. Effect of P application level, placement and seed P content on mean shoot P content measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean shoot P content (mg/3 plants)						
WS	High	1.2	3.6	5.6	7.3	7.5	8.7	**5.6**
	Low	1.2	3.2	5.9	7.2	6.1	6.2	**5.0**
B12	High	1.3	1.5	2.5	3.6	3.1	3.7	**2.6**
	Low	1.2	1.4	1.5	2.9	4.1	3.9	**2.5**
Overall mean:								
P level		1.3	2.4	3.9	5.3	5.2	5.6	
P placement:								
WS		1.2	3.4	5.8	7.3	6.8	7.4	**5.3**
B12		1.3	1.4	2.0	3.1	3.6	3.8	**2.5**
Seed P:								
High		1.3	2.6	4.1	5.5	5.3	6.1	**4.1**
Low		1.2	2.3	3.7	5.1	5.1	5.0	**3.7**

Statistics:	LSD ($P = 0.05$)	Probability
P level	1.0	$P<0.001$
P placement	0.5	$P<0.001$
Seed P	n.s.	$P = 0.12$
P level x P placement	1.5	$P<0.001$
P level x Seed P	n.s.	$P = 0.86$
P placement x Seed P	n.s.	$P = 0.31$
P level x P placement x Seed P	n.s.	$P = 0.15$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.9. Effect of P application level, placement and seed P content on mean root P concentration measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean root P concentration (%)						
WS	High	0.25	0.40	0.67	0.86	0.83	1.15	**0.69**
	Low	0.23	0.43	0.79	0.70	0.92	1.21	**0.71**
B12	High	0.22	0.25	0.32	0.40	0.54	0.33	**0.34**
	Low	0.21	0.24	0.27	0.36	0.36	0.34	**0.30**
Overall mean:								
P level		0.23	0.33	0.51	0.58	0.66	0.76	
P placement:								
WS		0.24	0.42	0.73	0.78	0.87	1.18	**0.70**
B12		0.21	0.24	0.29	0.38	0.45	0.34	**0.32**
Seed P:								
High		0.23	0.33	0.50	0.63	0.69	0.74	**0.52**
Low		0.22	0.33	0.53	0.53	0.64	0.78	**0.51**

Statistics:	LSD (P = 0.05)	Probability
P level	0.12	P<0.001
P placement	0.06	P<0.001
Seed P	n.s.	P = 0.63
P level x P placement	0.18	P<0.001
P level x Seed P	n.s.	P = 0.77
P placement x Seed P	n.s.	P = 0.28
P level x P placement x Seed P	n.s.	P = 0.50

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.10. Effect of P application level, placement and seed P content on mean root P content measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/3 kg soil)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean root P content (mg/pot)						
WS	High	0.92	1.32	1.84	2.51	2.53	3.12	**2.04**
	Low	0.85	1.38	2.34	1.77	2.86	3.53	**2.12**
B12	High	0.97	0.89	1.09	1.36	1.29	1.11	**1.12**
	Low	0.76	0.84	0.82	1.11	1.02	0.91	**0.91**
Overall mean:								
P level		0.87	1.11	1.52	1.69	1.93	2.17	
P placement:								
WS		0.88	1.35	2.09	2.14	2.70	3.33	**2.08**
B12		0.87	0.86	0.96	1.24	1.16	1.01	**1.01**
Seed P:								
High		0.94	1.10	1.47	1.93	1.91	2.12	**1.58**
Low		0.80	1.11	1.58	1.44	1.94	2.22	**1.52**

Statistics:	LSD ($P = 0.05$)	Probability
P level	0.23	$P<0.001$
P placement	0.13	$P<0.001$
Seed P	n.s.	$P = 0.34$
P level x P placement	0.33	$P < 0.001$
P level x Seed P	n.s.	$P = 0.11$
P placement x Seed P	0.19	$P = 0.04$
P level x P placement x Seed P	n.s.	$P = 0.10$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

Appendix 3.11. Effect of P application level, placement and seed P content on mean plant P content measured at 4 weeks from sowing (1994 glasshouse experiment).

		Applied P (mg/pot)						
P placement	Seed P content	*0*	*15*	*45*	*90*	*135*	*180*	**Overall mean**
		Mean plant P content (mg/3 plants)						
WS	High	2.09	4.95	7.71	9.82	9.43	11.90	**7.65**
	Low	2.01	4.61	8.27	9.02	9.00	10.02	**7.16**
B12	High	2.56	2.38	3.63	5.44	4.67	4.59	**3.88**
	Low	1.95	2.21	2.30	4.24	5.77	4.41	**3.48**
Overall mean:								
P level		2.15	3.54	5.48	7.13	7.22	7.73	
P placement:								
WS		2.05	4.78	7.99	9.42	9.21	10.96	**7.40**
B12		2.25	2.30	2.96	4.84	5.22	4.50	**3.68**
Seed P:								
High		2.32	3.67	5.67	7.63	7.05	8.25	**5.77**
Low		1.98	3.41	5.29	6.63	7.38	7.22	**5.32**

Statistics:	LSD ($P = 0.05$)	Probability
P level	0.98	$P<0.001$
P placement	0.57	$P<0.001$
Seed P	n.s.	$P = 0.12$
P level x P placement	1.24	$P < 0.001$
P level x Seed P	n.s.	$P = 0.75$
P placement x Seed P	n.s.	$P = 0.88$
P level x P placement x Seed P	n.s.	$P = 0.46$

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B12 = fertiliser banded 12 cm below seed. Seed P contents were 0.75 mg/seed (High) and 0.53 mg/seed (Low)

CHAPTER 4

EFFECTS OF DEPTH OF P PLACEMENT AND APPLICATION LEVEL ON GROWTH AND P ACCUMULATION OF FIELD PEAS (*PISUM SATIVUM* L, c.v. ALMA) UNDER GLASSHOUSE CONDITIONS.

4.1 SUMMARY

Two glasshouse experiments were conducted to test the effects of depth of placement and level of P on growth of field peas. $KH_2 PO_4$ was placed at either seed level (WS) (seed was sown 2,5cm below the surface) or 4, 7, and 10 cm (B4, B7,B10) below the seed level with 0, 15, 45, 90, 135 and 180 mg P per pot. A P deficient sandy loam soil was used in both experiments. Two harvests in Experiment 1 (4 and 6 weeks after sowing) and 3 harvests in Experiment 2 (3, 5 and 7 weeks after sowing) were conducted. Shoot and root dry matter, nodule fresh weight and root length were measured. P concentration of shoots and roots was also determined.

Plants responded to increasing P supply strongly in both experiments. Plant growth with P placed at B4 was equal to that of WS and nodulation was better at B4. Applying P fertiliser very deep in the soil profile (B7 or B10) depressed plant growth and nodulation significantly. Growth of roots was stimulated by the addition of P but only in the fertilised zone. Root proliferation in the fertilised zone declined at higher P supply. The results of these experiments suggest that it will be beneficial to apply P fertiliser 4 cm below the seed level for P supply. Furthermore, placing P fertiliser 4 cm below the seed will reduce the toxic effect of P on nodulation where higher P levels are being used.

4.2 INTRODUCTION

Results from the previous experiment in Chapter 3 indicated that deep placement of P fertiliser decreased the early seedling growth, and especially nodulation of pea plants below that achieved when P was applied at the depth at which the seed was sown. However, in that experiment, only two depths were used (seed level and 12 cm below the seed) and it is possible that the distance of 12 cm was so deep that the delay in root-applied P contact during seedling growth may have caused early plant growth depression. Applying P at a shallower depth may provide the benefits hypothesised for deep placement, and at the same time reduce the delay in root-fertiliser P contact.

The effect of P deficiency on nodulation of field peas was much greater than on plant growth (Chapter 3) which differs from the results in similar experiments but with different species (Robson 1983, Jakobsen 1985). In addition, roots appeared to proliferate in the fertiliser zone more than in other layers. Thus, root length must be measured at different layers of the soil profile including the fertilised layer.

To confirm the results from Chapter 3, the experiments presented in this chapter were conducted with several depths of P placement. Detailed root measurements were also taken.

4.3 MATERIALS AND METHODS

Experiment 1, 1994

4.3.1 Soil and location

The experiment was conducted in August 1994, in pots in a glasshouse at the Northfield Laboratories located in Adelaide, South Australia using the same soil employed for the experiment described in Chapter 3.

4.3.2 Experimental design

A factorial completely randomised block experiment was employed consisting of two factors. Each treatment was replicated three times. The factors were 6 levels of P (0, 15, 45, 90, 135 and 180 mg P pot^{-1} designated hereafter as P_0, P_{15}, P_{45}, P_{90}, P_{135} and P_{180}) and 4 depths of P placement (with seed and 4, 7 and 10 cm below the seed level, designated hereafter as WS, B4, B7 and B10, respectively).

The same basal nutrients used in the Chapter 3 experiment (Table 3.2) were applied as solutions to 3 kg portions of sieved soil, allowed to dry for 2 days, and then thoroughly mixed.

The pots used were 30 cm deep and 10 cm in diameter and contained 3 kg of soil. P treatments applied as $KH_2 PO_4$ solution were pipetted onto the soil at four depths as the pot was progressively filled. Five pea, cv. Alma, seeds inoculated with group E inoculum (*Rhizobium leguminosarum*) were planted in each pot at 2.5 cm below the soil surface and 5 days later thinned to three plants. The pots were placed at random in a water bath controlled at 12 °C and were re-randomised twice during the course of the experiment. The means of the minimum and maximum daily glasshouse temperatures during the 6-week experimental period were 11.5°C and 22.5 °C, respectively (mean = 17 °C). Pots were watered to field capacity (12% w/w) with deionised water at regular intervals.

4.3.3 Experimental procedures and measurements

One half of the pots were harvested at 4 weeks (5-6 nodes per stem) and the remainder at 6 weeks after sowing (8-9 nodes per stem). At harvest, shoots of all 3 plants in each pot were cut at soil level, weighed and then dried at 70 °C in an air-forced oven for 72 hours before measuring shoot dry weight pot^{-1}.

The three intact root systems were then separated from the soil and washed with a spray of water over a 2 mm sieve. Nodules were cut from roots with a scalpel and weighed to obtain nodule fresh weight per pot (pale nodules were ignored). One of these roots was then preserved in 30% ethanol, stored at 4 °C and prepared for root length measurement (Pederson *et al.* 1994). Scanning of individual root images and root length, area and diameter (0.2, 0.3,...0.8, 1.0, 2.0, 3.0 mm) was estimated using a flat-bed, optical character recognition scanner, set at 300 dpi resolution, and associated IBM computer software (Kirchhof 1992). The other two roots were dried at 70 °C in an air-forced oven for 72 hours prior to measuring root dry weight. After the root length measurements were recorded, the first root sample was also oven dried and its weight added to the other two roots to obtain total root weight per pot.

Shoot and root samples were ground to <1 mm in diameter, digested with nitric acid and analysed for P by inductively coupled plasma spectrometry (Zarcinas *et al.* 1987).

Experiment 2, 1995

This experiment was conducted in April 1995, in a glasshouse at Waite Research Precinct, in Adelaide, South Australia using the virgin soil collected from Avon. The soil was prepared and basal nutrients were applied using the same procedure as was described for Experiment 1. The design of the experiment and the measurement procedures were also similar to the first experiment, except that in this experiment only 4 levels of P (0, 15, 45 and 135 mg P pot^{-1}) were placed at either seed level (WS) or 4 and 10 cm below the seed level (B4 and B10) and 3 harvests were taken at 3, 5 and 7 weeks after sowing. During the 7 weeks of the experimental period, the glasshouse temperature ranged between 21 and 27 °C (mean = 24 °C) and the water temperature in the bath was maintained at 16 °C.

Following each harvest in this experiment, the soil was sectioned into 6 layers at harvest (0-3, 3-6, 6-9, 9-12, 12-15 and 15-27 cm below the seed) and total root length was measured in each section using the procedures described in experiment 1.

4.3.4 Statistical analyses

The data from all measurements in both experiments were analysed by using a randomised fully factorial block design ANOVA Model (Genstat 5 release 1993). Least significant differences (LSD) were calculated to compare treatment means. The LSD was calculated from the following formula:

$$LSD = t(0.05, n)\ \sqrt{2Mse / n}$$

where, t is obtained from t-distribution table at the 5% level of probability, Mse (residual mean squares) is obtained from the table of analysis of variance and n is the number of values attended in the related means.

Where skewness existed in the distribution of treatment means, the data were transformed with a square root or a base 10 logarithm transformation and then subjected to the ANOVA.

Regression analysis was used to determine the effect of level of applied P on the relative shoot dry weight. Wherever possible, the relationship between yield and applied fertiliser P levels was fitted to the Mitscherlich function (Campbell and Keay 1970):

$$Y = A\ (1\text{-}Be^{-CP})$$

where Y is shoot yield (g per 3 plant); A is the maximum yield achieved, P is the level of P applied (mg); B is responsiveness to applied P and C is the curvature coefficient for the relationship.

Apparent recovery of P by the pea plant was determined for all P levels at different depths of P placement by the following formula:

$$\%\text{Apparent P Recovery} = (P_f - P_0 / P) \times 100$$

where P_f and P_0 are total P uptake by pea plant from fertilised and from corresponding P_0 treatments, respectively, and P is the quantity of P applied.

4.4 RESULTS

Since most of the materials and methods used in each experiment were similar, the results from both experiments are discussed together, except where differences occurred.

Variance ratios for all measured variables in Experiments 1 and 2 are shown in Tables 4.1 and 4.2, respectively.

4.4.1 Plant symptoms

The soil used in these experiments was extremely deficient in P for the growth of field peas and in the absence of applied P, plants were severely stunted. During further development, these plants showed light yellow spots on the margins of the leaf blades (week 4). At week 7, most of the older leaves in P_0 pots were completely yellow and dry (Plate 4.2,).

In Experiment 2, the P_{135} also caused yellowish spots to develop on leaf blades, but these occurred only in plants of the WS and B4 treatments and at late harvests (Plate 4.1,). However, the effect did not depress shoot yield (Table 4.4).

Table 4.1. Statistical significance of the main effects of the experimental variables and their interactions on measured plant parameters (1994 glasshouse experiment 1)

	Harvest one (4 weeks)			Harvest two (6 weeks)		
Variables	P level	P placement	P level X P placement	P level	P placement	P level X P placement
Shoot FW	***	***	**	***	***	**
Shoot DW	***	***	**	***	***	n.s.
Root DW	***	**	n.s.	n.s.	**	n.s.
Plant DW	***	***	n.s.	***	***	n.s.
Nodule FW	***	***	***	***	***	n.s.
Root length	**	**	n.s.	n.s.	n.s.	n.s.
Root area	n.s.	n.s.	n.s.	***	**	n.s.
Root : Plant DW	***	***	n.s.	***	***	n.s.
Root : Plant P content	***	n.s.	*	***	*	n.s.
Shoot P content	***	***	***	***	***	$P = 0.07$
Root P content	***	***	***	***	***	n.s.
Plant P content	***	***	***	***	***	*
Shoot P concentration	***	***	**	***	n.s.	n.s.
Root P concentration	***	***	***	***	***	n.s.

The probability of F statistic at * is $P = 0.05$, at ** is $0.05>P\geq0.002$ and at *** is $P\leq0.001$. n.s = not-significant

Table 4.2. Statistical significance of the main effects of the experimental variables and their interactions on measured plant parameters (1995 glasshouse experiment 2)

	Harvest one (3 weeks)			Harvest two (5 weeks)			Harvest three (7 weeks)		
Variables	P level	P placement	P level X P placement	P level	P placement	P level X P placement	P level	P placement	P level X P placement
Shoot FW	***	***	n.s.	***	*	n.s.	***	*	n.s.
Shoot DW	***	***	$P = 0.09$	***	*	n.s.	***	*	$P = 0.08$
Root DW	*	*	**	***	n.s.	$P = 0.08$	***	n.s.	n.s.
Plant DW	***	***	*	***	n.s.	n.s.	***	n.s.	n.s.
Nodule FW	***	***	***	***	***	**	***	n.s.	n.s.
Root length	$P = 0.06$	***	n.s.	***	n.s.	$P = 0.08$	***	***	**
Root:Plant DW	***	n.s.	n.s.	***	n.s.	n.s.	***	n.s.	n.s.
Root:Plant P content	***	**	n.s.	***	n.s.	n.s.	***	n.s.	n.s.
Shoot P content	***	***	***	***	***	***	***	*	n.s.
Root P content	*	$P = 0.09$	n.s.	***	n.s.	n.s.	*	n.s.	n.s.
Plant P content	***	***	***	***	***	**	***	n.s.	n.s.
Shoot P concentration	***	***	***	***	***	**	***	***	*
Root P concentration	***	n.s.	n.s.	***	n.s.	n.s.	*	n.s.	n.s.

The probability of F statistic at * is $P = 0.05$, at ** is $0.05>P\geq0.002$ and at *** is $P\leq0.001$. n.s = not-significant.

4.4.2 Shoot growth

Shoot dry weight increased with increasing P rates in all harvests. For example, the dry weight of shoots was doubled with high levels of P in most of the harvests (Tables 4.3, 4.4). Shoot dry weight was higher for WS and B4 and lower for B7 and B10 at all harvests of both experiments. The yield of WS and B4 treatments at comparable P levels were similar at all harvests except at 6 weeks after sowing where applying P at the seed level produced a higher shoot yield than placing P at 4 cm below the seed. Shoot dry weight was the lowest in the B10 treatments at all harvests. A significant P placement x P level interaction for shoot dry weight occured in Experiment 1 at both the 4 and 6 weeks harvest (Table 4.1), while such an interaction was not observed in Experiment 2 at any harvest (Table 4.2). Effects of treatments on fresh weights of shoots were similar to those on dry weights (data not presented).

Table 4. 3. Effects of P application level and placement on mean shoot dry weight measured at 4 and at 6 weeks from sowing (1994 glasshouse experiment 1).

Applied P (mg/pot)	Mean shoot dry weight (g/3 plants)									
	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	**Mean**	WS	B4	B7	B10	**Mean**
0	0.68	0.79	0.77	0.75	**0.75**	1.18	1.24	1.28	1.24	**1.24**
15	1.11	1.04	0.88	0.76	**0.95**	2.85	2.02	1.95	1.70	**2.13**
45	1.24	1.10	0.98	0.78	**1.03**	3.37	3.24	2.43	1.96	**2.75**
90	1.25	1.22	1.08	0.87	**1.11**	3.58	3.36	3.05	2.64	**3.16**
135	1.31	1.29	1.10	0.86	**1.14**	3.75	3.24	3.31	3.20	**3.38**
180	1.37	1.34	1.17	1.04	**1.23**	3.61	3.16	3.54	2.42	**3.20**
Mean	**1.16**	**1.13**	**1.00**	**0.84**		**3.06**	**2.71**	**2.59**	**2.20**	
LSD ($P = 0.05$)										
P level			**0.09**	**$P < 0.001$**				**0.35**	**$P < 0.001$**	
P placement			**0.07**	**$P < 0.001$**				**0.28**	**$P < 0.001$**	
P level x P placement			**0.17**	**$P = 0.04$**				**n.s.**	**$P = 0.10$**	

n.s. = not-significant ($P > 0.05$). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Plate 4.1 (Top). Yellow and dry leaflets on old leaves due to possible toxic effect of high P levels (P_{135}) where P was placed at WS and B4, 7 weeks after sowing. Yellowish spots were absent at B10 (1995 glasshouse experiment 2).

Plate 4.2 (Bottom). Effect of P deficiency on shoot growth of P_0 pots, 7 weeks after sowing (1995 glasshouse experiment 2).


45
B10
45
WS
45
B4


III
O
B4
III
O
WS.
P5

Table 4.4. Effects of P application level and placement on mean shoot dry weight measured at 3, 5 and 7 weeks from sowing (1995 glasshouse experiment 2).

Applied P (mg/pot)	Mean shoot dry weight (g/3 plants)											
	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**
0	0.84	0.77	0.76	**0.79**	1.23	1.23	1.33	**1.26**	2.03	2.07	2.17	**2.09**
15	0.97	0.97	0.77	**0.90**	2.50	2.27	1.93	**2.23**	4.87	5.1	4.23	**4.73**
45	1.11	0.99	0.94	**1.01**	2.83	2.93	2.42	**2.73**	5.07	5.4	4.87	**5.11**
135	1.22	1.24	0.94	**1.13**	3.05	2.86	2.90	**2.94**	5.13	5.37	5.4	**5.30**
Mean	**1.04**	**0.99**	**0.85**		**2.40**	**2.32**	**2.15**		**4.28**	**4.49**	**4.17**	
LSD (*P*=0.05)												
P level			**0.08**	***P*** **<0.001**			**0.23**	***P*** **<0.001**			**0.29**	***P*** **<0.001**
P placement			**0.07**	***P*** **<0.001**			**0.2**	***P*** **= 0.04**			**0.25**	***P*** **= 0.05**
P level x P placement			**n.s.**	***P*** **= 0.09**			**n.s.**	***P*** **= 0.14**			**n.s.**	***P*** **= 0.08**

n.s. = not-significant (*P*>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

4.4.3 Root growth

At the early harvests (3 and 4 weeks), P deficiency increased the total dry weight of roots (Tables 4.5, 4.6), but the effect was smaller than the depression caused to shoot yield. For example, after 4 weeks the increase in root dry weight of P deficient plants was about 22% but shoot yield was depressed by 39% (Tables 4.3, 4.5). At the 3, 4 and 6 weeks harvests, root dry weights did not differ between the placement treatments, except at B10 where root growth was markedly reduced (Tables 4.5, 4.6). In Experiment 2, root dry weight at 5 and 7 weeks after sowing did not differ between the three placement treatments, viz. WS, B4 and B10 (Table 4.6).

Total root length was stimulated under P deficient conditions at early harvests (weeks 3 and 4), but total root length was depressed in nil P pots at the later harvests (Tables 4.7, 4.8, 4.9, 4.10). Although P deficiency stimulated root length in earlier harvests, root proliferation in the fertilised layer of soil was lowest in the least effective P placement (B10). (Plates 4.3, 4.4, 4.5, 4.6; also compare WS and B10 treatments in Table 4.7).

Table 4.5. Effects of P application level and placement on mean root dry weight measured at 4 and at 6 weeks from sowing (1994 glasshouse Experiment 1).

Applied P	Mean root dry weight (g/3 plants)									
(mg/pot)	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	**Mean**	WS	B4	B7	B10	**Mean**
0	0.40	0.42	0.38	0.36	**0.39**	0.74	0.67	0.69	0.64	**0.68**
15	0.38	0.39	0.39	0.38	**0.38**	0.81	0.70	0.75	0.68	**0.74**
45	0.32	0.36	0.30	0.32	**0.33**	0.82	0.81	0.73	0.65	**0.75**
90	0.33	0.35	0.32	0.29	**0.32**	0.87	0.85	0.78	0.72	**0.81**
135	0.30	0.30	0.37	0.28	**0.31**	0.79	0.78	0.80	0.78	**0.79**
180	0.34	0.35	0.30	0.31	**0.32**	0.83	0.76	0.90	0.65	**0.79**
Mean	**0.35**	**0.36**	**0.34**	**0.32**		**0.81**	**0.76**	**0.78**	**0.69**	
LSD (P = 0.05)										
P level			**0.03**	***P* <0.001**				**n.s.**	***P* = 0.11**	
P placement			**0.02**	***P* = 0.03**				**0.07**	***P* = 0.02**	
P level x P placement			**n.s.**	***P* = 0.21**				**n.s.**	***P* = 0.90**	

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 4.6. Effects of P application level and placement on mean root dry weight measured at 3, 5 and 7 weeks from sowing (1995 glasshouse Experiment 2).

Applied P	Mean root dry weight (g/3 plants)											
(mg/pot)	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**
0	0.31	0.27	0.32	**0.30**	0.41	0.44	0.47	**0.44**	0.46	0.49	0.49	**0.48**
15	0.27	0.29	0.23	**0.26**	0.46	0.49	0.43	**0.46**	0.69	0.68	0.61	**0.66**
45	0.28	0.25	0.26	**0.26**	0.52	0.50	0.52	**0.51**	0.56	0.52	0.54	**0.54**
135	0.29	0.30	0.23	**0.27**	0.50	0.47	0.57	**0.52**	0.55	0.49	0.57	**0.54**
Mean	**0.29**	**0.28**	**0.26**		**0.47**	**0.48**	**0.50**		**0.57**	**0.55**	**0.55**	
LSD (P=0.05)												
P level			**0.025**	***P* = 0.02**			**0.04**	***P* <0.001**			**0.08**	***P* <0.001**
P placement			**0.021**	***P* = 0.04**			**n.s.**	***P* = 0.32**			**n.s.**	***P* = 0.83**
P level x P placement			**0.042**	***P* = 0.009**			**n.s.**	***P* = 0.08**			**n.s.**	***P* = 0.69**

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Results from Experiment 2 in which roots were sectioned into 6 parts showed that root dry weight increased with addition of P (in later harvests), but only at the layer of P application. Root dry weight was the same, regardless of the level of applied P, in any soil layer outside the P zone and the root length in any of the unfertilised layers was approximately the same as the root length in the corresponding layer in the P_0 pots. For example, where 15 mg P was applied at a depth of 2.5cm (WS treatments), root length did not increase in any layers below 3 cm compared to P_0 (Figures 4.1, 4.2, 4.3). Similarly, in the B4 and B10 treatments where P was applied in the 6.5 cm or 12.5 cm soil layer respectively, root proliferation was much higher in the layer of application than in the other layers. However, root proliferation of plants grown in the B10 treatments was only evident in the layer of application at weeks 5 and 7 (Tables 4.9, 4.10); at week 3, the root length in the 9-12 cm layer was even less than that obtained in the P_0 pots. Root length distribution in the six soil layers is shown only for P_{15} and P_{135} applied levels because the effects at other levels of P were similar to P_{15} and P_{135}.

Table 4.7. Effects of P application level and placement on mean root length measured at 4 and at 6 weeks from sowing (1994 glasshouse experiment 1).

Applied P (mg/pot)	Mean root length (m/3 plants)									
	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	**Mean**	WS	B4	B7	B10	**Mean**
0	12.32	12.19	10.84	10.27	**11.41**	17.37	15.93	16.84	16.31	**16.61**
15	12.38	10.64	8.97	10.35	**10.59**	23.41	23.39	18.76	16.45	**20.50**
45	10.12	9.15	9.33	8.44	**9.26**	19.48	19.61	18.09	22.07	**19.81**
90	10.44	10.39	10.10	8.16	**9.77**	21.01	20.34	17.96	16.39	**18.93**
135	11.33	8.35	10.89	7.51	**9.52**	20.70	22.24	19.25	18.76	**20.24**
180	8.9	9.45	7.62	8.15	**8.53**	19.55	19.40	20.12	16.11	**18.80**
Mean	**10.92**	**10.03**	**9.63**	**8.81**		**20.25**	**20.15**	**18.50**	**17.68**	
LSD (P = 0.05)										
P level			**1.40**	**P = 0.003**				**n.s.**	**P = 0.10**	
P placement			**1.14**	**P = 0.006**				**n.s.**	**P = 0.08**	
P level x P placement			**n.s.**	**P = 0.61**				**n.s.**	**P = 0.68**	

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

A comparison between 3 and 7 weeks after sowing shows a 4-fold increase in root length where P_{15} was placed with seed, whereas the increase in P_0 pots was less than two-fold over the same time period.

Levels of P higher than 15 mg P per pot depressed root elongation in the fertiliser zone. For example, P_{45} or P_{135} applied at 2.5 cm (WS) reduced root length at 7 weeks after sowing to less than one half of that where P_{15} was applied at 2.5 cm (WS) (Table 4.10). However, root length in these treatments was still higher than in P_0 treatments at both 4 and 7 weeks after sowing.

Plate 4.3. Root proliferation of field peas where 135 mg P /pot was placed at seed level, 6 weeks after sowing (1994 glasshouse experiment 1).

