Chapter 1.

INTRODUCTION

In soil, phosphorus (P) is an immobile macronutrient (diffusion limited) and manganese (Mn) an immobile micronutrient; both are readily rendered unavailable to the developing plant by soil chemical and biological processes. This also means that in many soils much of the applied fertiliser is not readily available to the developing plant. Applying these fertilisers to the seed rather than the surrounding soil may increase the availability of these nutrients to developing seedlings, improve early seedling nutrition and may confer other agronomic advantages such as resistance to diseases. However, this close proximity of fertiliser and seed may be detrimental during germination and emergence.

The aims of this project were: (i) to assess the potential of P seed coatings for summer and winter crops and Mn seed coatings for winter cereals, (ii) to develop an understanding of the potential problems associated with coating seeds with these nutrients, and (iii) to investigate possible remedies. In order to understand the overall possibilities of seed coating for nutrient application, the literature review covers the methods of applying fertilisers, their relative efficiencies and the problems associated with seed coating materials.

1.1 Fertiliser usage in Australian cropping systems

Due to prolonged leaching and weathering, Australian soils are amongst the poorest nutritionally in the world; being deficient in many nutrients (Donald and Prescott 1974). Acute deficiencies of P, nitrogen(N) and many other nutrients have been found to be widespread. The first report of P deficiency in Australia was in 1882 in wheat by

J. D. Custance at Roseworthy, South Australia (Storrier 1975). The first field response to Mn fertiliser in the world, was also in South Australia (Samuel and Piper 1928).

In Australia, approximately 25 million ha of land is fertilised annually for crop and pasture systems, requiring 3.7 million tonnes of fertiliser yearly. Of this, approximately 2.4 million tonnes is superphosphate, 0.4 million tonnes is nitrogenous fertiliser and 0.94 million tonnes is compound fertiliser containing N, P, K and trace elements in various proportions (Table 1.1).

Table 1.1. Fertiliser usage in Australia (modified from Castles (1994) Australian Bureau of Statistics Australian Year Book 1994)

	1986/87	1987/88	1988/89	1989/90	1990/91	1991/92
Area fertilised (million ha)	24.1	26.6	27.9	27.4	23.6	19.5
Superphosphate (million tonne)	2.0	2.5	2.5	2.4	n.a.	n.a.
Nitrogenous (million tonne)	0.41	0.43	0.44	0.48	n.a.	n.a.
Other	0.83	0.95	0.97	1.01	n.a.	n.a.
Total fertiliser (million tonne)	3.2	3.8	3.9	3.9	3.2	2.7

Australia imports most of its rock phosphate, potassium (K), sulphur (S), high analysis and specialised fertilisers. With the rising cost of fertilisers and diminishing supply there is a need to research methods of increasing the efficiency of fertiliser applications.

1.2 Fertiliser Efficiency

Fertiliser efficiency can be described in various ways. For the purpose of this thesis I have defined fertiliser efficiency as yield per unit applied fertiliser.

As early as 1948, Winifred Roberts identified the need to increase fertiliser efficiency:

"It is hardly necessary to emphasise the economic importance, under the present world conditions, of any possible saving in the use of phosphate."

Much research has been conducted into methods of increasing fertiliser efficiency, that is, to gain the highest yield per unit of fertiliser input. Little effort has concentrated on breeding fertiliser efficient high yielding varieties, because most selections are conducted on fertile soils with further additions of fertiliser (Graham 1978), and consequently there is no selection pressure for varieties efficient at extracting nutrients. Graham (1978) argued that even deficient soils contain enough total P, Mn, copper (Cu), zinc (Zn) and molybdenum (Mo) to supply thousands of crops, and enough EDTA extractable Mn, Cu and Zn and Mo to supply hundreds of crops. The problem is that current genotypes are not able to extract the nutrients from the soil. He highlighted the need for plant breeders to include nutrient efficiency as an objective in their breeding programs. As yet this challenge has not been accepted by the breeders; this is due in part to a lack of selection criteria and in part to a lack of understanding of mechanisms of efficiency for each nutrient, as well as the increase in resources required to tackle a new objective. Currently the problem lies with agronomists to find methods of supplying nutrients in plant available forms.

A large research effort has been directed at studies of improved fertiliser placement (e.g.: Roberts (1948), Prummel (1957), Klepper *et al.* (1983), Barber and Kovar 1985)), positioning fertiliser for the best access of crop roots, and minimising fertiliser injury. Prummel (1957) suggested that localised fertiliser placement minimised fixation of the applied fertiliser by soil chemical and microbial processes and resulted in improved early growth of seedlings. Barber and colleagues (Anghinoni and Barber 1980, Barber 1984, Barber and Kovar 1985) using computer simulation techniques argued that only a small volume of soil needs to be fertilised in order to supply the plant requirement of nutrients which are taken up by the plant by mass flow and diffusion, any further treatment is superfluous. Klepper *et al.* (1983) suggested that fertiliser placement must take into account the geometry of the plant root system to ensure that the roots have contact with the fertiliser granules, so that crops benefit optimally from fertiliser

placement. In addition to plant requirement, soil factors, such as soil type, pH and cation exchange capacity (CEC), are important considerations in determining optimal placement. Hence the optimal fertiliser placement depends on fertiliser type and rate, soil type and fertility and plant species and requirement. In general, closer placement of fertiliser enables a 'starter' effect. There has been a move away from broadcasting fertiliser to banding to the side and below the seed and to drilling fertiliser in the same furrow with the seed.

Nutrient seed coating provides an opportunity to supply each seed with precise amounts of nutrients, thus fertilising the micro-environment of the seed. By supplying nutrients to the immediate vicinity of the seed rather than a large volume of soil growers may be able to reduce inputs, decrease access of weeds to the fertiliser and still maintain yield and quality (Scott 1986). Seeds are already used as carriers for fungicides, insecticides and rhizobia. However, reliable and effective nutrient seed coatings are not available for broad scale cropping. Where large amounts of macronutrients are applied, seed coating may in fact be deleterious and reduce emergence. This project began as part of a program to improve the efficiency of fertiliser applications. Since seeds provide a unique opportunity of supplying precise amounts of nutrients the potential of supplying a macro nutrient (P) and a micro nutrient (Mn) as seed coatings was explored. These elements were selected because they are both diffusion limited in soil and would benefit crop plants from localised placement.

1.3 Details of the project

Phosphorus and manganese are both nutrients which are readily rendered unavailable in the soil system, so that much of the fertiliser applied is not available to the plant. Both are applied (on deficient soils), as an annual cropping requirement. The literature on fertiliser application methods, effectiveness of these methods and availability of the applied fertiliser is discussed in Chapter 2. Other approaches to supplying the seed

with nutrients including selecting seed with high nutrient status, soaking seeds in nutrients prior to sowing and nutrient seed coating are also discussed. The experiments discussed in Chapters 3 and 4 concentrate on supplying P to a range of summer and winter crops using seed coating. The extent of injurious effects of P seed coatings are investigated in Chapter 3 and the effectiveness of P seed coating compared with the more conventional drilled applications are tested in Chapter 4. Chapters 5 and 6 describe experiments conducted to explore Mn seed coating for barley and wheat. Several sources of Mn were investigated as seed coating materials; the most effective of these was compared with conventional soil applications of Mn. The concluding discussion, Chapter 7, integrates the main results of all the experiments conducted and discusses the implications for broad scale cropping in Australia.

Chapter 2.

REVIEW OF THE LITERATURE

2.1 Introduction

Phosphorus: Phosphorus (P) deficiency is often a major limitation to crop and pasture production in Australia (Norrish and Rosser 1983). Results of a survey reported by Wild (1957) indicated that, compared to soils of the United States and northern Europe, Australian soils were generally lower in P. This is mostly due to leaching over extended periods of soil development since the same study showed that Australian parent materials were higher in P. Superphosphate is the main fertiliser used in Australian agriculture (Castles 1984; Table 1.1). On P-responsive soils, P is readily rendered unavailable in the soil and commonly needs to be applied with every crop. Although Lazenby (1976) predicted that large deposits of rock phosphate would meet the world demands for 50 years or more, deposits of high-purity "A" grade ore (used for superphosphate manufacture) at Christmas Island and Nauru are almost exhausted (Cook 1983). The lower grade "C" rock has been investigated for cropping (McClelland and Price 1970; Palmer and Jessop 1982; Mason and Cox 1969) but has shown little potential for annual cropping systems. Australia is dependent on overseas supplies since Australian sources are remote and of poor quality, with high levels of contamination of iron, aluminium silica and fluorine (Smith 1983). With the rising cost of superphosphate (Commodity Statistical Bulletin 1986) and the diminishing supply, an investigation of systems to give greater economic return to applied P is justified. This may result in the adoption of different cultural practices. McWilliam (1976) described P as essentially a non-renewable resource and indicated the need to improve the efficiency of P utilisation.

The wheat plant requires P for early growth (Miller 1939; Boatwright and Haas 1961), so it must be available in the soil solution early in the season. Phosphorus is required for the generation of energy in the ATPase Krebs cycle, for respiration and photosynthesis (Sutton *et al.* 1983; Epstein 1972) and it also has a role in plant membrane phospholipids (Price 1970). Through its role in DNA, P is involved directly or indirectly in all plant processes. Phosphorus is comparatively mobile within the plant and, at maturity, large amounts of P are deposited in the grain as phytic acid (Lipsett and Dan 1983, Lipsett 1964). It is this removal of P in the harvested grain and losses in organic matter, together with the sorption of P, that ensure the continuing demand for phosphatic fertilisers in cropping.

Symptoms of P deficiency which have been reported by many workers include: an increase in root/shoot ratio, a decrease in root surface area per unit root weight, an increase in root surface area per unit shoot weight (Hallmark and Barber 1984), a reduction in hydration and an increase in leuco-anthocyanin content resulting in a reddish/purplish colouration, which may be related to an increase in carbohydrates indicating a failure in the metabolic pathway (Atkinson 1973). Leaf growth and development are severely reduced and the calcium content in both shoots and roots is increased. Plants also look stunted and are darker green than normal.

Manganese: Manganese deficiency occurs world-wide on a large range of soil types, and in numerous crops and management practices. It is most common on high pH soils, inherently low in total Mn (Reisenauer 1988). Manganese availability is principally determined by the balance between oxidation and reduction reactions in the soil. This balance is affected by a complex set of interactions between microbial activity, pH, temperature, moisture, soil texture, organic matter and aerobic conditions. On alkaline, Mn-deficient soils both applied and native sources of Mn are relatively immobile (Reisenauer 1988), being rapidly fixed by oxidation at high pH (equations 1 and 2).

$$Mn^{2+} + 2OH^- + (O) \rightleftharpoons MnO_2 + H_2O \qquad (1)$$

$$MnO_2 + 4H^+ + 2e- \rightleftharpoons Mn^{2+} + 2H_2O \qquad (2)$$

Banding Mn-enriched acidifying fertilisers is a relatively effective method of treating Mn deficiency, particularly for deficiency during the seedling development phase (Reuter *et al.* 1988). However the residual value of soil-applied Mn is low on alkaline soils and it must be applied with every crop. Foliar applications of Mn are more efficient in terms of the amount of Mn applied.

Manganese is relatively immobile within the phloem of the plant while moving freely in the xylem. As the phloem sap is unable to supply roots with adequate Mn (Loneragan 1988), this questions whether foliar-applied Mn can supply any of the Mn requirements of the roots.

The most important role of Mn within the plant is in photosynthesis and electron transport (Burnell 1988). It has a major role in metabolism of N and sequential reduction of nitrate. Manganese is involved in the synthesis of aromatic ring compounds as precursors for amino acids, hormones, phenols and lignin.

Symptoms of Mn deficiency are usually visible only when growth and yield are severely depressed (Hannam and Ohki 1988); they include interveinal chlorosis on young expanded leaves, dark brown necrotic patches on leaves and premature senescence of older leaves. Plants appear pale green and flaccid. In severe cases, the growing point collapses and the plant dies. Manganese deficiency can also result in reduced growth and yield without the occurrence of visual symptoms (Reuter *et al.* 1973a, b and c).

Efficiency of fertiliser use: Fertiliser efficiency can be defined in several ways (Jones *et al.* 1992):

(1) nutrient uptake per unit of applied nutrient.

(2) economic yield per unit of applied nutrient.

(3) yield per unit nutrient uptake

(4) nutrient harvest index = grain nutrient content / unit nutrient uptake x 100

(5) root efficiency ratio = nutrient uptake / unit root dry weight or root length

$$\text{(6) nutrient uptake efficiency} = \frac{\text{nutrient uptake (time 2-time 1)}}{\text{root dry weight or length} \frac{\text{(time 2+time1)}}{2}}$$

In this, review fertiliser efficiency refers to the vegetative yield per unit of applied nutrient.

Both P and Mn fertilisers are applied by a range of methods, including aerial, top-dressing, surface broadcasting, drilling with the seed, and foliar sprays. These methods represent a range of efficiencies as monitored by the yield / unit of applied fertiliser. In general, close placement of fertiliser near to the seed is more efficient than treating the bulk of soil.

Nutrient seed coating provides the unique opportunity of supplying precise amounts of fertiliser in close proximity to seeds. Because the micro-environment of the seed is being treated rather than the bulk of soil, smaller amounts of fertiliser may be required. These may also be available to the seedling for a longer time before being immobilised by chemical reactions with the soil. Phosphorus coating of seed, particularly for pasture seeds, has been found to increase fertiliser efficiency (Scott and Blair 1985) and reduce the competition from weeds (Scott 1986). Seed coating with Mn has also been shown to increase yields of barley and to be more cost-effective than soil applications (McEvoy *et al.* 1988). Some fertiliser coated pasture and vegetable seeds are commercially available

in Australia; farmers on highly calcareous soils in South Australia are currently coating barley seed with Mn prior to sowing.

It has been known for a long time that placement of fertiliser close to the seed can result in substantial plant injury (e.g. Olsen and Drier 1956; Carter 1969). Nutrient seed coatings need to be assessed for both efficiency of nutrient uptake and deleterious effects before recommendations can be made regarding their future potential in cropping systems.

This review is directed at the question "Is seed coating with phosphorus or manganese a viable proposition for Australian cropping?" A limited amount of work has been reported in this area, most of which is encouraging. Other nutrients may also be supplied by seed coating but this thesis concentrates on P and Mn as nutrients which are diffusion-limited in soil and commonly applied annually to deficient soils.

The approach taken is to discuss each nutrient separately in terms of chemistry, current application methods, fertiliser injury, methods of reducing this injury, and the status of seed coating. The intention is to draw conclusions as to where nutrient seed coating may be beneficial and to identify its limitations.

2.2 Phosphorus

Plants take up P primarily as the mono-valent orthophosphate ion which arrives at absorption sites in the roots by diffusion through the soil solution (Barber 1984). But the diffusion coefficient of P in soil is low since the phosphate ion readily reacts with soil surfaces. Thus, the volume of soil that can supply orthophosphate ions by diffusion in a given time interval is small. Phosphorus is taken up along the whole length of the root including the root tip (Ferguson and Clarkson 1975). Nye and Marriot (1969), in their

theoretical study of diffusion characteristics and the absorbing power of roots, reported that a segment of root will absorb nutrients for many days after it is produced.

In a review concerning breeding cereals for nutrient efficiency, Graham (1984) suggested that there were large reserves of P in most soils to sustain P-efficient crops but, as yet, there had been little success in identifying and selecting for the P-efficiency character (Graham 1978). A study by Jones (1986); which investigated the mechanisms involved in the storage of phytic acid in wheat grain, with the aim of selecting varieties with a low synthesis of phytic acid, in order to reduce the amounts of P removed from the field, in the grain, was not encouraging. The varieties tested did not differ greatly in P content of grain.

Interactions between plant nutrition and disease have been the subject of much research. In a review of this topic, Graham (1983) suggested that it may be an advantage to supply immobile nutrients via the roots rather than using foliar applications, in order to more effectively supply limiting nutrients to root cells and thereby to reduce the damage by root pathogens. Increased levels of soil-applied superphosphate can reduce soil-borne plant disease; for example, take-all (*Gaeumannomyces graminis*) has been reduced in wheat with increased rates of P application (Hornby 1985, Huber 1980).
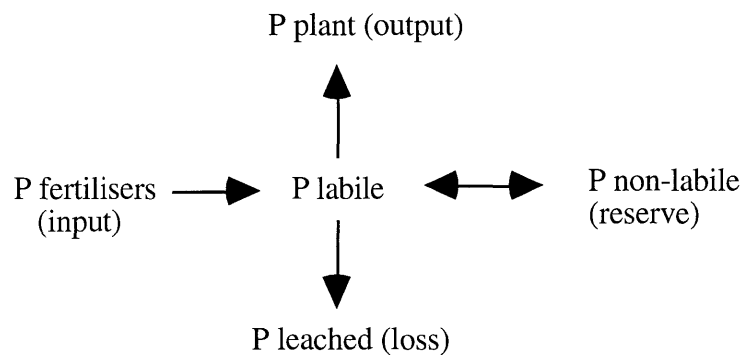
2.2.1 Phosphorus chemistry and fertiliser availability

When considering changes in fertiliser management, it is necessary to consider all aspects including the physical feasibility with respect to machinery and manpower and the soil-plant system. In order to improve the efficiency of fertiliser utilisation it is essential to understand some of the soil chemistry involved. It was mentioned earlier that P is taken up from the soil solution primarily by diffusion and that P is readily sorbed onto soil particles rendering it less available to the plant. This section is intended as a brief

synopsis of considerations of plant-available P and factors which influence the equilibrium of labile and non-labile P.

The total P content of even a P-deficient soil greatly exceeds the normal plant requirement. Graham (1978) reported that the extractable P reserves of a deficient wheat growing soil, were sufficient to support 25 crops without further fertiliser addition and noted that current management practices input at least three times the amount of P that is harvested in the grain. For these reasons it is important to understand the reactions between phosphate and the soil in order to influence the amount of available P in the system and to improve the efficiency of fertiliser usage.

The processes that determine the level of available P in a soil are illustrated in a set of reactions by Larsen (1976) :

$$
\begin{array}{ccc}
 & \text{P plant (output)} & \\
 & \uparrow & \\
\text{P fertilisers} \longrightarrow & \text{P labile} & \longleftrightarrow \text{P non-labile} \\
\text{(input)} & & \text{(reserve)} \\
 & \downarrow & \\
 & \text{P leached (loss)} &
\end{array}
$$

By considering each of these processes individually in terms of pool size and dynamics of reaction, Larsen simplified the model to one which considered only the quantity of labile P in the soil and the rates of immobilisation and mobilisation of labile and non-labile P respectively.

$$\text{P(labile)} \underset{k_2}{\overset{k_1}{\rightleftharpoons}} \text{P (non-labile)}$$
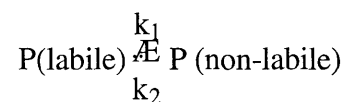
Rajan (1976) discussed in detail both the reactions between phosphate and the soil particles and those between phosphatic fertilisers and soil particles with respect to the availability of phosphate from these reactions. After considering the chemistry in detail, he concluded that low-solubility fertilisers may be more efficient than superphosphate which is highly soluble and produces an acid environment around the granule. However, for annual cropping situations, partially soluble fertilisers are unable to adequately meet the urgent demand for P in the early growth of the plant; Palmer and Jessop (1982) reported that for maximum wheat yields, low-solubility rock phosphates have little to offer.

Plant uptake of P is greatly influenced by applying nitrogen with the P-fertiliser. Studies using autoradiographs of the fertilised zone led to the conclusion that the ammonium ion increases the transfer of P across the root symplast to the xylem (Leonce and Miller 1966). This phenomenon may be due to an unequal uptake of anions and cations affecting the pH at the root soil-interface and hence increasing the P uptake. Other factors that could feasibly contribute to the increase in P uptake are greater N uptake and a larger root system due to the applied nitrogen (Blair *et al.* 1971).

2.2.2 Methods of phosphorus application

Fertiliser may be applied by several methods, the choice of which is governed by the machinery available, the crop being sown and the fertiliser product applied. These methods are discussed separately with a view to the efficiency of their usage. Phosphorus fertiliser is usually supplied to crops via soil applications: foliar applications are not commonly used in broad scale cropping for supplying large amounts of P.