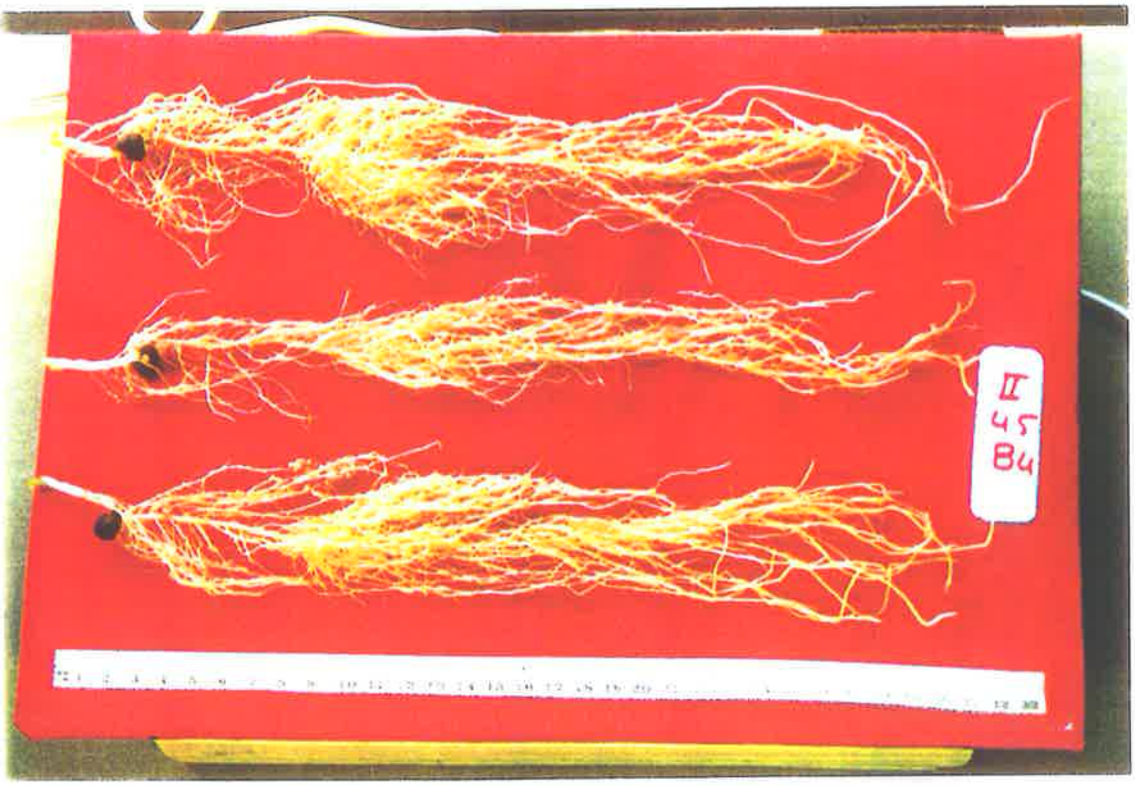


Plate 4.4. Root proliferation of field peas where 135 mg P /pot was placed at 4 cm below the seed level, 6 weeks after sowing (1994 glasshouse experiment 1).

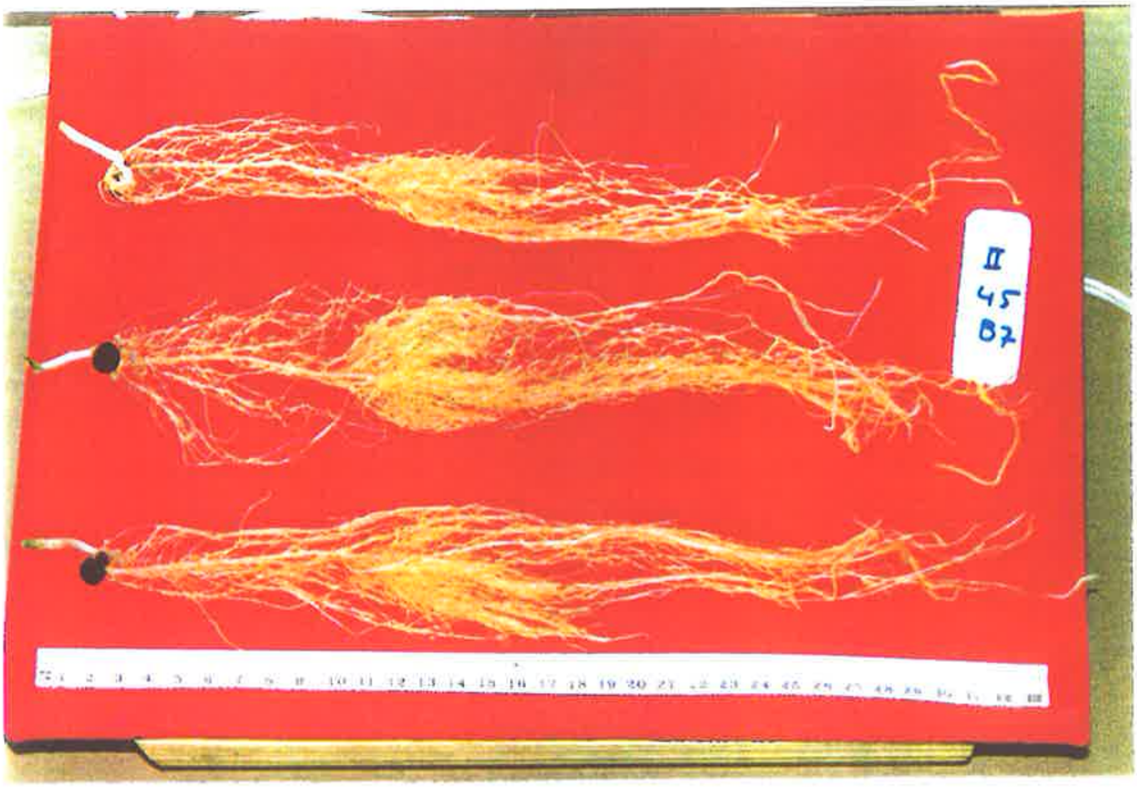


Plate 4.5. Root proliferation of field peas where 135 mg P /pot was placed at 7 cm below the seed level, 6 weeks after sowing (1994 glasshouse experiment 1).

Plate 4.6. Root proliferation of field peas where 135 mg P /pot was placed at 10 cm below the seed level, 6 weeks after sowing (1994 glasshouse experiment 1).

Plate 4.7. Root growth of field peas under the condition of P deficiency (Po), 6 weeks after sowing (1994 glasshouse experiment 1).

Table 4.8. Effects of P application level and placement on mean root length in 6 different soil depths measured at 3 weeks from sowing (1995 glasshouse Experiment 2).

Soil depth (cm)	Mean root length (m/3 plants)												
	Applied P (mg/pot)												**Overall mean**
	0			*15*			*45*			*135*			
	WS	***B4***	***B10***	***WS***	***B4***	***B10***	***WS***	***B4***	***B10***	***WS***	***B4***	***B10***	
0-3[A]	11.1	9.1	9.8	13.0	7.6	6.6	13.5	7.9	7.6	8.8	7.0	8.5	**9.2**
3-6	8.1	9.0	8.0	8.0	12.5	8.4	8.4	10.5	8.1	10.0	10.7	7.0	**9.1**
6-9	6.4	6.5	6.6	6.1	5.4	5.7	5.7	5.5	5.0	5.7	6.1	6.5	**5.9**
9-12	6.1	5.8	5.8	5.3	5.7	4.9	4.9	5.0	3.8	5.4	5.4	3.6	**5.1**
12-15	4.2	4.7	4.0	3.6	4.2	2.1	3.7	4.2	2.4	4.3	4.6	2.5	**3.7**
15-27	2.3	3.0	1.8	2.1	2.2	2.3	2.3	2.7	2.5	2.0	2.3	2.1	**2.3**

Overall means:

P level	37.5	35.4	34.6	34.2	
P placement:					
WS	38.1	38.1	38.5	36.3	**37.7**
B4	38.2	37.6	35.8	36.1	**36.9**
B10	36.1	30.4	29.4	30.3	**31.6**

Soil depth:	P level				P placement		
	0	*15*	*45*	*135*	*WS*	*B4*	*B10*
0-3	10.0	9.1	9.7	8.1	11.6	7.9	8.2
3-6	8.4	9.9	9.0	9.2	8.6	10.7	8.1
6-9	6.5	5.9	5.4	6.1	6.0	5.9	6.0
9-12	5.9	5.0	4.5	4.8	5.4	5.5	4.3
12-15	4.3	3.3	3.5	3.8	4.0	4.5	2.8
15-27	2.4	2.2	2.5	2.2	2.2	2.6	2.2

	LSD ($P = 0.05$)	Probability
P level	**n.s.**	**$P = 0.1$**
P placement	**2.5**	**$P < 0.001$**
Soil depth	**0.5**	**$P < 0.001$**
P level x P placement	**n.s.**	**$P = 0.46$**
P level x Soil depth	**1.2**	**$P = 0.009$**
P placement x Soil depth	**1.0**	**$P < 0.001$**
P level x P placement x Soil depth	**2.9**	**$P = 0.007$**

[A] Zero is the seed level. n.s. = not-significant ($P > 0.05$). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 4.9. Effects of P application level and placement on mean root length in 6 different soil depths measured at 5 weeks from sowing (1995 glasshouse Experiment 2).

Soil depth (cm)	Mean root length (m/3 plants)												
	Applied P (mg/pot)												**Overall mean**
	0			*15*			*45*			*135*			
	WS	***B4***	***B10***	***WS***	***B4***	***B10***	***WS***	***B4***	***B10***	***WS***	***B4***	***B10***	
0-3[A]	13.0	12.7	13.2	32.0	12.4	13.0	24.2	9.3	10.0	18.3	11.5	8.3	**14.8**
3-6	12.3	15.6	13.1	10.2	19.6	13.8	9.7	18.3	13.1	12.9	16.9	9.1	**13.7**
6-9	8.6	8.6	9.5	7.0	10.2	10.4	7.8	6.8	10.3	6.9	8.5	8.2	**8.6**
9-12	8.4	8.4	8.9	7.7	8.3	15.9	6.8	7.1	10.7	7.7	6.0	12.9	**9.1**
12-15	7.0	7.1	7.7	7.4	9.0	7.0	6.9	6.7	6.8	6.4	6.0	6.7	**7.0**
15-27	6.9	7.6	7.9	7.9	7.9	7.8	8.2	8.1	9.8	8.6	7.9	8.9	**8.1**

Overall means:

P level	57.9	69.1	60.1	57.2	
P placement:					
WS	51.3	72.1	63.5	60.8	**61.9**
B4	62.2	67.3	56.3	56.7	**60.6**
B10	60.3	67.8	60.60	54.2	**60.7**

Soil depth:	P level				P placement		
	0	*15*	*45*	*135*	*WS*	*B4*	*B10*
0-3	12.9	19.1	14.5	12.7	21.9	11.5	11.1
3-6	12.8	14.5	13.7	13.0	10.1	18.2	12.3
6-9	8.9	9.2	8.3	7.9	7.6	8.5	9.6
9-12	8.6	10.6	8.2	8.9	7.7	7.4	12.1
12-15	7.3	7.8	6.8	6.4	6.9	7.2	7.0
15-27	7.5	7.8	8.7	8.5	7.9	7.9	8.6

	LSD ($P = 0.05$)	Probability
P level	**7.1**	**$P = 0.003$**
P placement	**n.s.**	**$P = 0.87$**
Soil depth	**1.1**	**$P < 0.001$**
P level x P placement	**n.s.**	**$P = 0.24$**
P level x Soil depth	**2.5**	**$P = 0.008$**
P placement x Soil depth	**2.1**	**$P < 0.001$**
P level x P placement x Soil depth	**6**	**$P < 0.001$**

[A] Zero is the seed level. n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 4.10. Effects of P application level and placement on mean root length in 6 different soil depths measured at 7 weeks from sowing (1995 glasshouse Experiment 2).

Soil depth (cm)	Mean root length (m/3 plants) Applied P (mg/pot)												Overall mean
	0			*15*			*45*			*135*			
	WS	***B4***	***B10***	***WS***	***B4***	***B10***	***WS***	***B4***	***B10***	***WS***	***B4***	***B10***	
0-3[A]	17.8	14.5	16.7	52.6	12.3	14.3	25.2	15.3	12.9	24.5	13.6	16.6	**19.7**
3-6	14.0	13.8	12.2	11.4	44.6	12.8	12.8	32.0	11.8	20.0	22.6	12.4	**18.4**
6-9	9.2	11.0	10.9	9.5	7.3	10.2	7.3	8.3	7.6	12.3	12.7	10.3	**9.7**
9-12	9.1	11.6	9.4	9.4	9.7	23.6	8.4	7.3	18.1	15.6	7.6	13.7	**11.9**
12-15	7.7	10.6	10.0	11.7	10.1	6.8	8.6	7.3	5.5	10.7	7.3	7.4	**8.6**
15-27	9.2	12.5	9.7	10.9	12.8	11.0	10.9	8.6	11.1	12.1	9.0	11.3	**10.7**

Overall means:

P level	69.9	93.7	72.9	79.9	
P placement:					
WS	67	105.5	73	95.2	**85.2**
B4	74	69.8	78.7	72.7	**80.6**
B10	68.8	78.7	67	71.7	**71.6**

Soil depth:	P level				P placement		
	0	*15*	*45*	*135*	*WS*	*B4*	*B10*
0-3	16.4	26.4	17.8	18.2	30.0	13.9	15.2
3-6	13.3	23.0	18.9	18.4	14.6	28.3	12.3
6-9	10.4	9.0	7.7	11.8	9.6	9.8	9.8
9-12	10.0	14.2	11.2	12.3	10.6	9.1	16.2
12-15	9.4	9.5	7.1	8.5	9.7	8.8	7.4
15-27	10.5	11.5	10.2	10.8	10.8	10.7	10.8

	LSD ($P = 0.05$)	Probability
P level	**13**	**$P = 0.002$**
P placement	**10.9**	**$P = 0.04$**
Soil depth	**1.57**	**$P < 0.001$**
P level x P placement	**n.s.**	**$P = 0.23$**
P level x Soil depth	**3.50**	**$P < 0.001$**
P placement x Soil depth	**2.90**	**$P < 0.001$**
P level x P placement x Soil depth	**8.56**	**$P < 0.001$**

[A] Zero is the seed level. n.s. = not-significant ($P > 0.05$). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

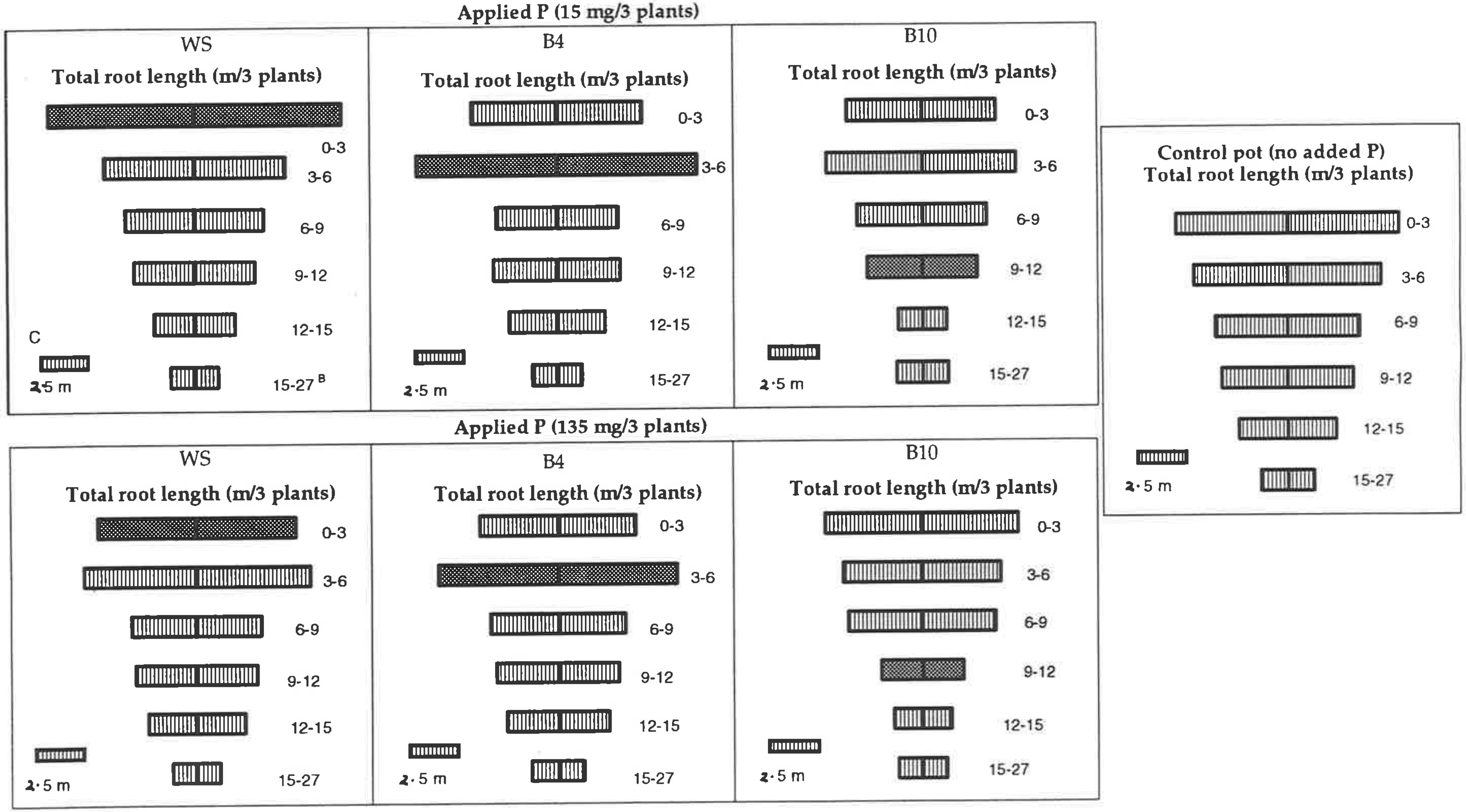


Figure 4.1. Effects of P level and placement on distribution of roots with depth, 3 weeks after sowing.[B] Depth of soil layer from seed level. [C] Horizontal bar represents 2.5 m of root. The dark zone in each chart indicates the layer where P was placed (1995, glasshouse experiment 2).

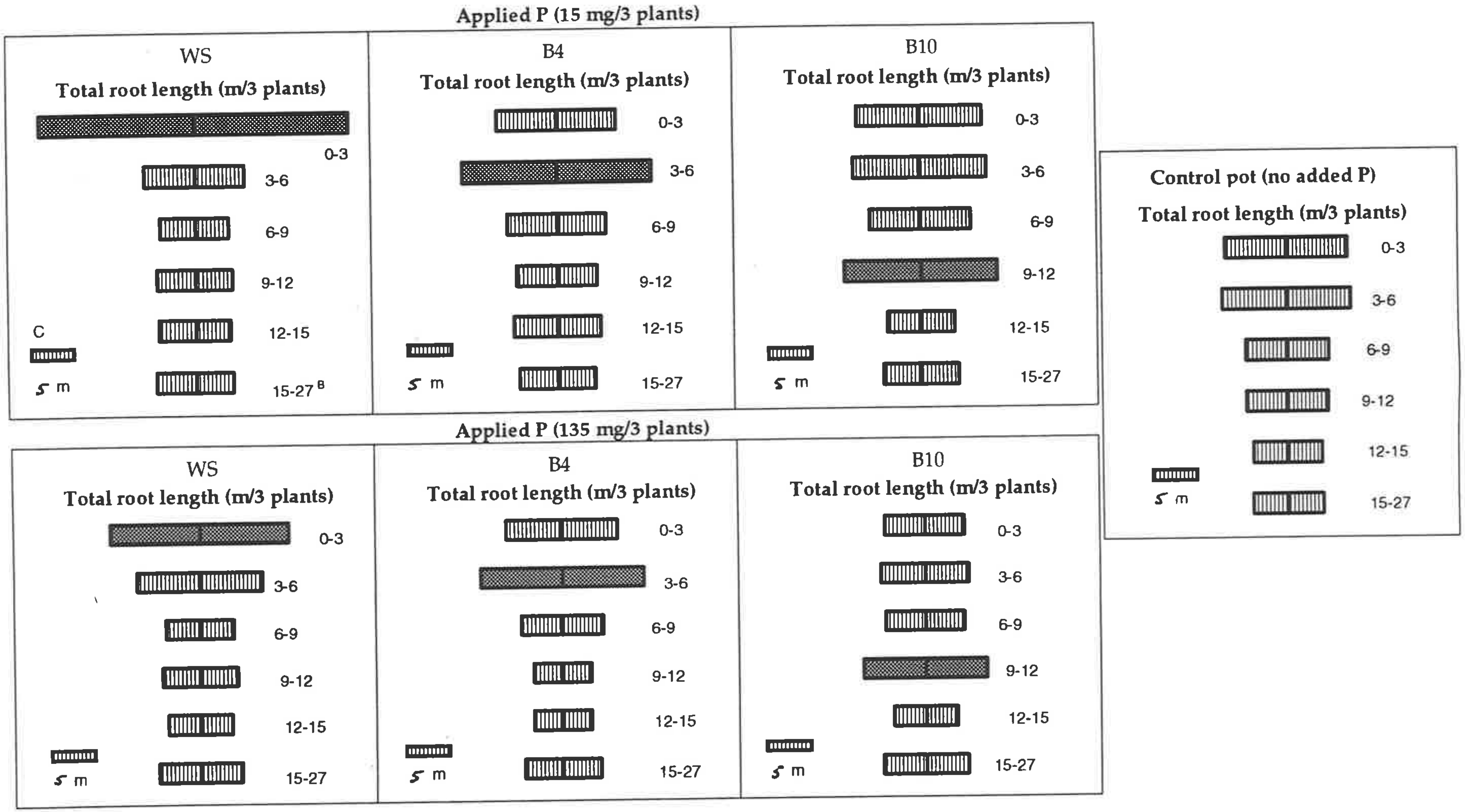


Figure 4.2. Effects of P level and placement on distribution of roots with depth, 5 weeks after sowing. [B] Depth of soil layer from seed level. [C] Horizontal bar represents 5 m of root. The dark zone in each chart indicates the layer where P was placed (1995 glasshouse experiment 2).

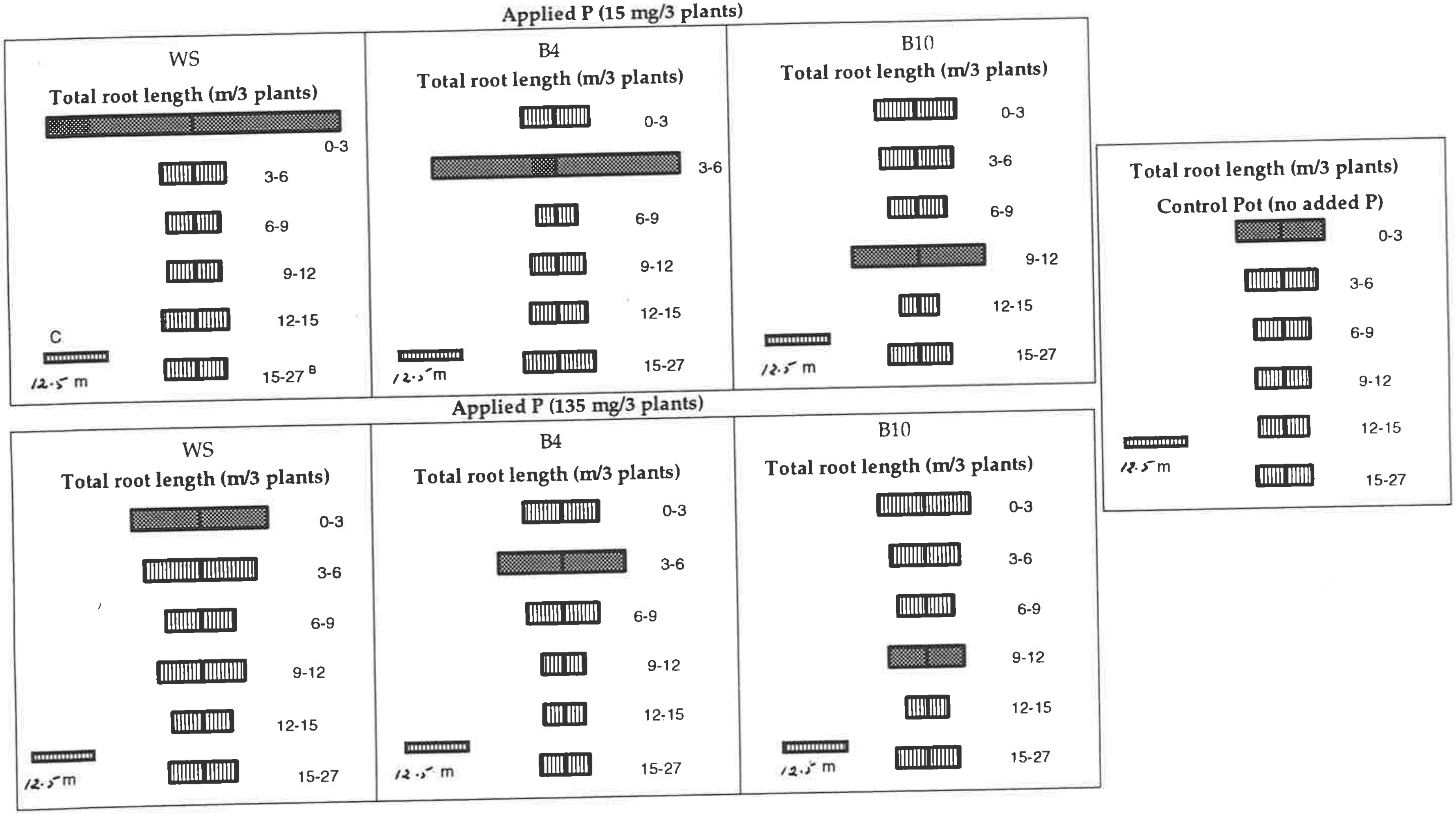


Figure 4.3. Effects of P level and placement on distribution of roots with depth, 7 weeks after sowing. [B] Depth of soil layer from seed level. [C] Horizontal bar represents 12.5 m of root. The dark zone in each chart indicates the layer where P was placed (1995 glasshouse experiment 2).

4.4.4 Nodule fresh weight

Nodulation was extremely poor when pea plants were grown in the P_0 treatments and mean nodule fresh weights at P_0 were only 3-12% of the maximal weights obtained at P_{180} and P_{135} (Tables 4.11, 4.12). Nodulation was also sensitive to the depth of P placement. For example, at the early harvests (3 and 4 weeks), P applied with the seed increased nodule fresh weight more than deeper P placements, but at the late harvest (7 weeks), P applied 4 cm below the seed enhanced nodulation more than WS treatments. However, P placed at B10 depressed nodule fresh weight significantly in all harvests and even the highest applied P level at this depth did not improve nodulation.

Table 4.11. Effects of P application level and placement on mean nodule fresh weight measured 4 and at 6 weeks from sowing (1994 glasshouse experiment 1).

Applied P (mg/pot)	Mean nodule fresh weight (mg/3 plants)														
	4 weeks from sowing					6 weeks from sowing									
	WS	B4	B7	B10	**Mean**	WS		B4		B7		B10		**Mean**	
0	5	5	5	5	**5**	10	(1)[A]	7	(0.85)	9	(0.95)	8	(0.90)	**8**	**(0.91)**
15	65	8	8	5	**22**	90	(1.83)	67	(1.82)	9	(0.95)	12	(1.07)	**44**	**(1.38)**
45	126	12	12	8	**40**	200	(2.29)	243	(2.39)	117	(2.07)	50	(1.70)	**153**	**(1.98)**
90	112	22	18	12	**41**	227	(2.35)	370	(2.55)	230	(2.36)	113	(2.05)	**235**	**(2.26)**
135	138	45	8	12	**51**	230	(2.36)	293	(2.45)	230	(2.36)	220	(2.34)	**243**	**(2.36)**
180	138	72	18	12	**60**	267	(2.43)	280	(2.44)	263	(2.42)	230	(1.36)	**260**	**(2.25)**
Mean	**97**	**27**	**12**	**9**		**171**	**(2.05)**	**210**	**(2.04)**	**143**	**(1.81)**	**106**	**(1.53)**		
LSD (P = 0.05)															
P level			**19**	***P*<0.001**						**(0.26)[B]**	***P*<0.001**				
P placement			**15**	***P*<0.001**						**(0.21)**	***P*<0.001**				
P level x P placement			**55**	***P*<0.001**						**(0.77)**	***P* = 0.04**				

[A] Values in parentheses are $\log_{10}$ transformations, calculated to adjust for a skewed distribution. Transformation of the values at harvest one did not improve the skewness of the data significantly. n.s. = not-significant (P>0.05).WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed. [B] LSDs apply to transformed data only.

The response of nodule fresh weight to increasing P changed with advancing plant age, being nearly linear at 3 weeks and more curvilinear at later harvests. However, the external P requirement for nodule fresh weight at all harvests was higher than for shoot yield (Figures 4.4, 4.5).

The external P requirements for maximum yield of shoot dry matter and nodule fresh weight were higher at 3 and 4 weeks than at 7 and 6 weeks (Figure 4.4, 4.5).

Table 4 .12. Effects of P application level and placement on mean nodule fresh weight measured at 3, 5 and 7 weeks from sowing (1995 glasshouse Experiment 2).

Applied P	Mean nodule fresh weight (mg/3 plants)											
(mg/pot)	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**
0	18	15	14	**15**	37	47	40	**41**	56	131	47	**78**
15	81	9	15	**35**	251	260	43	**185**	328	486	227	**347**
45	193	30	18	**80**	461	648	122	**410**	744	932	468	**715**
135	243	119	19	**127**	589	693	299	**527**	690	1068	517	**758**
Mean	**134**	**43**	**17**		**335**	**412**	**126**		**455**	**654**	**315**	
LSD (*P*=0.05)												
P level			**25**	***P* <0.001**			**90**	***P* <0.001**			**137**	***P* <0.001**
P placement			**22**	***P* <0.001**			**78**	***P* <0.001**			**114**	***P* <0.001**
P level x P placement			**43**	***P* <0.001**			**156**	***P* = 0.003**			**n.s.**	***P* = 0.08**

n.s. = not-significant (*P*>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

4.4.5 Root : plant dry weight and P content ratio

The proportion of plant dry weight and plant P content accumulated in the root increased as the P supply decreased or as the P was applied deeper (root P content is considered only for Experiment 1) (Tables 4.13, 4.14, 4.15). However, the root : plant dry weight or root : plant P content ratio was the same with P placed either at WS or at B4 (except that the root : plant dry weight ratio was higher at B4, at week 4). The root : plant dry weight and P content ratios both increased with the plant age. The root : plant P content ratio was higher than the root : plant dry weight ratio in all treatments.

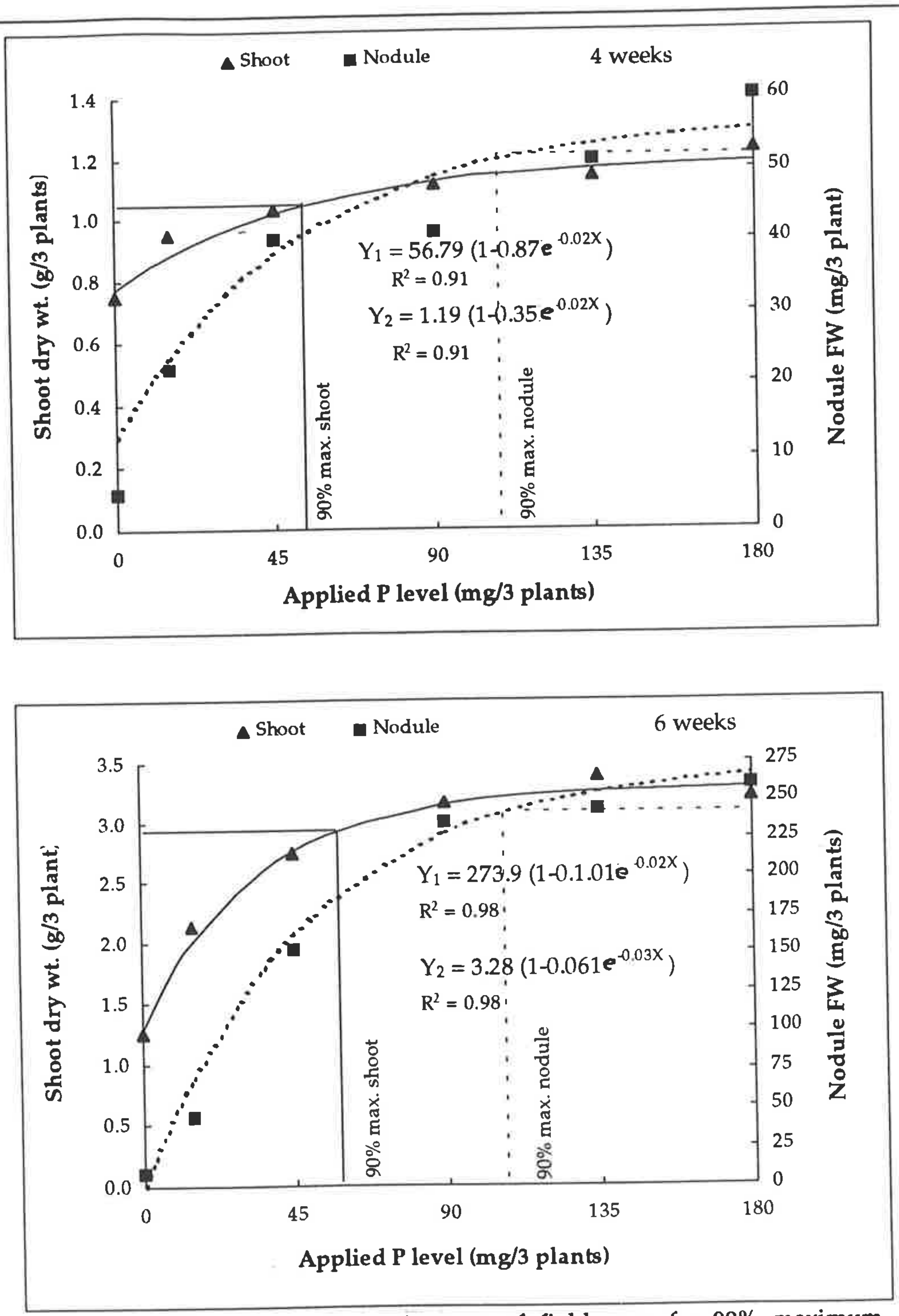


Figure 4.4. The external P requirement of field peas for 90% maximum nodulation and shoot dry matter at two harvest times. Y_1 and Y_2 are fitted Mitscherlich equations for nodule fresh weight and shoot dry weight yield, respectively. "Maximum yield" was calculated from the fitted equations. (1994 glasshouse Experiment 1).

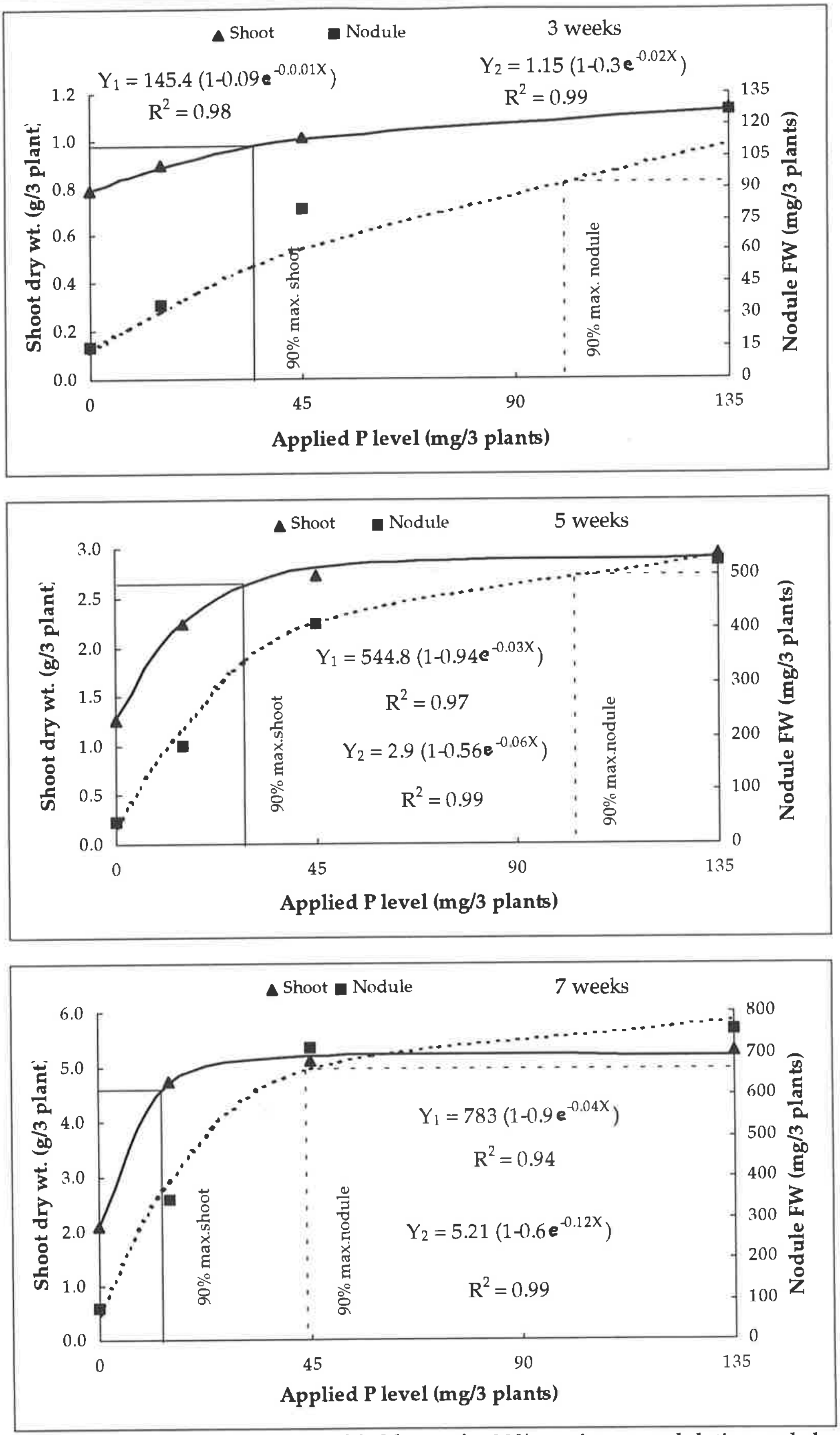


Figure 4.5 The external P requirement of field peas for 90% maximum nodulation and shoot dry matter at three harvest times. Y_1 and Y_2 are fitted Mitscherlich equations for nodule fresh weight and shoot dry weight. yield, respectively."Maximum yield" was calculated from the fitted equations (1995 glasshouse Experiment 2).

Table 4.13. Effects of P application level and placement on mean root:plant dry weight ratio measured at 4 and 6 weeks from sowing (1994 glasshouse experiment 1).

Applied P (mg/pot)	Mean root : plant dry weight ratio (%)														
	4 weeks from sowing					6 weeks from sowing									
	WS	B4	B7	B10	**Mean**	WS		B4		B7		B10		**Mean**	
0	37.1	34.5	33.1	32.5	**34.3**	38.3	(1.58)[A]	35.1	(1.55)	34.9	(1.54)	34.0	(1.53)	**36**	**(1.55)**
15	25.4	27.0	30.5	33.5	**29.1**	22.1	(1.34)	26.8	(1.42)	27.8	(1.44)	28.4	(1.45)	**26**	**(1.41)**
45	20.7	24.8	23.9	29.4	**24.7**	19.4	(1.28)	20.0	(1.3)	24.1	(1.30)	25.0	(1.40)	**22**	**(1.34)**
90	20.9	22.3	22.9	24.3	**22.6**	19.5	(1.29)	20.1	(1.3)	20.2	(1.30)	22.2	(1.34)	**20**	**(1.31)**
135	18.5	18.8	25.1	24.7	**21.8**	17.3	(1.24)	19.5	(1.29)	19.4	(1.29)	19.7	(1.29)	**19**	**(1.33)**
180	19.8	20.7	20.0	23.0	**20.9**	18.7	(1.27)	19.4	(1.29)	20.2	(1.31)	24.3	(1.38)	**21**	**(1.31)**
Mean	**23.7**	**24.7**	**25.9**	**27.9**		**22.5**	**(1.33)**	**23.5**	**(1.36)**	**24.4**	**(1.38)**	**25.6**	**(1.40)**		
LSD ($P = 0.05$)															
P level			**0.11**	**P<0.001**								**(0.04)**	**P<0.001**		
P placement			**0.08**	**P<0.001**								**(0.03)**	**P<0.001**		
P level x P placement			**n.s.**	**$P = 0.23$**								**n.s.**	**$P = 0.19$**		

[A] Values in parentheses are log base 10 transformations, calculated to adjust for a skewed distribution. n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed. [B] LSDs apply to transformed data only.

4.4.6 P concentration in shoot and root

Shoot P concentrations

At the early harvests, the shoot P concentration at any given P rate was maximal where P was applied with the seed. But at later harvests (e.g., 6 and 7 weeks after sowing), this difference became less and shoot P concentrations in the B4 treatments were similar to those in the WS treatments suggesting that the field peas can gain as much P from its placement a few cm below the seed as from fertiliser placed at seed level. Deeper application of P (B10), however, did not increase shoot P concentrations to the same degree, even at higher P levels (Tables 4.16, 4.17).

Relationships between shoot yield and shoot P concentration

The relationships between P concentration in shoot and shoot dry weight with different methods of application at late harvests showed that the estimated critical P concentration for all placement depths was 0.17% (Figure 4.8). In the early harvests, no definable plateau was produced with deep P placements, so it was not possible to estimate a critical concentration (Figures 4.6, 4.7).

Table 4.14. Effects of P application level and placement on mean root : plant dry weight ratio measured at 3, 5 and 7 weeks from sowing (1995 glasshouse Experiment 2).

Applied P (mg/pot)	Mean root : plant dry weight ratio (%)											
	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	**Mean**	WS	B4	B10	Mean	WS	B4	B10	**Mean**
0	26.9	25.6	29.5	**27.3**	21.1	25.0	27.9	24.6	18.5	19.2	18.4	**18.7**
15	21.9	23.1	22.6	**22.5**	18.4	16.2	19.5	18.0	12.3	11.8	12.5	**12.2**
45	19.9	20.5	21.7	**20.7**	17.3	14.9	15.7	16.0	10.0	8.8	10.1	**9.6**
135	19.2	19.2	19.9	**19.4**	16.5	13.4	17.4	15.8	9.7	8.3	9.6	**9.2**
Mean	**22.0**	**22.1**	**23.4**		**18.3**	**17.4**	**20.1**		**12.6**	**12.0**	**12.6**	
LSD (P=0.05)												
P level			**1.9**	**P <0.001**			**3.8**	**P <0.001**			**1.4**	**P <0.001**
P placement			**n.s.**	**P = 0.11**			**n.s.**	**P = 0.19**			**n.s.**	**P = 0.45**
P level x P placement			**n.s.**	**P = 0.53**			**n.s.**	**P = 0.46**			**n.s.**	**P = 0.69**

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 4.15. Effects of P application level and placement on mean root : plant P content ratio measured at 4 and 6 weeks from sowing (1994 glasshouse Experiment 1).

Applied P (mg/pot)	Mean root : plant P content ratio (%)									
	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	Mean	WS	B4	B7	B10	**Mean**
0	57	49	45	48	**49**	51	48	49	47	**49**
15	32	37	41	39	**37**	32	28	39	38	**35**
45	28	34	34	38	**34**	24	24	30	27	**26**
90	31	29	28	29	**29**	22	24	25	22	**23**
135	28	25	32	30	**29**	24	24	25	25	**25**
180	32	30	25	23	**27**	22	24	25	21	**23**
Mean	**35**	**34**	**34**	**34**		**29**	**29**	**32**	**30**	
LSD (P = 0.05)										
P level			**4**	***P*<0.001**				**3**	***P*<0.001**	
P placement			**n.s.**	***P* = 0.99**				**3**	***P* = 0.05**	
P level x P placement			**9**	***P* = 0.05**				**n.s.**	***P* = 0.39**	

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed

Table 4.16. Effects of P application level and placement on mean shoot P concentration measured at 4 and 6 weeks from sowing (1994 glasshouse Experiment 1).

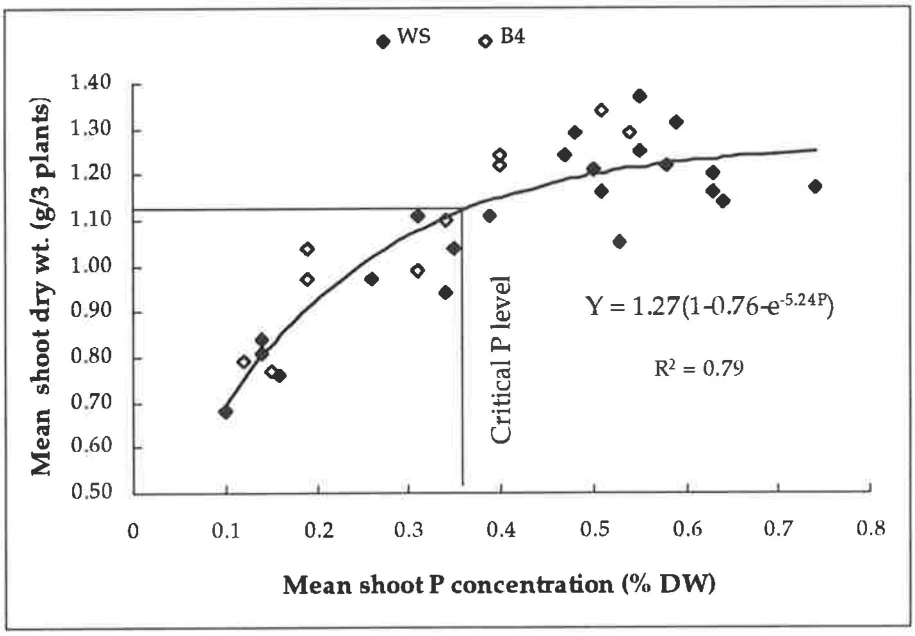
Applied P (mg/pot)	Mean shoot P concentration (%)									
	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	**Mean**	WS	B4	B7	B10	**Mean**
0	0.10	0.12	0.14	0.13	**0.12**	0.12	0.11	0.11	0.11	**0.11**
15	0.31	0.19	0.16	0.20	**0.22**	0.19	0.18	0.17	0.17	**0.18**
45	0.47	0.34	0.26	0.26	**0.33**	0.36	0.34	0.30	0.31	**0.33**
90	0.55	0.40	0.34	0.34	**0.41**	0.46	0.41	0.39	0.34	**0.40**
135	0.59	0.54	0.39	0.38	**0.47**	0.42	0.42	0.40	0.52	**0.44**
180	0.55	0.51	0.39	0.49	**0.48**	0.53	0.48	0.43	0.37	**0.45**
Mean	**0.43**	**0.35**	**0.28**	**0.30**		**0.35**	**0.32**	**0.30**	**0.30**	
LSD ($P = 0.05$)										
P level			**0.05**		**$P<0.001$**			**0.05**		**$P<0.001$**
P placement			**0.04**		**$P<0.001$**			**n.s.**		**$P = 0.11$**
P level x P placement			**0.14**		**$P = 0.003$**			**n.s.**		**$P = 0.21$**

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed

Table 4.17. Effects of P application level and placement on mean shoot P concentration measured at 3, 5 and 7 weeks from sowing (1995 glasshouse Experiment 2).

Applied P (mg/pot)	Mean shoot P concentration (%)											
	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	**Mean**	WS	B4	B10	Mean	WS	B4	B10	**Mean**
0	0.14	0.15	0.13	**0.14**	0.11	0.13	0.12	0.12	0.11	0.12	0.11	**0.11**
15	0.26	0.19	0.19	**0.22**	0.23	0.20	0.18	0.20	0.16	0.15	0.14	**0.15**
45	0.39	0.31	0.21	**0.30**	0.37	0.34	0.26	0.32	0.26	0.24	0.17	**0.23**
135	0.58	0.40	0.36	**0.44**	0.60	0.50	0.33	0.48	0.45	0.43	0.28	**0.38**
Mean	**0.34**	**0.26**	**0.22**		**0.33**	**0.29**	**0.22**		**0.24**	**0.23**	**0.17**	
LSD (P=0.05)												
P level			**0.03**	**$P <0.001$**			**0.04**	**$P <0.001$**			**0.04**	**$P <0.001$**
P placement			**0.03**	**$P <0.001$**			**0.03**	**$P <0.001$**			**0.03**	**$P <0.001$**
P level x P placement			**0.08**	**$P <0.001$**			**0.1**	**$P = 0.003$**			**0.10**	**$P = 0.02$**

n.s. = not-significant ($P>0.05$). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.



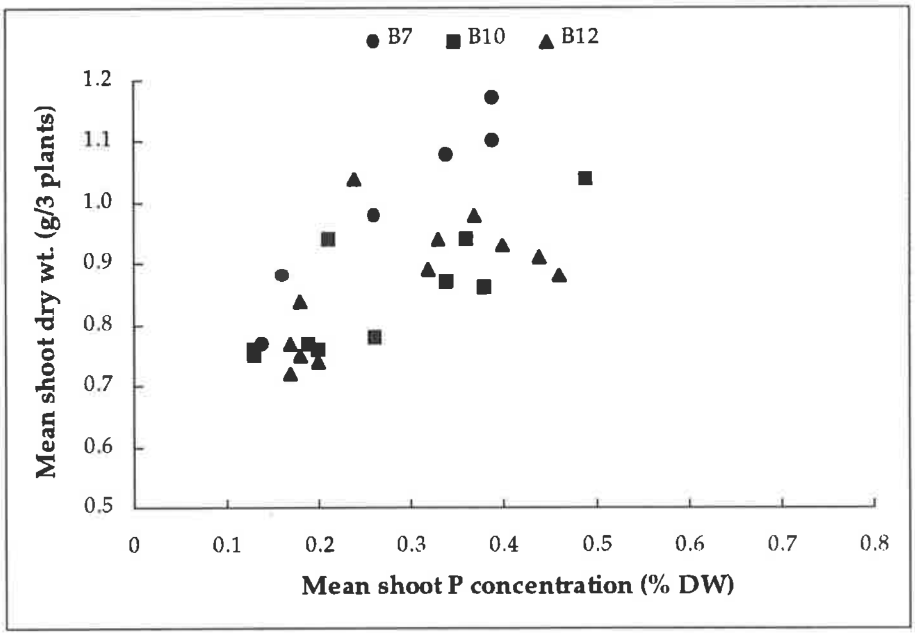
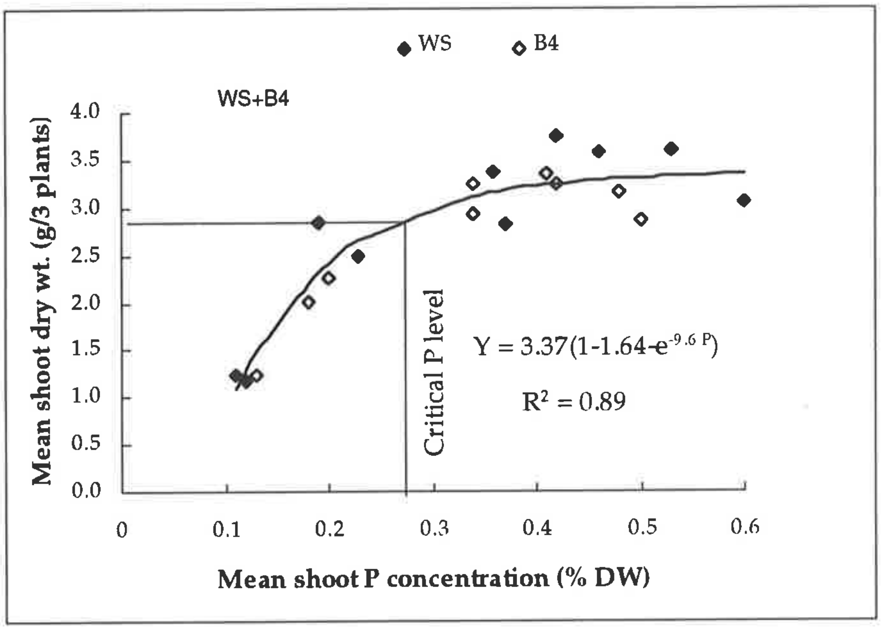


Figure 4.6. The relationship between mean shoot P concentration and mean shoot dry weight of field peas where the fertiliser was placed either at WS and B4 (top) or at B7, B10 and B12 (bottom), measured at 3 and 4 weeks after sowing (1994, 1995 glasshouse Experiments 1 and 2) (data for B12 are used from the experiment in Chapter 3)



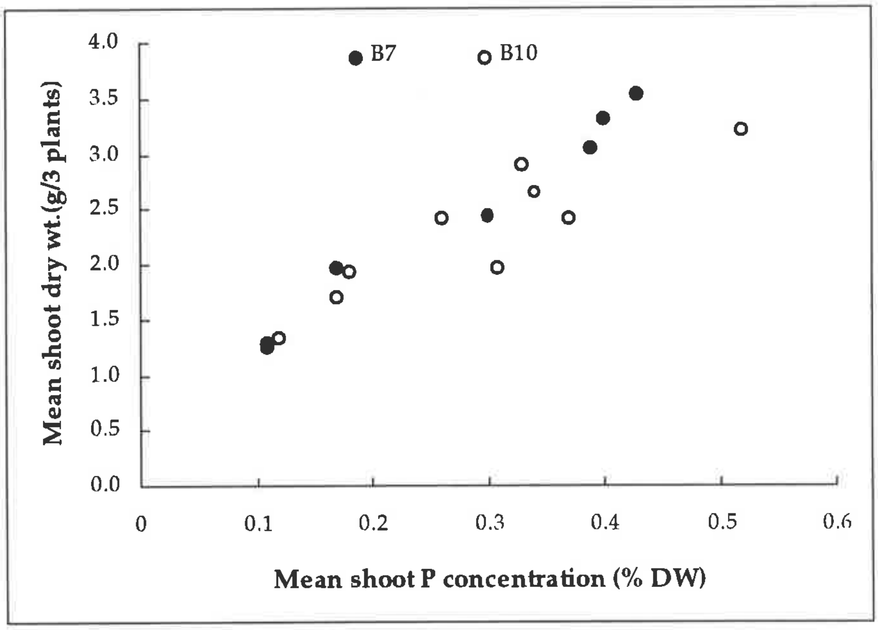
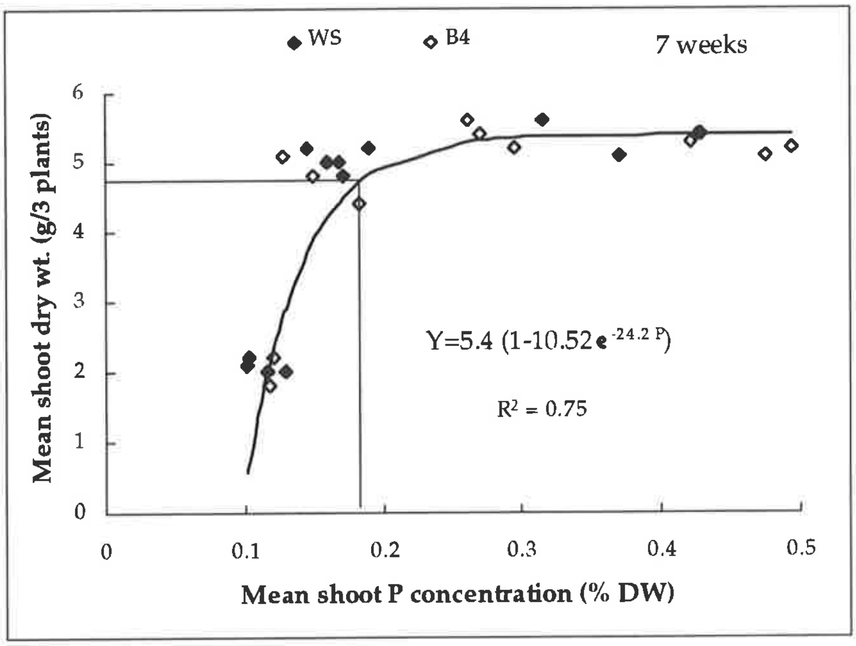


Figure 4.7. The relationship between mean shoot P concentration and mean shoot dry weight of field peas where the fertiliser was placed either at WS and B4(top) or at B7 and B10 (bottom), measure at 5 and 6 weeks after sowing (1994, 1995 glasshouse Experiments 1 and 2).



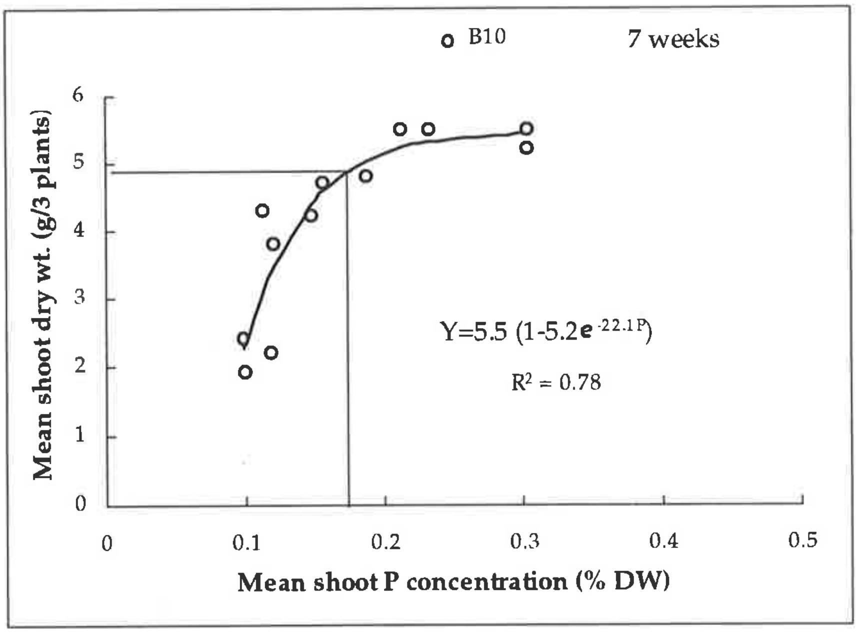


Figure 4.8. The critical P concentration for the field peas shoots where the fertiliser was applied at WS and B4 (top) or at B10 (bottom), measured at 7 weeks after sowing (1995 glasshouse Experiment 2).

Root P concentrations

Root P concentration was higher in WS treatments than in the other treatments at 4 weeks after sowing for P_{135} only (Table 4.18). However, 2 weeks later this effect became insignificant and there was no difference between WS and other placement treatments, except for B10 which had root P concentration less than the others. Similar to the previous experiment in Chapter 3, root P concentrations were generally higher than shoot P concentrations.