Broadcast vs banded applications

Solid fertiliser broadcast over the soil surface and later incorporated into the soil by cultivation or planting operations has the following advantages: (1) the fertiliser may be

spread quickly (aerially or conventionally) prior to seeding to relieve the pressures on manpower at the critical time of sowing, and (2) the applied fertiliser is diluted in a large volume of soil, thus reducing plant injury due to osmotic or toxic effects (Ignatieff and Page 1960). Broadcasting also allows the dissolution of sparingly soluble forms of P fertiliser granules prior to germination so that some P will be available for early crop growth . However, a major limitation for nutrients such as P and Mn, which are readily immobilised in the soil by chemical reactions, is that a large proportion of broadcast fertiliser will be in an unavailable form by the time the roots have reached the fertiliser granules.

In a study of fertiliser placement, Klepper *et al.* (1983) discussed the relevance of root system geometry and suggested that fertiliser placement must take into account the accessibility of the fertiliser granule to the roots, which may necessitate different placement for cereals and legume species. They indicated that since cereal roots grow straight down for approximately 5 cm from the seed before branching, a large volume of surface soil between the rows may be unexplored, resulting in more of the fertiliser being available for weeds. They noted that, if fertiliser injury is sustained by the first seminal root of wheat, then the later seminal roots can supply water and nutrients for emergence. For dicotyledons, if the tap root (which does not normally branch until later) is injured, the damage sustained would have a greater effect on plant health. This study of root system geometry may help in part to explain the different susceptibilities of crops to fertiliser injury. Klepper *et al.* (1983) also noted that roots tended to branch around a placed fertiliser granule to exploit the reserves. The same observation was reported by Hackett (1972).

The work of Barber and colleagues in modelling nutrient uptake (e.g. Barber 1984) demonstrated that only a small volume of soil surrounding the root can supply P to the plant. Similarly, Nye and Marriot (1969) indicated that nutrients diffuse through the soil

at the rate of a few mm day^{-1} and roots move through the soil at approximately 1 cm day^{-1}. These studies suggest that much of the fertiliser applied by broadcasting is not utilised by the plant. Thus, a more strategic fertiliser placement may result in increased fertiliser efficiency.

The disadvantages of broadcasting were also pointed out in studies by Ignatieff and Page (1960) and Russell (1973) where the maximum recovery of P from a broadcast application was found to be 10%, compared with banded applications which gave recoveries of 30%.

Banding (or drilling) fertiliser with the seed, to the side of the seed, or below the seed has been found to be a more efficient method of fertiliser application, but seedling injury may be experienced depending on which fertiliser salts are being applied, soil moisture, soil temperatures and susceptibility of the crop to injury. Prummel (1957), working with a range of crops, and with soils of differing nutrient status found that the efficiency of fertiliser placement (to the side and below the seed) compared to broadcasting applications varied with the species and element being investigated. For example, in the soil he studied, banded applications of P were 7.5 times more effective than broadcast applications for pulse crops, 2.9 times more effective for maize and 2.5 times more effective for cereals. Prummel (1957) suggested localised placement of fertiliser enables better early growth and prevention of fixation of applied fertiliser by soil chemical processes.

In a simulation model computing P uptake proposed by Claasen and Barber (1976) a number of plant and soil parameters were considered including the sorption or buffering capacity of the soil and the initial soil P concentration. Using this model for corn and soybeans, Barber and Kovar (1985) calculated the volume of soil that can supply nutrients to the plant and showed that a placement which fertilised 5% of the soil volume

would give the maximum P uptake and hence is the optimum placement to achieve in fertilizer practice under the conditions of their model. They considered application methods in terms of the volume of soil fertilised and showed that applying P as a band by the row would only fertilise 1 or 2% of the soil, broadcasting and incorporating would fertilise 100%, whereas applying the P in a strip on the soil surface before ploughing would fertilise the desired 5 to 10% of the soil. Similarly, Anghinoni and Barber (1980) used the simulation model described above to predict the most efficient placement of P to maximise uptake and plant yield for 3 soil types. The theoretical placements correlated well with the yield responses recorded from their experiments. It should be noted that the model was developed to study elements which are taken up primarily by diffusion and mass flow; it is not applicable where interception dominates uptake.

The effect of banded fertilisers on the establishment of crops has been investigated by many researchers. In glasshouse and field trials with oats, Sherrell *et al.* (1964) found that, not only was the P more available under a strategic placement, but that it was available for a longer time. These workers also reported that the effectiveness of placement depended on soil fertility. They investigated various positional placements of P granules and concluded that placement below the seed was more beneficial than to the side. Placement 5 cm to the side and 5 cm below the seed gave the highest yield at high application rates indicating this as a safe position when considering seedling injury, but, at low application rates, this treatment yielded less than broadcast fertiliser. Other workers have investigated placement positions. In field experiments on soils low in soluble P, Lutz *et al.* (1961) found that placement of P 2.5 cm to the side of the seed increased the yield of wheat and oats compared to placement in contact with the seed.

Peterson *et al.* (1981) reviewed the literature concerning the effectiveness of banded compared to broadcast fertiliser applications for winter wheat and noted that, for a valid comparison, thorough incorporation of the broadcast fertiliser is essential. In a series of

experiments to quantify the efficiency of broadcast compared with banded fertilisers they found that there was no constant ratio of efficiency of banded : broadcast application. However, when the field sites were ranked from low to high on the basis of available P content (Bray and Kurtz No.1), banded applications of superphosphate resulted in a three-fold yield increase over a broadcast application at the same rate where available P was low; yet at moderate levels of soil fertility both methods of application yielded similarly. Thus, available P in the soil can influence the relative efficiency of application methods. Barber (1984) also reported that P-fertiliser placement was more critical in soils low in available P that adsorb large quantities of added P. These reports emphasise that, in P-deficient situations, banded placement of the phosphate is desirable to obtain maximum yields.

Placement of fertiliser next to the seed by banded or drilled applications can result in fertiliser injury during germination and emergence. Since P is not the only element applied at seeding, consideration must also be paid to the injury caused by placement of other fertiliser salts with the seed. In fact, P is one of the least injurious elements to the germinating seedling (Olsen and Drier 1956). Studies have indicated the most appropriate salts for avoiding seedling injury when banding fertilisers with the seed. Olsen and Drier (1956) reported that moderate applications of N and potassium (K) with the seed resulted in yield losses in some conditions. In this and several other studies, applying N to the band dramatically increased P uptake; this enhancement of P uptake was discussed in more detail in Section 2.2.1, whilst fertiliser damage is considered more fully in Section 2.2.3.

Some of the advantages of placement for N, P and K fertilisers were summarised by Murphy (1983) as possibly delaying the immobilisation of P and K owing to poor contact with the soil, and secondly, increasing the soil acidity and consequently the P availability by preferential uptake of the ammonium ion. Modern farm equipment commonly places

the fertiliser in the same furrow in contact with, or at random but small distances from the seed. The availability of nutrients during seedling emergence before the root system has become well developed and the incidence of fertiliser injury is therefore somewhat a matter of chance.

Applications of fertiliser directly to the seed rather than the soil, so that each seed has access to a precise amount of fertiliser may lead to further increases in fertiliser efficiency by ensuring each seedling has equal access to applied nutrients. The natural nutrient content of the seed also makes an important contribution to early seedling growth and was the subject of a review by Asher (1987). Two methods of nutrient application to seeds will be discussed below: (1) soaking the seeds in nutrient solution prior to sowing and (2) applying solid fertilisers to the seed coat.

Phosphorus Content of Seed

Seed with high mineral content has been shown to increase early seedling vigour and nutrition in a similar way to a starter fertiliser effect. Reserves of nutrients in the seed must be sufficient to sustain growth until the root system has developed sufficiently to supply nutrients from the growth medium. During plant establishment, nutrients are supplied partly from the seed reserves and partly from the soil. High levels of seed nutrients are particularly important in soils of low nutrient availability as a larger root system is required before the soil can supply the needs of the crop. Low nutritional status of seeds has been reported to reduce plant growth when grown under conditions of low nutrient availability (Asher 1987).

The nutrient status of seed has been shown to affect both seed viability and seedling vigour. There are reports in the literature of minimum seed concentrations below which seedlings will not grow normally (for examples see Table 2.1, Section 2.3.2). Whilst the critical level for seedling growth was not determined, Harris and Brolmann (1966)

demonstrated that peanut seed with low boron (B) content had hollow-heart defect and development of cotyledons was not normal. Low calcium (Ca) content of peanut seed resulted in darkened plumules, reduced germination and death of 60% of seedlings within 2 months; those that survived had deformed roots and shoots (Harris and Brolmann 1966). Subterranean clover seeds with high P concentration (7.5 g kg^{-1}), had both a faster rate of emergence and greater percentage emergence compared to seed of the same size, but with lower P concentration (4.8 g kg^{-1}, Thomson and Bolger 1993). In this study seed with high P content resulted in faster leaf emergence and greater shoot dry matter production only where P fertiliser was not applied; P concentration of shoots of 2 week old seedlings was higher in plants grown from seeds with high P content, however, at 4 weeks plants from high and low P seed had similar concentrations of P in their shoots.

Austin (1966) reported an increase in vigour of watercress grown from seed varying upward in P concentration from 0.47 to 0.95 g kg^{-1} of seed; these differences were apparent 7 to 9 weeks after sowing but had disappeared at maturity. For barley, Schjorring and Jensen (1984) demonstrated that the dependence on seed reserves is influenced by the external supply of P. Barley grown without added P utilised 86% of P contained in the seed, whereas when grown with an external supply of 2000 µM P, only 59% of the seed P was utilised.

For wheat grown in pots in the glasshouse, Bolland and Baker (1988) reported that seed with higher P concentrations of 2.5 g P kg^{-1} of seed resulted in a yield increase at three times of sampling when compared to plants grown from seed with a lower P concentration of 1.4 g P kg^{-1} seed (Figure 2.1). The influence of seed P decreased when the soil was fertilised with P but did not disappear entirely.

Lupins (*Lupinus angustifolus*) grown from seed with higher concentrations of P had increased grain yield in a field study in Western Australia (Bolland *et al.* 1989). When

grown under a P-deficient regime, narrow-leafed lupin seed with low P seed levels produced seedlings with greatly reduced root length, fewer lateral roots and depressed nodule numbers (Thomson *et al.* 1992). These workers concluded that adequate seed P may be particularly important for nodulation of narrow leafed lupins. Increasing levels of P in *Medicago polymorpha* and *Trifolium balansae* seed increased herbage yields under field conditions for each harvest (up to maturity) and increased seed yields (only measured for *M. polymorpha*). There was no effect of seed P concentration on establishment or nodulation (Bolland and Baker 1989).
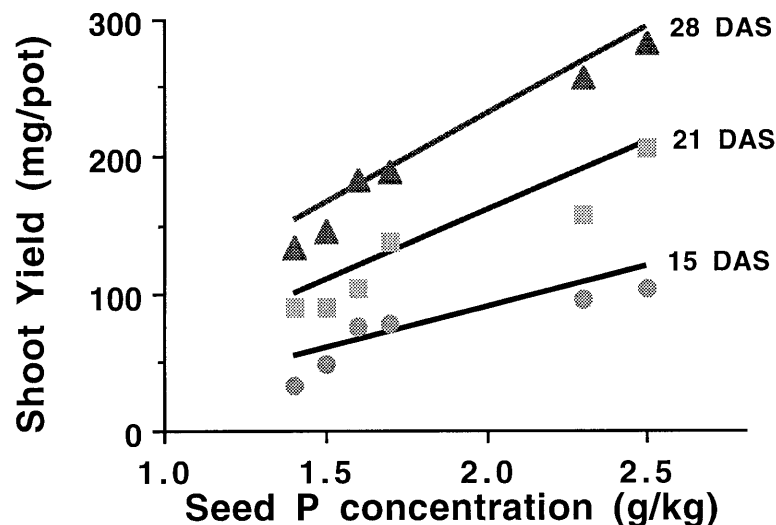

Figure 2.1. Effect of seed P concentration on dry matter yield of Jacup wheat sown in pots (modified from Bolland and Baker 1988). DAS= days after sowing.

De Marco (1990) investigated the effect of seed size, and P and N concentration of wheat seeds on seedlings in a pot experiment. He found no effect of seed N concentration or content on seedling growth; however, within the seed P treatments, heavier seeds produced larger leaves, more dry matter, and longer root systems. High seed P content resulted in greater rate of emergence, larger area of youngest leaves and greater root length of seedlings, 10 days after emergence. This larger root system would have added advantages in acquisition of nutrients from both soil and fertiliser sources. The effects of

seed weight and seed P concentration were additive. He concluded that P contained in the seed could partially compensate for low P availability during early seedling growth.

In contrast to De Marco (1990), several workers have reported that increased protein content of wheat seed improves seedling vigour and yield of wheat (Schweizer and Ries 1969; Ries *et al.* 1970; Lowe *et al.* 1972; Ayers *et al.* 1976).

Seed Soaking

The soaking of seeds in nutrient solutions as a means of supplying needed nutrients has been investigated for a long time. Smith and Bressman (1930) reviewed the literature and cited 18 papers in which most of the reported studies were concerned with the effects of soaking on germination without considering vegetative growth. Indeed most fertiliser injury occurs during germination prior to emergence (Klepper *et al.* 1983); however, when considering fertiliser application techniques, it is essential to study early growth, nutrient uptake and final yield.

Supplying nutrients to crops by seed soaking has been shown to be feasible for micronutrients as the plants only require small amounts of these elements to overcome deficiencies. This is discussed in detail in Section 2.3.2. The nutrient solution is imbibed by the seed, so care must be taken to avoid germination damage due to either toxic or osmotic stress from too concentrated an application, as well as from physical damage from the earlier wetting and drying stages.

When applying a nutrient which is required in large quantities by the plant, it may not always be possible to supply the full requirement without sustaining injury. Soaking seed for 12 hours in a solution containing 3% KCl increased grain yield of wheat (Subrahmanyam and Misra 1980). Abdou and El Kobbia (1976) soaked seed of barley in a 0.25% suspension of superphosphate for 3 hours or for 6 hours in 0.25 M solution

of KH_2PO_4 and reported increased yield and P uptake in a pot experiment in two Danish soils. In contrast, Mujumdar and Somawanshi (1979) reported that soaking wheat seeds for 12 hours in KH_2PO_4 or NaH_2PO_4 decreased emergence, and reduced dry matter yields and P uptake.

In a series of experiments mainly concerning P but also including Mn on wheat, oats and barley and in one case rye, Roberts (1948), reported that the efficiency of P when used for soaking was 7.5 times greater than soil applied treatments. At sowing rates of 44 kg ha^{-1} for oats, after soaking the seed in 1M K_3PO_4 (equivalent to 8.2 kg of K_3PO_4) Roberts (1948), calculated that it would require 41 kg superphosphate ha^{-1} to achieve the same yield with soil applications. Unfortunately, this study was complicated by the use of K_3PO_4 as the P source in the soaking solution, so it is unclear whether the yield advantage of the treated seed was due solely to P or was confounded by a response to K. Nevertheless, the potential for seed soaking as a more efficient means of fertiliser application was demonstrated.

In the same study, Roberts reported that while it was not possible to supply the full P requirement of cereals by soaking seed in phosphate solutions prior to sowing, this may not be essential; the advantages of seed soaking could be supplemented by a foliar application of P to ensure maximum yield and still maintain a cost advantage over conventional application methods. However, for cereals which acquire most of their P in the first eight weeks (Brenchley, 1929; Sutton *et al.*, 1983) foliar applications may be ineffective. Schultz (1975), demonstrated on a P responsive site, that higher rates of P (fourfold) were required as a foliar application to achieve similar grain yield to applications in which P was drilled with the seed.

Seed Coating

Seed soaking is not a system easily adapted to Australian cropping since the seeds may need to be stored after treatment until soil moisture conditions are suitable for sowing.

Seed that has imbibed water and nutrients may also be more prone to injury during storage, handling and sowing operations. This section is intended as an introduction to the concept of nutrient seed coatings in the scheme of fertiliser applications. The feasibility of this technique will be discussed in Section 2.4.

Nutrient seed coating is the application of finely ground fertiliser to the seed so that each seed is supplied with a precise amount of fertiliser. Coating of seeds with fungicides to control seed-borne pathogens or with *Rhizobium* inoculum to ensure nodulation of leguminous species is a practice that is widely used and which has been the subject of numerous reviews (e.g. Callan, 1975). However, incorporating nutrients in the seed coating is a relatively new concept. Consideration must be given to fertiliser injury and varietal susceptibility to such injury; these topics will be covered in more detail in Sections 2.3 and 2.4.

The application of concentrated sources of soluble fertiliser to seeds has been shown to be injurious to germination and establishment of pasture seeds (Scott 1975). However, low rates of N, P and K fertiliser incorporated in seed coatings have been shown to be safe for red clover seeds (Hirota 1972a and b). To avoid injury during establishment, relatively insoluble sources of nutrient have been incorporated in coatings. Although less damaging than more soluble sources these are generally less effective in supplying nutrients. For example, Scott (1986) selected 3 sources of calcium phosphate (with a range of solubility in water) for coating phalaris and lucerne seed. The more soluble source, monocalcium phosphate (MCP), although more injurious, than the other two sources, to emergence of lucerne at high rates of application resulted in higher dry matter production and greater uptake of P than the other less soluble sources.

It may be possible to formulate nutrient coatings that are more slowly released so that the nutrients are not immediately taken up during imbibition, but are available to the developing seedling and are therefore less injurious.

2.2.3 Fertiliser injury

The germinating seed and newly developed seedling are particularly vulnerable to external stresses. The germination process involves many steps that are complex and affected by environmental factors (Cardwell 1984). Stresses, such as under- or over-supply of moisture, soil texture, concentration of the soil solution, micro organisms and pathogens are all a threat to the germinating seed, each parameter interacting with the other. Klepper *et al.* (1983) pointed out that most fertiliser injury was incurred by the first roots emerging from the seed; other workers have also observed injury to the coleoptile and cotyledons (Court *et al.* 1964).

Fertilisers increase the salt concentration of the soil solution (Tisdale and Nelson 1975) and therefore affect the environment of the germinating seed. Fertilisers may be characterised by the extent of damage to germination but, unfortunately, species differ in their susceptibility to injury by different salts, making any ranking difficult to standardise. Moisture and temperature may also play a role in influencing the severity of damage.

Fertiliser induced injury is a complex topic; evidence for this may be found in the many discrepancies reported in the literature. Both fertiliser availability and germination are influenced by environmental variables (e.g. soil temperature, moisture, pH, CEC, texture, hydraulic conductivity) thus making it difficult to compare the findings of one researcher with another since many of the variables are different. Unfortunately, the conditions under which the observations have been recorded are not always reported.

This section discusses fertiliser injury with respect to relative effects of fertiliser salts, application methods, and the different tolerance of species to injurious conditions.

Damage by phosphatic fertilisers

In an attempt to resolve some of the uncertainties with respect to early seedling damage and decreased emergence, Olsen and Drier (1956), investigated experiments from 40 different field locations; and concluded that P is less detrimental per unit weight than either K or N. Straight phosphate carriers produced less damage than nitrogen or potassium phosphates. However, Guttay (1957) concluded from pot trials with wheat and oats that the P content was as important in producing injury as N and K with mixed fertilisers at rates of nutrients 112 kg ha^{-1} or higher. He could not identify any of the major constituents of superphosphate as the cause of the plant injury.

In general most reports agree that superphosphate is less injurious than N or K fertilisers. It is a soluble form of P and readily migrates away from the seed under conditions of high moisture, but is likely to be drawn towards the seed where moisture is limiting. Superphosphate reacts readily with soil particles and consequently phosphate can become unavailable to plants (Carter 1967).