Root P concentration measurements in Experiment 1 contrasted with those in the second experiment, which were much lower , especially at the higher P levels (Table 4.19). Different root preserving and storing procedures may possibly have been responsible for these differences. In the first experiment, roots were oven dried soon after careful washing with water, whereas in the second experiment, the sectioned roots were washed and preserved in 30% ethanol and stored at 4 °C for nearly 3 weeks. These roots were oven dried and analysed after the long procedure of root length measurement. It is possible that a significant quantity of root P may have been lost from the roots during this period.

Because of the root growth stimulation under P deficient conditions that occurred at early stages of plant growth, (Table 4.5) a critical P concentration for roots could only be determined at 6 weeks after sowing. The critical concentration for P was slightly higher at B4 compared to WS (Figure 4.9, A and B). The relationship between the relative root dry weight and root P concentration, where P was placed deeper, appeared to be exponential suggesting that where root P was less than 0.4 % the curves were shallower than where the root P was greater than 0.4 % (Figure 4.9B).

Table 4.18. Effects of P application level and placement on mean root P concentration measured at 4 and 6 weeks from sowing (1994 glasshouse Experiment 1).

Applied P	Mean root P concentration (%)									
(mg/pot)	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	**Mean**	WS	B4	B7	B10	**Mean**
0	0.22	0.22	0.23	0.25	**0.23**	0.20	0.18	0.20	0.19	**0.19**
15	0.43	0.39	0.26	0.25	**0.33**	0.33	0.28	0.30	0.27	**0.29**
45	0.69	0.52	0.43	0.38	**0.51**	0.48	0.42	0.40	0.35	**0.41**
90	0.93	0.58	0.46	0.44	**0.60**	0.55	0.49	0.51	0.46	**0.50**
135	1.07	0.76	0.56	0.49	**0.72**	0.63	0.54	0.55	0.53	**0.56**
180	1.02	0.83	0.53	0.48	**0.72**	0.64	0.64	0.57	0.47	**0.58**
Mean	**0.73**	**0.55**	**0.41**	**0.38**		**0.47**	**0.43**	**0.42**	**0.38**	
LSD (P = 0.05)										
P level			**0.08**	***P*<0.001**				**0.06**	***P*<0.001**	
P placement			**0.06**	***P*<0.001**				**0.05**	***P*<0.001**	
P level x P placement			**0.22**	***P*<0.001**				**n.s.**	***P* = 0.81**	

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 4.19. Effects of P application level and placement on mean root P concentration measured at 3, 5 and 7 weeks from sowing (1995 glasshouse Experiment 2).

Applied P	Mean root P concentration (%)											
(mg/pot)	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	Mean	WS	B4	B10	Mean	WS	B4	B10	**Mean**
0	0.17	0.17	0.19	0.18	0.11	0.11	0.10	0.11	0.10	0.09	0.08	**0.09**
15	0.21	0.22	0.20	0.21	0.11	0.11	0.10	0.11	0.12	0.12	0.12	**0.13**
45	0.25	0.23	0.20	0.23	0.19	0.14	0.15	0.16	0.14	0.12	0.11	**0.13**
135	0.26	0.28	0.24	0.26	0.23	0.19	0.19	0.20	0.16	0.13	0.13	**0.13**
Mean	**0.22**	**0.23**	**0.21**		**0.16**	**0.14**	**0.13**		**0.13**	**0.12**	**0.11**	
LSD (P=0.05)												
P level			**0.04**	***P* <0.001**			**0.05**	***P* <0.001**			**0.04**	***P* = 0.04**
P placement			**n.s.**	***P* = 0 .28**			**n.s.**	***P* = 0 .32**			**n.s.**	***P* = 0.42**
P level x P placement			**n.s.**	***P* = 0.65**			**n.s.**	***P* = 0.90**			**n.s.**	***P* = 0.97**

n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

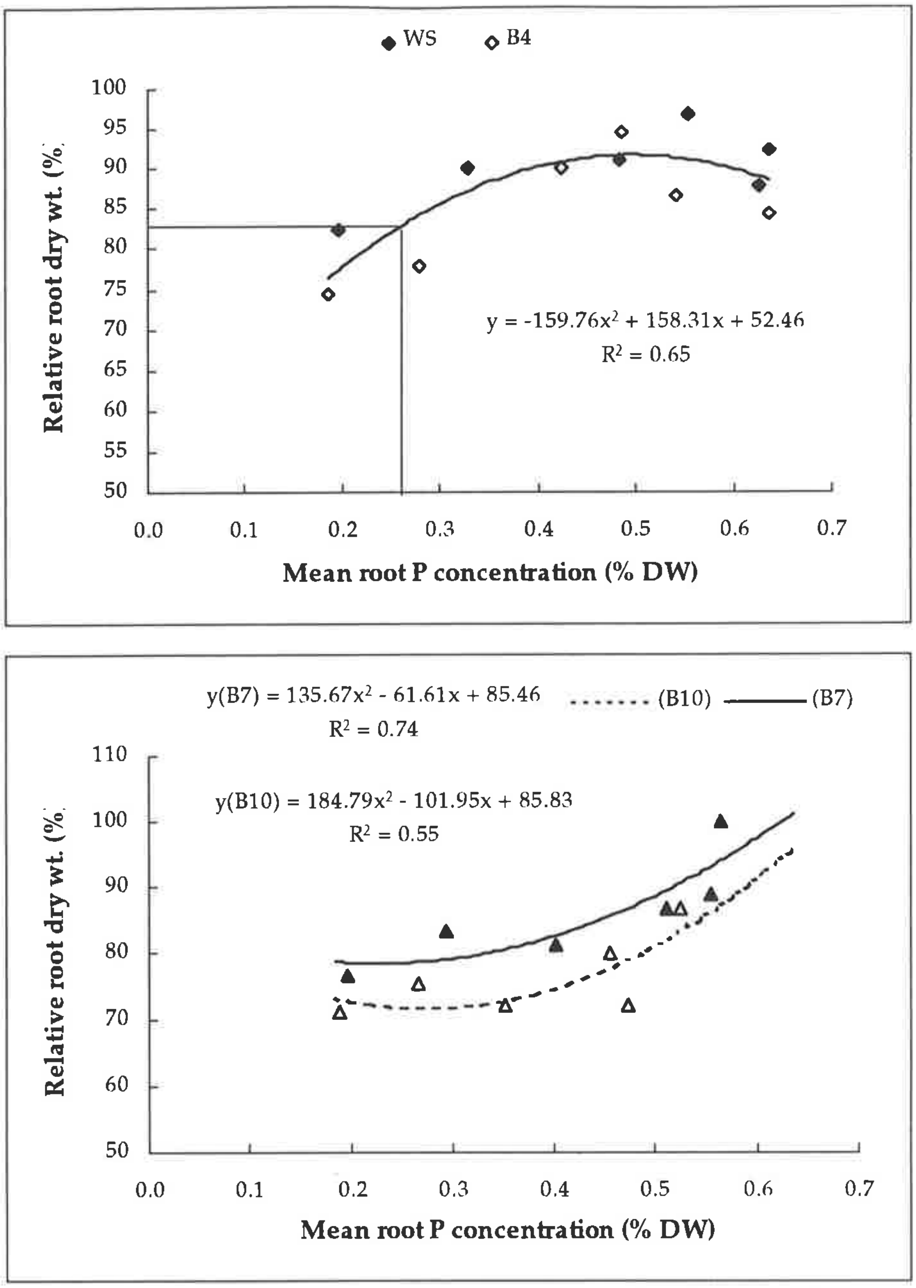


Figure 4.9. Relationships between relative dry weight of roots and mean P concentration in the roots of field pea plants grown for 6 weeks in (A) the WS and B4 placement treatments and in (B) the B7 and B10 P placement treatments (1994 glasshouse Experiment 1).

4.4.7 The effectiveness of applied P fertiliser

The relationship between applied P level and mean shoot dry weight for each depth of P placement in both experiments and at all harvests fitted well to a Mitscherlich equation. However, at deep P placement (B10), a linear relationship fitted better (Figures 4.10, 4.11).

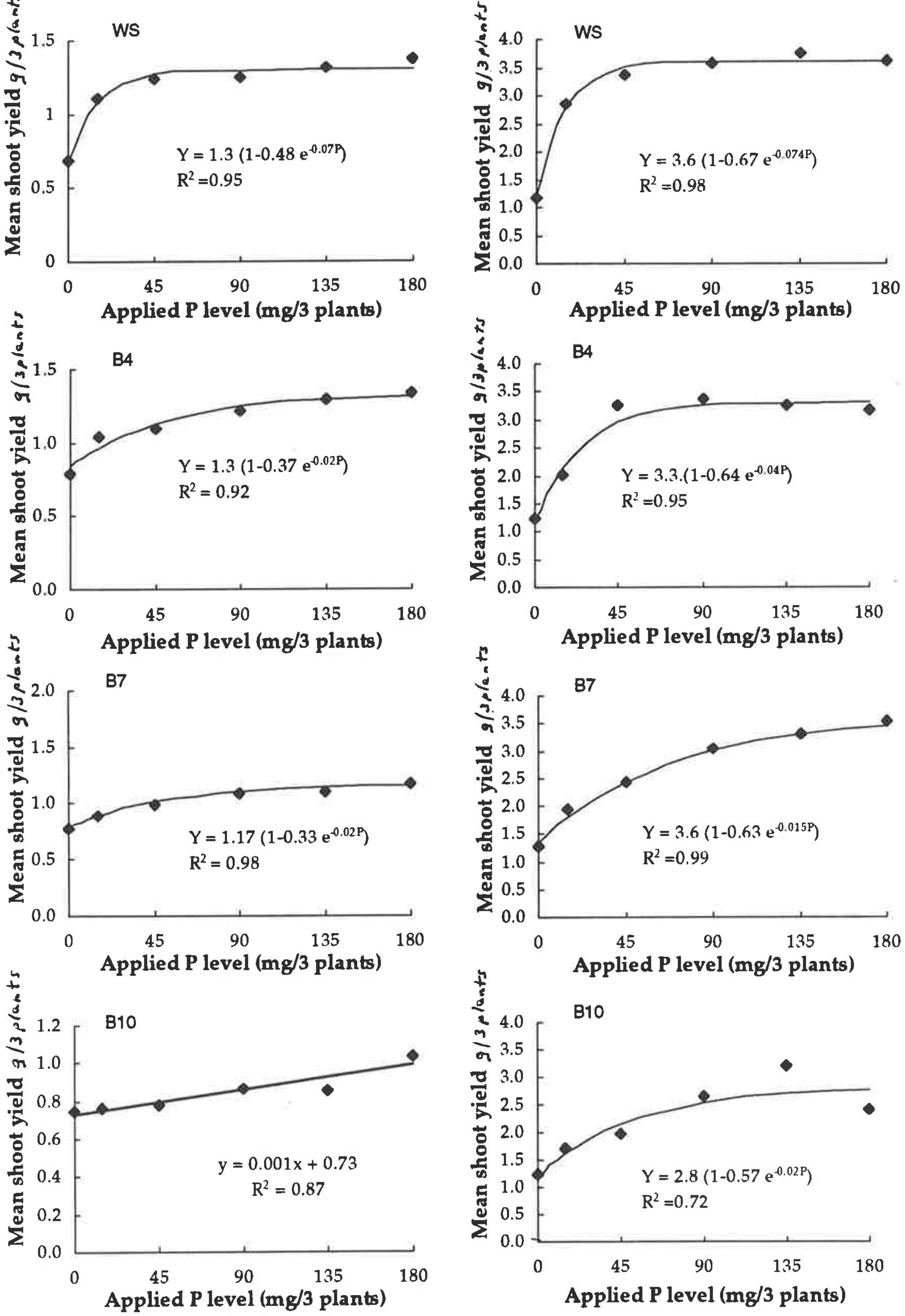


Figure 4.10. The relationships between the mean shoot dry weight of field pea and applied P level where P was placed at WS, B4, B7 or at B10, measured at 4 weeks (left graphs) or 6 weeks (right graphs) after sowing (1994 glasshouse experiment 1). R^2 = 1-(Residual Ms/total Ms)

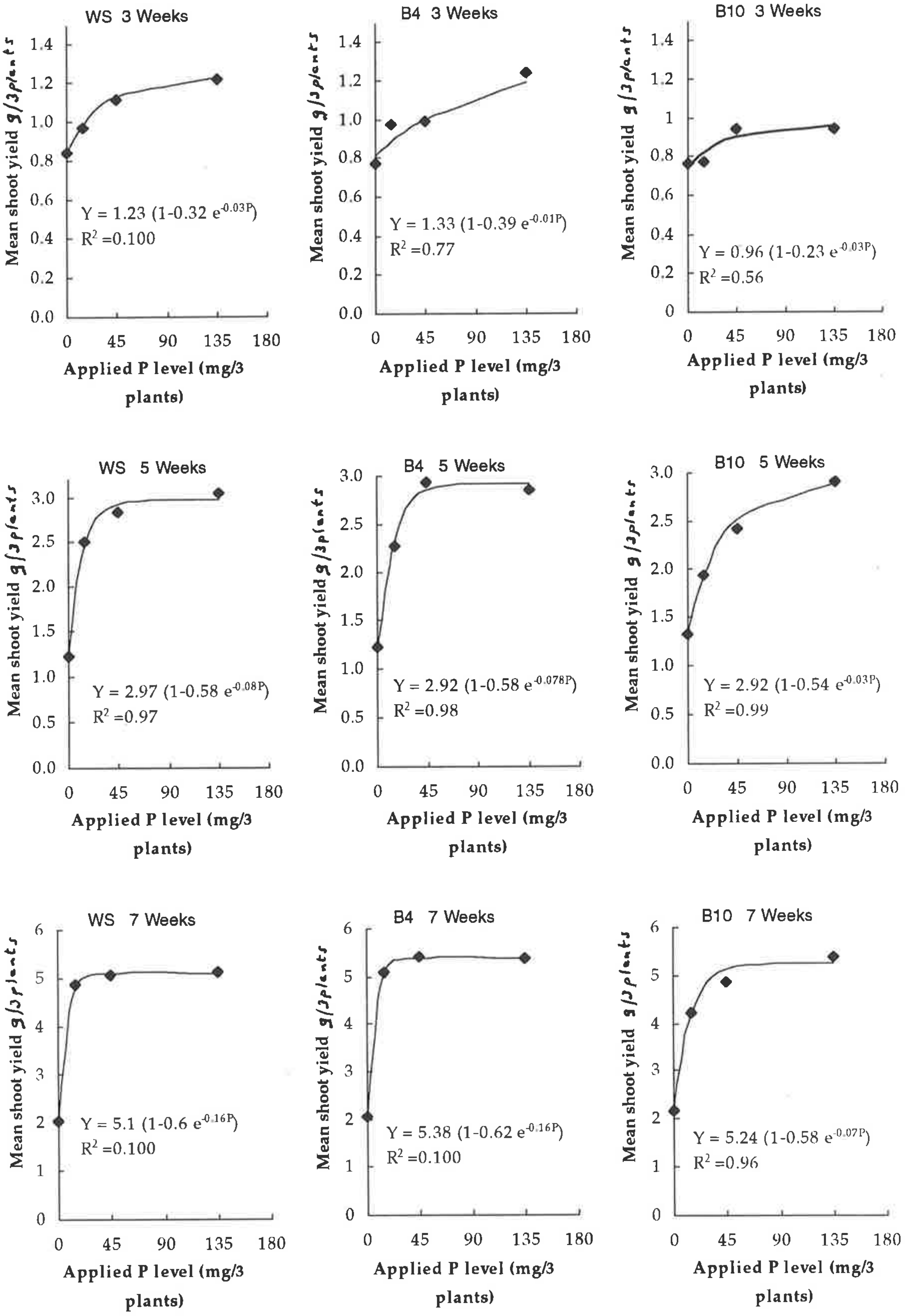


Figure 4.11. The relationships between the mean shoot dry weight of field pea and applied P level where P was placed at WS, B4 or B10, measured at 3, 5 and 7 weeks after sowing (1995 glasshouse experiment 2). R^2 = 1-(Residual Ms/total Ms)

The estimated parameters for these equations at various P placements within both experiments are shown in Table 4.20. The effectiveness of P applied at different soil depths was estimated from the slope of the relationship between the level of applied P and mean shoot dry matter yield in the deficient zone which indicates that the most effective method of P application was WS in Experiment 1 and B4 in Experiment 2.

Table 4.20. The estimated parameters for the Mitscherlich equation fitted to the relationship between applied P level and mean shoot dry weight at various P placement depths, calculated for different harvests (1994, 1995 Experiments 1 and 2).

Experiment 1

P placement	4 weeks				6 weeks			
	A	B	C	Slope[A]	A	B	C	Slope
WS	1.3	0.48	0.07	0.1	3.6	0.67	0.07	0.34
B4	1.4	0.37	0.02	0.01	3.3	0.64	0.04	0.13
B7	1.2	0.33	0.02	0.01	3.6	0.63	0.02	0.06
B10[B]	-	-	-	-	2.8	0.58	0.02	0.04

Experiment 2

	3 weeks				5 Weeks				7 weeks			
	A	B	C	Slope	A	B	C	Slope	A	B	C	Slope
WS	1.23	0.32	0.03	0.16	2.97	0.58	0.08	0.31	5.10	0.60	0.16	2.4
B4	1.33	0.62	0.16	0.02	2.93	0.58	0.07	0.24	5.38	0.62	0.16	2.6
B10	0.96	0.23	0.03	0.01	2.92	0.54	0.03	0.06	5.24	0.58	0.07	0.43

[A] The slope is calculated by A*B*C*EXP(-CP), where P (applied P) is equal 10 mg/pot. [B] The relationship between applied P and relative shoot dry weight did not fit to the Mitscherlich equation.

4.4.8 Apparent P recovery by the pea plant

The apparent recovery of P by the whole plant (Experiment 1) or by the plant shoot (Experiment 2) declined progressively as the level of applied P increased for the WS and B4 treatments only (Tables 4.21, 4.22). At deeper P placement (B7 or B10), the apparent recovery of P was similar at 4 weeks at the different levels of applied P. P recovery from the WS treatment was slightly higher than that from the B4 treatments at the early harvests (3 or 4 weeks after sowing), while P recovery from these two treatments was very similar at the later harvests particularly at 7 weeks after sowing.

Table 4.21. Effects of P application level and placement on mean apparent P recovery in plant shoot measured at 4 and 6 weeks from sowing (1994 glasshouse Experiment 1).

Applied P (mg/pot)	Mean plant P recovery (%) ^A^									
	4 weeks from sowing					6 weeks from sowing				
	WS	B4	B7	B10	**Mean**	WS	B4	B7	B10	**Mean**
15	21.7	15.9	4.0	4.4	**11.5**	36.0	28.3	19.3	13.3	**24.2**
45	13.8	8.4	4.5	3.1	**7.5**	29.3	25.7	17.7	13.3	**21.5**
90	9.0	5.7	3.7	2.6	**5.2**	20.7	16.7	14.3	13.3	**16.3**
135	6.5	5.5	3.4	2.1	**4.4**	13.0	10.7	11.3	11.7	**11.7**
180	5.1	4.4	2.3	2.7	**3.6**	12.3	10.0	10.0	6.3	**9.7**
Mean	**11.21**	**7.95**	**3.58**	**2.98**		**22.27**	**18.27**	**14.53**	**11.60**	
LSD (P = 0.05)										
P level			**1.80**	***P*<0.001**				**11.39**	***P*<0.001**	
P placement			**1.58**	***P*<0.001**				**3.41**	***P*<0.001**	
P level x P placement			**5.28**	***P*<0.001**				**3.90**	***P* = 0.02**	

^A^ Apparent P recovery = 100x(P content in fertilised plants-P content in control plants in mg.)/applied P level (mg.). n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = P fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 4.22. Effects of P application level and placement on mean apparent P recovery in plant shoot measured at 3, 5 and 7 weeks from sowing (1995 pea glasshouse Experiment 2).

Applied P (mg/pot)	Mean plant shoot P recovery (%) ^A^											
	3 weeks from sowing				5 weeks from sowing				7 weeks from sowing			
	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**	WS	B4	B10	**Mean**
15	9.4	5.1	2.5	**5.7**	27.7	22.3	13.0	**21.0**	36.4	34.4	24.8	**31.9**
45	7.1	4.4	1.8	**4.4**	20.1	18.8	10.4	**16.4**	25.2	23.8	18.0	**22.3**
135	4.4	2.9	1.7	**3.0**	12.4	9.4	6.1	**9.3**	15.3	15.2	9.5	**13.3**
Mean	**7.0**	**4.1**	**2.0**		**20.1**	**16.8**	**9.8**		**25.6**	**24.5**	**17.4**	
LSD (P=0.05)												
P level			**1.4**	***P*<.002**			**6.6**	***P* = 0.004**			**7.6**	***P*<0.001**
P placement			**1.4**	***P*<.001**			**6.6**	***P* = 0.009**			**7.6**	***P* = 0.056**
P level x P placement			**n.s.**	***P* = 0.15**			**n.s.**	***P* = 0.79**			**n.s.**	***P* = 0 .96**

^A^ Apparent P recovery = 100x(P content in fertilised plants-P content in control plants in mg.)/applied P level (mg.). n.s. = not-significant (P>0.05). WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B10 = P fertiliser banded 10 cm below seed.

4.5 DISCUSSION

Depth of P placement

The results of these experiments suggest that placing P a few cm below the pea seed produced plants of similar size to those grown in the WS treatments. Although in some measurements WS was superior to B4 at early harvests, in later harvests, this difference became insignificant. In the case of nodule fresh weight, B4 resulted in a higher nodulation yield than WS at all stages of growth measured. Potentially, B4 might be superior to WS. This is firstly, because B4 produced better nodulation which could result in better growth (this did not happen in these experiments possibly because of the basal N addition). Secondly, placement of P at B4 avoids direct contact of the seed with fertiliser thereby negating the possibility of toxic effects on root growth occurring especially at the higher applied P rates (Bhatti and Loneragan 1970, Miller and Ohlrogge 1977, Bowden and Smith 1984); it also avoids the potential toxic effects of excess P and/or acidity on nodule-forming rhizobia (Robson 1982). However, in the present experiments, no toxicity at the levels of P used was measured (except perhaps in nodulation). Thirdly, B4 will result in the applied P being in moist soil longer in the field situation–a benefit not realised in these experiments because all pots were well watered throughout both experiments. The early set back in plant growth in the B4 treatments may be due to the increased time necessary for enough of the root system to reach the fertiliser P source and in the meantime P deficiency decreases shoot growth. Perhaps a split application– some with the seed, most at B4 would be the best approach.

Effects of B7 and B10 show that this early set back can be sufficiently severe that plants do not appear to recover, or are unable to compensate for P deficiency occurring during the early stages of growth.

Stimulation of root growth

Root growth was stimulated under P deficient conditions at early harvests which agrees with Jakobsen (1985) and Srihuttagum and Sivasithamparam (1991) findings as well as the results from the experiment described in chapter 3. It seems that young pea roots preferentially use the absorbed P for their own growth to explore the soil extensively for more P but later this trend changes, i.e.; root growth is depressed and maximum plant metabolism is provided for shoot growth. For example, the overall average of root : plant P content ratio at week 4 was 34%, but reduced to 30% at week 6, or root : plant dry weight ratio, in Experiment 2, showed an 80% reduction between week 3 and week 7. It is also possible that, the plant exhausts its reserves by supporting early root growth and consequently, root growth slows.

The sectioned root study indicated that the effect of localised P on pea root growth is limited to the zone containing the fertiliser (Figures 4.1 ,4.2 ,4.3). This contrasts with the results of pot experiments with sorghum plants grown under growth chamber conditions (De Miranda *et. al.* 1989), which suggested that the effect of placed P on root growth is not necessarily limited to the fertiliser zone.

Maximum root lengths were obtained at moderate levels of P and were reduced at high levels of P, although they were still much higher than in P_0 plants. The reductions at high P levels may have been due to the levels being toxic to root growth. This hypothesis is supported by the symptoms which were observed on some old leaves of the plants in P_{45} and P_{135} treatments (Plate 4.1)

Where only part of the root system of a plant is exposed to a higher external concentration of P fertiliser, that portion of the root system will proliferate to absorb maximum P per unit area of root surface (Marta and Brown 1989). When the concentration of P around the root is great enough to evoke the maximum uptake rate, further increase in P concentration resulting from addition of a greater quantity of the P fertiliser will not increase root growth further. In other words, it seems that both increasing P concentration or root length will increase P absorption by the plant roots. Where the P concentration around the roots is sufficiently high to supply adequate P for plant growth, plants preferably utilise their potential for shoot growth rather than root growth. This may explain why root length was lower in unfertilised soil layers of high P treatments.

A comparison between total root length and sectioned root length measurements shows that, in the total root study, valuable information has been missed compared to sectioned root measurements. For example, there was no significant difference in total root length when P_{15} and P_{135} were applied in the WS treatment at all three harvests (Tables 4.8, 4.9, 4.10), whereas the actual root length in the fertilized WS (0-3 cm) layer was much less when P_{135} was applied than when P_{15} was applied. Thus, at 3, 5, and 7 weeks after sowing, the mean root length of P_{135} plants in the fertilized layer of the WS treatment was 68, 57, and 47% of that of the P_{15} plants, respectively. Sectioned root measurements showed that root length in unfertilised layers did not respond to the application of P, which is not detectable through total root measurements. Thus, in studies of P fertiliser placement it is important to measure plant root growth in fertilised and unfertilised soil layers separately.

P translocation in the plant

In P deficient plants, root : plant dry weight and P content ratios were higher than those of P adequate plants; this is consistent with reports for other plant species (Loneragan and Asher 1967, Gates and Wilson 1974, Smith *et. al.* 1990). P deficiency stimulates root growth at the expense of shoot growth because recently absorbed P is preferentially retained in roots (i.e.; less transported to shoots) and also shoot P is translocated to the roots to stimulate root growth. The magnitude of this activity in plants declines as plant age increases which indicates a change in the direction of P movement in the plant (Smith *et al.* 1990). In the present experiments, the root : plant dry weight and P content ratios of plants grown in WS and B4 treatments, although different at the early harvests were very similar by 6 or 7 weeks after sowing. The very small differences in these ratios where P was applied at WS or at B4 suggest that applying P fertiliser 4 cm below the seed does not prevent pea crops from accessing supplied P.

Nodulation

Results from both experiments indicate that nodulation in field peas was very sensitive to P deficiency and no active nodules were produced on plants without P fertiliser. Indeed, nodule fresh weight is closely correlated with shoot yield

(Cassman *et al.* 1981b, Robson *et al.* 1981, Israel, 1987) and there is also a correlation between shoot dry weight and root yield in most legumes (Fageria and Baligar 1989). However, under the conditions of the present experiments, these effects were not mirrored in shoot growth even at the latest harvest, but the trend could be changed in later plant growth stages or under different conditions.

Furthermore, the external P requirement for nodule fresh weight, at all harvests, was higher than for shoot yield. These results which are in agreement with the results from the experiment in Chapter 3, contrast with the findings of Robson (1983) and Jakobsen (1985). The results presented here suggest that P supply to field pea affects nodulation dramatically and directly rather than indirectly by enhancement of plant growth, as concluded by previous workers.

Nodule growth was also greater in Experiment 2 which may have been due to higher temperatures. For example, average nodule fresh weight measured at week 3 (Experiment 2) was 78% higher than nodule fresh weight at week 4 (Experiment 1). Similarly, it was 85% higher at week 5 (experiment 2) compared to week 6 (Experiment 1) The mean glasshouse temperatures in Experiments 1 and 2 was 17 °C and 24 °C, respectively.

Critical concentration of P

The critical nutrient concentration in plant species is usually defined as the nutrient concentration that is just deficient for maximum growth, or that which is just adequate for maximum growth, or the concentration separating the zone of deficiency from the zone of adequacy (Ulrich 1952).

Critical P concentrations for different treatments in both experiments were lower than those reported in previous studies with field peas. For example, critical P concentrations in the shoots of field peas of field peas at 36 and 96 days after sowing were 0.6% and 0.43%, respectively (Fageria 1977). On the other hand, the critical P concentration at vegetative growth-pre-flowering, in youngest open leaves (YOL) of field peas, was 0.25-0.3% and in whole shoots was 0.2% (Lamb and Poddar 1987); these concentrations are closer to the critical P concentrations obtained in the present experiments. However, review of other studies suggests that the critical P level in different field pea genotypes and under various growth conditions varies markedly.

The critical level of P appeared to be similar where the P was placed at either WS or B4 at all harvests in the vegetative stage of plant growth. Where the P was placed deeper (B7 or B10) shoot yield did not increase with further increase in shoot P concentration (Figure 4.7). This is possibly because in deep placement roots reached the P with some delay, compared to WS or B4 treatments, and consequently, root-P fertiliser contact time was shorter. Thus, the total P uptake by roots of plants from the deeply placed P was reduced. On the other hand, the rate of P absorption is much higher than the rate of shoot growth. Therefore, once root-P fertiliser contact occurs roots absorb P immediately, whereas shoot production due to the supplied P is slow and possibly slow enough not to be observed at early harvests. However, at the late harvest (7 weeks) the critical concentration of P in the shoots was similar at both deep and shallow P placement (Figure 4.8).