Nevertheless, under some conditions, such as low soil moisture status or high application rates, some species do show deleterious effects. Drilling superphosphate with lupin seed has been reported to reduce plant establishment by up to 40% on acid siliceous sands in the south-east of South Australia (Hawthorne 1986). Monocalcium phosphate, the major constituent of superphosphate, produces phosphoric acid when it reacts with water (Brady 1974). This has the effect of increasing the acidity of the environment around the granule and may account for Hawthorne's observations. Lime pelleting of the seed only partially improved establishment. These observations have led to the South Australian

Department of Agriculture recommending broadcast application of superphosphate prior to sowing lupins on these soils.

Pot experiments reported by Oruk and Kilic (1975) demonstrated that single superphosphate reduced the emergence of wheat to a greater extent than the more concentrated triple superphosphate.

Applying nitrogen with the P-fertiliser is nutritionally advantageous, since it increases plant uptake of P. However, the addition of nitrogen in the fertiliser band increases the salt load near the seed and is thus likely to induce more damage. The N carriers of P are more damaging than the straight P-carriers; mono-ammonium phosphate (MAP) has also been found to be less inhibitory to germination than the diammonium (DAP) source (Carter 1969) but both of these are less damaging than urea, ammonium nitrate or ammonium sulphate. The method of comparison and the cation exchange capacity of the soil influences the relative ranking of DAP and MAP (Stevenson and Bates 1968). Fertilisers have been compared at equal inputs of N, or P, or at equal units of N adjusted to equal units of P.

Damage caused by other fertilisers

Nitrogen: Plant injury caused by N fertilisers has been the subject of much research. Again, the severity of injury depends on the mode and time of application, the concentration and the form of N used.

Anhydrous ammonia applied in bands prior to planting corn resulted in fewer, more stunted plants, poor root development and frequently P-deficiency (Colliver and Welch 1970a, 1970b). Since urea is hydrolysed to ammonium ions and thence to ammonia depending on soil pH, most of the injury observed as urea damage is really due to ammonia. Cooke (1962) postulated that since plants injured by ammonia tend to recover

whereas those subjected to high rates of urea did not, at least one other factor may be operative in urea toxicity. Creamer and Fox (1980) considered ammonia toxicity as the main cause of inhibited root growth for both urea and DAP applications. Phytotoxicity from applications of poultry manure was associated with high levels of ammonium nitrites and soluble salt, resulting in severe plant moisture stress (Weil *et al.* 1979).

Raza and Tiagi (1977) investigated the effects on germination of five nitrogen sources at fertiliser concentrations ranging from 100 to 6000 μg g^{-1}. Germination was not affected by ammonium nitrate but was reduced 10% by thiourea, 40% by ammonium phosphate and 50% by both ammonium sulphate and urea. Olsen and Drier (1956), also ranked the nitrogenous fertilisers in order of decreasing detrimental effect on germination :

$CaCN_2$ and $NH_4OH > CO(NH_2)_2 > NaNO_3 > KNO_3 > (NH_4)_2SO_4 > NH_4NO_3$

Although Olsen and Drier (1956) tested different fertiliser salts, the relative damage of ammonium nitrate and ammonium sulphate was consistent with the nitrate source being the least injurious. Similarly Gupta and Singh (1973) found that, when compared on an equal unit of nitrogen basis, ammonium chloride was more inhibitory to wheat than ammonium sulphate. A 10-20% reduction in establishment of onions was observed when calcium nitrate was applied at rates of 150 kg N ha^{-1} (Henriksen 1978); this led to a recommendation that nitrogen application for onions be delayed until after full emergence.

Potassium: Potassium deficiency is rarely a limitation to yield of the cropping soils in South Australia (R. D. Graham pers. comm.). Few reports have implicated K alone as a source of fertiliser injury. Most occurrences have been for phosphates and nitrates of K. The study reported by Olsen and Drier (1956) found K less injurious per unit weight than N. Potassium sulphate is a beneficial source of K for saline sensitive crops (Saurat and

Boulay 1985, Zehler 1982). Additions of K have been reported to reduce the damage to crops by ammonium chloride (Tanaka and Fujinuma 1974).

In vegetable production, short-term accumulation of sodium and chloride has been frequently observed although generally the plants recover from this damage. Sulphate accumulation can also be a problem. However, longer term injury is likely only where the ratio of sulphate-S to calcium is greater than 8.7 (Drews 1974). For crops growing in glasshouse conditions, sulphate accumulation was more hazardous than chloride accumulation.

Effect of application method

The method of fertiliser application affects the concentration of salts in the vicinity of the seed. Injury is likely to be more severe when the fertiliser is banded near the seed than when it is broadcast and incorporated in a large volume of soil. Drilled applications of nitrogen are harmful and can often result in plant death (Widowson and Penny 1977).

Although most of the literature supports the concept that drilled fertiliser applications are more injurious than broadcast applications, Allison (1918), (as reviewed by Olsen and Drier 1956) found that the injury was independent of mode of application. Nevertheless, reports of reduced injury for broadcast fertiliser can be found (Guttay (1957); Nyborg (1961); Olsen and Drier (1956); Mason (1971)). Again, qualifications as to salts being applied, moisture, temperature and species are required to assess Allison's findings. Guttay suggested that placing fertiliser in contact with the seed seriously affected germination, whereas placement 2.5 cm to the side and 2.5 cm below the seed had no negative effect on germination. This same placement was also reported by Nyborg (1961) to eliminate any injury to cereals, flax and rape.

Mechanisms involved

In order to reduce any injurious effects of fertilisers it is necessary to understand the mechanisms involved in incurring the injury. Various processes have been suggested as the cause of injury including toxicity, osmotic drought due to the salt concentration surrounding the germinating seedling, and nutrient imbalance affecting metabolism and enzyme activity. Depending on the environmental conditions, any of these mechanisms may predominate.

Toxicity

From the commencement of imbibition, the germinating seedling remobilises the stored nutrients from the aleurone tissue and starchy endosperm to the developing tissue (Eastwood and Laidman 1971). The P content of the bran decreases markedly in the first six days accompanied by a proportional increase in the P content of the shoot and scutellum. This redistribution requires several mechanisms which are controlled by the developing seedling (Eastwood and Laidman 1971). These mechanisms can be influenced by the concentration of the external nutrient solution and an imbalance may result in fertiliser injury.

Toxicity from nitrate accumulation in soils (as it does following urea-induced injury) is not a toxicity seen in seedlings, but later stages of crop development.

Osmotic stress

The osmotic pressure of root cells is generally of the order of 1 MPa; if the osmotic pressure of the soil solution is too high, the pressure gradient will result in water being drawn from the root causing dehydration which may ultimately result in cessation of root elongation (Klepper et al. 1983). Crop death has been reported when the osmotic pressure of the soil solution reaches 0.45 MPa (Magistad et al. 1943). By germinating seeds in sucrose solutions with osmotic pressures ranging from 0 to 2.26 MPa, Stankov and Ladonina (1976) were able to demonstrate that the germination of a range of crop

seeds was decreased by increasing osmotic pressures especially above 1 MPa. High rates of fertiliser applications produce osmotic pressures of 1 to 1.5 MPa in the soil solution (Stankov and Ladonina 1976).

The osmotic pressure depends on the amount of salt, soil moisture, base exchange, soil temperature and microbial activity (Rader et al. 1943). These authors proposed the idea of a 'salt index' to express the probable effects of fertiliser constituents on the soil solution. They defined the salt index as the ratio of increase in osmotic pressure of the material to that produced by the same weight of sodium nitrate expressed as a percentage. The emergence of soybeans and snap beans was found to be inversely proportional to the salt index of fertiliser in a trial investigating the extent of damage by NH_4NO_3, MAP, concentrated superphosphate, KCl, DAP and KNO_3 on a silt loam (Hoeft et al. 1975).

In fertiliser trials comparing wheat with banded or broadcast fertiliser applications, Pearson and Kirkham (1980), measured the osmotic potentials of leaves. During early seedling growth the osmotic potential of the leaves was 0.2 to 0.3 MPa lower for banded treatments and this was accompanied by an increase in concentrations of shoot N and P, although banding caused lower nutrient uptake. The difference in leaf osmotic pressure between the two treatments had disappeared by 20 days after sowing (DAS) but the effects on plant dry weight were still apparent 70 DAS.

The observation that certain salts are more toxic to seeds than others indicated that salt injury is not a simple osmotic effect (Ensminger et al. 1965). Conversely, Gupta and Singh (1973) concluded that, since the inhibition of shoot and root elongation was proportional to the osmotic pressure, ionic pressure was more influential on germination than osmotic effects. Hadas (1982) also suggested that the major mechanism of fertiliser injury was toxic amounts of nutrients taken up rather than osmotic stress.

From studies with tomato seeds at very high salinities, Kurth *et al.* (1986) concluded that cell enlargement just prior to radicle emergence is sensitive to low water potentials. Bliss *et al.* (1986) investigated salt toxicity for barley and found that salt entry does not account for the inhibitory effect of sodium chloride; in the earliest stage of germination the principal effect of NaCl is osmotic, the range of hydration threshold varying for salt-sensitive and salt-resistant cultivars. For N and P fertiliser applications to a range of crops, the osmotic effects dominate the inhibition of radicle elongation at pressures of 0.6 MPa or below; above this, toxicity is the predominant mechanism (Tanaka and Fujinuma 1974).

To separate the effects of nutrient toxicity from osmotic effects it is possible to use an osmotic agent, (e.g. polyethylene glycol (PEG) or sucrose) to simulate the osmotic pressures of the fertilisers under investigation. Another technique is to measure the osmotic potential of the seed sap at various times during germination (Kurth *et al.* 1986). Studies of these types are used routinely for investigating toxicities of NaCl but the technique has not been readily adopted for separating the mechanisms of injury due to N, P and K fertilisers.

Induced deficiency

In investigations of the mechanism of ammonium phosphate injury to cotton seedlings, Adams (1966) found that the ratio of Ca to total cations was critical for normal root growth. Root growth was inhibited where this ratio was <0.15, and root death occurred when the value was <0.05. From these observations, he concluded that the injury was an induced Ca deficiency caused by Ca precipitating out as calcium phosphates and by the preferential absorption of ammonium ions by the roots. Ca is important for membrane integrity, and has been implicated as an important factor in injury due to NaCl (Bliss *et al.* 1986).

Hood and Ensminger (1964) further investigated this mechanism and found that soaking the seeds in $CaSO_4$ prior to soaking in DAP did not improve germination. However, soaking in $MgCl_2$ or $MgSO_4$ after DAP reduced the injurious effects of DAP. As magnesium (Mg) is essential for enzyme activity in the germinating seed (Ensminger *et al.* 1965), these authors postulated that DAP inactivated Mg, since $MgPO_4$ is insoluble, and therefore affected enzyme activity and hence germination. Vines and Wedding (1960) suggested that ammonia toxicity resulted from reactions of ammonia inside the cells and hypothesised that the site of ammonia toxicity to plants is located in the electron transport system, specifically the NADPH Æ DPN reaction.

Environmental effects

The physical and chemical conditions of the soil greatly influence the degree of fertiliser injury. Cool soil temperatures reduce root growth and hence nutrient uptake. At warmer soil temperatures, fertiliser injury is likely to be greater (Klepper *et al.* 1983). Conversely, at lower soil temperatures, the volatilisation of ammonia is reduced and plant injury is greater (Creamer and Fox 1980). Temperatures ranging from $10^{o}C$ to $30^{o}C$ had no effect on the tolerance of corn and wheat to salt concentrations (Cummins and Parks 1961). Again, the effect of temperature was dependent on the salts being used.

Soil texture has also been reported as influencing the injury brought about by fertilisers. Damage appears greatest on coarse textured sandy soils with low water holding capacity and least on fine clay soils (Carter 1969; Hoeft *et al.* 1975; Olsen and Drier 1956). Teows and Soper (1978) found there was an inverse relationship between the cation exchange capacity (CEC) and damage caused by drilling urea with barley seed grown on a range of soils of differing pH. CEC and pH jointly influence the volatilisation of urea to ammonia (Toews and Soper 1978). Soils with a high CEC adsorb NH_4^+ and therefore toxic amounts of ammonia are largely eliminated. For soils with a low CEC, the hydrolysis of ammonia is retarded and the ammonia remains in the soil in toxic

amounts (Stevenson and Bates 1968). These authors noted that, for this mechanism to be correct, the toxic effects of ammonium fertilisers should be less at low pH. This was not in agreement with their observations and they suggested another mechanism must be operating. Creamer and Fox (1980) however did observe greater damage at high pH.

Where soil moisture is limiting but still sufficient for germination, damage due to fertilisers is greater (Carter 1967, Olsen and Drier 1956). This is attributed to both higher concentrations of fertiliser (since it is not diffused away from seed) and the higher osmotic pressures.

Micro organisms antagonise the injurious effects of fertiliser since they are more tolerant of low moisture and high salt concentrations and may even be able to utilise the water from the seed (Hunter and Erickson 1952).

Species tolerance

There are many reports in the literature of differential species tolerance to fertiliser injury. Species differ in their susceptibility to osmotic stress, ion toxicity, and moisture limitations. The ranking of species for tolerance to fertiliser injury is therefore complicated by many factors. Carter (1969) constructed a complex table of factors affecting such injury and ranked the species in order of minimum to maximum injury.

In general, crucifers are least tolerant of injurious conditions and cereals are most tolerant (Carter 1969). In addition, damaged seed is more susceptible to injury (Linss 1984; Guttay 1957). Within related species there is a range of tolerance. For example, Olsen and Drier (1956) reported that rye and oats were more tolerant than wheat or barley.

The same level of fertiliser may have different effects on wheat and oats, with wheat being less tolerant to injury. Guttay (1957) suggested this difference was related to seed

structure, since seeds with the caryopsis attached to the lemma and palea were less susceptible. It was suggested by Kotowski (1927, as reviewed by Roberts 1948), that the nature of seed coverings limited the intake of salts. This possible exclusion mechanism was investigated further by Roberts (1948) who reported that, after soaking oat grain for 24 hours in 1M K_3PO_4, 85% of the P imbibed was located in the husk. Although wheat and barley were not compared in this study, the author suggested that the nature of the seed coat may explain why wheat could only tolerate 5% P in the soaking solution compared with oats which can tolerate over 30%. Seed structure has also been reported as a mechanism by which pasture seed is protected from fertiliser injury (McWilliam and Phillips 1971; Silcock and Smith 1982; Scott 1986; Garotte *et al.* 1987, Garotte *et al.* 1989a).

Emergence of wheat, oats and barley was delayed by high concentrations of N and P fertilisers, whereas it was both reduced and delayed for flax and rape (Nyborg 1961). Ranking these species in order of decreasing tolerance to N and P fertilisers, at the same rates of application, Nyborg concluded that oats were more tolerant than barley which, in turn were more tolerant than wheat, which was much more tolerant than flax and rape. In contrast, Mason (1971) found that at 'low' rates of urea application (112 kg ha^{-1}) the order of tolerance to fertiliser injury was barley=oats>wheat, but at a higher rate of application (336 kg ha^{-1}) the order changed to barley>wheat>oats. In the same study linseed and rape were more severely affected by urea than the other crops.

Root system geometry may also be a key factor in the different susceptibilities of species to injury (Klepper *et al.*, 1983). Damage to cereal seminal roots may be less important with cereals (with three to five seminal roots) than with the single tap root in the early stages of legume development. Within the cereals, root geometry and branching rate could be a factor affecting the degree of fertiliser injury. As the root development is

dependent on external factors including nutrient availability, it is difficult to distinguish the mechanism of tolerance within a plant family on the basis of root geometry.

Tolerance to injury within a species has also been shown to vary. Gupta and Singh (1973) reported that dwarf wheats tolerated higher doses of ammonium sulphate and nitrate than tall varieties. Similarly, the tolerance to chloride and sulphate varied for the six wheat varieties tested.

Comparison of crop tolerance to fertiliser injury is difficult since row spacings and application rates vary between species. Comparisons on the basis of a single fertiliser rate may not be a realistic approach. The ranking of a range of fertilisers for increasing damage was different for corn and oats although trends did exist (Cummins and Parks 1961). Corn was tolerant of higher salt concentrations than wheat.

2.3 Manganese

The literature on Mn in soil and plant systems was extensively reviewed by 33 authors for an international symposium on Mn in soils and plants in 1988 (Graham et al. 1988).

Manganese is the tenth most abundant element in the earth's upper crust. It exists in the soil in solution, sorbed onto the surfaces of minerals and organic matter, or incorporated into organisms (Gilkes and McKenzie 1988). Manganese deficiency is a problem of availability of Mn rather than one of absolute deficiency. This was demonstrated in a study by Aubert and Pinta (1977) in which two soils with similar levels of total Mn resulted in plants with either Mn toxicity or Mn deficiency. Plant available Mn is determined by the oxidation/reduction reactions of Mn between the soluble reduced state and the insoluble oxidised states (Equations 1 and 2, Section 2.1).

Plants take up Mn as the Mn^{2+} ion; like P the diffusion coefficient of Mn in the soil is low, since the Mn^{2+} ion is adsorbed onto soil surfaces or readily oxidised to less available forms (Leeper 1947). Plants can access Mn as Mn^{2+} from soluble sources in the soil solution, from exchangeable Mn on soil colloid surfaces, from easily reducible Mn or by contact reduction of Mn oxides at the root surface. The reductive capacity of the root system determines the ability of plant species to use these oxidised forms of Mn (Bromfield 1958; Uren 1981).

Manganese is mobile within the plant, possibly being transported in the xylem sap as Mn^{2+}. The movement of Mn in the phloem however is complex and does not fit into the category of mobile, immobile, intermediate or variable (Bukovak and Wittwer 1957, Epstein 1972, Loneragan *et al.* 1976, Marschner 1986, Loneragan 1988); Mn was traditionally described as phloem immobile since symptoms tend to appear in the young leaves. Mn accumulated in the leaves cannot be remobilised whilst that in roots and stems can supply adequate amounts to developing seeds (Hocking *et al.* 1977, Hannam *et al.* 1985, Loneragan 1988). This phenomenon makes the correction of Mn deficiency difficult since Mn accumulated in leaves or applied to foliage by foliar applications is not remobilised into new tissue and deficiency symptoms may appear in young leaves.

2.3.1 Manganese chemistry/fertiliser availability

Manganese fertilisers release Mn^{2+} which reacts with the soil; under conditions of low pH, the Mn^{2+} may remain in solution or in exchangeable forms but, under alkaline conditions, it is strongly adsorbed or oxidised to less available forms (Leeper 1947). The effectiveness of fertiliser-applied Mn is related to the solubility of the product used, the more soluble forms being more available (Fitts *et al.* 1967, Shuman *et al.* 1979, Mascagni and Cox 1985, Miner *et al.* 1986). However, when applied as finely divided particles distributed throughout the soil, MnO (a slowly soluble product), was as effective as $MnSO_4$ (Mortvedt and Giodarno 1975, Mascagni and Cox 1985).

Application of Mn as chelates has produced variable results since Mn may be displaced by other cations, making these elements more available to the plant and exacerbating the Mn deficiency.

Fertiliser products that influence pH have a large impact on the availability of Mn to crop plants. Applying Mn with acidifying phosphatic fertilisers decreases soil pH and increases soluble and exchangeable Mn^{2+} (Fujimoto and Sherman 1948; Grasmanis and Leeper 1966). Application with strongly acidic sources (e.g. monocalcium phosphate (MCP)) may reduce the localised pH near the granule and consequently increase the effectiveness of applied Mn. Similarly ammonium sources lower the pH and therefore increase mobility and availability of applied Mn (Petrie and Jackson 1984). Application of urea and ammonium phosphates may temporarily raise the pH and consequently lower the availability of Mn.

Manganese may react to form insoluble compounds which result in reduced mobility of Mn in the soil solution. The availability of fertiliser applied Mn is very much dependent on the composition and pH of the fertiliser and the pH of the soil (Norvell 1988). Manganese incorporated in phosphatic fertilisers may react to form insoluble products with limited mobility; for example Mn incorporated with di ammonium phosphate (DAP) or mono ammonium phosphate (MAP) can react to form $MnNH_4PO_4.H_2O$ and Mn applied with ammonium polyphosphates (APP) can result in the formation of several compounds with low solubility e.g. $Mn(NH_4)_2H_4(P_2O_7)_2.2H_2O$, $Mn(NH_4)_2P_2O_7.(1$ or $2)H_2O$, $Mn_3(NH_4)_2(P_2O_7)_2.2H_2O$ (Norvell 1988), the reaction products being determined by the composition and pH of the applied fertiliser, as well as the pH of the soil.