CHAPTER 5

INTERACTIVE EFFECTS OF THE DEPTH OF FERTILISER P PLACEMENT AND LEVEL OF P SUPPLY ON THE EFFICIENCY OF P USE IN FIELD GROWN PEA CROPS (*PISUM SATIVUM* cv. ALMA).

5.1. SUMMARY

Two field experiments were conducted in 1994 and 1995 on soils of moderate P status located at Roseworthy, South Australia to determine the interactive effects of P levels and P application methods on field pea growth and P use efficiency. Five levels of applied P (0, 5, 10, 20 and 40 kg P ha^{-1}) applied as triple superphosphate were either topdressed without incorporation, broadcast with incorporation just before sowing, drilled with the seed or banded at 4, 7 and 10 cm below the seed.

In 1994 because of a severe drought condition the experiment appeared not to be a rigorous test of the potential benefits of deep banding P fertiliser. However, shoot dry weight measured at 12 and 17 weeks after sowing, and root dry weight measured at week 12 and also the estimated seed yield responded to the applied P fertiliser.

The results from the experiment in 1995 clearly showed that, where the applied P fertiliser had been placed 5 cm below the seed, pea plants grew vigorously and most of the measured parameters such as shoot and root dry matter yield, nodule score, shoot P concentration and content at weeks 7 or 12, and also seed yield increased markedly compared to the other methods of application. However, superiority of the B5 treatment occurred only at the higher applied P levels (20 and 40 kg P ha^{-1}), while at lower P supply (5 and 10 kg P ha^{-1}), different methods of P placement did not change the plant growth or the seed yield significantly. Broadcast P with incorporation (BR) appeared to be the most inferior method of P application; at 40 kg P ha^{-1} seed yield in the BR treatment was only 47% of that achieved with the B5.

The effectiveness of applied P fertiliser was greater at B5 than with the other methods of application. For example, the required P (kg P ha^{-1}) to produce seed yields of 1.0 and 1.2 t ha^{-1} at B5 was 10 and 24 kg P ha^{-1} , respectively which was less than the

others. Here again, BR was the least effective method for P fertiliser application (B5>B10>WS>BR).

Pea roots developed mostly in the 6-12 cm soil layer where the soil remained moister than it did in the upper 0-6 cm layer for most of the growing period This may suggest that banding P fertiliser 5-10 cm below the seed would benefit from higher soil moisture content and create more root-P contact, whereas P mixed with the surface soil, which remains dry for most of the growing season and contains less plant roots, will be restricted with consequent effects on yield.

5.2. INTRODUCTION

Several field experiments in both Australia (Scott 1973, Jarvis and Bolland 1990, Jarvis and Bolland 1991) and overseas (Barber 1977, McCannell *et al.* 1986, Sander *et al.* 1990) have evaluated the interactive effects of depth of P fertiliser placement and applied P level on the efficiency of P use in crops. Although root behaviour under varied soil P concentrations could be an important factor in this evaluation, it has not been considered in most of these studies. In previous glasshouse experiments (Chapters 3 and 4), the effects of fertiliser P placement and seed P content on yield and the efficiency of P nutrition in field peas were evaluated during early vegetative growth using an extremely P deficient soil. In two of these experiments, it was found that placing P fertiliser 4 cm below the seed was as effective as banding the fertiliser with the seed. However, unlike glasshouse conditions, soil moisture contents in fields vary throughout the growing season, and therefore, the results of these glasshouse experiments need to be confirmed under field conditions.

In 1994 and 1995, field experiments were conducted to evaluate the effectiveness of P fertiliser placed with and below the depth of seed placement on growth and P uptake by field peas. Treatment effects were measured from early vegetative growth until crop maturity.

5.3. MATERIALS AND METHODS

5.3.1 Soil and climate

Both experiments were conducted on soils (Um 5.1.2; Northcote 1979) of moderate soil P status located at Roseworthy, 50 km North of Adelaide on the Adelaide Plains. The properties of the soils in the zone of P placement indicate that extractable soil P and K, organic C and total N concentrations decreased with soil depth, but soil pH and extractable sulfur were higher in the deeper soil layers (Tables 5.1.and 5.2).

Table 5.1. Soil properties in the zones of fertiliser placement (Roseworthy 1994 field experiment).

	Depth from soil surface (cm)		
<2 mm fraction of soil	*0-10*	*10-20*	*20-30*
pH (water)	8.1	8.4	8.5
pH (0.01M $CaCl_2$)	7.5	7.6	7.7
Extractable P, mg/kg^A	15	6	4
Extractable K, mg/kg^B	345	263	119
Extractable S, mg/kg^C	10	36	33
Organic Carbon (%)^D	0.94	0.81	0.61
Total N (%)^E	0.11	0.07	0.06
Electrical conductivity (1:5) (mS/cm)	0.42	0.50	0.66

^{A} Colwell, 1963. ^{B} Sodium bicarbonate extract. ^{C} Potassium chloride extract ^{D} Walkley and Black (1934). ^{E} Kjeldahl 1883.

Table 5.2. Soil properties in the zones of fertiliser placement (Roseworthy 1995 field experiment).

	Soil depth from soil surface (cm)		
<2 mm fraction of soil	*3-5* *(WS)*	*6-8* *(B5)*	*9-11* *(B10)*
pH (water)	8.3	8.3	8.5
pH (0.01M $CaCl_2$)	7.8	7.9	7.9
Extractable P, mg/kg^A	10	7	4
Extractable K, mg/kg^B	325	268	238
Extractable S, mg/kg^C	7.3	10.9	26.5
Organic Carbon (%)^D	1.03	0.93	0.85
Total N (%)^E	0.12	0.10	0.08
Electrical conductivity (1:5) (dS/m)	1.03	1.09	1.41
Free Lime	high	high	very high

^{A} Colwell, 1963. ^{B} Sodium bicarbonate extract. ^{C} Potassium chloride extract. ^{D} Walkley and Black (1934). ^{E} Kjeldahl 1883.

Monthly rainfall recorded near the sites during the year of the experiment and the average for the past 105 years at Roseworthy are listed in Table 5.3. Rainfall for the effective growing season in 1994 and 1995 (May to October) was 169 and 277 mm respectively. Compared to the long term mean of 292 mm,. the crop grown in the 1994 experiment suffered severe water-stress, particularly in late winter and during crop maturation.

Table 5.3. Monthly rainfall (mm) recorded at Roseworthy, S A. in 1994 and 1995 compared to the average monthly totals (1883-1988).

Month	1994	1995	105-year average (1883-1988)^A
January	28	18	21
February	12	29	19
March	0	14	20
April	11	27	38
May	17	45	49
June	75	55	53
July	32	87	49
August	11	17	52
September	9	24	46
October	25	49	43
November	28	8	27
December	0	8	23
Total	*249*	*382*	*440*
May-October	*169*	*277*	*292*

^A Roseworthy Agricultural College, Weather Station.

5.3.2 Experimental design

The statistical design for both experiments was a randomised fully factorial block design with 3 replicates.

Experiment 1 (1994)

Plots were 20 m long and 1.4 m wide with 8 rows of seed sown per plot. The treatments comprised 5 levels of applied P (0, 5, 10 ,20 and 40 kg P ha^{-1} , designated hereafter as P_0, P_5, P_{10}, P_{20} and P_{40}) applied as granulated triple superphosphate (20% P; 1.5% S) that were either topdressed without incorporation (TD), broadcast with incorporation just before sowing (BR), drilled with the seed (WS) or banded 4, 7 or 10 cm below the seed (B4, B7 and B10). Fertiliser application and seed placement were carried out in separate machine passes except for the WS treatment which was accomplished in the one pass. Pea seed was inoculated with group E inoculum (*Rhizobium leguminosarum*) by mixing the two together a few hours before sowing. Seed was sown at 130 kg ha^{-1} on 22 June 1994. Average 100-seed weight was 22 grams. Germination percentage (88%) was estimated by germinating seeds on moist paper in a Petri dish for 6 days in an incubation cabinet.

All plots were cultivated prior to sowing to a depth of 14-16 cm both to control weeds and to break the hard pan present at 13 cm depth. This tillage operation eliminated any deep cultivation effects which could have occurred and confounded the deep fertiliser placement treatments in comparison with broadcast and WS treatments. A light harrow operation levelled the soil, after which trifluralin and zinc (trifluralin, 2 L ha^{-1} and $ZnSO_4$ 7 H_2O, 3.9 kg Zn ha^{-1}) were applied. Two harrowings then followed. A basal application of gypsum at 114 kg ha^{-1} was also broadcast and incorporated 1 week before sowing.

The seeding machine used in this experiment could only apply the deep banded fertiliser in a separate pass and thus due to the two-pass seeding operation used it could not be guaranteed that the fertiliser was always sown directly beneath the seed rows. Since deep banding fertiliser between seed rows is not as effective as directly banding under seed rows , the ability to rigorously test the benefits of deep banded fertiliser was partly compromised. P fertiliser was placed at different depths and levels of application for all treatments before sowing except for the TD treatment in which it was broadcast immediately after sowing.

During the vegetative stage of growth, Quizalofop-P-ethyl was sprayed (300 mL. ha^{-1}) to control ryegrass (*Lolium rigidum*), it resulted in a 70% reduction in ryegrass number. Some broad-leaf weeds including wild turnip (*Brassica tournefortii*), Indian hedge mustard (*Sisymbrium orientale*) and wild radish (*Raphanus raphanistrum*) were removed by hand. Furalaxyl (160 g ha^{-1}) was applied by a hand sprayer to control a 30% infection of downy mildew. Cypermethrin (200 g ha^{-1}) was applied to control native budworm.

Experiment 2 (1995)

Plots were 18 m long and 2.4 m wide with 10 rows of seed sown per plot. The same levels of P fertiliser used in Experiment 1, were either broadcast with incorporation just before sowing (BR), drilled with the seed (WS) or banded 5 or 10 cm below the seed (B5 and B10). Fertiliser application and sowing were carried out in one machine pass. Seed was sown at 140 kg ha^{-1} on 29 June 1995. Average 100-seed weight was 21 grams and the seed had a germination percentage of 70.

A mixture of paraquat and trifluralin was sprayed for pre-sowing weed control. No basal fertiliser was applied in this experiment.

The sowing machine was modified so that fertiliser could be drilled with the seed through 2 rows of rear tines, or banded at depth through boots fitted to the 2 front rows of tines. The deep banding treatments had the seeding tine 0.5 m in line behind the fertiliser placement tines so that the seed was sown directly above the P fertiliser bands. Narrow tines were fitted with 70 mm wide points on the fertiliser and sowing tines.

During vegetative growth, Quizalofop-P-ethyl was sprayed to control ryegrass and resulted in a 60% reduction in ryegrass number. Black spot (Ascochytal blight) and downy mildew were evident during the growing season with about 30% infection. No chemical control was applied for these diseases. Some broad-leaf weeds including wild turnip, Indian hedge mustard and wild radish were removed by hand.

5.3.3 Measurements

The variables measured in both experiments are summarised in Table 5.4.

In *Experiment 1 (1994)*, emerged plant numbers were counted at 2, 3 and 4 weeks from sowing by locating a 0.5 m^2 quadrat randomly within each plot.

Growth of field pea shoots was measured by placing a single 0.5 m^2 quadrat in every plot. Plants inside the quadrat were visually judged to be representative of the whole plot. To prevent bias, identification signs for each treatment were removed prior to each sampling. Plant shoots were harvested at the ground level, oven dried at 70 °C in a forced draught oven for 72 hours and weighed.

Table 5.4. The variables measured in the two experiments conducted in 1994 and 1995.

Measurements	Sampling time (weeks from sowing)	
	Experiment 1 (1994)	Experiment 2 (1995)
Plant establishment count	W_2, W_3, W_4	W_4
Shoot dry matter yield	W_7, W_{12}, W_{19}	W_7, W_{12}
Root yield:		
dry weight	W_7, W_{12}, W_{19}	W_7, W_{12}
length	–	W_7, W_{12}
Nodulation	–	W_7, W_{12}
Components of yield	W_{21}	W_{21}
Seed yield	W_{21}	W_{23}

Three root samples were taken within each quadrat using a hydraulic soil coring machine. The core size taken was 10 cm in diameter and 20 cm in depth. Roots were washed and one sample was preserved in 30% ethanol at 4 °C. The other two samples were oven dried at 70 ^{0}Cfor 72 hours for the determination of root dry matter.

Shoot dry matter yields were determined at 7, 12, and 19 weeks after sampling in Experiment 1; however root yields were unable to be determined at 19 weeks because the soil was too hard for the coring machine.

Yield components were measured at week 21 by counting and then cutting all plants contained in a 0.5 m^2 quadrat representative of the whole plot. Plant number, number of pods per plant, number of seeds per pod and 100-seed weight were then derived. Seed yield and total shoot yield per hectare were estimated from the yield components because plants were too small and short to be machine harvested.

In *Experiment 2 (1995)*, the number of emerged plants was recorded on July 27 (week 4), on either side of a 1 metre ruler placed alongside rows at three random locations per plot. This value corresponded to the number of plants in one square metre.

Plant shoots and roots were sampled twice during growth at week 7 and week 12 after sowing when plants had 4-5 and 15-16 nodes per stem, respectively. At week 12, the plants were at flower initiation. Yields of shoots were measured by cutting, at ground level, 20 plants at random from the 8 middle rows.

Root samples for root length measurement were taken from nine replicated treatments of 3 P levels (0, 10 and 40) and 3 P placement positions (WS, B5 and B10). Root sampling was achieved by the same method as in Experiment 1. Two samples were taken from each plot randomly. Because soil moisture content was low, it was not possible to cut core samples into three distinct sections as was intended. Instead, after washing, each intact root system, was cut into three sections (0-6, 6-12 and 12-18 cm from seed level) corresponding to 3 different depths in the soil profile, where the fertiliser was placed (i.e., WS, B5, B10) (Figure 5.1). In addition, the roots of 3 plants were taken randomly with a trench spade from all treatments to obtain root dry matter.

Yield components were measured on 14 November (week 21) by collecting 6 pods per plant at 10 locations within each plot. Pods were picked randomly from the bottom to the top of each plant. Seed yield was measured on 27 November (week 23) by harvesting the plots with a plot harvester.

Soil samples for moisture content measurements were taken 8 times during the growing season at the seed level and 5 and 10 cm below the seed level.

5.3.4 Experimental procedures

Dried shoots were weighed and shoot dry matter calculated on a per m^2 (Experiment 1) or per plant (Experiment 2) basis. Sub-samples of dried shoots were ground (<1 mm), digested with nitric acid and analysed for P by inductively coupled plasma spectrometry (Zarcinas *et al.* 1987).

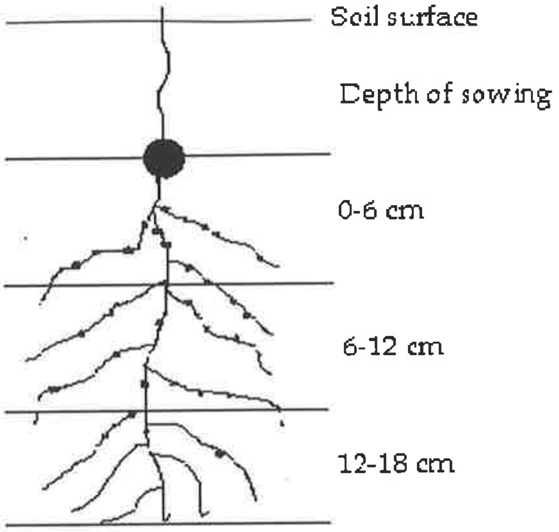


Figure 5.1. Sectioning each root sample into 3 sections corresponding to 3 depths of applied P fertiliser zone (1995, field experiment).

Shoots from the replicates of 3 P rates (P_0, P_{10} and P_{40}) and 3 P placement treatments (WS, B5 and B10) of Experiment 2, harvested at week 12, were analysed for total nitrogen by the Leco nitrogen combustion analyser (AOAC 1995).

All root samples were washed free of soil with a spray of water over a 1 mm sieve. Root samples for root dry matter estimation were weighed after oven drying at 70° C for 72 hours. Root length and nodulation measurements were done only in Experiment 2 (1995). Root samples taken by the coring machine from selected treatments (see above) were cut into three sections, preserved in 30% ethanol, stored at 4 °C and prepared for root length determinations (Pederson *et al.* 1994). Scanning of individual root images and root length, area and diameter measurements (mean diameter class sizes 0.2, 0.3, ..., 0.8, 1.0, 2.0, and 3.0 mm) was accomplished using a flat-bed optical character recognition scanner set at 300 dpi resolution, and used IBM computer software (Kirchhof 1992).

The active nodules in each core segment (0-6, 6-12 and 12-18 cm from the seed level) were scored by multiplying the number of nodules present in each segment by the visually judged class size of each counted nodule (i.e., 0.5 = small nodule; 1 =

medium sized nodule; 2 = large nodule; 3 = very large nodule). Only nodules with internal pink pigmentation were scored. The procedure adopted was essentially similar to that used by Howieson and Ewing (1989).

5.3.5 Analysis of data

The data from all measurements were analysed by using a randomised fully factorial block design ANOVA Model (Genstat 5 Released 3.1). Least significant differences (LSD) were calculated for treatments and used as a measure to compare treatment means. The LSD is calculated by the following formula:

$$LSD = t(0.05, n)\ \sqrt{2 Mse / n}$$

where, *t* is obtained from t-distribution table at 5% level of probability and *n* is the number of values attended in the related means.

The relationships between shoot P concentration and shoot yield at week 7 and week 12 were established to derive critical plant P concentrations in the shoots of field peas for the different P placement depths.

Apparent P recovery was also determined in shoots and seeds for all P levels and P placements by the following equation:

$$\%\mathit{Apparent\ P\ Recovery} = (P_f\text{-}P_0\ / P)\ \mathrm{X}\ 100$$

where P_f and P_0 are shoot P content from fertilised and from corresponding control plots, respectively.

5.4. RESULTS (*Experiment 1, 1994)*

1994 was a severe drought year where water content in the soil profile was extremely low for most of the season and plant growth clearly restricted. The drought conditions resulted in very poor and uneven crop growth which made it extremely difficult to identify treatment effects. For example, there was no measured increase in mean shoot mass between week 12 and week 19 after sowing which is normally a period of rapid growth (Table 5.5). At week 17, 90% of plants, especially in low P treatments (0, 5, and 10 kg P ha^{-1}), were stunted, dry and matured early which could be attributed to the dry soil conditions. The number of emerged plants at week 2, 3 and 4 was affected only by the applied P level but no response was obtained to the method of P application (Table 5.5).

Because of the severe drought conditions and also because sowing and applying fertiliser were carried out in two separate machine passes, this field experiment was not a rigorous test of the potential benefits of deep banding P fertiliser for field pea growth.

Despite these conditions, the field peas did show a reasonably large positive response in shoot yield to increasing levels of applied P at 12 and 17 weeks from sowing (Table 5.6). The response at 7 weeks was only marginally significant ($P = 0.07$). At the 12 and 17 weeks harvests, shoot yields approached maximum levels at P_{20}. However, at all harvests shoot yield was not affected significantly by the method of P placement and by the interaction between level of applied P and method of P placement.

Similarly, root dry weight measured at 7 weeks from sowing was not affected by treatment, but at 12 weeks from sowing, root dry weight was increased with increased rate of P applied (Table 5.7). Root yield reached a maximum at P_{10}. Again, method of P placement and the interaction between level of P and method of P placement did not influence root dry weight.

In this experiment, only the main effect of P level influenced shoot and seed yield (Table 5.8) and yield components (Table 5.9). Application of 20 kg P ha^{-1} approximately doubled both shoot and seed yield; the increase in seed yield was associated with an increase in pod density and an increase in seed weight.

Table 5.5. **Effects of P application level and placement on mean plant density measured at 2,3, and 4 weeks from sowing (1994 field experiment).**

Applied P (kg/ha)	Mean plant density/m^2																				
	2 weeks from sowing							3 weeks from sowing							4 weeks from sowing						
	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**
0	16	7	23	5	5	3	**10**	47	45	53	41	39	33	**43**	59	48	61	49	49	45	**52**
5	31	15	13	7	7	3	**13**	57	59	51	63	54	44	**55**	61	71	56	72	62	56	**63**
10	14	10	17	6	5	4	**9**	47	33	53	43	45	41	**44**	63	41	62	50	51	47	**52**
20	19	12	9	5	9	6	**10**	55	53	47	49	49	43	**49**	59	61	53	61	62	53	**58**
40	11	9	13	7	5	5	**8**	53	57	56	51	43	53	**52**	56	65	65	64	58	61	**61**
Mean	**18**	**11**	**15**	**6**	**6**	**4**		**52**	**49**	**52**	**49**	**46**	**43**		**59**	**57**	**59**	**59**	**56**	**53**	
LSD (P=0.05)																					
P level				**n.s.**	**(P = 0.35)**						**9**	**(P = 0.03)**						**9.5**	**(P = 0.05)**		
P placement				**5**	**(P < 0.001)**						**n.s.**	**(P = 0.37)**						**n.s.**	**(P = 0.71)**		
P level x P placement				**n.s.**	**(P = 0.38)**						**n.s.**	**(P = 0.95)**						**n.s.**	**(P = 0.87)**		

n.s. = not-significant (P>0.05). TD = P topdressed . BR = P broadcast and incorporated. WS = P sown with seed. B4 = P banded 4 cm below seed. B7 = P banded 7 cm below seed. B10 = P banded 10 cm below seed.

Table 5.6. Effects of P application level and placement on mean shoot dry weight measured at 7, 12 and 17 weeks from sowing (1994 field experiment).

Applied P (kg/ha)	Mean shoot dry weight (g/m^2)																				
	7 weeks from sowing							12 weeks from sowing							17 weeks from sowing						
	TD	BR	WS	B4	B7	B10	Mean	TD	BR	WS	B4	B7	B10	Mean	TD	BR	WS	B4	B7	B10	Mean
0	11.0	7.3	11.0	8.1	7.9	7.3	**8.8**	39.6	34.4	89.2	61.6	73.4	45.2	**57.2**	56.4	23.8	50.4	46.0	55.4	60.2	**48.7**
5	13.5	11.3	8.5	14.6	11.9	8.7	**11.4**	52.0	41.2	63.4	50.2	67.4	64.0	**56.4**	59.6	56.8	43.2	57.0	40.2	69.2	**54.3**
10	11.2	6.4	11.4	9.0	9.8	7.9	**9.3**	65.2	47.4	60.8	78.4	59.8	72.8	**64.1**	72.2	62.8	77.2	49.6	103.8	107.0	**78.8**
20	11.3	10.8	9.7	11.4	12.1	10.1	**10.9**	101.0	94.4	89.2	89.0	107.2	122.6	**100.6**	136.0	101.6	65.8	141.0	102.2	120.0	**111.1**
40	11.1	8.7	10.4	11.7	11.1	12.0	**10.8**	82.6	114.4	106.6	101.0	102.2	110.8	**102.9**	88.4	118.4	69.0	101.8	110.8	123.2	**101.9**
Mean	**11.6**	**8.9**	**10.2**	**11.0**	**10.6**	**9.2**	***10.2***	**68.1**	**66.4**	**81.8**	**76.0**	**82.0**	**83.1**	***76.2***	**82.5**	**72.7**	**61.1**	**79.1**	**82.5**	**95.9**	***79.0***
LSD (P=0.05)																					
P level				**n.s.**	**(*P* = 0.07)**						**21**	**(*P* < 0.001)**						**34**	**(*P* = 0.05)**		
P placement				**n.s.**	**(*P* = 0.16)**						**n.s.**	**(*P* = 0.37)**						**n.s.**	**(*P* = 0.71)**		
P level x P placement				**n.s.**	**(*P* = 0.78)**						**n.s.**	**(*P* = 0.95)**						**n.s.**	**(*P* = 0.87)**		

n.s. = not-significant (*P*>0.05). TD = P topdressed . BR = P broadcast and incorporated. WS = P sown with seed. B4 = P banded 4 cm below seed. B7 = P banded 7 cm below seed. B10 = P banded 10 cm below seed.

Table 5.7. Effects of P application level and placement on mean root dry weight measured at 7 and 12 weeks from sowing (1994 pea field experiment).

Applied P (kg/ha)	Mean root dry weight (g/2 plants)													
	7 weeks from sowing							12 weeks from sowing						
	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**
0	0.14	0.10	0.14	0.14	0.18	0.14	**0.14**	0.22	0.29	0.21	0.31	0.23	0.27	**0.25**
5	0.12	0.15	0.18	0.13	0.17	0.13	**0.15**	0.24	0.45	0.33	0.41	0.27	0.33	**0.34**
10	0.18	0.15	0.14	0.18	0.14	0.14	**0.16**	0.26	0.41	0.37	0.43	0.39	0.39	**0.38**
20	0.13	0.12	0.16	0.15	0.13	0.14	**0.14**	0.4	0.43	0.37	0.34	0.41	0.53	**0.41**
40	0.17	0.13	0.15	0.13	0.15	0.14	**0.15**	0.47	0.49	0.41	0.32	0.44	0.45	**0.43**
Mean	**0.15**	**0.13**	**0.15**	**0.15**	**0.15**	**0.14**		**0.32**	**0.41**	**0.34**	**0.36**	**0.35**	**0.39**	
LSD (*P*=0.05)														
P level				**n.s.**	**(*P* < 0.59)**						**0.07**	**(*P* < 0.001)**		
P placement				**n.s.**	**(*P* = 0.28)**						**n.s.**	**(*P* = 0.37)**		
P level x P placement				**n.s.**	**(*P* = 0.40)**						**n.s.**	**(*P* = 0.95)**		

n.s. = not-significant (*P*>0.05). TD = P topdressed. BR = P broadcast and incorporated. WS = P sown with seed. B4 = P banded 4 cm below seed. B7 = P banded 7 cm below seed. B10 = P banded 10 cm below seed

Table 5.8. Effects of P application level and placement on mean seed and total yield (seed and straw), measured at 19 weeks from sowing (1994 field experiment).

Applied P (kg/ha)	Mean total yield (kg/ha)							Mean seed yield (kg/ha)						
	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**
0	472	395	934	537	1001	580	**653**	117	72	297	92	309	281	**195**
5	1085	975	864	1038	664	746	**895**	363	284	374	398	232	317	**328**
10	872	611	1220	1177	726	736	**890**	296	135	435	405	214	463	**325**
20	1394	996	726	1823	969	1213	**1187**	**463**	423	198	639	327	432	**414**
40	1060	1043	830	1694	1429	1529	**1264**	323	336	215	534	525	505	**406**
Mean	**977**	**804**	**915**	**1254**	**958**	**961**		**312**	**250**	**304**	**414**	**321**	**400**	
LSD (P=0.05)														
P level				**417**	**(*P* = 0.02)**						**172**	**(*P* = 0.04)**		
P placement				**n.s.**	**(*P* = 0.28)**						**n.s.**	**(*P* = 0.47)**		
P level x P placement				**n.s.**	**(*P* = 0.40)**						**n.s.**	**(*P* = 0.76)**		

n.s. = not-significant (P>0.05). TD = P topdressed. BR = P broadcast and incorporated. WS = P sown with seed. B4 = P banded 4 cm below seed. B7 = P banded 7 cm below seed. B10 = P banded 10 cm below seed

Table 5.9. Effects of P application level and placement on mean number of pods per m^2 and 100-seed weight, measured at 19 weeks from sowing (1994 field experiment).

Applied P	Mean pod number per m^2							100-seed weight (g)						
(kg/ha)	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**
0	22.3	20.0	30.3	16.7	33.3	29.7	**25.4**	11.7	9.4	16.8	10.4	15.2	13.9	**12.9**
5	33.3	32.0	39.3	36.0	30.7	33.3	**34.1**	16.4	17.4	17.0	18.5	11.7	14.3	**15.9**
10	32.0	23.7	38.7	37.7	30.7	32.0	**32.5**	15.6	11.5	16.3	14.0	12.7	14.0	**14.0**
20	47.0	41.0	25.3	54.0	29.7	37.3	**39.1**	18.7	15.9	14.5	16.7	15.0	16.1	**16.1**
40	39.0	37.7	34.7	59.7	46.7	50.3	**44.7**	13.1	16.4	12.1	13.4	15.1	14.6	**14.1**
Mean	**34.7**	**30.9**	**33.7**	**40.8**	**34.2**	**36.5**		**15.1**	**14.1**	**15.3**	**14.6**	**13.9**	**14.6**	
LSD (P=0.05)														
P level				**14.7**	**(P = 0.005)**						**2.4**	**(P = 0.03)**		
P placement				**n.s.**	**(P = 0.60)**						**n.s.**	**(P = 0.37)**		
P level x P placement				**n.s.**	**(P = 0.75)**						**n.s.**	**(P = 0.95)**		

n.s. = not-significant (P>0.05). TD = P topdressed . BR = P broadcast and incorporated. WS = P sown with seed. B4 = P banded 4 cm below seed. B7 = P banded 7 cm below seed. B10 = P banded 10 cm below seed

5.5. RESULTS *(Experiment 2, 1995)*

The statistical significance of variance ratios for all measured variables in this experiment are shown in Table 5.10.

Table 5.10. Statistical significance of the main effects of the experimental variables and their interactions on measured plant parameters (1995 field experiment)

	Harvest 1 (7 weeks)			Harvest 2 (12 weeks)		
Variables	P level	P placement	P level X P placement	P level	P placement	P level X P placement
Shoot DW^A	***	***	n.s.	***	***	***
Root DW	n.s.	n.s.	**	***	n.s.	n.s.
Root:Plant DW ratio	n.s.	n.s.	n.s.	***	n.s.	n.s.
Root length	n.s.	**	n.s.	**	n.s.	n.s.
Nodule FW^B	***	***	n.s.	***	n.s.	n.s.
Shoot P concentration	***	**	n.s.	***	***	***
Shoot P content	***	**	n.s.	***	***	***
Shoot N concentration	-	-	-	**	n.s.	n.s.
Shoot N content	-	-	-	***	***	***

* = (P < 0.05); ** = (P<0.01); *** = (P < 0.001); n.s. = not significant. ^{A} Dry weight. ^{B} Fresh weight.

5.5.1 Deficiency symptoms and phasic development

Plant establishment, measured 1 month after seeding, was satisfactory (Lamb and Poddar 1987) and unaffected by treatments. The average plant number per square meter (mean ± s.d.) was 42 ± 4. Other than reduced growth, no foliar symptoms of P deficiency appeared in any of the control (P_0) plots at any stage of growth. However, the development of nodes was delayed in the P_0 and P_5 treatments and differences in plant weight between the highest and the lowest P levels were obvious beyond 28 days after sowing. The largest plants occurred where the highest P levels were placed 5 and 10 cm below the seed (Plate 5.1).

Flowering started 12 weeks after sowing when the plants had 14 to 16 nodes. Flower initiation in P_0 and P_5 plants occurred 1 to 3 days later than in plants grown at higher levels of applied P. One week after flower initiation, all plants had fully flowered, except those in the P_0 treatments, which at that stage still only had a few flowers per plant.

Branching occurred frequently at the highest level of P when placed either with or below the seed. No branching was observed in plants grown at low P levels and where P fertiliser was broadcast (all P levels).

5.5.2 Shoot dry weight

The site was very P deficient for the growth of field peas. For example, 12 weeks after sowing shoot dry matter yield was nearly trebled by applying the highest level of applied P (Table 5.11). Over all levels of P supply, application of P with the seed (WS) produced slightly superior shoot yields than the other methods of application by 7 weeks from sowing. By contrast, at 12 weeks the mean shoot yield of the P_{40} (B5) treatment was greatly enhanced compared to that of the other treatments (Table 5.11). These data suggest that at 7 weeks sufficient root had not reached the deeper placed fertiliser, but they had 5 weeks later. In addition, the data also show that at 12 weeks, the P broadcasting treatments (BR) were the most inefficient method of applying higher levels of applied P (Table 5.10).

Plate 5.1 A comparison of field pea growth in the treatment B5 P_{40} (right) and a P_0 treatment (left).

Table 5.11. Effects of P application level and placement on mean shoot dry weight measured at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Mean shoot dry weight (g/plant)									
	7 weeks from sowing					12 weeks from sowing				
	BR	WS	B5	B10	Mean	BR	WS	B5	B10	Mean
0	0.17	0.18	0.17	0.15	**0.17**	0.93	0.95	0.90	0.85	**0.91**
5	0.18	0.18	0.16	0.18	**0.17**	1.24	1.44	1.57	1.61	**1.46**
10	0.18	0.18	0.18	0.17	**0.18**	1.51	1.96	1.99	1.78	**1.81**
20	0.19	0.22	0.19	0.18	**0.19**	1.68	2.26	2.12	1.91	**1.99**
40	0.20	0.22	0.22	0.22	**0.21**	1.74	2.29	4.05	2.62	**2.67**
Mean	**0.18**	**0.20**	**0.18**	**0.18**		**1.42**	**1.78**	**2.13**	**1.75**	
LSD (*P*=0.05)										
P level			**0.01**	***P*<0.001**				**0.26**	***P*<0.001**	
P placement			**0.01**	***P* = 0.02**				**0.24**	***P*<.0.001**	
P level x P placement			**n.s.**	***P* = 0.30**				**0.53**	***P*<0.001**	

n.s. = not significant (*P*>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

5.5.3 Root growth, root:plant dry weight ratio and root length

At the 7 week sampling, root dry weight was unaffected by treatments, except that mean yields were higher in the P_{40} (B5) and P_5 (B10) treatments (Table 5.12). At 12 weeks, root yield was stimulated by approximately 50 per cent in the P_{40} treatments, but the interaction between P level and P placement was not significant (Table 5.12)

Similarly, the total root length per plant was independent of rates of P application from 0 to 40 kg ha^{-1} at 7 weeks after sowing; however, plants grown in the WS and B5 treatments produced 25% and 18% greater root length, respectively, than plants grown in the B10 treament (Table 5.13). However, at 12 weeks after sowing, root length was only increased with the application of 10 kg ha^{-1}.

Sectioning the root zone into three sections below the seed also proved useful in distinguishing treatment effects on root length measurements (Table 5.14). For example, at both harvests, about 86-90 per cent of the total root length produced was located in the zone 12 cm below the seed. At 7 weeks, the level of P supply did not affect root length in any zone, but in the WS treatments, root length was stimulated in the zone of 0-6 cm immediately below the seed (meaned over 3 levels of P supply) compared to other methods of P placement. At this early harvest, the effects of P level and the interaction between P level and P method of application were also not significant.

On the other hand at 12 weeks, the P deficient P_0 plants had produced less root length than the P fertilised plants (Table 5.13). In addition, the spatial distribution of root length with soil depth was affected by both the level and method of P placement. The data firstly indicate that in plants of the WS and B5 series, a large proportion of their roots were located in the 12 cm of soil immediately below the seed. Secondly, the root length of B10 plants appeared (with one exception P_{40}, B10) to be greater in the 12-18 cm zone than that achieved by plants grown in the WS and B5 treatments. Moreover, the total root length for B10 plants at P_{10} and P_{40} was inferior to that of plants of the other series (Table 5.14). These data suggest that root growth appears to be stimulated near the zone of P placement and depressed when the P fertiliser is placed too deep.

Table 5.12. Effects of P application level and placement on mean root dry weight measured at 7 and 12 weeks from sowing (1995 field experiment).

Applied P	Mean root dry weight (g/plant)									
(kg/ha)	7 weeks from sowing					12 weeks from sowing				
	BR	WS	B5	B10	Mean	BR	WS	B5	B10	Mean
0	0.10	0.09	0.10	0.08	**0.09**	0.15	0.14	0.14	0.13	**0.14**
5	0.08	0.08	0.07	0.12	**0.09**	0.15	0.17	0.16	0.16	**0.16**
10	0.10	0.09	0.08	0.08	**0.09**	0.17	0.19	0.14	0.20	**0.17**
20	0.09	0.10	0.10	0.11	**0.10**	0.16	0.16	0.16	0.16	**0.16**
40	0.11	0.09	0.12	0.09	**0.10**	0.19	0.20	0.23	0.20	**0.21**
Mean	**0.10**	**0.09**	**0.09**	**0.10**		**0.16**	**0.17**	**0.17**	**0.17**	
LSD (P = 0.05)										
P level	**n.s. (P = 0.22)**					**0.03 (P = 0.009)**				
P placement	**n.s. (P = 0.56)**					**n.s. (P = 0.90)**				
P level x P placement	**0.03 (P= 0.04)**					**n.s. (P = 0.93)**				

n.s. = not significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Table 5.13. Effects of P application level and placement on mean root length [A] of peas measured at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Mean root length (cm/plant)[B]							
	7 weeks from sowing				12 weeks from sowing			
	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**
0	341	378	290	**336**	369	401	631	**467**
10	383	339	299	**340**	815	867	680	**787**
40	350	295	269	**305**	627	853	518	**666**
Mean	**358**	**337**	**286**		**604**	**707**	**609**	
LSD (P=0.05)								
P level			**n.s. (P = 0.23)**				**197 (P = 0.008)**	
P placement			**44 (P = 0.007)**				**n.s. (P= 0.51)**	
P level x P placement			**n.s. (P = 0.47)**				**n.s. (P = 0.17)**	

[A] Plants sampled for mean root length were different to those plants sampled for root dry weights. [B] The root length was measured in a zone 18 cm below the seed. n.s. = not significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

At seven weeks from sowing, no treatment effects were evident on root:plant dry weight ratio (Table 5.15). However, this ratio appeared to be the highest in P_0 plants and the least in WS plants. At week 12, the root : plant dry weight ratio decreased with increasing applied P level, but P placement did not change this ratio and no interaction effects occurred in this measurement (Table 5.15)

Table 5.14. Effects of P application level on mean root length of field peas measured in three root zones below the seed at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	7 weeks from sowing													12 weeks from sowing												
	Root sections (cm from sown seed level)													Root sections (cm from sown seed level)												
	0-6				*6-12*				*12-18*					*0-6*				*6-12*				*12-18*				
	WS	B5	B10	Mean	WS	B5	B10	Mean	WS	B5	B10	Mean	Overall P level means	WS	B5	B10	Mean	WS	B5	B10	Mean	WS	B5	B10	Mean	Overall P level means
0	145	120	119	**128**	155	219	152	**175**	41	39	18	**33**	**112**	159	198	202	**186**	166	174	302	**214**	44	28	126	**66**	**155**
10	151	145	109	**135**	199	152	158	**170**	34	43	32	**36**	**114**	418	357	244	**340**	335	428	268	**344**	62	82	168	**104**	**263**
40	161	138	97	**132**	160	119	143	**141**	30	39	29	**32**	**102**	465	220	179	**288**	155	449	231	**278**	7	184	108	**100**	**222**
Mean	**152**	**134**	**108**		**171**	**163**	**151**		**35**	**40**	**26**			**347**	**258**	**208**		**219**	**350**	**267**		**37**	**98**	**134**		
Overall P placement means					**WS = 118**		**B5 = 112**			**B10 = 95**								**WS = 201**		**B5 = 248**			**B10 = 173**			
Overall depth means				***132***				***162***				***34***					***271***				***279***				***90***	
LSD (*P*=0.05)																										
P level					**n.s. (*P* = 0.34)**													**66 (*P* <0.001)**								
P placement					**24 (*P* = 0.04)**													**n.s. (*P* = 0.13)**								
Depth below seed					**20 (*P* = 0.003)**													**n.s. (*P* = 0.79)**								
P level X P placement					**n.s. (*P* = 0.46)**													**115 (*P* = 0.04)**								
P level X depth					**n.s. (*P* = 0.28)**													**n.s. (*P* = 0.85)**								
P placement X depth					**n.s. (*P* = 0.63)**													**94 (*P* = 0.003)**								
P level x P placement X depth					**n.s. (*P* = 0.11)**													**163 (*P* = 0.02)**								

Since there were several cases where no roots were present in the deepest layer of soil, therefore, the root length values for the third section (12-18 cm) below the seed are not entered intothe statistical analysis. ^{B} 0 is seed level. n.s. = not significant (P>0.05). WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Table 5.15. Effects of P application level and placement on mean root:plant dry weight ratio of peas measured at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Root:plant dry weight ratio (%)									
	7 weeks from sowing					12 weeks from sowing				
	BR	WS	B5	B10	**Mean**	BR	WS	B5	B10	**Mean**
0	39	34	37	35	**36**	14	13	14	14	**14**
5	32	31	31	40	**34**	11	11	10	9	**10**
10	36	32	31	31	**33**	10	9	7	10	**9**
20	32	32	35	37	**34**	9	7	7	8	**8**
40	36	28	34	30	**32**	10	8	5	7	**8**
Mean	**35**	**31**	**34**	**35**		**11**	**10**	**9**	**10**	
LSD (P=0.05)										
P level			**n.s. (P = 0.1)**			**2 (P< 0.001)**				
P placement			**n.s. (P = 0.08)**			**n.s. (P = 0.1)**				
P level x P placement			**n.s. (P = 0.09)**			**n.s. (P = 0.9)**				

n.s. = not significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

5.5.4 Active Nodulation score, shoot N concentration and uptake

Active nodulation

The active nodulation score was markedly depressed in P_0 plants at both sampling times: at 7 weeks from sowing the score was one half that of P_{40} plants and at 12 weeks, the score was 39% of that of P_{40} plants (Table 5.16). The main effects of increasing P supply from P_{10} to P_{40} resulted in an increase at 7 weeks and no significant difference at 12 weeks (Table 5.16). In addition, at the 7 weeks sampling the nodulation score was highest in the B5 series plants (averaged over 3 levels of P supply), but at 12 weeks, although there existed a strong positive response in nodulation score, to increasing levels of applied P, treatment response to methods of P application were not apparent (Table 5.16).

Data for the active nodulation score measured in the three zones of the root system indicated that, on both sampling occasions, nodulation was confined predominantly to the 12 cm immediately below the seed (Table 5.17). Applying P fertiliser markedly increased the score at both harvests in both the 0-6 cm and 6-12 cm zone. At 7 weeks, the highest scores were recorded in plants grown at P_{40} for B5 (0-6 cm) and B10 (6-12 cm). At 12 weeks, nodulation scores were not affected by the method of P placement, and differences in the scores for P_{10} and P_{40} plants were generally small (Table 5.17).

Table 5.16. Effects of P application level and placement on mean total active nodule score estimated at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Total nodule score per plant (0-18 cm)							
	7 weeks from sowing				12 weeks from sowing			
	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**
0	8	10	8	**9**	20	22	24	**22**
10	12	13	12	**12**	53	41	58	**51**
40	14	22	18	**18**	40	68	61	**56**
Mean	**11**	**15**	**13**		**38**	**44**	**48**	
LSD (P=0.05)								
P level	**2 (P<0.001)**				**15 (P<0.001)**			
P placement	**2(P = 0.02)**				**n.s. (P = 0.34)**			
P level x P placement	**n.s. (P = 0.17)**				**n.s. (P = 0.26)**			

n.s. = not-significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Shoot N concentrations and uptake

Nitrogen concentrations in shoots at week 12 were not affected by the method of P placement, but were increased by 20% as the P level was increased (Table 5.18). The N content in plant shoots increased markedly as P supply increased, and at P_{40} the N content of shoots in B5 plants was substantially greater than that in shoots of plants grown in the WS or B10 treatments (Table 5.18).

There was also a strong curvilinear relationship (R^2 = 0.76) established between shoot N content and active nodulation score (Figure 5.2). Given the marked depressive effect that P deficiency had on nodulation score, shoot yield and N concentration, such a relationship suggests that P has an important role in N fixation and the N status of pea plants.

Table 5.17. Effects of P application level and placement on mean active nodule score in 3 root sections [A], estimated at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Active nodule score																							
	7 weeks from sowing												12 weeks from sowing											
	Root sections																							
	0-6 (cm) [B]				6-12 (cm)				12-18 (cm)				0-6 (cm)				6-12 (cm)				12-18 (cm)			
	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**
0	4.2	4.8	2.5	**3.8**	3.9	4.8	5.2	**4.6**	0.0	0.1	0.4	**0.2**	5.4	10.6	5.8	**7.3**	10.2	11.2	9.6	**10.3**	0.8	0.3	2.5	**1.2**
10	6.8	6.3	5.8	**6.3**	5.0	5.8	6.5	**5.8**	0.0	0.4	0.0	**0.1**	37.1	23.6	25.0	**28.6**	14.2	15.9	28.2	**19.4**	2.0	1.2	5.3	**2.8**
40	7.7	10.3	5.3	**7.8**	6.0	6.2	12.3	**8.2**	0.0	4.9	0.4	**1.3**	35.2	23.4	32.0	**30.2**	4.2	39.2	23.8	**22.4**	0.1	5.0	4.9	**3.3**
Mean	**6.2**	**7.1**	**4.5**	***6.0***	**5.0**	**5.6**	**8.0**	***6.2***	**0.0**	**1.3**	**0.3**	***0.5***	**25.9**	**19.2**	**20.9**	***22.0***	**9.5**	**22.1**	**20.5**	***17.4***	**1.0**	**2.2**	**4.2**	***2.5***
LSD (P = 0.05)																								
P level					**1.7**											**5.5 (P <0.001)**								
P placement					**n.s. (P = 0.06)**											**n.s. (P = 0.46)**								
depth below the seed					**n.s.(P = 0.76)**											**4.5 (P = 0.05)**								
P level X P placement					**n.s.(P = 0.83)**											**n.s. (P = 0.12)**								
P level X depth					**n.s.(P = 0.71)**											**n.s. (P = 0.06)**								

[A] Since there were several cases with nil root in deepest layer of soil, therefor, in this analysis, the nodule score for the third section (12-18 cm) was ignored. [B] 0 is seed level. n.s. = not-significant (p>0.05). BR = P fertiliser broadcasted. WS = P fertiliser sown with seed. B5 = fertiliser banded 5 cm below seed. B10 = fertiliser banded 10 cm below seed.

Table 5.18. Effects of P application level and placement on mean total nitrogen concentration and mean total nitrogen content of pea shoots measured at 12 weeks from sowing (1995 field experiment).

	Shoot N concentration (% DW)				Shoot N content (mg/plant)			
Applied P	12 weeks from sowing.				12 weeks from sowing.			
(kg/ha)	WS	B5	B10	**Mean**	WS	B5	B10	**Mean**
0	2.8	3.1	3.0	**3.0**	27	28	25	**26**
10	3.2	3.2	3.2	**3.2**	63	63	57	**61**
40	3.5	3.8	3.2	**3.6**	81	152	91	**108**
Mean	**3.2**	**3.3**	**3.2**		**57**	**81**	**58**	
LSD (P=0.05)								
P level			**0.3**	**(P< 0.001)**			**14**	**(P< 0.001)**
P placement			**n.s.**	**(P = 0.36)**			**14**	**(P = 0.003)**
P level x P placement			**n.s.**	**(P = 0.79)**			**24**	**(P = 0.002)**

n.s. = not-significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Furthermore, at 7 weeks a positive near-linear relationship existed between applied P level and nodulation score (Table 5.3). The slope for the same relationship developed for shoot yield was considerably lower, implying a higher external P requirement for nodulation. However at 12 weeks, this comparison had reversed, maximum nodulation score was achieved at P_{10} and maximum shoot dry weight per plant at P_{40} (Figure 5.3).

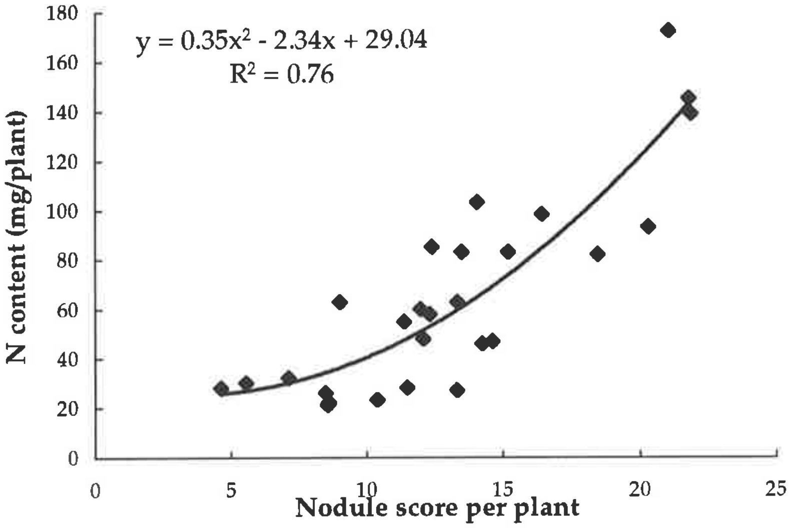


Figure 5.2. The relationship between N content of pea plants at 12 weeks from sowing and active nodulation score per plant at 7 weeks after sowing (1995 field experiments)

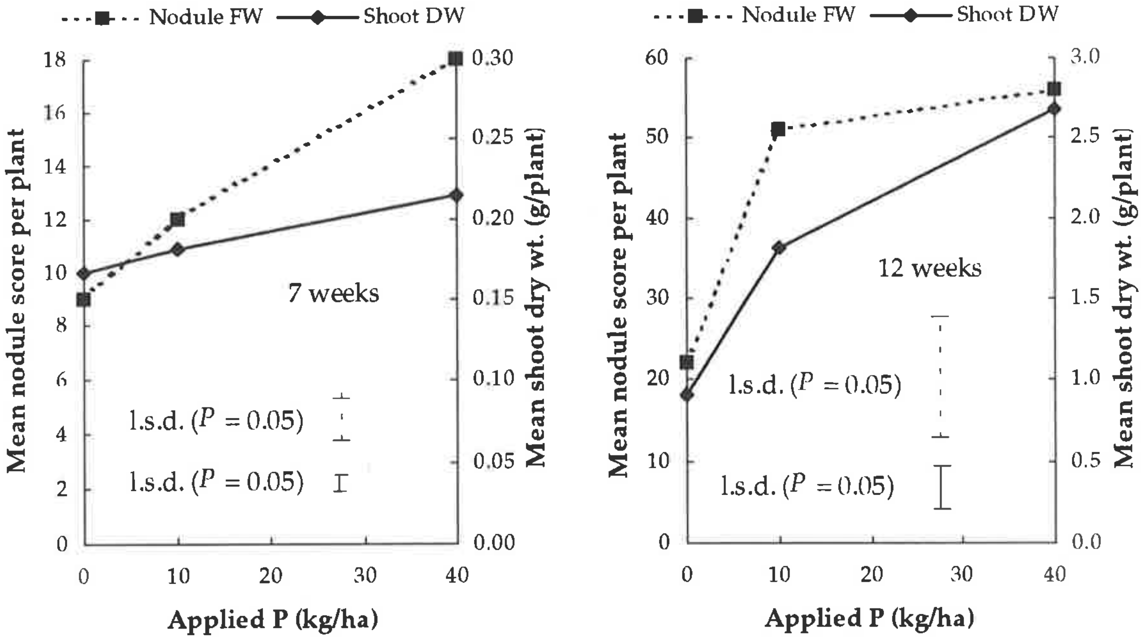


Figure 5.3. Relationships between nodule score and rate of applied P and mean shoot dry weight and rate of applied P for field peas harvested at (A) 7 weeks after sowing and (B) at 12 weeks after sowing (1995, field experiment).

5.5.5 Seed yield and yield components

Seed yield

Seed yield responded strongly to P application showing more than a 2.5 times increase at the highest level of applied P (Table 5.19). Application method also affected the seed yield and followed almost the same pattern as shoot dry matter yield measured at 12 weeks after sowing. B5 produced the highest seed yield at P_{40} and the second highest seed yield at P_{20}. At P levels $\geq P_{10}$, the seed yield produced by BR plants were noticeably inferior. At P levels < P20 the seed yields of peas were similar for the WS, B5 and B10 treatments. Only at P_{40}, the seed yield of B5 and B10 plants was superior to that achieved by plants grown in the WS treatment.

Yield components

The study of 100-seed weight indicates that the only significant treatment effect was due to P level (the interactive effect between P level and P placement seemed to be marginal) (Table 5.19). At P_0, it would appear that P deficiency had been sufficiently severe to reduce the mean seed size, whereas at P_5, P_{10} and P_{20} there is no suggestion of a P limitation on mean seed size (despite the P limitation on plant growth and on seed yield). The 100-seed weight, in P_{40} treatments was less than that in P_{20} treatments.

Table 5.19. Effects of P application level and placement on mean seed yield and mean 100-seed weight of pea measured at 21 and 19 weeks from sowing respectively, (1995 field experiment).

Applied P (kg/ha)	Seed yield (t /ha)					100-seed weight (grams)				
	21 weeks from sowing (maturity)					19 weeks from sowing				
	BR	WS	B5	B10	**Mean**	BR	WS	B5	B10	**Mean**
0	0.44	0.51	0.42	0.45	**0.46**	22.9	22.7	23.0	22.3	**22.7**
5	0.68	0.74	0.77	0.77	**0.74**	23.6	23.1	23.1	22.5	**23.1**
10	0.73	0.99	1.02	0.94	**0.92**	23.6	23.2	22.4	22.9	**23.0**
20	0.76	1.04	1.12	1.06	**1.00**	24.5	23.8	23.2	23.3	**23.7**
40	0.99	1.06	1.52	1.34	**1.23**	21.2	22.2	22.7	22.8	**22.2**
Mean	**0.72**	**0.87**	**0.97**	**0.91**		**23.2**	**23.0**	**22.9**	**22.8**	
LSD ($P = 0.05$)										
P level			**0.10**	**($P<0.001$)**				**0.9**	**($P = 0.03$)**	
P placement			**0.09**	**($P<0.001$)**				**n.s.**	**($P = 0.73$)**	
P level x P placement			**0.21**	**($P = 0.02$)**				**n.s.**	**($P = 0.63$)**	

n.s. = not-significant ($P>0.05$). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Moderate P deficiency (eg, < P_{10}) depressed seed number/pod (Table 5.20). The interactions between P level and P placement and seed number/pod were not significant.

5.5.6 Shoot and seed P concentration and P content

Shoot P concentrations

At both the 7 and 12 week harvests (4-5 and 15-16 nodes per stem, respectively), increasing the level of P supply up to and beyond P_{10} significantly increased P concentrations in shoots compared to plants grown at lower levels of P supply (Table 5.21). At both harvests BR plants had lower concentrations (averaged over all levels of P). At P_{40}, P concentrations in shoots of B5 plants were higher than for plants grown under other methods of P application (i.e., B5 ≥ B10 ≥ WS ≥ BR).

Table 5.20. Effects of P application level and placement on mean seed number per pea pod, measured at 19 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Seed number per pod				
	BR	WS	B5	B10	**Mean**
0	3.9	4.0	4.0	3.9	**4.0**
5	4.4	4.7	4.6	4.6	**4.6**
10	4.5	5.0	4.9	4.7	**4.8**
20	4.7	4.9	4.9	4.9	**4.9**
40	4.9	5.0	5.3	5.0	**5.0**
Mean	**4.5**	**4.7**	**4.7**	**4.6**	
LSD (*P*=0.05)					
P level			**0.20 (*P*<0.001)**		
P placement			**0.19 (*P* = 0.04)**		
P level x P placement			**n.s. (*P* = 0.9)**		

n.s. = not-significant (*P*>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

The relationships between mean shoot dry weight and mean P concentration in pea shoots at 7 and 12 weeks after sowing for the different methods of P application were essentially linear, except for the WS treatment at 7 weeks.

Table 5.21. Effects of P application level and placement on mean shoot P concentration of pea measured at 7 and 12 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Shoot P concentration (%)									
	7 weeks from sowing					12 weeks from sowing				
	BR	WS	B5	B10	**Mean**	BR	WS	B5	B10	**Mean**
0	0.29	0.31	0.29	0.33	**0.31**	0.18	0.19	0.21	0.22	**0.20**
5	0.31	0.31	0.33	0.31	**0.32**	0.20	0.20	0.19	0.22	**0.20**
10	0.35	0.41	0.44	0.38	**0.39**	0.19	0.22	0.22	0.23	**0.22**
20	0.37	0.41	0.47	0.37	**0.41**	0.22	0.21	0.24	0.22	**0.22**
40	0.45	0.49	0.58	0.54	**0.52**	0.22	0.26	0.35	0.31	**0.29**
Mean	**0.35**	**0.40**	**0.42**	**0.42**		**0.20**	**0.22**	**0.24**	**0.24**	
LSD (*P*=0.05)										
P level			**0.04 (*P*<0.001)**					**0.02 (*P*<0.001)**		
P placement			**0.03 (*P* = 0.04)**					**0.02 (*P*<0.001)**		
P level x P placement			**n.s.(*P* = 0.32)**					**0.04 (*P* = 0.002)**		

n.s. = not-significant (*P*>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Since no definable plateau in the relationship between shoot yield and P concentraion was produced with these treatments, it was not possible to estimate a critical concentration for each method of application. However, when all treatment mean data were plotted together for each harvest, curvilinear relationships were obtained (Figure 5.4). From these relationships, a critical P concentration at 90% maximum shoot yield was estimated to be 0.45 %P and 0.34 %P for the 7 and 12 week harvests, respectively (Figure 5.4).

Shoot P content

Treatment differences in shoot P content (Table 5.22) tended to reflect treatment differences in P concentration (Table 5.21). Thus, as the level of P supply was increased shoot P content increased, plants grown under the BR regime accumulated less P in their shoots than plants fertilised by the other methods. At 12 weeks, this was generally true for levels ≥ P_{10}. At P_{40}, the P content in the shoots was markedly greater in B5 plants sampled 12 weeks from sowing (i.e., B5 ≥ B10 >WS>>BR).