The mobility of Mn applied with macronutrient fertilisers is dependent on the macronutrient carrier used. Mortvedt and Giordano (1970) ranked the diffusion of Mn

from the fertiliser granule in an acidic soil (initial pH 5.1) in its decreasing order of diffusion; this was $NH_4NO_3=KCl>no$ carrier$=MCP\geq MAP>>DAP=APP=TPP$. When the soil pH was increased to 7.6 by the addition of lime the order was similar but the extent of diffusion much smaller. A different order of mobility was reported by Hossner and Richards (1968) in neutral soils; however, their preparation of APP was more acidic with different proportions of polyphosphates. Norvell (1988) used this discrepancy to emphasise the importance of fertiliser composition and pH on mobility of Mn.

Other anions have been reported to affect the mobility and solubility of Mn and hence its availability to crop plants. Again there have been conflicting reports and several interacting factors are almost always involved (Norvell 1988). The absorption of Mn by oats from a mixed fertiliser in neutral soil varied with the anion associated with the applied NH_4^+ in the order $Cl^->SO_4^=>NO_3^-$ (Hamilton 1966). Applications of KCl increased the Mn uptake of sweet corn compared with applications of K_2SO_4, whereas Petrie and Jackson (1984) could not differentiate between NH_4Cl and $(NH_4)_2SO_4$ in alkaline soil and Mortvedt and Giordano (1975) reported KCl and NH_4NO_3 as equal in their effect on the movement of Mn^{2+} from the applied $MnSO_4$.

2.3.2 Methods of Mn fertiliser application

Management of Mn deficiency is complex and dependent on soil type, crop rotation and seasonal conditions. In South Australian cropping systems, Mn is traditionally applied by drilling Mn-enriched phosphatic fertilisers with the seed. Incorporating Mn into the macronutrient fertiliser facilitates the application of small quantities over a large area, avoids costs associated with a separate application and can improve the availability of applied Mn (Walter 1988). This application may be inadequate in preventing deficiency but will ensure enough leaf surface to intercept foliar Mn sprays applied when symptoms appear. Since yield loss may have resulted from Mn deficiency before the expression of foliar deficiency symptoms the effectiveness of this foliar application may be reduced.

The effectiveness of fertiliser-applied Mn is influenced by fertiliser composition and the method of application. The effectiveness of fertiliser strategies for preventing and overcoming Mn deficiency is dependent on the rate of immobilisation of the soil-applied Mn, the extent of contact between labile soil Mn and the root system, and by the redistribution of Mn within the plant itself.

Historically, soil applications of fertiliser Mn in the 1930's used heterogenous mixtures (variously called cold, bulk or physical blends) of Mn and single superphosphate, which were relatively ineffective on calcareous, high pH soils. Homogeneous superphosphate-$MnSO_4$ products with the Mn incorporated in the superphosphate granule were produced for better performance (Reuter *et al.* 1973b) since there was no segregation of constituents. Recent coating technology has meant that Mn can now be coated onto high analysis fertiliser granules so that every granule is a carrier of Mn (Walter and Wetherley 1985, Walter 1989). This has resulted in increased flexibility of Mn fertiliser products, reduced costs and improved performance. Manganese applied in combination with acidifying fertilisers is more effective in supplying Mn. Application of ammonium forming fertilisers creates a micro environment of lower pH due to nitrification or excretion of protons from roots which can increase the uptake of Mn by plants.

Manganese chelates are more expensive per unit of Mn and are less effective than sulphates when applied to the soil (Fitts and Forbes 1968; Voth and Christenson 1980). The Mn-chelate molecule is relatively unstable, the Mn can be replaced by Fe, Zn and Cu and therefore chelates may increase the availability and uptake of the wrong element, which can in turn exaggerate the Mn deficiency.

Manganese has been included in silica glass frits (containing 8 to 20% Mn dissolved in glass) in order to slowly release Mn at rates determined by the nature of the glass matrix

and the particle size. Glass frits have in some cases been reported as effective sources of Mn (Shepherd *et al.* 1960; Shuman *et al.* 1979) whilst in other cases they have been ineffective (Henkens and Smilde 1967, Draycott and Farley 1973, Shuman *et al.* 1979). Manganese frits have not been accepted as Mn fertilisers in Australia owing to their low solubilities (Walter 1988). Reuter *et al.* 1988 discussed the development of a soluble Mn silicate for correcting Mn deficiency in crops grown on alkaline soils. Since Si is beneficial in the distribution and utilisation of Mn within the plant and Mn-silicates are stable, Reuter *et al.* (1988) predicted that this new formulation would be advantageous. This product was developed by Boxma and deGroot (1985) and tested in a pot experiment with oats; the Mn-silicate was more effective in alleviating symptoms of Mn deficiency, increasing Mn uptake and increasing grain yield than either Mn-EDTA, Mn-DTPA or $MnSO_4.4H_2O$ at equal units of Mn. Micronutrient-enriched ammonium phosphates have been formulated as slow release fertilisers to avoid injury on coarse textured soils, even at high rates of application (Bridger *et al.* 1962). These have not been adopted for correcting Mn deficiency in Australia because of their low solubility.

Broadcast vs Banded Applications

Broadcast applications which are not incorporated into the soil fail to correct Mn deficiency in annual crops because the applied Mn is inaccessible to the plant roots. Drilled applications of Mn with the seed are more efficient per unit of applied fertiliser than broadcast applications. For soybean, 17 kg Mn ha^{-1} applied in the band resulted in yields equivalent to those obtained when 45 kg Mn ha^{-1} were broadcast (Alley *et al.* 1978). From their experiments with soybeans, Boswell *et al.* (1981) concluded that differences in efficiency between application methods were small. In a review paper Reuter *et al.* (1988) tabulated results from 23 papers on optimum application rates of soil-applied $MnSO_4$ for field crops. The application rate required to prevent Mn deficiency is dependent on soil types and properties, fertiliser placement and macronutrients applied with the Mn. Optimum application rates are generally much lower for drilled than

broadcast applications. Reuter *et al.* (1988) concluded that broadcast applications of Mn are ineffective due to more contact with reactive soil constituents and poor contact with the acidic environment of the fertiliser granule.

Banded applications of Mn, although effective, have been reported to be injurious to soybeans (Alley *et al.* 1978; Boswell *et al.* 1981) and peanuts (Hallock 1979) on sandy soils, especially where moisture is limiting.

On soils of high pH, because of the rapid reversion of manganous salts to less available forms, there is almost no residual value of fertiliser Mn; indeed, in these soils applications may even fail to correct deficiency in the year of application. This system is inefficient in terms of productivity per unit of applied Mn fertiliser. Other methods of ensuring adequate Mn nutrition of seedlings until enough leaves have been produced to intercept foliar applications are required.

Foliar Applications of Mn

Foliar applications of Mn began in 1925 (McLean and Gilbert 1925) and have been a common practice on calcareous soils ever since. Foliar applications of Mn allow more uniform distribution to the crop and are more effective per unit of applied Mn than soil applications. Application rates, source and concentration of sprays, timing and frequency of foliar applications are critical considerations in achieving the most efficient use of foliar applied fertiliser.

Sulphates, chelates and Mn-containing fungicides have been effective in correcting Mn deficiency in crops and fruit trees. $MnSO_4$ is most widely used at high rates (≥ 5 kg Mn ha^{-1}) and high volumes ($\geq 1000l$ ha^{-1}) to maximise absorption by the foliage; additions of $Ca(OH)_2$ or Na_2CO_3 can be used to neutralise the spray solution and reduce leaf damage (Labanauskas *et al.* 1969). Although the amount of Mn applied in one foliar application

may be greater than the total requirement of the whole crop, foliar symptoms of Mn deficiency may reappear. This is because the Mn absorbed by the foliage is poorly redistributed to the new tissue. The use of lower rates (≤ 1 kg Mn ha^{-1}) and volumes (100 to 200 l ha^{-1} but can be as low as 20 l ha^{-1}), using ultra low volume spray equipment and the 'little and often' approach is now recommended (Reuter *et al.* 1988).

The timing of the first spray and the frequency of further applications are critical parameters in achieving the most efficient use of foliar applications. The first spray should be applied when foliar symptoms are first observed; when symptoms reappear further sprays should be applied immediately with the sprays being timed to maintain an adequate concentration of Mn in the plant during the exponential phase of growth (Reuter *et al.* 1973a). To maximise absorption, foliar sprays are best applied early in the morning or late afternoon under dewy conditions. Surfactants should be included in the spray solution to reduce runoff of solution from the leaves and to increase the rate and amount of nutrient absorbed (Cantliffe and Wilcox 1972).

Manganese Content of Seed

The nutrient status of seed has been shown to affect both seed viability and seedling vigour. Boswell *et al.* (1981) demonstrated that, for maximum yield of soybeans, the critical concentration of Mn in the seed was 16 μg g^{-1}. Marcar (1986) reported a critical concentration of Mn in wheat seed of 5 μg g^{-1} for maximum yield of the subsequent crop. *Lupinus angustifolius* seed low in Mn (7 mg kg^{-1}) had 35% non-viable seed and emergence reduced to 60% compared with 100% emergence for seed high in Mn (35 mg kg^{-1}) (Crosbie *et al.* 1993). Table 2.1 shows a list of critical nutrient concentrations below which seedling growth is impaired.

Table 2.1. Critical levels of nutrients in seeds for normal seedling growth.

Element	Species	Critical Level (mg/kg)	Reference
Molybdenum	maize	0.08	Wier and Hudson (1966)
Nickel	barley	0.1	Brown et al. (1987)
Boron	green gram	15	Rerkasem et al. (1990)
Boron	black gram	14	Rerkasem et al. (1990)
Manganese	lupins	10	Hannam et al. (1984)
Manganese	soybeans	16	Boswell et al. (1981)
Manganese	wheat	5	Marcar (1986)
Zinc	wheat	5-10	Al-Samerria (1984)

As with P, the Mn content of seed has been shown to increase early seedling vigour and in some cases grain yield of wheat (Marcar and Graham 1985; Singh and Bharti 1985; Marcar and Graham 1986), barley (Longnecker et al. 1988; McEvoy et al. 1988) and soybean (Boswell et al. 1981). The Mn content of barley seed has been demonstrated to affect both dry matter production, and subsequently grain yield, when grown in a highly calcareous soil of low Mn availability, regardless of whether the soil had been fertilised with Mn or not. Longnecker et al. (1988) reported that high amounts of seed Mn increased dry weight of roots and shoots, plant survival and in some cases grain yield. The roots were more sensitive to increased seed Mn than the shoots; these workers suggested this was because Mn in the seed was concentrated in the embryonic root tissue. The most successful treatment in overcoming Mn deficiency was a combination of seed of high Mn content and fertiliser applied Mn (Longnecker et al. 1988).

For farmers in southern Australia on soil types low in Mn, seed Mn concentration may be an important consideration for the successful establishment of cereal crops (Marcar and Graham 1986; Longnecker et al. 1991). Whilst soil applications of Mn at sowing have been shown to increase levels of Mn in the grain (Graham et al. 1985) in conditions of severe Mn deficiency (highly calcareous soils of high pH), the increases are not large. This is because Mn applied at sowing is quickly rendered unavailable (Reuter and Alston

1975) and inadequate to supply the full Mn requirement of cereals. Applications must be followed by at least one and sometimes two or three foliar applications of Mn during tillering for optimal grain yield. Even then, in spite of large increases in yield, this will still result in low levels of Mn in the seed (as low as 5 mg Mn kg^{-1} of seed or on average 0.17 μg of Mn seed^{-1} for barley). This is at the lower end of the range of seed Mn levels reported by White *et al.* (1981) in a survey involving 15 sites in Western Australia, where barley seed concentrations ranged from 6 to 118 mg Mn kg^{-1}. Longnecker and Uren (1990) reported that seasonal effects had a small influence on the Mn content of seed, whereas site variations (soil type, pH, Mn availability) had a large effect.

In addition to being important for subsequent plant growth, seed nutrient levels may also be an important consideration in quality for end-product use (Welch and House 1984, Welch 1993), especially in areas where a high dependency on grain food may result in nutrient deficiencies (notably iron (Fe) and Zn) in susceptible human populations. Seedling nutrition has also been shown to be an important factor in plant susceptibility to pathogens (as reviewed by Graham 1983, Graham and Webb 1991); seed nutrient levels which fail to maintain adequate nutritional status of seedlings in infertile soils may result in a decrease in plant resistance to some seedling diseases.

The Mn nutrition of wheat has been shown to affect the incidence of take-all (*Gaeumannomyces graminis* var. *tritici*) (Graham and Rovira 1984). Since the effects of Mn on the incidence of take-all have been demonstrated as early as 26 days after sowing, it seems probable that early acquisition of Mn from the seed may also reduce disease incidence.

Seed Soaking

Soaking seeds in solutions containing one or more micronutrients prior to sowing has been effective in overcoming deficiencies of these nutrients. Dutoit (1962), soaked maize

seed in solutions containing Mn, Zn, Fe, B, molybdenum (Mo), or cobalt (Co) and recorded the highest yields in a field experiment where ammonium molybdate had been the soaking solution. In this study, where Mo was the limiting nutrient, no deleterious effects were reported from any of the treatments.

Donald and Spencer (1951) investigated whether the full requirement of subterranean clover for Mo could be met by seed soaking; they found that both soil- and seed-applied treatments were equally effective but concluded that, for perennial species, there was no value in seed soaking since in subsequent years an additional application of Mo to the soil would be required. These workers did not however investigate the residual value of Mo applied either to the soil or the seed.

Soaking seeds in solutions containing Mn was first tested by Voelcker in 1903. Another study (Drennan and Berrie 1961), using seed soaked in manganous chloride to alleviate Mn deficiency in oats, demonstrated that the full requirement of the crop could be supplied by seed soaking without reducing germination. In a similar study Marcar and Graham (1986), reported that, although soaking wheat seed in $MnSO_4$ prior to sowing increased the Mn content of seeds, only 15-20% of this was recovered in the seedlings 26 days after sowing. This study was conducted on an extremely Mn deficient, calcareous soil (pH 8.5), and the experiment was not taken through to grain yield. In other studies by these workers, sowing seed that had been soaked in $MnSO_4$ was not sufficient to supply the full Mn requirement of cereals under extremely deficient conditions.

It is possible that in less severe situations, similar to those of Drennan and Berrie (1961) that the full requirement of wheat for Mn could be supplied by seed soaking without detrimental germination effects. Marcar (1986) reported a critical Mn seed concentration of wheat for maximum yield. Artificially enhancing seed Mn by soaking seeds in $MnSO_4$ prior to sowing was effective in supplementing internal seed Mn (Longnecker *et al.*

1991). However, as mentioned earlier, this technique may not be easily adapted to broad scale farming. Wilhelm et al. (1988) demonstrated that artificially increasing the Mn content of wheat seed by soaking in 1.5% w/v $MnSO_4$ solution (using the method described by Marcar and Graham 1986) decreased by half the length of take-all lesions per plant when compared with the nil Mn treatment, for wheat grown in a severely Mn-deficient soil, but it was not as effective as a soil application of $MnSO_4$ (0.36 g Mn/kg of soil).

Soaking tomato seeds in $MnSO_4$, $ZnSO_4$ or H_3BO_3 prior to sowing increased germination, decreased disease and consequently increased yield of tomatoes (Beleva 1974).

In a study comparing methods of application of Cu and Mn for wheat, Khalid and Malik (1982) reported that seed soaking was superior to either soil application or foliar sprays and could supply the full plant requirement. In their studies, the period of soaking was not critical with no difference being found between soaking for 12 or 24 hours. This is an important result when considering damage due to imbibition of toxic amounts of fertiliser or to disturbance to the germination cycle during the critical stage of imbibition. Aleshin et al. (1989) soaked seeds of rice in solutions containing 0.05 or 0.1% Cu and compared these seed treatments with soil application (3 kg Cu ha^{-1}) and a foliar application of 0.1% Cu at tillering. Seed soaking increased germination of rice and increased grain yield more than the soil or foliar applications. Yield and 1000-seed weight of cotton seeds were increased by soaking seeds in a mixture of 0.005 % $CuSO_4$+$MnSO_4$+$AlSO_4$ (Khodzhaev and Stesnyagina 1989).

In a study with barley, Ismail et al. (1980) soaked seeds for 3 hours in 0.4% $ZnSO_4$, 0.6% $MnSO_4$ or 0.8% $FeSO_4$ or a mixture of these and observed shorter germination time and greater percentage germination. The largest yields were observed where seeds had been soaked in the mixed nutrient solution prior to sowing. Zinc uptake was increased where seed had been soaked in Zn or Zn+Mn solutions but decreased where Fe

had been added in addition to Zn. Uptake of Mn was increased by soaking seed in a Mn solution in combination with other trace elements; however, the uptake of Fe was greatest where seed had been soaked only in $FeSO_4$. In contrast, for maize seeds, soaking in solutions of B, Cu, Mn, Mo or distilled water depressed yields (Kereszteny 1973).

Seed Coating

The first report of seed coating with Mn was in 1910; Nazari coated seeds with Mn oxide (Nazari 1910, as cited by Graham and Quirk 1988). Seed coating with $MnSO_4$ has since been demonstrated as a cost-effective method of establishing barley plants under conditions of acute Mn deficiency (McEvoy *et al.* 1988); it can also ensure early seedling vigour and production of leaves to intercept foliar sprays. It can also be effective in protecting wheat plants against root diseases such as take-all. (Huber and Dorich 1988, Huber and Wilhelm 1988). Huber and Dorich (1988) showed that enhancement of seed Mn by coating seed with $MnSO_4$ (0.6 to 1.0 kg ha^{-1}) prior to sowing was effective both in supplying Mn and in reducing take-all.

Seed coating with Mn was also successful in alleviating Mn deficiency and increasing dry matter production of oats (Berkenkamp and McBeath 1966). These workers coated oat seed with Mn ammonium phosphate and included Ceresan M (active ingredient: ethyl mercury *p*-toluine sulfonanilide) in the pellet as an anti-microbial agent, to reduce the oxidation of applied Mn to unavailable manganic oxides by Mn-oxidising microorganisms. Grain yield was increased only when Ceresan M was used in combination with Mn ammonium phosphate. There were no deleterious effects on germination or any toxicity symptoms produced due to the coating treatments in this study.

Seed coating with Mn is particularly convenient for correcting Mn deficiency in sugarbeet; Mn deficiency in sugarbeet had been difficult to correct since growers do not

drill fertiliser with the seed but broadcast macronutrients prior to seeding and band N between the rows away from the seed. Sugarbeet seeds are commercially pelleted to facilitate planting; consequently, the incorporation of Mn into the pelleting material is a unique opportunity of supplying Mn at sowing without changing farmer practice. In a study by Farley and Draycott (1978), Mn incorporated into the pellet prevented early symptoms of Mn deficiency and reduced the number of foliar sprays required. However, it was deleterious when Mn ammonium phosphate was the source of Mn. Incorporating Mn in the pelleting material substantially increased the concentration of Mn in tissue of sugarbeet. Of the materials tested, Mn sulphate and Mn oxide incorporated in the pellet material were most effective; the sulphate increased Mn concentration of tissue more than the oxide but was phytotoxic in slightly acid soil conditions whilst the manganous oxide was not. Farley and Draycott (1978) concluded that incorporating manganous oxide in the pelleting material was an economic and effective method of supplying Mn to sugarbeet.

In subsequent experiments, Farley (1980) studied pellets containing 50% MnO (62% Mn) under a range of soil conditions to investigate any adverse effects during germination and emergence. There was no deleterious effect due to incorporating MnO in the pellet; in fact seed pelleted with MnO germinated more quickly, probably due to enhanced availability of water to the germinating seed (Farley 1980).

Steeping sugarbeet seeds in the fungicide thiram for 8 hours at 25^{0}C was introduced as a control measure for *Phoma betae* (which causes black leg in sugarbeet); this treatment also increased the speed of germination and improved establishment. However, when this was used in combination with manganous oxide in the seed pellet, emergence was both delayed and reduced and the Mn was no longer in a plant-available form (Fletcher and Prince 1987). Consequently, commercial production of manganous oxide seed pellets was discontinued.

2.3.3 Fertiliser Injury associated with Mn fertilisers

At normal fertiliser application rates, seedling damage by micro-elements is rare, since they are applied only in small amounts. However, some instances of damage occur where the soil supply is already plentiful so that toxicity may be induced, or interactions between the fertilisers can cause injury. The calcium/boron ratio has been implicated as important for B toxicity of seedlings (Gupta *et al.* 1985).

Trace element fertiliser studies indicated that soybean accumulated less zinc than maize when fertilised with liquid digested sludge, but expressed toxicity symptoms and reduced growth whereas maize, with higher tissue concentrations did not show toxicity (Lutrick *et al.* 1980). Species difference in tolerance to toxicities is important and needs to be considered in devising fertiliser practices.

Since the plant requirement and amount of Mn applied at seeding is much less than for the macronutrients, there are relatively few reports in the literature of fertiliser injury due to rates and placement of Mn fertilisers. Banded applications of 11.2 and 16.8 kg Mn ha^{-1} prevented emergence of soybean in a coarse textured sandy loam under drought conditions and delayed emergence for 4 to 5 days when grown on a loamy sand under adequate moisture (Alley *et al.* 1978). Side dressing of soybeans with 22.4 kg Mn ha^{-1} resulted in crinkle leaf (a symptom of Mn toxicity in this crop) (Boswell *et al.* 1981). Manganese applied in the row with peanut seed has been reported to suppress early growth on light soils where moisture is limiting.

Manganese sulphate incorporated in the pellet material of sugarbeet seeds reduced seedling emergence by 17%, whilst incorporating Mn chelate reduced emergence by 42% when sown in acid potting soil, but the latter had no effect when sown in alkaline soil

(Farley and Draycott 1978). Manganese oxide in the pelleting material, however, was not injurious under any conditions and in fact improved emergence.

2.4 Nutrient seed coating

Seed coating is the application of solids to seeds to form a continuous layer covering the seed. Coatings may be used to increase the size and weight of seeds, to modify the shape to facilitate planting (e.g. rounding of sugarbeet seeds), to improve ballistics for aerial sowing, and to apply fungicides, microorganisms, osmoconditioning agents, insecticides and nutrients to seeds.

The preceding sections have introduced the concept of coating seeds with nutrients, a technique that may be most advantageous for nutrients which are rapidly reverted to unavailable forms, thereby ensuring that sown seeds are supplied with a precise readily accessible amount of nutrient. Nutrient seed coatings need to be evaluated for efficiency of fertiliser usage and injurious effects on plant establishment. Methods of reducing the injury can be developed to increase the prospects of economic systems of seed coating. This may require incorporating other compounds within the coating to reduce deleterious effects. A combination of nutrients may be included in the coating to increase the potential applications for coated seeds. The practicalities involved in sowing coated seeds and the safety to seedlings need to be considered in detail. Similarly, the period over which seeds remain viable after coating is an important consideration that requires resolution.

Much of the research into seed coating has concentrated on the applications for pastures and horticultural crops. Relatively few reports of seed coating for cereals are available.

2.4.1 Macronutrient Coatings

Seed coatings containing concentrated salts of soluble fertilisers have been shown to be injurious to germination and early growth (Scott 1975). In contrast, low rates of macronutrient fertilisers used for coating have in some cases produced substantial benefits. Seed coating with P increased total dry matter, nodulation and N-fixation of *Centrosema pubescens* (Paterno and Bayani 1978, Paterno and Espiritu 1978); increased by a factor of 2 to 4 the establishment of ryegrass (Vartha and Clifford 1973); increased survival of lettuce (Sharples and Gentry 1980); was shown to be superior to broadcast applications of P for wheat (Fiedler *et al.* 1983), and was 3 to 4 times more effective in supplying P for corn than banded applications (Smid and Bates 1971). Pelleting of maize seed with a mixture of P, K, B and humic acid delayed emergence but increased grain yields (Mao, Lock and Wang 1980).

Sulphur incorporated into coating materials has been effective in overcoming S deficiency in clover (Lowther and Johnstone 1979). It has also been more effective than broadcast applications on *Stylosanthes guianensis* (Gilbert and Shaw 1979), and has doubled the establishment of oversown legumes (Scott and Archie 1978). A combination coating containing Mo, S and P increased establishment of clovers (Scott and Hay 1974).

2.4.2 Micronutrient Coatings

There are many reports in the literature of coating seeds with Mo, most often for legumes, since Mo is required for nitrogen fixation. Molybdenum seed coatings have been reported to increase establishment of clover (Scott and Hay 1974); increase yield of soybeans (Boswell 1980); increase dry matter and yield of cowpeas (Rhodes and Nangju 1979); alleviate Mo deficiency in *Desmodium intortum, Neonotonia wightii, Lotononis bainesii* and *Macroptilium atropurpureum* (Kerridge *et al.* 1973); and to correct Mo deficiency in cauliflowers (Scheffer 1978). In a study testing compatibility of Mo coating

materials with rhizobia, Gault and Brockwell (1980) found that of 4 sources of Mo tested only sodium molybdate suppressed nodulation. For pigeon pea, Khan and Hedge (1989), reported that seed coatings of Mo increased nodule number, nodule dry weight, shoot and root dry weight. Lapinskas (1990) reported increased yields of clover and lucerne from combination coating of inoculum with treatments of B and/or Mo.

Seed dressings of B, Cu, Mn, Mo or Co have been shown to increase yield of spring wheat (Kudashkin 1989) whereas in the same study dressings of Zn or a mixture of all trace elements were not effective. For sunflowers, Glushchenko *et al.* (1991) reported yield increases of 0.49-0.57 t ha^{-1} from seed treatments of Mo, Co or Zn chelate but this was less effective than chelates. Zinc seed coatings have increased yields of rice (Thomson and Kasireddy 1975; Mengel *et al.* 1978) and, when used in combination with P, seed coating with $ZnSO_4$ increased plant available P and Zn in the soil surrounding the seed of wheat (Gawade and Somawanshi 1979).

2.4.3   Efficiency of seed coating compared with conventional fertiliser applications

The placement of fertiliser in close proximity with the seed has generally been shown to be more effective in terms of yield/unit of applied fertiliser than broadcast methods of application. The application of nutrients directly to the seed in precise amounts that may be preferentially available to the sown seed rather than fertilising a larger volume of soil and weed species (Scott 1986), could be the ultimate progression in terms of efficiency of fertiliser use. The effectiveness of nutrient seed coatings is dependent on several interacting factors; these include species, time of sowing, soil type, texture and fertility and the coating materials used. This section concentrates on the efficacy of usage and the possibility of supplying the full plant requirement of the element concerned.

In a series of three pot trials comparing the efficiency of banded applications with coating corn seeds with N, P and K, Smid and Bates (1971) reported that the coated fertiliser was 3 to 4 times more efficient in supplying phosphorus to the seedlings for the first 20 days, after which roots of the banded treatments were able to explore the fertiliser band and take up P more quickly.

Another trial exploring the possibility of using a combination coating of P and Zn on wheat (Gawade and Somawanshi 1979) was conducted in a situation where zinc was not limiting. The authors concluded that the technique was advantageous; their study used dicalcium phosphate (DCP) a relatively insoluble and unavailable form of P. Mengel *et al.* (1978) reported that coating rice seed with zinc oxide increased yields. Similarly, coating maize seed with a mixture of superphosphate, potassium sulphate, humic acid additive and borax increased grain yields but delayed emergence (Mao *et al.* 1980).

The relative efficiency of coating wheat seed with monocalcium phosphate (a soluble P source) was demonstrated in an experiment conducted in pots (Scott *et al.* 1991) in which rates of drilled monocalcium phosphate (MCP) were compared with rates of MCP coated. They demonstrated that low rates of P (5 kg ha^{-1}) applied as a seed coat resulted in vegetative yields equivalent to yields that would be attained from drilled applications of 17 kg ha^{-1} and 20 kg ha^{-1} for low and high P-sorbing soils respectively. Similarly plant P uptake during early growth for a coating equivalent to 5 kg ha^{-1} was as efficient as drilled applications of 10 kg ha^{-1} on a low P-sorbing soil and slightly less (8 kg ha^{-1}) for a soil with high P sorption capacity.

Phalaris seeds coated with either MCP or DCP yielded more than either drilled or broadcast treatments (Scott and Blair 1988). These authors found that lucerne in contrast showed no response to the DCP coating and yields were reduced by MCP, owing to reduced emergence.

Sulphur incorporated in the seed coat of pasture seeds was more efficient than S broadcast as superphosphate at equivalent rates of S, and increased the N yields. There was a large residual effect lasting 3 years, possibly due to supplying a slowly available source of S (Gilbert and Shaw 1979).

2.4.4   Tolerance to injury

It was reported in Section 2.3 that fertiliser placement was important in avoiding damage to the germinating seedling. It seems probable that nutrient seed coatings would be more injurious than fertiliser granules placed in contact with the seed. Seed coating with nutrients may mean reduced inputs of fertiliser but, injury may still result due to the intimate contact between seed and fertiliser. The studies on fertiliser injury in relation to tolerance of species and effects of soil moisture and texture on injury (eg Olsen and Drier 1956, Nyborg 1961, Carter 1967, Mason 1971) need to be verified under conditions of nutrient seed coating. For seed coating to be adopted as a commercial practice in broad scale farming, the formulation of coatings that are safe to seeds under a wide range of soil moisture and texture is essential.

Seed structure has been reported as a mechanism by which pasture seed is protected from fertiliser injury (McWilliam and Phillips 1971, Silcock and Smith 1982, Scott 1986, Garrote *et al.* 1987, Garrote *et al.* 1989a). For five grass species Garrotte *et al.* (1987), showed by removing the lemma/palea, that the outer structure protected the seed from injury due to P coatings. Emergence was not affected by P seed coatings of intact seeds but was greatly reduced by P seed coating, when the outer seed structure was removed. In a later experiment, with phalaris and cocksfoot, Garrote *et al.* (1989a) suggested that the lemma/palea may protect the caryopsis from injury by slowing down germination and not by slowing imbibition.

Combined fertiliser seed coatings containing N, P and K were more damaging to the emergence of corn than were banded fertilisers (Smid and Bates 1971). These authors investigated protective pre-coatings as a method of reducing injury. Sucrose and polyvinyl acetate improved germination considerably. The reduction in injury attained by using polymer coatings may be due to delayed imbibition until the phosphate has been rendered less available, rather than to reducing ion uptake (Scott and O'Donnell 1987).

The emergence of wheat seeds was not affected by seed coatings of $Ca(NO_3)_2$ but was reduced and delayed by coatings of MCP, or $(NH_4)_2SO_4$ and was further reduced and delayed by coating with $MCP+Ca(NO_3)_2$, or $MCP+(NH_4)_2SO_4$ (Scott et al. 1987)). The presence of a urease inhibitor included in a urea coating markedly reduced germination injury caused by the urea coating. In the same study the pH of the seed coat was not correlated with germination as Scott (1975) had suggested for seed coatings on pasture seeds.

There may be potential for seed coating with slow release fertilisers as a means of reducing injury while still supplying the desired amount of nutrient (Scott and Hay 1974). Scott (1975) suggested that the detrimental effects on germination may be offset by the increased seedling vigour, early availability of nutrients and increased fertiliser efficiency. Delayed emergence however, can be detrimental; seedlings are prone to attack by pathogens between imbibition and emergence (Farley 1980).

Some evidence for species difference in fertiliser tolerance for coated seeds has been reported. In general the trends follow those for banded fertiliser placement (Scott and Blair 1985; Ascher et al. 1987). The effects of limiting moisture also need investigation.

2.4.5 Combination Coatings

Coatings containing several nutrients have been investigated (Gawade and Somawanshi 1979, Scott *et al.* 1987, Garrote *et al.* 1989c, Kudushkin 1989, Glushenko *et al.* 1991). There are no reports in the literature of coatings containing multi-element, fungicide, herbicide and herbicide-antidote combinations (Scott 1989). With greater understanding of the behaviour and performance of coating materials it should be possible to formulate combination coatings to improve the establishment of crop species.

In their studies of nutrient seed coating for wheat and barley, Scott *et al.* (1987) combined P and N coatings with urease inhibitors and bentonites of differing pH in an attempt to reduce the injury. More research effort is needed into overcoming the adverse effects of seed coating if this is to be adopted for commercial practice.

2.5 Conclusions: The potential of nutrient seed coating for cropping

This review has highlighted the importance of seedling nutrition in enhancing seedling vigour and early growth of crops. Nutrient seed coating provides a unique opportunity of supplying precise quantities of nutrients close to the seed to enhance the nutrient status of seedlings. Nutrient seed coating may have an added advantage in that smaller amounts of nutrients applied to the seed may be as effective as large quantities applied to the soil, thus achieving an environmentally safer, more economic application of fertilisers.

Nutrient seed coating however may in some cases be injurious to seedlings due to the close proximity of seed and fertiliser. Fertiliser injury is a particularly complex phenomenon; many interacting mechanisms are involved and all of these are altered by environmental factors. This review has covered some soil chemistry in order to understand the mechanism of P and Mn uptake by the plant, particular attention having been paid to the efficiency of P and Mn fertiliser application methods. It has been argued

that, with the decline in availability of high grade rock phosphate, the low residual values of applied P and Mn fertilisers, and financial considerations, more efficient fertiliser practices need to be investigated. Nutrient seed coating has been suggested as one means of increasing the efficacy of fertiliser use.

Crops vary in their susceptibility to osmotic, toxic, moisture and temperature stresses. In considering nutrient seed coating as a potential technique for fertiliser application it is necessary to identify situations that should be avoided. Examples of these are coating seeds of sensitive species, sowing under conditions of limited moisture (if indeed this is a limitation for nutrient seed coatings), coating seeds at concentrations likely to be damaging, and sowing coated seeds on coarse textured soils.

The technology for seed coating needs to be developed further. There is potential for a combination, multi-element seed coating which may also include a herbicide, fungicide or *Rhizobium* inoculum. Large inputs into developing protective preparations to be included in the coating e.g. polymer pre-coatings, slow release fertiliser formulations and herbicide antidotes could return benefits through reduced use of herbicides, more efficient usage of fertilisers, and more effective inoculation. It is also feasible that nematicides and other agents could be applied via seed coating to reduce the incidence of soil-borne diseases.

The experiments presented in the following chapters were designed to investigate the potential for P and Mn seed coatings for crops. Field studies have been undertaken over several seasons, because it is important to assess performance of seed coating under variable, uncontrolled field conditions. Fertiliser injury due to P seed coating is investigated in Chapter 3; the tolerance of 8 species to P-coating and the influence of soil moisture and texture on fertiliser injury are described, with a view to avoiding situations that may cause delayed and reduced emergence. The efficacy of P and Mn seed coating is

discussed in Chapters 4 and 5. Chapter 6 addresses the importance of seed Mn content on seedling vigour, Mn uptake and subsequent grain yield of barley. In this same chapter a method of ensuring enhanced Mn content of seeds from barley grown under extreme Mn deficiency is described. The relative importance of seed Mn content and Mn-coating are also discussed in Chapter 6. The concluding discussion, Chapter 7 integrates the results of all of the experiments and discusses their implications.

Chapter 3

FERTILISER INJURY DUE TO PHOSPHORUS SEED COATINGS: INFLUENCE OF SPECIES, SOIL MOISTURE AND TEXTURE.

3.1 Introduction

Nutrient seed coating has been shown to increase the effectiveness of fertiliser applications when compared with drilled applications (Smid and Bates 1971, Scott *et al* 1991). However, this close placement of fertiliser and seed has also been shown to be detrimental during germination/emergence. Two components of fertiliser injury are a delay in emergence, and a reduction in the number of plants finally emerged. The degree of fertiliser injury due to close placement of drilled fertiliser has been shown to depend on fertiliser type, species, soil texture and soil moisture (Carter 1969, Olsen and Drier 1956), but little has been reported concerning injurious conditions for coated seeds. Nutrient seed coatings with relatively insoluble fertilisers were reported to be less damaging for pasture seeds than soluble fertilisers but they were also less effective as measured by yield per unit of applied fertiliser (Scott, *et al* 1985). If nutrient seed coating is to be developed as a technology which not only is effective in promoting growth but is also safe to agricultural seeds, there is a need to identify conditions under which coating may adversely affect emergence and establishment and, ultimately, to ameliorate any injurious effects.

Emergence experiments were conducted to identify when P-seed coatings would be likely to reduce, or cause a prolonged delay in emergence. Eight crop species were tested for tolerance to injury by P seed coatings. The environmental effects of soil moisture and soil texture on emergence of P coated seeds were investigated.

3.2 Materials and methods

Three emergence experiments were conducted under controlled environment conditions to investigate factors affecting the injury during emergence caused by phosphorus (P) seed coating with monocalcium phosphate (MCP). Tolerance of crop species to fertiliser injury and the effect of soil texture and moisture on fertiliser injury were studied.

General:

Seeds of uniform size were selected and coated in an inclined pharmaceutical tablet coating pan as described by Scott *et al.* (1987). The dry weight of adhesive incorporated in the coating was disregarded in calculating the amount of coating since it was less than 2% of the dry weight of material applied. In all experiments of this chapter there were two controls: one consisted of raw or uncoated seed and the other of an inert coating of diatomaceous earth, which had a volume of coating surrounding the seed similar to that of the medium P coating; this control treatment was included to enable the separation of the chemical and physical effects of the coatings. The experimental designs were randomised complete blocks with four replicates.

Emergence studies were conducted under controlled environment conditions with a temperature range of 20/15°C, on a 12/12 h cycle without lighting. The soil used in the first two experiments was the A_1 horizon of a gleyed podzolic (pH 5.4, 1:5 soil:water) known to be deficient in P with a bicarbonate extractable P level (Colwell 1963) of 5 mg kg^{-1}. Seeds were planted at a depth of 5 mm (canola) or 25 mm (all other species) in plastic trays 17.5 cm x 11 cm x 6 cm deep containing 590 g of air dry soil. Forty seeds of each treatment were planted in soil in these trays and were covered with friction fitting lids and placed in groups in large plastic bags to reduce moisture loss and avoid the necessity for further water addition. Emergence was counted twice daily during periods of rapid emergence and less frequently thereafter until emergence had ceased.

Experiment 1: Species tolerance

The eight crop species used were barley (*Hordeum vulgare* cv. Grimmett), oats (*Avena sativa* cv. Cooba), wheat (*Triticum aestivum* cv. Banks), sorghum (*Sorghum bicolor*-hybrid E57), canola (*Brassica napus* cv. Marnoo), sunflower (*Helianthus annuus* cv. Hysun), soybeans (*Glycine max* cv. Forrest), and lupins (*Lupinus angustifolius* cv. Chittick). They were coated with three levels of monocalcium phosphate (MCP), (32, 64, and 96 g/ 100g of uncoated seed of each species). Seeds were planted in soil with a moisture content equivalent to 69% of field capacity (FC).

Experiment 2: Soil moisture

The four species investigated in this study were sunflower, sorghum, soybeans and wheat. The cultivars sown were as in the first experiment with 3 seed treatments (uncoated, inert and 64 g MCP / 100g of seed) and 3 soil moisture regimes (69, 98 and 124% of FC). The two lower moisture treatments were prepared by mixing soil with distilled water atomised through a sprayer, in a cement mixer prior to planting. The 124% FC treatment was wetted to 98% in the same way and after planting the additional water was added to the soil surface to avoid the very moist soil forming balls during mixing. Water was added to super saturate the soil. The trays were wetted to the equivalent of 128% FC. However, because of drainage in the deep trays used the moisture content in the vicinity of the seeds was 124% FC.