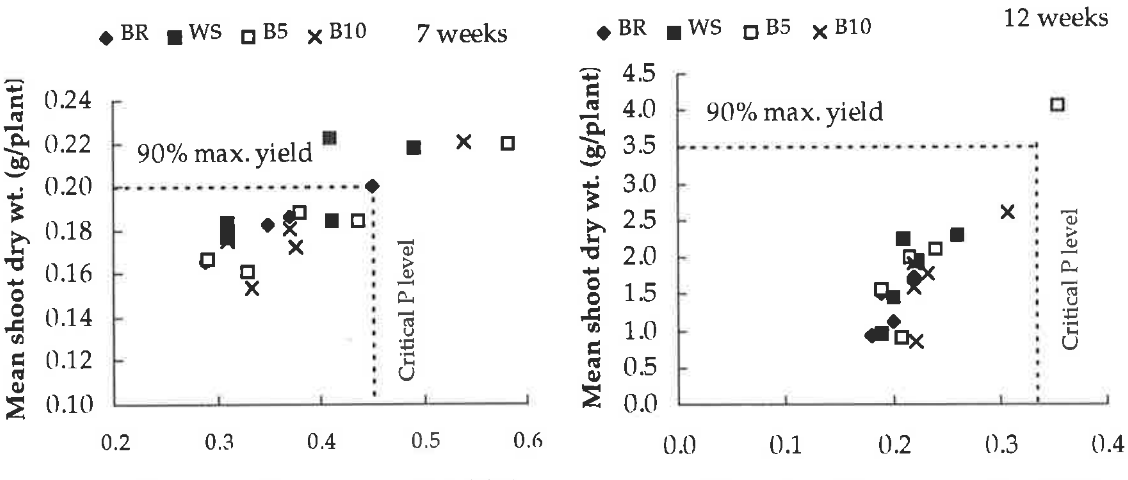


Figure 5.4. Relationship between shoot dry matter yield and P concentration in whole shoots for all methods of P application measured at 7 and 12 weeks after sowing (4-5 and 15-16 nodes/stem) (1995 field experiment).

Table 5. 22. Effects of P application level and placement on mean shoot P content measured at 7 and 12 weeks from sowing field experiment).

	Shoot P content (mg/plant)									
Applied P	7 weeks from sowing					12 weeks from sowing				
(kg/ha)	BR	WS	B5	B10	**Mean**	BR	WS	B5	B10	**Mean**
0	0.47	0.56	0.48	0.51	**0.50**	1.68	1.81	1.86	1.88	**1.81**
5	0.54	0.56	0.53	0.55	**0.55**	2.45	2.80	2.97	3.53	**2.94**
10	0.64	0.76	0.81	0.64	**0.71**	2.83	4.49	4.30	4.15	**3.94**
20	0.70	0.93	0.89	0.68	**0.80**	3.67	4.70	4.95	4.22	**4.39**
40	0.90	1.07	1.30	1.20	**1.12**	3.78	6.02	14.32	7.96	**8.02**
Mean	**0.65**	**0.78**	**0.80**	**0.72**		**2.88**	**3.96**	**5.68**	**4.35**	
LSD ($P<0.05$)										
P level			**0.10 ($P<0.001$)**					**0.62 ($P<0.001$)**		
P placement			**0.09 ($P = 0.02$)**					**0.55 ($P<0.001$)**		
P level x P placement			**n.s.($P = 0.08$)**					**1.24 ($P<0.001$**		

n.s. = not-significant ($P>0.05$). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Seed P concentrations and contents

As the level of P supply increased both the concentration and content of P in the harvested seed increased (Table 5.23). Although the interaction between applied P level and P placement for seed P concentration was significant ($P = 0.01$), at any level of applied P, treatment differences were reasonably small. However, the content of P inthe seed of BR plants were noticeably lower than for plants fertilised by the other methods of application. At P_{40}, the seed P content of the B5 plants was substantially higher than that of the plants grown in the other P placement treatments.

Table 5.23. Effects of P application level and placement on mean seed P concentration and seed P content measured at 21 weeks from sowing (1995 field experiment).

Applied P (kg/ha)	Seed P concentration (%)					Seed P content (kg/ha)				
	BR	WS	B5	B10	**Mean**	BR	WS	B5	B10	**Mean**
0	0.24	0.22	0.23	0.23	**0.23**	1.06	1.13	0.97	1.00	**1.04**
5	0.23	0.23	0.24	0.24	**0.24**	1.59	1.69	1.85	1.86	**1.75**
10	0.22	0.25	0.23	0.25	**0.24**	1.63	2.44	2.35	2.32	**2.18**
20	0.24	0.25	0.25	0.26	**0.25**	1.84	2.62	2.80	2.79	**2.51**
40	0.28	0.25	0.29	0.30	**0.28**	2.76	2.66	4.46	3.93	**3.45**
Mean	**0.24**	**0.24**	**0.25**	**0.26**		**1.78**	**2.11**	**2.49**	**2.38**	
LSD (P=0.05)										
P level			**0.01 (P<0.001)**					**0.25 (P<0.001)**		
P placement			**0.01 (p = 0.02)**					**0.23 (P<0.001)**		
P level x P placement			**0.02 (p = 0.01)**					**0.23 (P<0.001)**		

n.s. = not-significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

The relationships between P concentration in the harvested seed and seed yield for BR was C-shaped (Steenbjerg 1951), which shows that, P concentration of seed in P deficient plants was higher than P concentration of seed in P adequate plants (Figure 5.5). C-shaped curvature was not observed for the other methods of P placement. The critical P concentration in the seed estimated for 90% maximum seed yield for all treatments appeared to be about 0.29 %P (Figure 5.5).

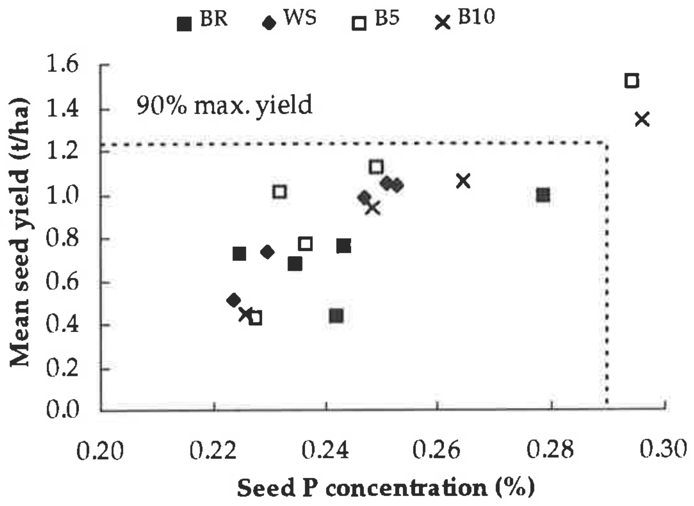


Figure 5.5. Relationship between seed yield and P concentration in the harvested seed for all methods of P application measured at maturity (1995 field experiment).

5.5.7 P fertiliser effectiveness

Because of the enhanced seed yield response achieved between P_{20} and P_{40} in the BR, B5 and B10 treatments (but not the WS treatment which achieved maximum yield at P_{10}) (Figure 5.6), it was not possible to compare the effectiveness of the placement treatments across all levels of applied P using a least square derived relationship (e.g., Mitscherlich function) common to all treatments as has been done in other published reports (Jarvis and Bolland 1990). Thus, the effectiveness was defined as the P required (kg P ha^{-1}) to produce a shoot yield of 1.5 and 2.5 grams per plant or a seed yield of 1.0 and 1.2 tonne per hectare. These indices of fertiliser effectiveness clearly show the superiority of the B5 treatment over the other placement treatments (Figures 5.6, 5.7 and Table 5.24).

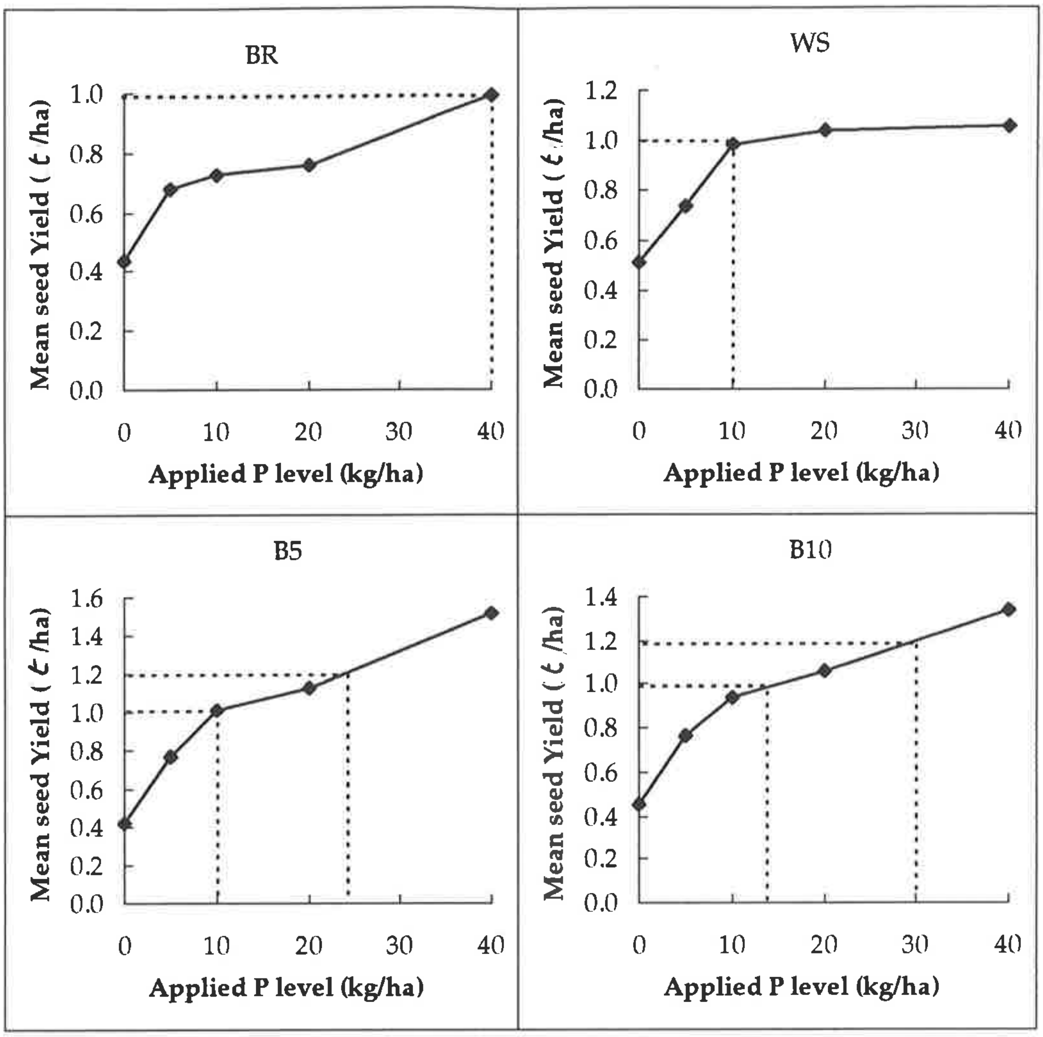


Figure 5.6. External P requirement for a field peas seed yield of 1.0-1.2 t/ha with **different method of P placement across all levels of applied P. BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.**

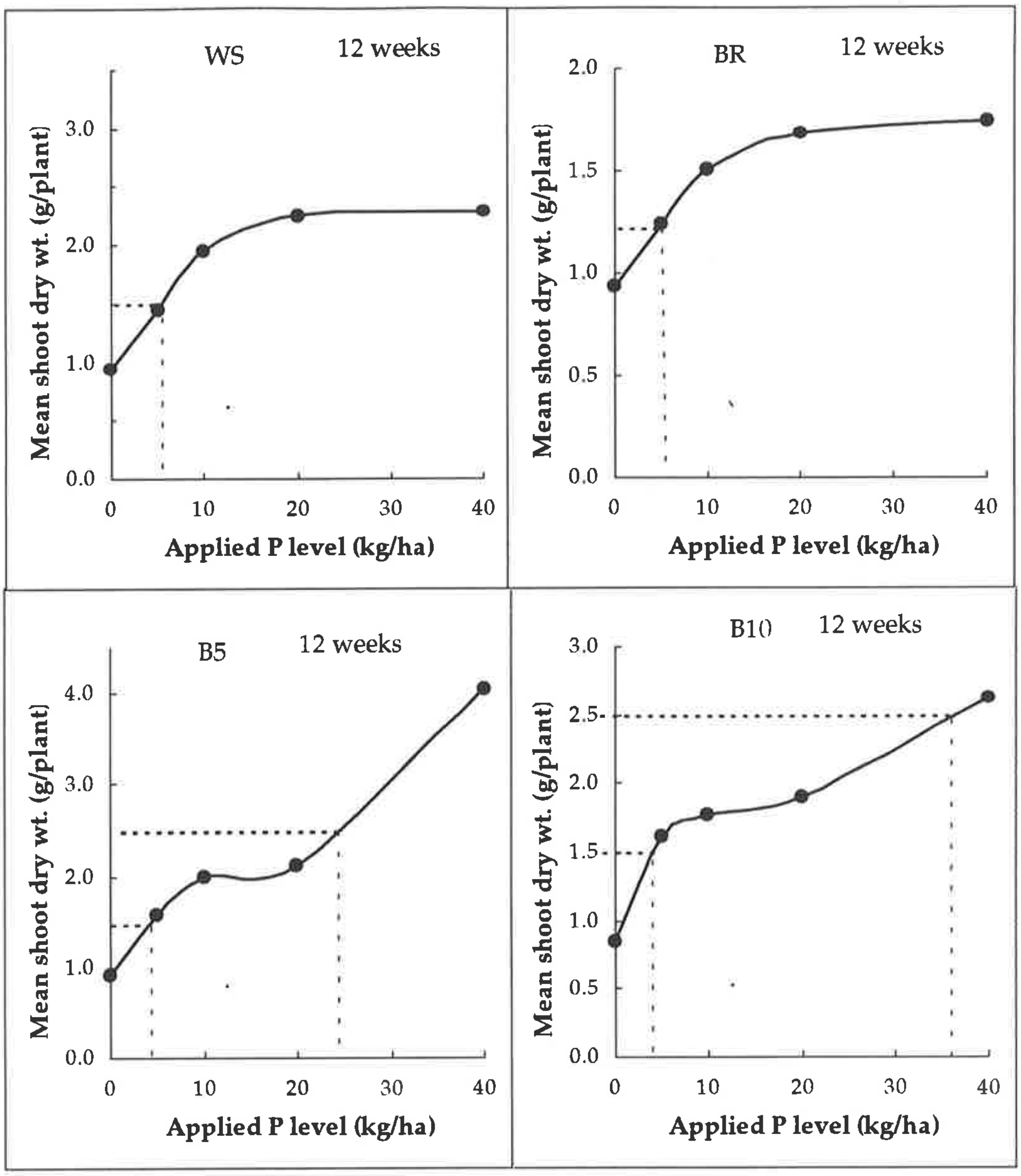


Figure 5.7. External P requirement for a field peas shoot yield of 1.5-2.5 g/plant with different methods of P placement across all levels of applied P. BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

Table 5.24. External P fertiliser requirements for 1.5 and 2.5 (g/plant) of shoot yield or 1.0 and 1.2 (t/ha) of seed yield with different P placement methods

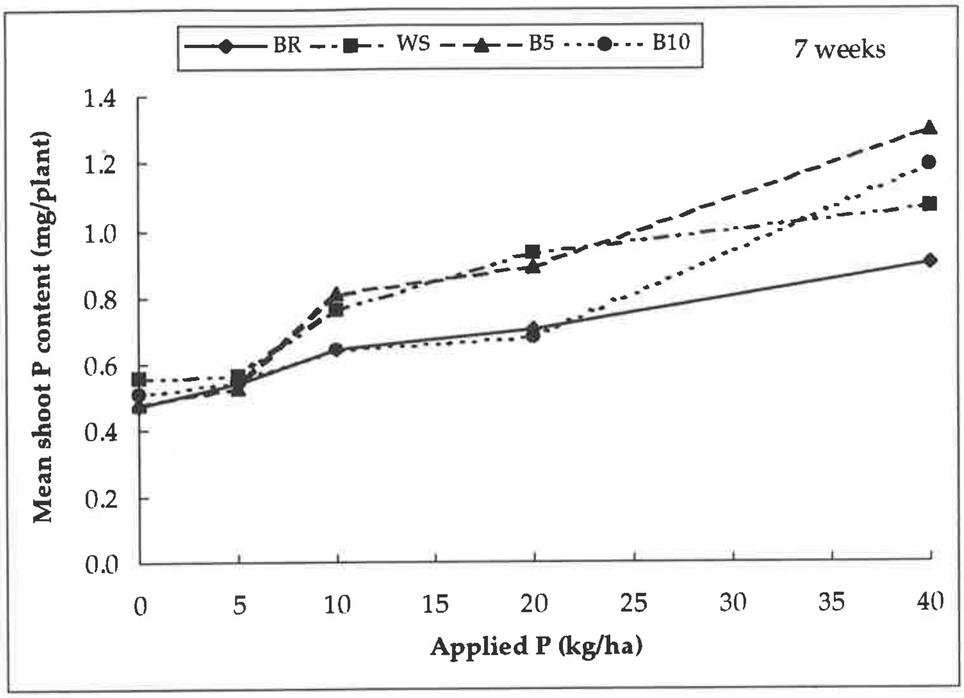
Method of P Placement	Fertiliser P required (kg/ha) For shoot yield (12 weeks)		For seed yield (maturity)	
	1.5 (g/plant)	2.5 (g/plant)	1.0 (t/ha)	1.2 (t/ha)
BR	6	ND [A]	40	ND
WS	6	ND	10	ND
B5	4	24	10	24
B10	6	36	14	30

[A] ND = not determined; shoot yield of 2.5 g/plant or seed yield of 1.2 t/ha in these treatments were not achieved. BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed.

The relationship between mean shoot P content and applied P level was also used to estimate the efficiency of plants to acquire P from different methods of placements (figure 5.7). At week 7, a sigmoidal response occurred at low levels of P supply but between P_{20} and P_{40}, the slope of this relationship was steeper. At week 12, again, the response at low levels of applied P was slow, but a large change in slope occurred between B5 and the other methods of P placement as the P rate was increased from 20 to 40 kg ha^{-1} . However,the slope of the relationship for plants grown in the BR treatment was very low at 7 weeks or reached a plateau at P_{20} at weeks 12 (Figure 5.10).

5.5.8 Apparent P recovery

Seven weeks after sowing, plants in different treatments recovered only a small per cent of the P fertiliser applied (Table 5.25). However, the maximum recovery of applied P fertiliser occurred in the P_{10} treatments and the difference among methods of application was only marginal (P = 0.09). At week 12, the recovery of applied P fertiliser was improved and reached maximum at P_5 (9%). Among the different methods of P placement plants grown in the B5 treatments recovered almost 3 times as much applied P as plants in the BR treatments (Table 5.25).



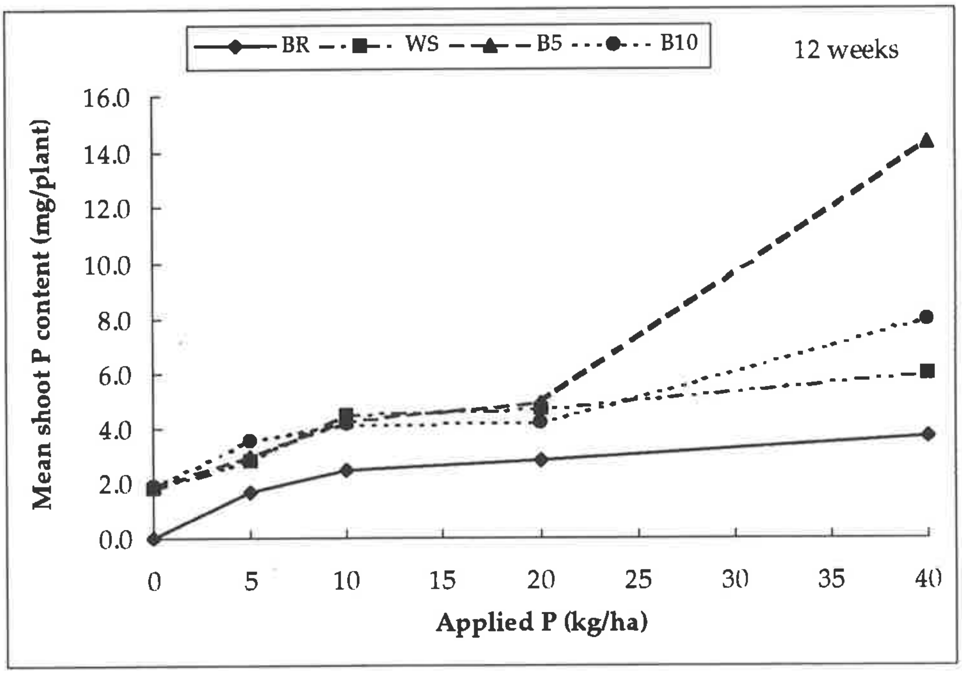


Figure 5.8. Effect of level and method of placement of applied P on mean shoot P content of field peas, 7 and 12 weeks after sowing BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed. (1995 Field experiment).

Table 5.25. Effects of P application level and placement on mean apparent P recovery in plant shoot measured at 7 and 12 weeks from sowing (1995 field experiment).

Applied P	Apparent P recovery (%)									
	7 weeks from sowing					12 weeks from sowing				
(kg/ha)	BR	WS	B5	B10	**Mean**	BR	WS	B5	B10	**Mean**
0	-	-	-	-	-	-	-	-	-	-
5	0.3	0.5	0.4	0.5	**0.4**	4.8	7.8	9.3	14.1	**9.0**
10	0.7	1.2	1.4	0.7	**1.0**	4.0	11.2	10.3	9.7	**8.8**
20	0.5	1.0	0.5	0.4	**0.6**	3.8	6.1	6.6	5.0	**5.4**
40	0.4	0.6	0.9	0.8	**0.7**	2.0	4.4	13.4	6.5	**6.6**
Mean	**0.5**	**0.8**	**0.8**	**0.6**		**3.7**	**7.4**	**9.9**	**8.8**	
LSD (P=0.05)										
P level			**0.3 (P = 0.02)**					**3 (P = 0.04)**		
P placement			**n.s. (P = 0.09)**					**3 (P<0.001)**		
P level x P placement			**n.s. (P = 0.55)**					**n.s. (P = 0.11)**		

n.s. = not-significant (P>0.05). BR = P broadcast. WS = P sown with seed. B5 = P banded 5 cm below seed. B10 = P banded 10 cm below seed

5.5.9 Soil moisture content

The distribution of water in the soil profile was measured at 3 P placement zones and repeated 8 times during the period of plant growth (Figure 5.9). These measurements clearly showed that, except during the first 5 weeks of the season, the soil moisture contents in the fertiliser zones were below field capacity and importantly, pod filling, stage they were even lower and reached wilting point. The soil moisture content was mostly higher in the B10 fertiliser zone than in the WS and B5 fertiliser zones. It was similar in the latter two zones on most measurement occasions, with the exception of 12 weeks after sowing when the B5 zone was wetter (Figure 5.9).

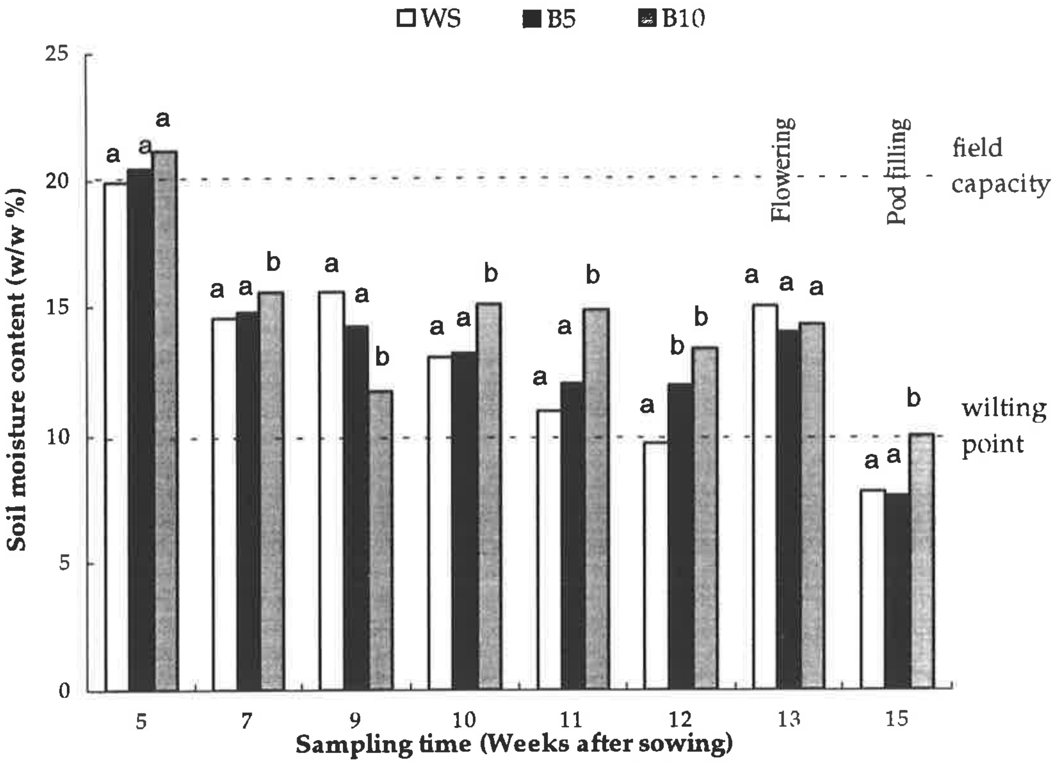


Figure 5.9. Soil moisture content at 3 different P fertiliser zones in the soil profile, taken 8 times during the growth season. WS = seed level, B5 = 5-7 cm below the seed level and B10 = 10-12 cm below the seed level. n.s. = not-significant (P>0.05). s.d. = significantly different (P<0.05)). Data were analysed for each soil sampling time only; bars labelled with the same letter are n.s. (1995 field experiment).

5.6. DISCUSSION

The results from both field experiments showed that P deficiency depressed shoot and root dry matter yield and seed yield, and in Experiment 2, it reduced the active nodulation score and shoot N and P concentrations without the pea plants exhibiting any distinctive deficiency symptoms.

In the 1994 experiment (a very dry season), the pea crop responded to the applied P fertiliser, but it did not respond to different methods of applying P. By contrast, in 1995 (a moderately wet season), shoot and root yield, P content and nodule fresh weight were affected by the method of P placement and often the interaction between fertiliser P level and P placement was significant. The failure to observe significant interactions between P fertiliser level and P placement in the 1994 experiment would appear to be due to the low soil moisture levels in the zones of fertiliser P placement, which limited plant growth and the uptake of P.

In the 1995 experiment, P applied 5 cm below the seed was superior to the other methods of application in most of the parameters measured. However, the superiority of the B5 treatment was most readily observed at 12 weeks after sowing and at maturity and was most pronounced at the near optimal P level of 40 kg ha^{-1} .

The above findings are generally consistent with the results from the glasshouse experiments (Chapters 3 and 4), where soil water was kept close to field capacity by regular waterings throughout the experimental period; after 7 weeks in those experiments the placement of P at 4 cm below the seed was as efficient or in some measurements superior to the WS treatment. The superiority of te B5 treatment in the 1995 field experiment at P40 can only be speculated upon. Firstly, the higher soil water content in this soil layer which is also the zone of root proliferation, may have resulted in a higher uptake of P and greater efficiency of water use by pea plants. Secondly, a secondary response to a nutrient impurity such as S or Zn added in TSP at the higher application levels may have been sufficient to overcome a moderate or marginal deficiency. At no stage of plant growth were any symptoms of S or Zn deficiency observed in plants grown in the P40 treatments in the experiment. Thirdly, the acidity derived the from free phosphoric acid present in the TSP (~2.5%) may have solubilised marginally deficient nutrients in the zone of fertiliser placement, or allowed the applied P to remain more available over an extended period. Fourthly, the applied P may have partially saturated the anion exchange complex in the zone of P placement (also the zone of stimulated root growth) and allowed remaining P to be available for uptake. The absence of a possible toxic effect of concentrated P on growth of young seedlings and on survival of rhizobia which may have occurred in the WS treatment may also be responsible for the superiority of the deep placement of P fertiliser.

The overall results from the 1995 experiment are in good agreement with the findings of similar experiments on barrel medic in New South Wales (Scott 1973), on winter wheat in USA (McConnell *et al.* 1986) and on lupin in Western Australia (Jarvis, Bolland 1990 and 1991). However, in the WA experiments, applying P fertiliser 10 cm below lupin seed was recorded to be beneficial in the utilisation of P fertiliser, whereas, for field peas and for the soil in this experiment, the B10 treatment appeared to be too deep to achieve maximum efficiency (especially at higher P levels). This may also be related to the root system of field peas which is shallower than the lupin root system (Hamblin and Hamblin 1985).

In some measured parameters (eg. shoot yield at 7 weeks) the WS treatment was superior to the B5 but its effectiveness often fell between that of B5 and B10. This is possibly because the roots of WS treatment reached the applied P earlier than those in B5 and B10 treatments during the early stages of plant growth when the soil moisture content was high. But later in the season, the surface soil became drier than the deeper soil (Figure 5.9), and hence, the P placed with the seed became progressively less accessible to the plant roots.