Experiment 3: Soil texture

The effect of soil texture on injury during emergence was investigated for wheat and sorghum using two natural soils and two mixtures of these in 1:2 and 2:1 proportions to produce soils with a range of clay contents (10, 26, 43 and 60%), each sown with 4 coating treatments (raw, inert, 96 and 128 g MCP/100 g raw seed).

The soils used were the gleyed podzolic described earlier (clay content 10%, CEC 36 m mol(p^+)kg^{-1}, pH 5.4 (1:5, soil:water)) and a black earth (clay content 60%, CEC 469 m mol(p^+)kg^{-1}, pH 6.1 (1:5, soil:water)). The soils were air dried, weighed and mixed

individually for each tray. A bottom layer was mixed, dumped into the tray quickly to avoid separation of particle sizes and wetted to field capacity using a fine spray of distilled water. After equilibrating for 24 hours, 40 seeds were placed on the surface of this lower layer, covered with a top layer of the appropriate soil or soil mixture and wetted to field capacity (appropriate for each soil) in the same way.

Mitscherlich functions were fitted to the raw emergence data providing three parameters: time to first emergence t_0; final emergence A; and the emergence rate factor, k (Scott *et al*, 1985). These parameters were analysed using Tukey's Honestly Significant Difference for each species (Sokal and Rohlf 1969).

3.3 Results

Emergence as a function of time fitted the general pattern described by the Mitscherlich equation $y = A(1-e^{-k(t_i-t_0)})$.

Where y is the number of seedlings emerged at t_i,

> A is the asymptote or final emergence,

> k is the emergence rate factor after emergence has begun, and

> t_0 is the number of days from sowing to first emergence.

In all three experiments the MCP coated treatments had an effect in both delaying emergence and reducing the final number of plants emerged. The emergence data for wheat seed coated with three levels of MCP and two controls (Experiment 1) are shown in Figure 3.1 as an example of emergence data.

Experiment 1: Species Tolerance

All MCP seed treatments delayed emergence of all species in a similar way to that shown for wheat in Fig 3.1. For the uncoated and inert treatments, 90% of sown wheat seed had germinated in 4 days; this level was not achieved by any rate of MCP coating. For wheat, after eight days, seeds in the MCP 96 treatment had 20% emergence whilst for
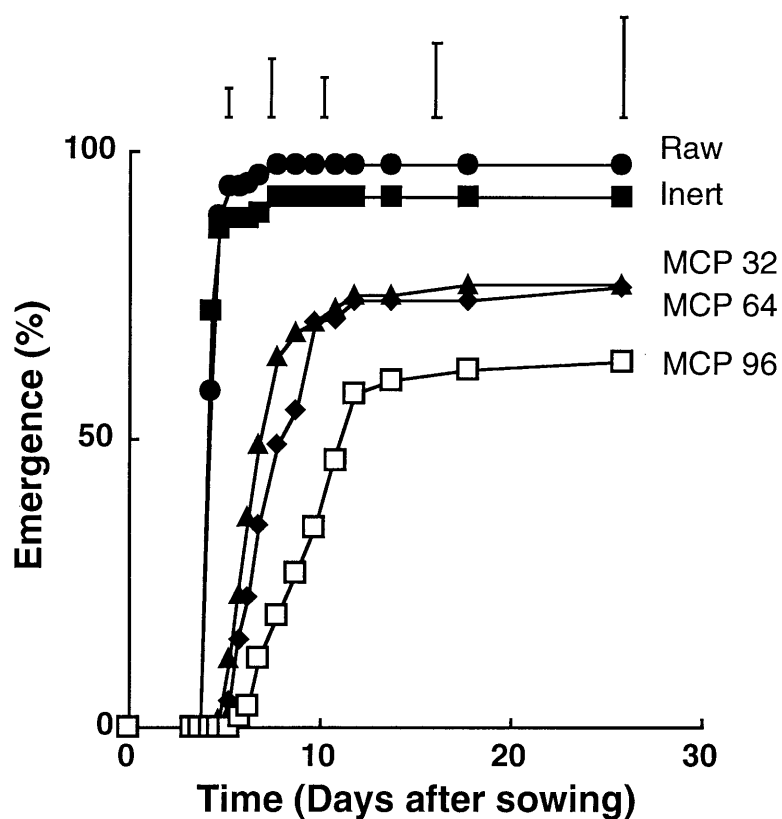
Figure 3.1. Effect of three rates of MCP seed coating on wheat emergence (Experiment 1). Vertical bars indicate the lsd values (P=0.05) for comparisons between treatments at various days after sowing.
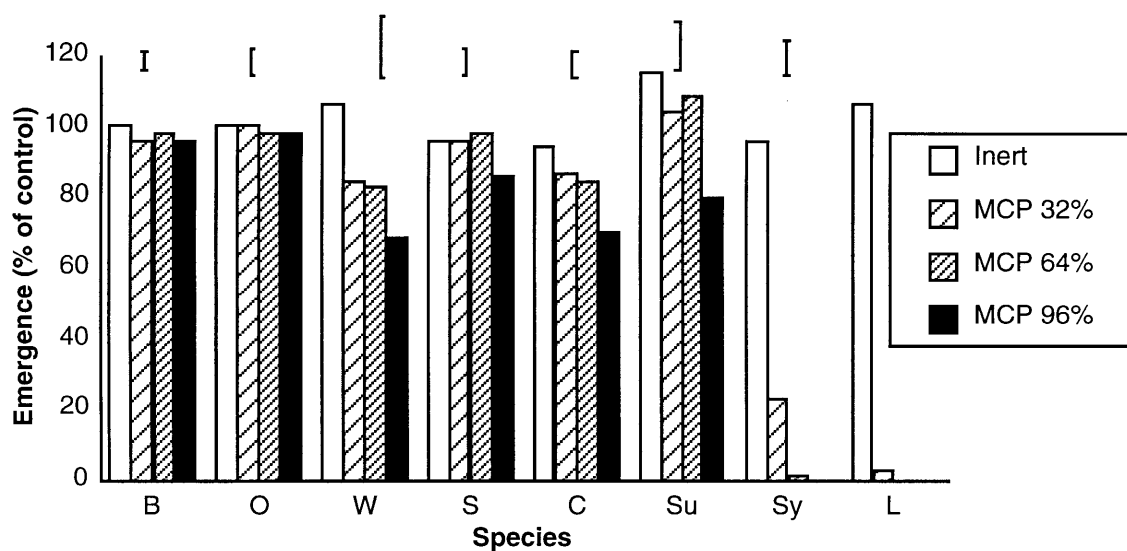

Figure 3.2. Final emergence of eight crop species coated with an inert coating or with MCP at three rates. B-barley, O-oats, W-wheat, S-sorghum, C-canola, Su-sunflower, Sy-soybean, L-lupins. Vertical bars indicate lsd values (P=0.05) for comparison of coatings within each species. Emergence is expressed as a percentage of the uncoated control of each species.

lower rates of MCP coating, emergence was greater than 50%. For final emergence, the species varied in tolerance (Fig 3.2). Barley and oats were most tolerant (no reduction in final emergence) wheat, sorghum and sunflower intermediate (reduction only at the highest rate) and canola, soybean and lupins were most sensitive (reduction at all rates of MCP). Soybean and lupins appeared particularly sensitive to even the lowest rate of MCP coating.

Experiment 2: Soil Moisture

MCP treatment both delayed and reduced emergence for all species at all soil moisture contents (Fig. 3.3). For all seed treatments, wetter soil conditions decreased time to first emergence. There was no effect of soil moisture on final emergence of MCP coated seeds for wheat or sorghum. For sunflower there was little effect of MCP coating on emergence at the 124%FC moisture (Fig 3.3c). However, emergence of the MCP coated seed in the two drier soil treatments was delayed, the emergence rate factor was slower and final emergence was reduced to 85% at 98%FC and 74% at 69%FC. For soybean no seeds emerged from MCP coated treatments at the 69% or 98% FC moisture treatments whereas 17% of seeds emerged under the wetter conditions (Fig. 3.3d).

Experiment 3: Texture

Species, clay content and rate of seed coating all significantly affected ($P<0.05$) seedling emergence. Mitscherlich functions were fitted using the process of least squares non-linear regression to all emergence curves. The parameters obtained were statistically analysed separately for each species . The values of these parameters for each coating over the four textures are shown for sorghum and wheat (in Tables 3.1 and 3.2 respectively).
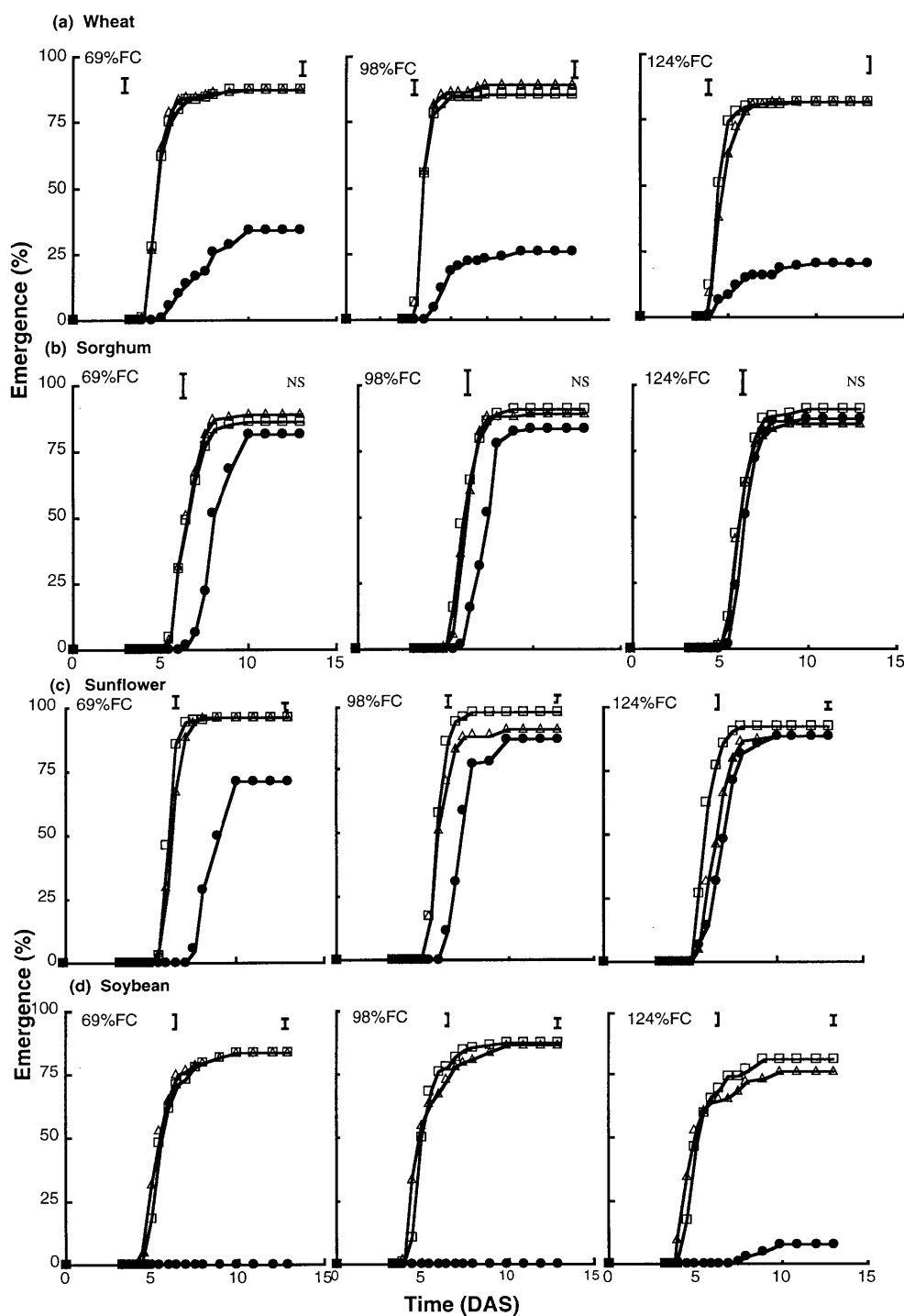
Figure 3.3. Effect of soil moisture and seed coating on emergence of coated seeds for 4 species. (a) Wheat (b) Sorghum (c)Sunflower (d) Soybean. Raw seed (□), inert coated seed (▲) and MCP coated seed (●). Vertical bars indicate lsd values (P=0.05) for comparison between treatments at various days after sowing.

Table 3.1. Parameters of Mitscherlich curves fitted to the emergence data for four coating treatments of sorghum sown in 4 soils of different texture.

Soil texture Clay (%)	Coat Treatment	Final Emergence (%)	Emergence rate factor	Time to first emergence (days)
10	Raw	78.0	0.91	6.6
	Inert	83.8	1.05	6.5
	96%	80.2	1.39	8.4
	128%	60.9	0.77	8.4
27	Raw	80.9	1.08	6.6
	Inert	90.6	0.77	6.2
	96%	82.4	0.69	7.0
	128%	72.6	0.92	7.6
43	Raw	80.0	1.26	6.3
	Inert	82.7	1.12	6.3
	96%	72.8	0.99	6.9
	128%	79.5	0.81	7.1
60	Raw	83.6	1.11	6.2
	Inert	83.1	1.05	6.2
	96%	70.2	0.84	6.8
	128%	84.3	0.81	7.0
Tukey's Honestly Significant difference (P,0.05)		15.7	0.83	0.4

Table 3.2. Parameters of Mitscherlich curves fitted to the emergence data for four coating treatments of wheat sown in 4 soils of different texture.

Soil texture Clay (%)	Coat Treatment	Final Emergence (%)	Emergence rate factor	Time to first emergence (days)
10	Raw	89.9	2.46	4.7
	Inert	86.7	1.47	4.4
	96%	72.5	0.62	5.8
	128%	49.6	0.50	6.7
27	Raw	91.1	3.98	4.8
	Inert	86.0	2.93	4.4
	96%	76.2	0.72	5.2
	128%	78.8	0.53	5.4
43	Raw	89.2	2.46	4.5
	Inert	90.1	1.81	4.2
	96%	74.8	0.94	4.9
	128%	65.5	0.75	5.1
60	Raw	88.8	2.03	4.3
	Inert	86.9	1.93	4.1
	96%	76.1	1.18	4.7
	128%	56.1	0.78	5.0
Tukey's Honestly Significant difference (P,0.05)		11.7.	1.8	0.5

Time to first emergence (t_o) was the parameter most sensitive to soil texture. The rate factor k was most affected by species, but for wheat was also dependent on clay content and coating treatment. The asymptote A (final emergence) was unaffected by clay content and most affected by coating treatment.

3.4 Discussion

The dominant effect of seed coating in these experiments was due to its chemical composition rather than physical effects, since the inert coating did not delay or reduce emergence. The deleterious effects of MCP seed coating may have been exaggerated by not watering after sowing compared with the field situation where subsequent rainfall may result in leaching of the nutrients away from the seed and consequently less injury.
In this study, of the cereal species, barley and oats were found to be most tolerant of seed coating and wheat less tolerant. This agrees with Guttay (1957) who attributed the tolerance of oats to injury from superphosphate to the protection provided by the lemma and palea compared to the exposed seed of wheat. The same argument would apply to barley (also found tolerant in this study) and perhaps even to sunflower, with its hard natural seed coat (intermediate in tolerance this study). Oats were also reported to be more tolerant of seed coating with MCP than wheat in a similar study comparing amounts of MCP per seed (Scott et al 1987).

The tolerance of species to MCP seed coating generally follows the trends for drilled fertiliser (Carter 1969) in which cereals were found to be more tolerant than legumes with crucifers being the least tolerant. However, in the present study Marnoo canola was found more tolerant than either the lupin or soybean cultivars. This apparent tolerance of canola could be a result of comparing the rate of MCP coating on seed size rather than per seed, average seed size of canola being 3.6 mg compared with lupin or soybean at 168 and 133 mg respectively.

It could be argued that a better comparison could be made by comparing the same amount of P to each seed rather than comparing weights of material per weight of seeds. To consider this argument the emergence of species was plotted against the amount of MCP coating (Figure 3.4). Although the full range of coatings was not covered for all species, at 50 mg MCP coated per seed barley was more tolerant than sunflower which was in turn more tolerant than soybean or lupins. Canola appeared to be most sensitive, with reduction in emergence at smaller amounts of coating than any of the other species, but was tested over a narrow range only because of its small seed.
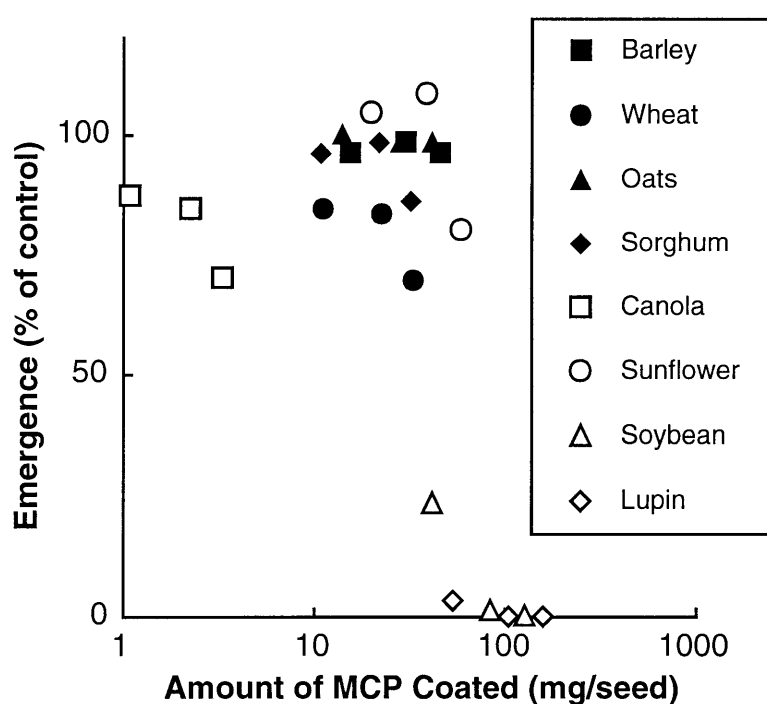

Figure 3.4. Effect of amount of MCP coating applied per seed on final emergence for eight crop species.

Scott (1986) further explored the hypothesis (proposed by Guttay in 1957 for oats) that the lemma and palea could be physically protecting the seed from fertiliser injury due to MCP by removing the lemma and palea of phalaris. Garrote *et al.* (1987) confirmed the hypothesis by removing the lemma and palea of five grass species and showed increased injury from MCP coatings when the lemma and palea were not present. In a series of three experiments, Scott (1989) showed that the lemma/palea protected the emerging

seedling from injury by delaying emergence and allowing some of the MCP to react with the soil, hence reducing the toxic effects.

In his synopsis of factors affecting fertiliser injury, Carter (1969) reported that conditions where moisture was limiting but sufficient for germination were more likely to reduce emergence. Similarly, Mason (1971) and Olsen and Drier (1956) reported a larger reduction in germination due to fertiliser injury at low levels of soil moisture. However, Oruk and Kilic (1975) did not observe any effect of soil moisture on injury during emergence of wheat sown with a band of P superphosphate above the seed. In studies with perennial ryegrass Scott *et al.* 1985 and Scott 1989 reported an interaction between seed coating and soil moisture content on seedling damage during emergence. The study of Scott *et al.* (1987) using the same soil as the present study demonstrated that when wheat was coated with urea (14.8 mg seed^{-1} equivalent to 10 kg N ha^{-1}) emergence was severely reduced; at a soil moisture of 69% FC, only a few seeds emerged, however, when soil moisture was increased to 124% FC, emergence from coated seeds was increased to 10%.

In the present study low soil moisture was found to delay time to first emergence and reduce the rate of emergence for all species, but had little effect on final emergence for wheat and sorghum. Low soil moisture (69%FC) did reduce final emergence of MCP coated seed for sunflower and soybean. The moisture treatments in this study were designed to be 68%, 96% and 128% of FC. However, in the highest moisture treatment because of the depth of the trays used the soil moisture content in the vicinity of the seeds was actually 124% due to drainage. Thus the water contents investigated were limited in range to those likely to be encountered at sowing in the field. Since MCP coating is less damaging to emergence than urea coating (Scott et al 1987) we would expect the effect of soil moisture on injury to be smaller for MCP coatings than urea coatings. A wider range of soil moisture levels and a more damaging level of seed coating for wheat and sorghum in the present study may have enabled better interpretation in terms of final emergence.

Carter (1969) also reported that fertiliser injury would be less in soils of finer texture than in coarse textured sand. Soils with higher CEC are likely to demonstrate less injury because toxic cations are adsorbed by the soil exchange complex (Stevenson and Bates 1968). In the current study both the uncoated and coated seeds in the finer textured black earth with greater CEC emerged earlier and had greater final emergence than those in the coarse podzolic sand with lower CEC. Maximum emergence and rate of emergence was at 26% clay for both species. However, this could be due to the movement of water to the seed (Collis-George and Lloyd 1979). Delay in emergence due to fertiliser injury was greatest in the coarse textured sand with lower CEC; however, final emergence was not affected.

This study has shown that injury due to close proximity of fertiliser with seed is greater on coarse textured soils with lower CEC and in conditions where soil moisture is limiting. Time to first emergence and rate of emergence were also more sensitive to fertiliser injury than final emergence. Seeds where the embryo is protected by lemma and palea are more tolerant of injury due to seed coating with MCP; cereals were more tolerant of P seed-coating than legumes and brassicas.

This study has extended the results of Carter (1967 and 1969) for injury due to placement of fertiliser drilled with the seed to the potentially more deleterious placement of fertiliser seed coating. The effects of soil moisture, texture and species on fertiliser injury are similar in both cases.

Chapter 4.

COMPARISON OF THE EFFICIENCY OF DRILLED AND SEED COATING APPLICATIONS OF PHOSPHORUS

4.1 Introduction

Phosphorus deficiency is a major limitation to crop production in Australia since it governs the fertility of many Australian soils (Norrish and Rosser, 1983). Deposits of high purity 'A' grade ore are rapidly diminishing (Cooke, 1983); since the lower grade 'C' rock has shown little potential for annual cropping systems (Palmer and Jessop, 1982), there is a need to investigate systems which may give greater biological and economic return to applied phosphorus.

Since wheat and barley plants take up most of their P requirement in the first eight weeks of growth (Brenchley, 1929; Sutton *et al.* 1983), early P nutrition of cereals is important in determining grain yield. However, in contrast, it has been reported (Jones *et al.* 1992), that one cultivar of wheat accumulated 70% of its total P requirement after anthesis. Tailoring the fertiliser type, method of application and availability to the plant requirement may achieve greater returns per unit of applied P than traditional systems of P application. Fertiliser may be applied by air, be broadcast or be drilled with the seed. In most studies the most efficient placement is in a localised zone close to the seed. Seed coating provides a unique opportunity to place fertiliser in the immediate vicinity of each seed.

In a series of three pot experiments comparing the efficiency of banded N and P for corn with coating N and P on seed, Smid and Bates (1971), found that coating was three to four times more efficient in supplying phosphorus for the first 20 days, after which the seedlings in the

banded treatments were able to explore the fertiliser band and take up phosphorus more quickly than those in the coated treatments.

The relative efficiency of coating wheat seed with monocalcium phosphate (MCP, a soluble P source) was demonstrated in a pot trial comparing drilled MCP granules with MCP coatings Scott et al. (1991); 5 kg P ha^{-1} as a seed coat resulted in dry matter yields equivalent to those attained by applications of 20 kg P ha^{-1} in two soils with widely different P-sorption capacities. Similarly, plant P uptake during early growth was higher for the coated treatments; the greatest effect of seed coating on plant growth was on root development.

The experiments reported here were designed to further investigate the efficacy of seed coating with MCP for a range of crop species under glasshouse and field conditions. Since superphosphate had been shown both to reduce and to delay the emergence of cereals (Guttay, 1957), MCP, the major P-containing constituent of superphosphate, was used as the soluble P source. The species chosen had been shown, by using emergence studies, to be tolerant to seed coating with MCP (Ascher et al. 1987; Scott et al., 1987; Chapter 3).

The efficacy of P seed-coating during early seedling growth was investigated for four species in a temperature-controlled glasshouse. Two field trials were also conducted to investigate whether any benefit of seed coating could be established under field conditions and to determine if these were sustained through to grain yield.

4.2 Materials and methods

General

Seeds were coated in an inclined, pharmaceutical tablet coating pan (30 cm diam.) rotating at approximately 30 rpm by sequentially spraying short bursts of a polyvinyl alcohol adhesive (Gelvatol 40-10: Air Products Inc., Pennsylvania) made up at 12.5 g / 100 ml of water followed by the addition of finely ground solids (<150 μm) and drying at 45°C while tumbling in the pan (Scott *et al.* 1987). Several complete cycles were required to attain the required weight of coating. The fertiliser granules were prepared in the same way. The dry weight of adhesive incorporated in the coatings and granules was less than 2% of the fertiliser. The granule sizes used for the drilled fertiliser were chosen to correspond to the major component granules of 'Starter 12', a widely used commercial high analysis fertiliser (Incitec Pty. Ltd.), with each granule having a similar amount of P as the commercial fertiliser granule. Two thirds of the granules were between 2.8 and 3.2 mm in diameter (separated by sieving) and these weighed 1.38 ± 0.4 g per 100 granules; the other third were between 2.2 and 2.4 mm diameter and these weighed 610 ± 30 mg per 100 granules.

Data for dry matter yields and total P in plant parts were statistically analysed, firstly comparing the effect of application of coated and drilled treatments over the 0, 5, and 10 kg P ha^{-1} treatments and secondly comparing all rates of application for the drilled treatments. Mitscherlich curves of the form y=A(1-e$^{-k(Prate-Po)}$) were fitted by the process of least squares to the dry matter yield, P uptake and critical concentration curves.

Pot experiment 1:

A randomised complete block experiment was conducted to investigate the effects of MCP nutrient coatings for barley (cv. Grimmett), wheat (cv. Banks), oats (cv. Cooba) and sorghum (hybrid E57). Each species was sown at a temperature and sowing rate appropriate

for that species. The experiment consisted of 5 rates of P as drilled MCP granules (0, 5, 10, 20 or 40 kg P ha^{-1}), 3 rates of P as coated seed and one combination treatment (coated plus drilled (C+D)). Both an inert-coated and an uncoated control were included to enable separation of the physical effects from the chemical effects of the coating process and fertiliser materials. For barley and oats the coated treatments were (0, 5, 10 kg P ha^{-1}) and the combination treatment (C5+D5). Because coatings of 10 kg P ha^{-1} had been shown to be damaging to wheat (Scott *et al* 1991), for wheat the coated treatments were (0, 5, 7.5 and 10 kg P ha^{-1}) and the combination treatment (C5+D5). The coated treatments for the sorghum were 0, 1 and 2 kg P ha^{-1} and the combination treatment was (C1+D5), since the recommended sowing rate of sorghum is much lower than that for other cereals and since the germination was known to be damaged by 5 kg P ha^{-1} applied to the seed (Ascher *et al.*, (1987). The treatments were replicated four times.

Each pot (24 cm diameter with a polythene liner) contained 9.5 kg of the A1 horizon of a gleyed podzolic soil (pH 5.4, 1:5 soil:water, available P content 5 mg kg^{-1} (Colwell 1963)), known to be deficient in N, P, K and S, and received basal nutrients at 60 kg N ha^{-1} (as NH$_4$NO$_3$), 56.1 kg K ha^{-1} (as K$_2$SO$_4$), 56.4 kg S ha^{-1} (as potassium, magnesium, copper and zinc sulphates), 6.9 kg Mg ha^{-1} (as MgSO$_4$.7H$_2$O), 0.8 kg B ha^{-1} (as H$_3$BO$_3$), 2.0 kg Cu ha^{-1} (as CuSO$_4$.5H$_2$O), 1.8 kg Zn ha^{-1} (as ZnSO$_4$.7H$_2$O) and 0.1 kg Mo ha^{-1} (as Na$_2$MoO.2H$_2$O). A basal level of 2 kg P ha^{-1} was applied to all treatments to ensure that the controls would not be severely deficient. All basal nutrients were added and mixed thoroughly through the soil prior to filling individual pots initially with 8.0 kg of soil.

For barley, 5 seeds were sown in a 15 cm diameter circle (equivalent to a sowing rate of 55 kg ha^{-1}) whilst for wheat and oats 6 seeds were sown (53 and 55 kg ha^{-1} respectively). The drilled granules were placed at random in the 15 cm diameter sowing circle. For sorghum,

only one seed was sown in the centre of each pot (8 kg ha^{-1}) and the drilled granules were placed in a row with the seed 4 cm to the side of the row, since the normal agronomic practice to avoid fertiliser injury is to band P to the side of sorghum seed (Dale 1984). A further 1.5 kg of the same soil mixed with basal nutrients were placed above the seeds to give a sowing depth of 3 cm. Pots were maintained at field capacity (FC) by watering them to weight with distilled water twice weekly. The wheat, barley and oats were grown for 30 days in a glasshouse with a minimum temperature of 12°C and a maximum of 20°C. The sorghum was grown for 25 days in a heated glasshouse with a minimum temperature of 22°C and a maximum temperature of 30°C. All pots were re-randomised weekly to minimise temperature and light gradient effects due to position in the glasshouse. The plants were cut at ground level and the roots washed free of soil and rinsed in distilled water prior to oven drying at 75°C. Dry matter yields were determined and total P in shoots and roots analysed using the autoanalyser technique (Murphy and Riley, 1962) after digestion in nitric/perchloric acid.

Pot experiment 2:

A second pot experiment was conducted in the growth chamber (10°C/17°C 12 hour daylength and light intensity 312 μm m^{-2} s^{-1}). The experiment was a factorial design with 4 replicates, comparing two sowing geometries (one 15 cm sowing circle or 2 concentric circles 7 cm and 15 cm), two soil moistures (field capacity (FC) and 75%FC) and two varieties of wheat (Banks and Kite) for three P treatments (Nil, Coat 5 and Drill 5). The experiment was harvested 29 days after sowing; plant height, dry matter yield, P concentration and P content were determined as in the previous experiment.

Gunnedah Field Experiment (barley):

A field trial using barley cv. Grimmett was conducted 38 km south-west of Gunnedah (500 km north west of Sydney) on the Liverpool Plains, from July to December 1987 on a grey

cracking clay soil (Ug 5.15, Northcote (1971)) with an available P content of 21 mg kg^{-1} (Colwell, 1963). Treatments consisted of drilled MCP fertiliser granules (0, 5, 10, 20 and 40 kg P ha^{-1}), 3 rates of coated fertiliser (5, 10 and 20 kg ha^{-1}) and 2 combination treatments (C5+D5 and C10+D10). Only an uncoated control was used in this experiment, since previous experiments had shown no difference between the uncoated seed and inert coated seed. Barley was sown at 55 kg ha^{-1} in 8 row plots of 1.4 m x 12 m with a cone seeder. Nitrogen as granular ammonium sulphate was applied at sowing as a basal dressing across all treatments at 55 kg N ha^{-1} distributed via the fertiliser box onto the soil surface, and incorporated with trailed harrows.

Plant establishment was counted on four 1 m sections of row at 37 days after sowing (DAS). Three vegetative harvests were conducted at 37 and 74 DAS and at maturity, by removing four 1 m sections of row at ground level in a grid pattern avoiding edge rows and neighbouring, previously sampled sections of row. Plant and tiller numbers, and dry matter yields were determined prior to grinding plant material through a 1 mm sieve and analysing for total P concentration as described previously. Plots were machine harvested for grain yield.

Monarto Field Experiment (wheat):

A similar trial using wheat cv Spear was conducted from June through to December 1991 on a mallee soil (Dy 4.43 Northcote (1971)) south of Monarto in South Australia with an available P content of 10 mg kg^{-1} (Colwell, 1963). Treatments were five rates of drilled commercial triple superphosphate (TSP 0, 3.5, 8.2, 20 and 40 kg P ha^{-1}), three rates of seed coating with MCP (0, 3.5 and 5.7 kg P ha^{-1}) and two combination treatments (C 3.5 + D 4.7 and C5.7 + D14.3). Wheat was sown at 53 kg ha^{-1} in 8 row plots, 1.25 m x 10 m. A basal fertiliser consisting of 150 kg ha^{-1} gypsum, 65 kg ha^{-1} ammonium nitrate, Cu (as Coppersol

30L ha^{-1}) and Zn (as Zincsol 30L ha^{-1}) was applied. Two vegetative harvests were conducted at 48 DAS (three 1m sections of row) and 76 DAS (four 1 m sections of row). Plant numbers, tiller numbers, vegetative growth stage, plant height and vegetative yield were determined. Plant material was dried, ground and digested in nitric acid prior to analysis by inductively coupled plasma spectrometry. Grain yield was determined by machine harvest at maturity.

4.3   Results

Pot Experiment 1:

Emergence was not adversely affected by the nutrient coatings (data not shown). All species responded to phosphorus application, in shoot and root yield and plant height (Plate2). Mitscherlich curves were fitted to the yield data (Figure 4.1). The response curve was steeper for oats and barley, reaching 90% of maximum yield at 9.5 and 12.5 kg ha^{-1} applied P respectively, than for sorghum or wheat (reaching 90% of maximum yield at 27.7 kg ha^{-1} applied P). This difference in species requirement for P is also evident in the shoot P uptake (Figure 4.2) and critical curves (Figure 4.3), 90% of maximum yield being attained at lower concentrations of P in the shoot for barley and oats than wheat and sorghum. For wheat, there was a non significant reduction in all growth parameters at all rates of coating (Figures 4.1 and 4.2). For barley, wheat and oats, vegetative yields, plant height, P concentration and P uptake for the coated treatments were not significantly different to the corresponding drilled treatment. Plants in the coated treatments for sorghum had increased dry matter production compared to those in the drilled applications, although for this species there was not a direct comparison between the rates of P used in the coating and drilled treatments.

The relative value of the two fertiliser application techniques is further quantified in Table 4.1 which shows the rate of P as a drilled application which was equivalent to 5 or 10 kg P ha^{-1} coated on the seed or combination of C5+D5. There was a trend towards greater plant
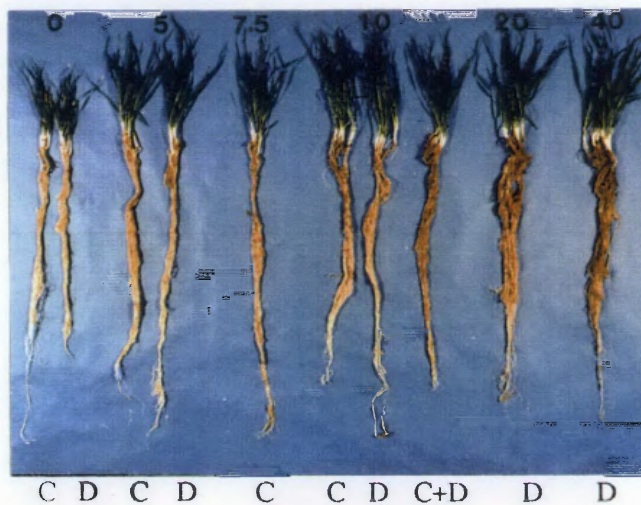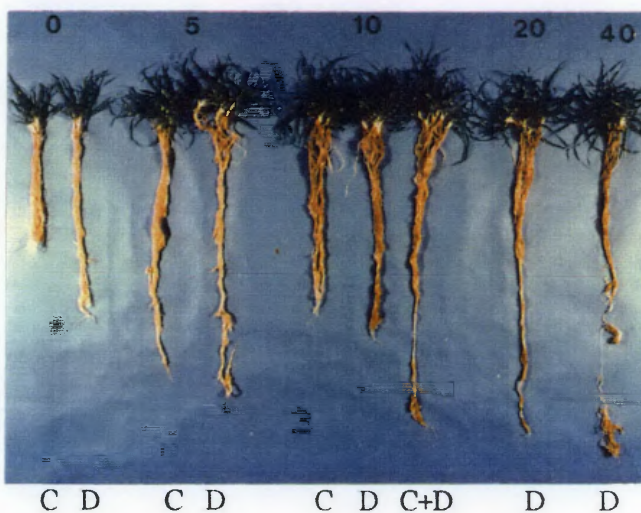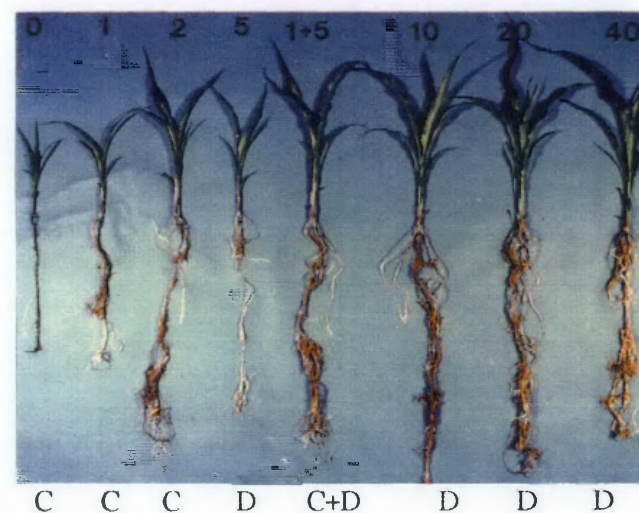
Plate 2. Response of crops to coated and drilled applications of P, grown in pot experiment 1. (a) wheat, (b) barley, (c) oats and (d) sorghum. Rate of P applied is indicated above the plant (kg ha^{-1}). Method of application is indicated below the plant; C = coat, D = drill.
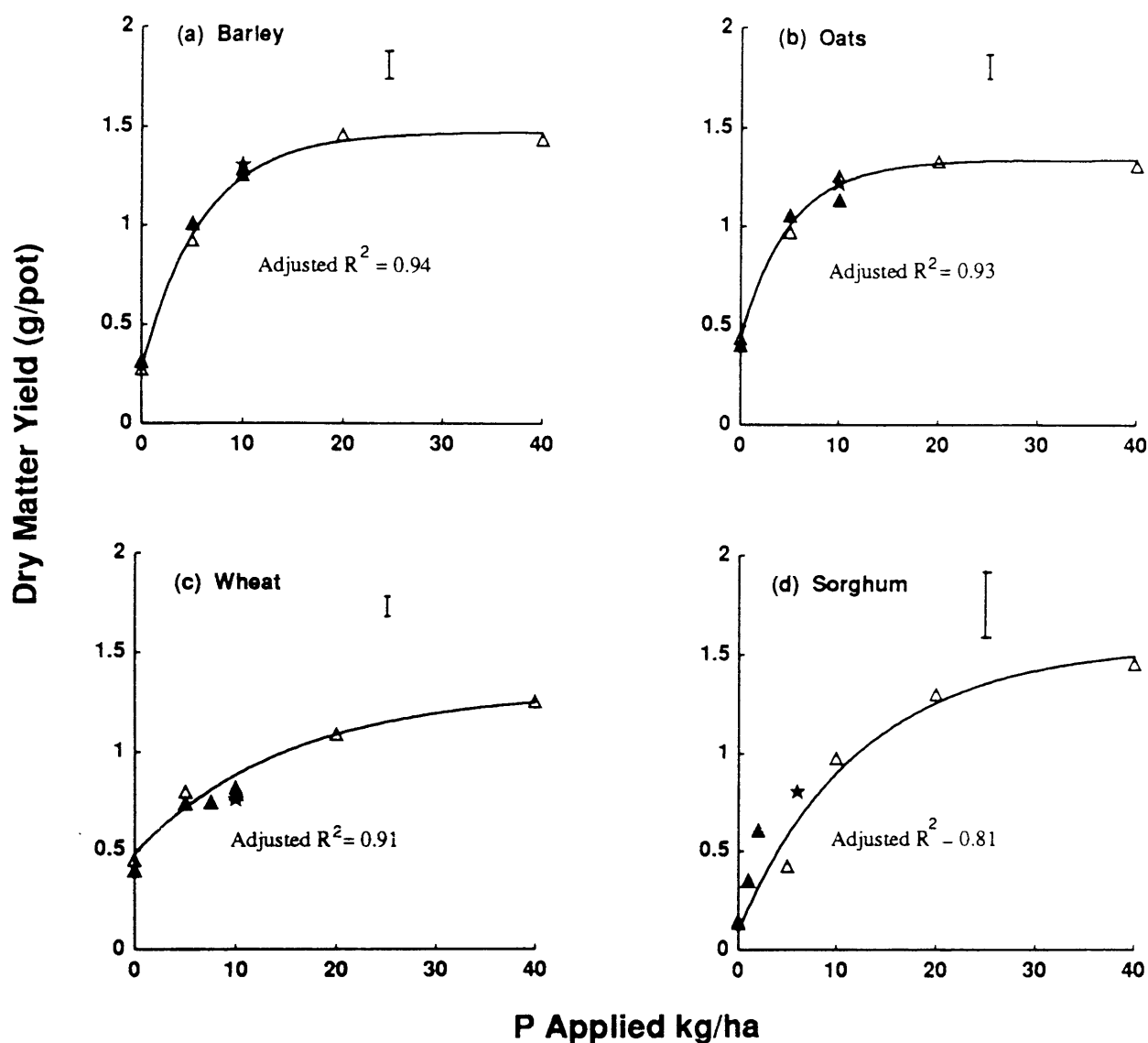
Figure 4.1. Effect of increasing P applied as seed coating or as drilled application on shoot dry matter yield of (a) barley, (b) oats, (c) wheat and (d) sorghum. The adjusted R^2 applies to the response curve $y=A(1-e^{(-k(Prate-Po))})$ fitted to the drilled applications. Application method was not significant for barley, wheat or oats. Drilled P ($\triangle$) , seed coated P ($\blacktriangle$), combination coat + drill ($\star$). Lsd's calculated for drilled response curve only since no significant difference between coated and drilled treatments.