The BR treatments appeared to be the least efficient method of P fertiliser application even at the highest P supply. This finding agrees with the results from other studies (Scott 1973, Sander *et al.* 1990, Jarvis and Bolland 1990, 1991)

Nodulation was again shown to be very sensitive to moderate P deficiency which supports the glasshouse findings that P deficiency somehow depresses nodulation and hence N_2 fixation processes. Nodulation was lower where P was applied with the seed which also occurred in the glasshouse experiments and may be linked to a toxic effect of applied P on rhizobium activity (Hicks and Loynachan 1987).

The relationship between P concentration in shoots and shoot dry weight derived at both 4-5 nodes per stem (7 weeks) and 15-16 nodes per stem (12 weeks) was linear for each method of application (except the WS treatment at 7 weeks). Indeed, in the experiment, yield data for P_{40} (B5) it was not possible to verify that this treatment had reached P adequacy, However, the diagnostic relationshps in (Figure 5.4) suggest this has occurred. The poor performance of treatments in the field experiment compared to the glasshouse experiment (Table 5.26) is in agreement with the amount of fertiliser P recovered in these experiments.

Table 5.26. A comparision of the mean percentage P recovery over all P application methods at weeks 4 and 6 (1994 glass Experiment 1) and at weeks 7 and 12 (1995 field experiment).

Glasshouse (1994)	6% (at week 4)	16% (at week 6)
Field (1995)	0.6% (at week 7)	7% (at week 12)

In the seed yield relationships with the seed P concentration, the relationships for each method of application were C-shaped. This has also been termed the "Piper - Steenbjerg effect" (Steenbjerg 1951) and can cause serious misinterpretations of plant analysis data , i.e., at P_0 the seed P concentration (e.g., in WS) is identical to the P_{20} seed P concentration and yet the yield of P_0 is 50% of P_{20}. This suggests that analysis of pea seed for P has limited value for diagnostic purposes because the same P concentration could mean two different levels of deficiency. However, when all data are plotted (Figure 5.5) the relationship is reasonable, suggesting a critical value around 0.29% P in the seed.

The apparent recovery of P fertiliser in the plant shoots, was not affected by the method of P placement at week 7, but later at week 12, the highest recovery occurred in the B5 treatments; the recovery of P in these treatments was almost 3 times greater than that of plants grown in the BR treatments. However, results from the glasshouse experiment (Chapter 4) showed that, at late harvests (7 weeks), P recovery in B4 was as high as in WS. This difference between field and glasshouse results could be attributed to the different soil moisture pattern in these experiments and may indicate that, even in wet seasons in which sufficient soil water for P absorption exists in both top and subsoil (similar to the soil condition in the glasshouse experiment), applying P fertiliser a few centimetres below the pea seed will result in similar P fertiliser recovery compared to that obtained in the WS treatments.

CHAPTER 6

RELATIVE EFFECTIVENESS OF FERTILISER P PLACED AT DIFFERENT SOIL DEPTHS ON YIELD AND P ACCUMULATION OF A FOLLOWING WHEAT CROP.

6.1. SUMMARY

The residual benefits of fertiliser P for following crops may be affected by the method by which it was applied. This experiment was conducted to determine the residual value of P fertiliser for wheat when P fertiliser was applied a year before at different depths in the soil profile.

The Roseworthy site used for the field peas experiment reported in Chapter 5, was re-sown with wheat (*Triticum aestivum* L. cv. Excalibur) in the following year. The wheat was sown with minimal soil disturbance to measure the relative effectiveness of residual P fertiliser. In 1994, P was applied as triple superphosphate at 0, 5, 10, 20 or 40 kg ha^{-1}. P was either topdressed, incorporated, drilled with the seed or banded at 4, 7, or 10 cm below the pea seed. No basal fertiliser was used for wheat plots.

The dry weight of shoots was measured at 10 and 20 weeks after sowing and seed yield was determined at maturity. Furthermore, YEBs (youngest emerged leaf blades) from the first harvest and whole shoots from the second harvest were analysed for P concentration.

The results from this experiment showed that P fertiliser applied the previous year improved the growth and seed yield of wheat but the method of application had no effect.

6.2. INTRODUCTION

The residual value of P fertiliser applied in previous years has been evaluated under various soil conditions and with different plant species (Bolland and Baker 1987, Kumar *et al.* 1991, Johnston and Poulton 1992, Bolland 1992a, Bolland 1992b, Sahrawat *et al.* 1995). The results of these studies indicated that applied P in the previous year has value for the next crop but this value decreases each year relative to freshly applied P. The residual effects of P fertiliser are influenced by its degree of mixing with the soil (Campbell 1965, Halvorson and Black 1985, Alessi and Power 1980). Mixing residual P with soil by tillage operations redistributes and enhances P-fertiliser contact with the soil and subsequent adsorption of applied P. Very high P applications may overcome the soil's P-adsorption capacity and increase the residual value of P. For example, Alessi and Power (1980) found that the residual P from 160 kg P ha^{-1} broadcast 6 year earlier resulted in an average increase of 10% in winter wheat yield per year. Wagar *et al.* (1986) also indicated that 8 years after broadcasting applications of 200 and 400 kg P ha^{-1}, approximately one half of the residual fertiliser P remained in plant-available form, whereas reducing the level of applied P fertiliser decreased its residual value in the following year (Bolland 1992b) However, very high applications of P fertiliser may induce Zn deficiency (e.g., for winter wheat (Singh *et al.* 1986, Wagar *et al.* 1986)).

It appears that undisturbed banded P fertiliser can remain available longer for plants than broadcast P (Eghball *et al.* 1990) because movement of P fertiliser in soils is relatively small and hence a longer period of time is required for the applied P to contact and react with the reactive soil constituents.

Studies on evaluation of the residual value of P fertilisers where P was applied by different methods of application are quite limited and there have been no studies involving field peas. In this experiment, the residual value of P fertiliser previously applied to field peas was evaluated by a following wheat crop because this rotation sequence occurs frequently in south eastern Australia.

6.3. MATERIALS AND METHODS

6.3.1 Soil and climate

This experiment was conducted in 1995 on a clay loam soil Um 5.1.2 (Northcote 1979) located at Roseworthy, 50 km north of Adelaide on the field site used in 1994. The properties of the untreated soil are described in Chapter 5 (see Table 5.1) together with rainfall data for 1995 (Table 5.3)

6.3.2 Experimental design

The statistical design for this experiment was a randomised, fully factorial block design with 3 replicates. In 1994, the site was prepared and sown with inoculated field peas (Chapter 5, Experiment 1). Plots were 20 m long and 1.4 m wide with 8 rows of seed sown per plot. The treatments comprised 5 levels of P (0, 5, 10 ,20 and 40 kg P ha^{-1} , designated hereafter as P_0, P_5, P_{10}, P_{20} and P_{40}) applied as granulated triple superphosphate (20% P; 1.5% S) that were either topdressed (TD) without incorporation, broadcast with incorporation just before sowing (BR), drilled with the seed (WS) or banded 4, 7 or 10 cm below the seed (B4, B7 and B10). Fertiliser application and seed placement were carried out in separate machine passes except for the WS treatment which was accomplished in the one pass. $ZnSO_4$. $7H_2O$ (3.9 kg Zn ha^{-1}) and gypsum (114 kg ha^{-1}) were also applied as basal fertiliser before the pea were sown. No fertiliser was applied to the wheat grown in the experiment reported in this present sttudy.

Because plants were too small and short to be machine harvested, Field peas were left on the site after the yield components were measured in November, 1994.. The site remained undisturbed until June 1995, when the previous plant residuals were collected by using a finger type light harrow (no soil disturbance) and a mixture of trifluralin (1.5 L ha^{-1}) and paraquat (800 mL ha^{-1}) was applied for pre-sowing weed control. On June 1995, wheat (*Triticum aestivum* cv. Excalibur) was then drilled at 4 cm depth at the rate of 110 kg ha^{-1} of seed to all plots using a cone type 8-row seeder with 50 mm wide points attached to the tines.

At the 3-leaf stage, Metsulfuron methyl (7 g ha^{-1}) and Diflufenican (350 mL ha^{-1}) were sprayed on all plots to control Indian hedge and wild turnip.

6.3.3 Measurements

Wheat shoots were sampled to measure dry matter production and P concentration both at tillering (10 weeks after sowing) and at the dough stage (20 weeks after sowing). At tillering, 20 plants were cut randomly at ground level in each plot. At the second harvest, all plants within three 1m lengths of drill row were removed at ground level from each plot. This sampling area was equivalent to 0.5 m^2.

At tillering, the youngest emerged leaf blades (YEB) in shoot samples were separated and prepared for P analysis. Grain yields were measured on 28 November by harvesting with a plot harvester.

Plant samples were oven dried at 65 °C for 72 hours, weighed and shoot dry matter calculated on a per 20 plants (harvest 1) or area basis (harvest 2).

YEB samples at the first harvest and whole shoots from the second harvest were ground (<1 mm), digested with nitric acid and analysed for P by inductively coupled plasma spectrometry (Zarcinas *et al.* 1987).

6.3.4 Data analysis

Data from all measurements were analysed by ANOVA using a randomised fully factorial block design (Genstat 5 released 1993).

6.4. RESULTS

6.4.1 Symptoms and phasic development

Throughout the course of this experiment, no characteristic symptoms of P deficiency or growth differences between treatments were observed.

6.4.2 Shoot dry matter and grain yield

P applications applied to field peas in 1994 increased the mean dry weight of wheat shoots in 1995 by a maximum of 45% at tillering and 29% at the dough stage. (Table 6.1). Grain yield was increased by up to 20% (Table 6.2). Generally, as the level of fertiliser P increased, wheat yields increased. Growth and yield responses were not affected by the method of P placement used in 1994 (Tables 6.2, 6.3). However, the main effect of P placement was marginally significant (P = 0.06), suggesting overall the residual effect of the TD treatment may have been inferior to other methods of application.

Table 6.1. Residual effects of P fertiliser level and method of placement applied to field peas in 1994 on mean shoot dry weight of wheat measured in 1995, at 10 (tillering) and 20 weeks from sowing (dough stage).

Applied P	Mean shoot dry weight													
(kg/ha)	10 weeks from sowing (g/20 plants)							20 weeks from sowing (g/m^2)						
	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**
0	2.90	3.41	3.11	3.57	3.33	3.41	**3.29**	513	467	480	484	487	441	**479**
5	3.40	4.23	4.00	3.74	4.24	4.10	**3.95**	501	517	534	467	512	488	**503**
10	3.67	3.77	3.86	4.31	4.91	3.96	**4.08**	531	534	545	468	598	512	**531**
20	3.70	4.62	4.74	4.22	3.92	4.71	**4.32**	569	645	554	510	648	520	**574**
40	3.90	4.80	5.00	4.80	5.17	5.02	**4.78**	634	676	572	569	680	567	**616**
Mean	**3.51**	**4.17**	**4.14**	**4.13**	**4.31**	**4.24**		**550**	**568**	**537**	**500**	**585**	**506**	
LSD (P=0.05)														
P level			**0.45**	**P = 0.001**						**60**	**P = 0.02**			
P placement			**n.s.**	**P = 0.06**						**n.s.**	**P = 0.19**			
P level x P placement			**n.s.**	**P = 0.09**						**n.s.**	**P = 0.20**			

n.s. = not-significant (P>0.05). TD = P fertiliser topdressed. BR = P fertiliser broadcast and incorporated . WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

6.4.3 P concentrations in YEB and whole shoots and P content in shoots.

Significant residual responses to P applied in 1994 on P concentrations in YEB and shoots of wheat sampled in 1995 were recorded (Table 6.3). The measured main effects of P fertiliser level on YEB P concentrations were essentially sigmoidal (i.e., the concentrations of P in P_0 and P_5 plants were similar and lower than P concentrations recorded in plants grown at higher levels of P supply). The method of P placement did not affect P concentrations in YEB, but had a marginal effect on P concentrations in whole shoots measured at 20 weeks from sowing. At both samplings, the interaction between P level and P placement was not significant (Table 6.3). Concentrations of P in the YEB of wheat plants grown at P_0 and P_5 at tillering (10 weeks after sowing) were within the critical concentration range (0.3 to 0.37 %P) determined at 90% of maximum shoot yield (Elliott *et al.* 1984).

Table 6.2. Residual effects of P fertiliser level and placement applied to field peas in 1994 on mean wheat grain yield measured in 1995.

Applied P	Mean wheat grain yield (t/ha)						
(kg/ha)	TD	BR	WS	B4	B7	B10	**Mean**
0	2.00	1.85	1.84	1.77	1.76	1.82	**1.84**
5	2.00	2.02	2.02	1.73	1.69	1.92	**1.90**
10	1.96	1.98	2.08	2.04	2.02	1.80	**1.98**
20	1.71	2.10	2.12	2.20	2.10	2.00	**2.04**
40	2.01	2.37	2.10	2.12	2.24	2.39	**2.21**
Mean	**1.94**	**2.06**	**2.03**	**1.97**	**1.96**	**1.99**	
LSD (*P*=0.05)							
P level			**0.17**	***P* = 0.002**			
P placement			**n.s.**	***P* = 0.85**			
P level x P placement			**n.s.**	***P* = 0.68**			

n.s. = not-significant (*P*>0.05). TD = P fertiliser topdressed. BR = P fertiliser broadcast. and incorporated WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

The content of P in wheat shoots at dough stage was only affected by the level of P applied in 1994 (Table 6.4); generally P uptake increased as the level of P supply increased.

Table 6.3. Residual effects of P fertiliser level and placement applied to field peas in 1994 on mean YEB of wheat and whole shoot P concentration measured in 1995, at 10 or 20 weeks from sowing, respectively.

Applied P (kg/ha)	Mean P concentration in YEB (%DW)							Mean shoot P concentration (%DW)						
	10 weeks from sowing							20 weeks from sowing						
	TD	BR	WS	B4	B7	B10	**Mean**	TD	BR	WS	B4	B7	B10	**Mean**
0	0.37	0.37	0.35	0.37	0.37	0.34	**0.36**	0.10	0.08	0.08	0.08	0.10	0.11	**0.09**
5	0.35	0.35	0.37	0.34	0.38	0.38	**0.36**	0.10	0.10	0.10	0.14	0.10	0.10	**0.11**
10	0.36	0.42	0.37	0.38	0.37	0.37	**0.38**	0.12	0.10	0.11	0.11	0.11	0.10	**0.11**
20	0.38	0.40	0.38	0.38	0.38	0.38	**0.39**	0.13	0.09	0.12	0.12	0.10	0.14	**0.12**
40	0.40	0.44	0.40	0.45	0.40	0.40	**0.41**	0.13	0.11	0.13	0.15	0.11	0.14	**0.13**
Mean	**0.37**	**0.40**	**0.37**	**0.39**	**0.38**	**0.37**		**0.12**	**0.10**	**0.11**	**0.12**	**0.10**	**0.12**	
LSD (P=0.05)														
P level			**0.02**	***P*< 0.006**						**0.01**	***P* = 0.004**			
P placement			**n.s.**	***P* = 0.65**						**0.02**	***P* = 0.01**			
P level x P placement			**n.s.**	***P* = 0.64**						**n.s.**	***P* = 0.12**			

n.s. = not-significant (P>0.05). TD = P fertiliser topdressed. BR = P fertiliser broadcast and incorporated. WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below seed. B7 = fertiliser banded 7 cm below seed. B10 = P fertiliser banded 10 cm below seed.

Table 6.4. Residual effects of P fertiliser level and placement applied to field peas in 1994 on mean shoot P content measured in 1995,at 20 weeks from sowing.

Applied P (kg/ha)	Mean shoot P content (kg/ha)						
	20 weeks form sowing						
	TD	BR	WS	B4	B7	B10	Mean
0	5.1	3.7	3.9	4.0	4.8	5.0	**4.4**
5	5.2	5.0	5.4	6.5	4.9	4.9	**5.3**
10	6.4	5.4	6.2	5.3	6.4	5.3	**5.8**
20	7.3	6.1	6.4	6.3	6.6	7.3	**6.7**
40	8.2	7.4	7.7	8.4	7.5	7.9	**7.8**
Mean	**6.4**	**5.5**	**5.9**	**6.1**	**6.0**	**6.1**	
LSD (P=0.05)							
P level		**1.1**	***P* < 0.001**				
P placement		**n.s.**	***P* = 0.60**				
P level x P placement		**n.s.**	***P* = 0.57**				

n.s. = not-significant (P>0.05). TD = P fertiliser topdressed. BR = P fertiliser broadcast and incorporated. WS = P fertiliser sown with seed. B4 = P fertiliser banded 4 cm below the seed. B7 = fertiliser banded 7 cm below the seed. B10 = P fertiliser banded 10 cm below seed.

6.5. DISCUSSION

The findings from this field experiment clearly demonstrated a positive residual response by wheat from P fertiliser applied to field peas in the previous year. With one minor exception, these responses were independent of the method of fertiliser P placement applied to the drought-affected field peas in the previous year. Such results agree with the findings of Sander *et al.* (1990) who showed that methods of P application (broadcast, drilled with seed and knifed in) did not affect the residual value of fertiliser P applied to wheat. Similarly, P applied to lupins (0-20 kg P ha^{-1}), either broadcast, drilled with the seed or banded 13 cm below the seed. did not affect wheat yields in the following year (Table 6.6; R. Jarvis, (pers. comm.)).

Table 6.5. Residual effects of P fertiliser level and placement applied to lupin in 1989 on lupin and wheat yield measured in 1989 and 1990, respectively (R. Jarvis (pers. comm.).

Method P of application	P applied (kg/ha)	1989 lupin seed yield (t/ha)	1990 wheat grain yield ^{A} (t/ha)
Broadcast	0	0.66	1.88
	10	0.80	2.18
	20	1.00	2.53
Drilled with seed	0	0.67	1.88
	10	0.98	2.18
	20	1.12	2.22
Banded 13 cm below seed	0	0.75	2.23
	10	1.20	2.42
	20	1.63	2.50

^{A} Residual response to P applied to lupin in 1989: no fertiliser applied to 1990 wheat crop.

The possible cause or causes for this lack of residual response to methods of P placement by wheat can only be speculated upon. Firstly, it is possible that wheat plants absorb most of their P early in the growing season when the soil profile is generally moist and hence access to residual P sources is high irrespective of the depth of P placement, particularly as the developing root wheat system proliferates beyond the surface horizon. Secondly, P placed deeper in 1994 may have been immobilised by reactive soil constituents (pH = 8.5) to a greater extent than P placed near the soil surface. This would mitigate against a strong residual response being obtained for the deeper placed P treatments. Thirdly, the yield of wheat produced in 1995 may have been limited by other site-specific factors, which negated a *full* residual response to P applied in 1994. For example, the highest grain yield achieved by any treatment was 2.39 t ha^{-1}, which is approximately 63% of potential yield as defined French and Schultz (1984). In retrospect, a basal application of N fertiliser should have been applied to the 1995 wheat crop to circumvent the possibility of N deficiency limiting the residual response to P applied in 1994.

However, data from this experiment agree generally with results from Western Australia that cereals tend to show at best a small response to P fertiliser drilled below the seed, whereas pulse crops, such as lupins and field peas respond more strongly to these applications.

CHAPTER 7

GENERAL DISCUSSION

Effect of depth of P fertiliser placement on field pea growth

All the evidence reported in the glasshouse and field studies demonstrate that root growth is enhanced in the zone of P fertiliser placement. Even though root proliferation will occur wherever P fertiliser is placed, the position of the fertiliser will have a marked effect on plant growth and the efficiency of P uptake. In the field, applying P fertiliser to the soil surface was very ineffective compared to drilling the fertiliser either in or below the seed row. In addition, the evidence from the glasshouse and field experiments show that applying P 4-5 cm below the seed is a more effective technique than deeper P placement (e.g., 7-10 cm). This occurred at all levels of P applied, except in the field experiment, where it only occurred at the highest level of P application.

Under field conditions, applying P fertiliser 5 cm below the pea seed (B5) resulted in higher P uptake by the plant, shoot dry matter yield and grain yield compared with the normal practice of drilling P with the seed (WS). Similar results have been observed from field experiments with lupin in Western Australia (Jarvis and Bolland 1990). However, the superiority of B5, in the present experiment, occurred in the mid vegetative stage (12 weeks after sowing) and only at the highest level of P supply (Tables 5.11 and 5.19). At lower levels of P application there were no differences between methods of P placement except for the plant performance. Possible reasons for the superiority of the B5 treatment are discussed in Chapter 5.

Data from the glasshouse experiments in Chapter 4 demonstrated that during the early vegetative stages of growth, applying P with seed was usually more effective than placing fertiliser below the seed. However, the superiority of the WS treatment progressively declined relative to the B4 treatment to the extent that at later harvests, B4 was equal to WS in most measurements of plant growth and P uptake.

Effects of P deficiency and fertiliser P placement on nodulation

Results from glasshouse and field experiments showed that nodulation in field peas was very sensitive to P deficiency. Under glasshouse conditions, active nodules were only produced on plants supplied with P fertiliser. Furthermore, the external P requirement for 90% maximum nodulation was much higher than the external P requirement for 90% maximum shoot yield. This indicates that nodulation has a greater requirement for the P than the host plant for growth and that P affects the nodulation process directly. This finding agrees with the results of Israel (1987) but contrast with the finding of Robson (1983) and Jakobsen (1985).

Under glasshouse conditions, placing P fertiliser 4 cm below the seed increased the fresh weight of active nodules, compared with fertiliser placed at WS, but only at the late vegetative stages. Placing P fertiliser more than 4 cm below the seed consistently reduced nodule fresh weight compared to other depths of P placement. The inferior nodulation of pea plants grown in the B10 treatment is most probably linked to the poor access of young plants to deep placed P fertiliser. Under the moderately P deficient field experiment conditions, no differences were found in nodule score between methods of placement at 12 weeks after sowing (Table 5.16). However, at 7 weeks after sowing, the nodule score was greater in the B5 than in the B10 treatments, a result consistent with that obtained in the glasshouse experiments.

Interactions between method of fertiliser P placement and variation in seed P content

Variations in the seed P content had at best only a minor impact on growth and P uptake of pea seedlings even when grown under severely P deficient conditions. Sowing seeds of higher P content resulted in a small positive effect on shoot and root yields and root P content, but only where the fertiliser P was applied 12 cm below the seed. These data suggest that utilisation of P reserves located in the sown seed may stimulate root growth of young pea seedlings grown on soils of low P status in the root zone. The scale of these findings is different to other studies using different plant species where seeds of higher P content increased early growth substantially at low levels of external P supply (Austin 1966b, Bolland and Baker 1990, Bolland and Paynter 1990, Bolland 1991). The reason for these contrasts is not entirely clear. The explanation may lie simply in the relatively small difference in P content between the low and high seed treatments (0.53 and 0.75 mg P/seed, respectively). Such a difference may not have been sufficiently large to produce a strong positive response during early seedling development. However, the difference in seed P content between both seed types (0.22 mg P/seed) comprised approximately 55% and 31% of the total P accumulated by the shoot and plant respectively in 4 weeks old plants grown at P_0.

Alternatively, it could be argued that a stronger effect might have occurred if the harvests had been performed at a later stage of growth. For example, Bolland and Baker (1988) reported that responses to variations in the P content of wheat seed were greater at 35 days after sowing than at an earlier harvest at 15 days after sowing.

Residual value of P fertiliser

Results from the field experiment described in Chapter 6 indicate that the residual effect of fertiliser P applied to peas grown on an alkaline clay loam soil was significant for the growth of wheat in the following year. However, the residual benefits were essentially the same for the all methods of P placement. Results from this experiment agree generally with results from Western Australia (Jarvis and Bolland 1990) that cereals tend to show at best a small response to P fertiliser drilled below the seed, whereas pulse crops, such as lupins and field peas respond more strongly to these applications.

Critical P concentration in shoots and effect of P placement

Critical shoot P concentrations in field peas dependent on plant age and growing conditions. The critical P concentration in whole shoots decreased with increasing plant age (Figure 7.1) in both field and glasshouse experiments. Such results agree with previous reports (Bradley and Fleming 1960, Fageria 1977).

Also, the critical P concentrations from the shoots derived in glasshouse experiments were noticeably lower than those obtained in field grown plants at similar growth stages (Figure 7.1). However, if growth is measured in terms of shoot dry weight per plant then the critical concentrations are similar regardless of the growing conditions (Figure 7.2). The critical P concentration derived from the second harvest of the field experiment (12 weeks) did not fit the trend suggested by all of the other harvests, but this was the only harvest conducted on plants after the onset of flowering. Methods of P application had no effect on critical P concentrations in shoots.

Suggestions for future work

Given the superiority of P fertiliser placed 4-5 cm below the seed on later stages of plant growth and the superiority of fertiliser with the seed on early stages of growth it is proposed that the most effective technique for applying P fertiliser to field peas maybe to apply some fertiliser with the seed and the majority 4-5 cm directly below the seed row. Research should be aimed to clarify this proposal.

In some of the glasshouse experiments, nodule reduction was observed at WS treatments where high P levels were applied, but in these experiments, only nodule fresh weight was measured. Thus further work is needed to investigate effects of different levels of applied P and depths of P placement on components of nodulation (rhizobia survival, infection, nodulation and N_2-fixation).

In all glasshouse experiments, soil water was kept constant thoughout the experimental period. However, soil moisture content has an important role in deep banding studies and little research has been reported on the interaction between method of P placement and soil moisture status on plant growth and P uptake

Also, experimental data is limited on the effect of deep placement of P fertiliser applied to crops grown from seeds with high or low P content. In the present experiment in Chapter 3, the variation in seed P content had a minor impact on growth and P uptake of the crop. Thus, it is suggested that, in future studies of the interactive effects of P placement and seed P content on plant growth and P uptake seed with a much larger P content difference (i.e., very low, normal and high P content) be used.

Finally, plant species with different P uptake patterns respond differently to the deep placement of P fertiliser. For example, cereals as determinate crops absorb most of their required P early in the growth stages, whereas pulse crops such as lupin and field peas are indeterminate and absorb P for a longer period during the growing season. Therefore, effects of deep placed P on growth of pulses and P uptake need to be researched independently and results not simply extrapolated from experimental data obtained from cereals.

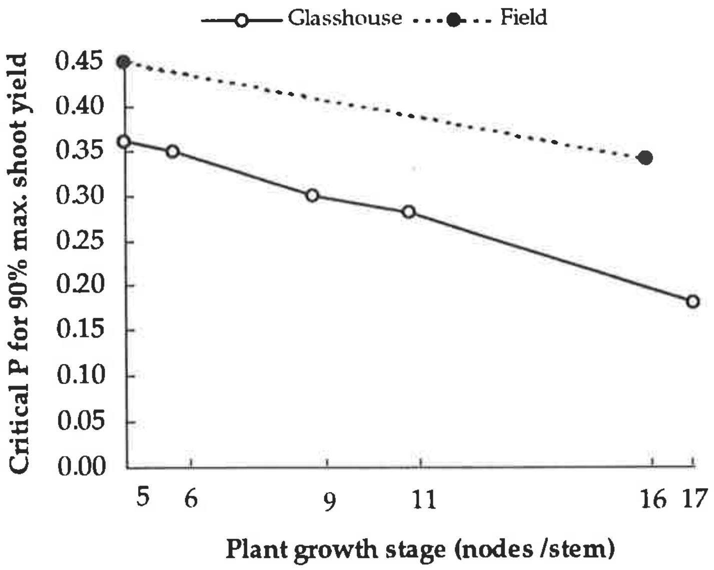


Figure 7.1. Variations in the estimated critical P levels for 90% maximum shoot growth in both field and glasshouse experiments. Critical P concentrations were estimated by using Cate-Nelson method (Cate and Nelson 1965) (averaged for all methods of P application).

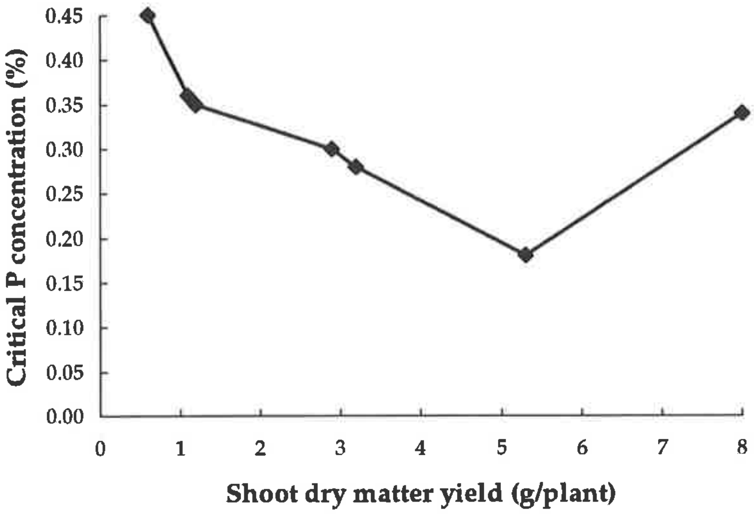


Figure 7.2. The relationship between critical P concentrations of shoots and shoot dry matter at the highest P level (data are derived from all experiments)

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