Figure 4.2. Effect of method and rate of P application on the P uptake of shoots of (a) barley, (b) oats, (c) wheat and (d) sorghum. The adjusted R^2 applies to the response curve $y=A(1-e^{(-k(Prate-P0))})$ fitted to the drilled applications. Application method was not significant for barley, wheat or oats. Drilled P ($\triangle$), seed coated P ($\blacktriangle$), combination coat + drill ($\bigstar$). Lsd's calculated for drilled response curve only since there was no significant difference between coated and drilled treatments.
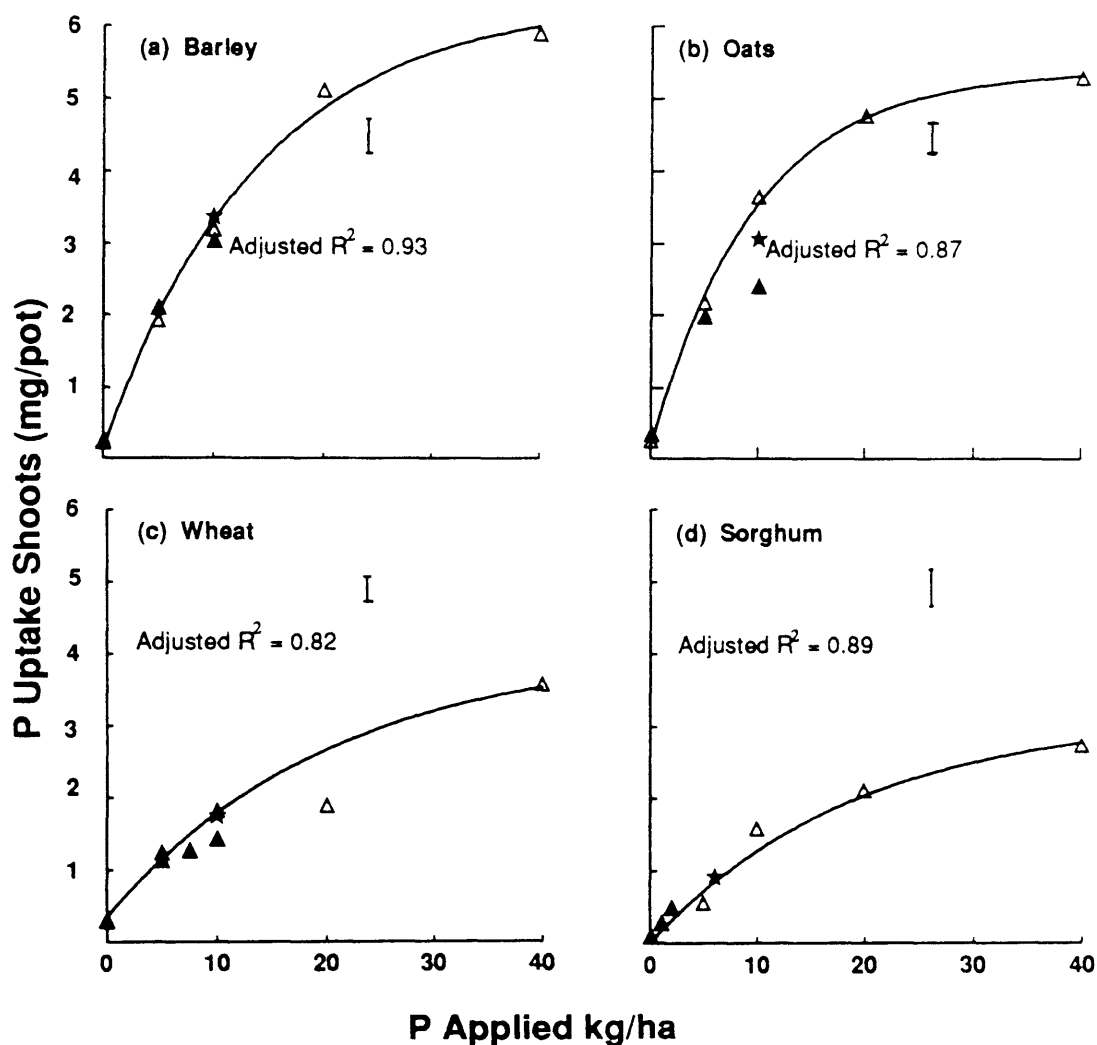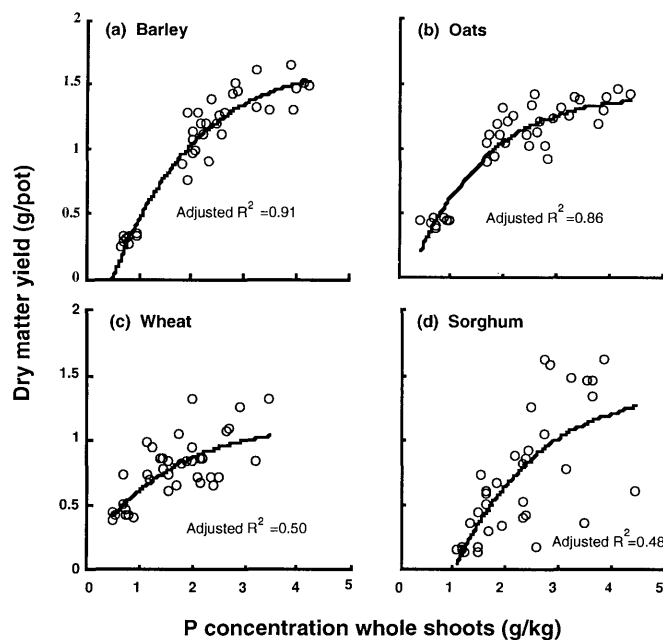
Figure 4.3. Critical curves for P in shoots of (a) barley, (b) oats, (c) wheat at early tillering 30 DAS and (d) sorghum 20 days after sowing. The adjusted R^2 applies to the response curve $y=A(1-e^{(-k(Pc-Po))})$

height, and vegetative yield due to coating at both rates for barley and at the lower rate (Coat 5) for oats (Table 4. 1).

Table 4.1. Rates of drilled P found to give equivalent growth to that of the coated P applications in the glasshouse study. (Data obtained by calculation using the parameters of the fitted Mitscherlich functions).

			Barley		Oats	
	C5	C10	C5+D5(10)	C5	C10	C5+D5(10)
Plant height 31 DAS	5.7	11.5	10.1	8.8	8.6	6.6
Shoot dry weight	5.7	11.4	12.1	5.8	7.5	10.3
Root Dry weight	8.9	8.8	10.3	4.4	6.7	7.5
Shoot P content	5.2	9.8	10.0	5.0	7.5	9.0
Root P content	9.6	13.0	13.0	7.6	8.8	12.4

			Wheat			Sorghum	
	C5	C7.5	C10	C5+D5(10)	C1	C2	C1+D5(6)
Plant height 31 DAS	4.8	5.8	7.3	5.0	2.9	6.5	9.2
Shoot dry weight	5.6	5.7	6.9	6.2	2.4	5.4	8.4
Root Dry weight	3.6	4.8	6.3	4.7	2.2	5.7	9.2
Shoot P content	5.4	7.5	9.0	10.0	2.0	5.0	8.0
Root P content	11.0	10.6	13.1	11.8	4.5	7.2	9.6

Pot Experiment: 2:

This experiment compared 3 of the 5 experimental conditions differing between pot experiment 1 and Scott *et al.* (1991), namely sowing geometry, soil water content, and variety. Light and temperature also differed but were set similar to Scott *et al.* (1991). Coated seed treatments produced more dry matter and consequently greater P uptake than those in the drilled P treatments (Table 4.2). There was no effect of sowing geometry on the efficacy of P coating (data not presented). Plants watered to FC produced more shoot dry matter than those at the lower soil moisture regime and the advantage of coated over drilled treatments was larger at the higher moisture regime. Kite was more responsive to P and benefited more from the coated treatment than Banks at both soil moistures.

Gunnedah Field Experiment (barley):

Coating did not affect plant establishment at any rate. The response to phosphorus was small and not apparent at the first sampling (data not presented). However, by the second sampling (74 DAS), there was a marked response to applied P (Figure 4.4a), demonstrated both by plant dry matter yields and phenological development. At this second sampling, the nil treatments were at late tillering (Feeke's scale 5 (Large 1954)) and the high P treatments at stem elongation / early boot (Feeke's scale 8). Dry matter production was highest for the Coat 10 treatment (Figure 4.4a). The 1987 season had a short grain filling period and the response to P applied by either method was no longer evident at maturity (Fig 4.4b); consequently the early trend towards coating being more effective than drilled fertiliser placement was not evident at harvest.

Table 4.2. Pot experiment 2 compares the experimental conditions used in pot experiment 1 with those used by Scott *et al.* (1991). Pot experiment 1 used Banks, 100% FC; Scott *et al.* (1991) used Kite, 75% FC. The experimental conditions in respect of light and temperature were not studied as variables and were set similar to that of Scott *et al.* (1991).

	0.75% Field Capacity				Field Capacity				Averaged across water treatments			
	Nil	**Coat5**	**Drill5**	Pooled Mean	**Nil**	**Coat5**	**Drill5**	Pooled Mean	**Nil**	**Coat5**	**Drill5**	Pooled Mean
Plant Ht (cm)												
Banks	21.8	27.5	25.4	24.9	24.4	29.6	25.2	26.4	23.1	28.6	25.3	25.6
Kite	20.9	28.5	23.1	24.2	20.7	31.3	26.9	26.3	20.8	29.9	25.0	25.3
Pooled Mean	21.3	28.0	24.3	24.5	22.6	30.5	26.1	26.4	21.9	29.2	25.2	25.4

Tukeys⁺ P = 1.6   moisture= 1.2   PxVariety = 2.8

Shoot Wt (g/pot)												
Banks	0.29	0.41	0.38	0.36	0.35	0.54	0.40	0.43	0.32	0.48	0.39	0.40
Kite	0.34	0.51	0.41	0.42	0.32	0.61	0.49	0.47	0.33	0.56	0.45	0.45
Pooled Mean	0.31	0.46	0.40	0.39	0.34	0.58	0.44	0.45	0.33	0.52	0.42	0.42

Tukeys P = 0.05   Variety = 0.04   moisture = 0.04

P concentration shoots (g/kg)												
Banks	1.4	3.8	3.6	2.9	2.0	3.6	3.1	2.9	1.7	3.7	3.4	2.9
Kite	1.2	4.5	3.3	3.0	1.6	4.6	3.5	3.2	1.4	4.6	3.4	3.1
Pooled Mean	1.3	4.1	3.5	3.0	1.8	4.1	3.3	3.1	1.6	4.1	3.4	3.0

Tukeys P = 0.4   PxVariety = 0.8

P concentration roots (g/kg)												
Banks	1.4	3.8	2.9	2.7	1.7	3.7	3.0	2.8	1.6	3.7	3.0	2.7
Kite	1.2	4.1	2.7	2.7	1.4	4.3	2.9	2.9	1.3	4.2	2.8	2.8
Pooled Mean	1.3	3.9	2.8	2.7	1.5	4.0	3.0	2.8	1.4	4.0	2.9	2.8

Tukeys P = 0.4   PxVariety = 0.7

P content shoots (mg)												
Banks	0.37	1.53	1.38	1.10	0.72	1.91	1.29	1.31	0.55	1.72	0.133	0.120
Kite	0.40	2.25	1.32	1.32	0.51	2.79	1.73	1.67	0.46	2.52	0.152	0.150
Pooled Mean	0.39	1.89	1.35	1.21	0.61	2.35	1.51	01.49	0.50	2.12	0.143	0.135

Tukeys P = 0.25   Variety = 0.18   moisture = 0.18   PxVariety = 0.43

P content roots (mg)												
Banks	0.36	1.00	0.83	0.73	0.46	1.17	0.82	0.82	0.41	1.09	0.083	0.077
Kite	0.40	1.22	0.87	0.83	0.44	1.45	0.95	0.95	0.42	1.33	0.091	0.089
Pooled Mean	0.38	1.11	0.85	0.78	0.45	1.31	0.89	0.88	0.41	1.21	0.087	0.083

Tukeys P = 0.1   Variety = 0.1

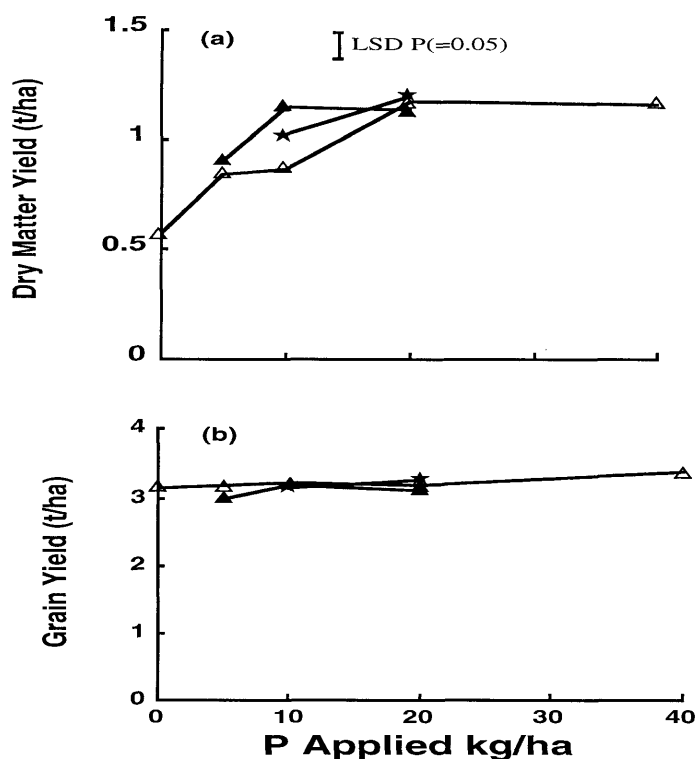⁺ Tukey's Honestly Significant difference (5% level)

Figure 4.4. Effect of P application on (a) vegetative yield 74 DAS and (b) grain yield (n.s.) of barley grown in the field experiment at Gunnedah. Drilled P (△), seed coated P (▲), combination coat + drill (★). Vertical bar represents lsd (P = 0.05) where significant.

Monarto Field Experiment: (wheat):

The site was responsive to P in terms of wheat dry matter production; however, seed coating with P (even at rates less than 7.5 kg P/ha which had previously been considered safe) resulted in reduced seedling emergence (Table 4. 3). Consequently, plots of the seed coated treatments yielded lower than those of the uncoated seed per unit of applied P and did not result in improved fertiliser efficiency at these rates. Although the P concentration in the shoots was higher where P had been coated (Table 4.3) this did not result in increased P uptake per unit of applied P. Much of the initial response to P had diminished by maturity and its effect on grain yield was small.

Table 4.3. Plant establishment, vegetative yield, P concentration, P uptake and grain yield due to seed coating with P compared to conventional drilled P applications. Monarto, S.A. 1991.

| P Application | Establishment | **Vegetative** **sampling** | | P uptake | **Maturity** Grain Yield |
| | | Dry matter | P concentration (shoots) | (shoots) | |
(kg ha⁻¹)	(plants/m)	t ha⁻¹	g kg⁻¹	kg ha⁻¹	t ha⁻¹
Drill 0	21	0.61	2.8	1.71	2.2
Drill 3.5	23	0.82	2.9	2.38	2.2
Drill 8.2	23	0.80	3.2	2.32	2.5
Drill 20	21	0.97	3.7	3.59	2.5
Drill 40	22	0.94	4.7	4.42	2.6
Coat 0	22	0.65	2.7	1.76	2.2
Coat 3.5	17	0.67	3.2	2.14	2.0
Coat 5.7	18	0.72	3.3	2.38	2.2
Coat 8.2	15	0.62	3.6	2.23	2.0
C3.5+D4.7	15	0.63	3.5	2.21	2.2
C5.7+D14.3	15	0.74	4.2	3.11	2.3
LSD(P<0.05)	2.4	0.10	0.2	0.40	0.3

4.4 Discussion

This study has shown that seed coating can, under some conditions, be equally or at times even more effective than drilled applications of P. The risk of reduced emergence due to fertiliser injury resulting in no effect or lower yields is however a major limitation.

Pot Experiment 1:

The concentrations of P in the plant tissue were marginal for optimum growth for wheat, oats and barley but below the critical level for sorghum (Reuter and Robinson 1986). In this study the critical tissue concentrations of P (in whole shoots) for 90% of maximum yield were determined to be 3 g kg⁻¹ for barley and oats (early tillering 30 days after sowing). However, for wheat (30 days after sowing) and sorghum (25 days after sowing), although the yield plateau was achieved by the application of 30 kg P ha⁻¹, the critical level of P in

whole shoots was not clearly defined (Figure 4.3). For barley and oats, C10 and the combination C5+D5 treatments achieved 90% of maximum yield; for wheat and sorghum however, the coated treatments were unable to supply enough P to reach the yield plateau.

In contrast to the results of earlier studies (Smid and Bates (1971); Gawade and Somawanshi (1979); Scott *et al.* (1991)) there was no significant increase in efficiency due to P-seed coating for any of the species studied. There was, for sorghum, a trend of increased yield due to coating compared with drilled, but this may have been an artefact due to the different sowing geometry (P granules drilled 4 cm to the side of the seed).

Scott and Blair (1988) reported increased yields and P tissue concentrations due to MCP coatings for phalaris. Lucerne however was severely damaged; any possible increases in efficiency of P utilisation through seed coating are masked in such species which are damaged during emergence. Species such as barley, oats and phalaris that are tolerant of MCP seed coatings during emergence are more likely to benefit from seed coating. However, more sensitive species (for example wheat and lucerne) can be severely damaged by coating and thus not benefit at all.

There were five differences in methodology between the present studies and those reported by Scott *et al.* (1991) which may account for the differences in results.

(a) *Sowing geometry:* Scott *et al.* used two concentric sowing circles (7 cm and 15 cm) where as the current trial used only one 15 cm diameter circle ; however it is considered unlikely that this geometry could account for the differences in relative effectiveness of P treatments.

(b) *Sowing rate*: The sowing rate used by Scott *et al.* was equivalent to 60 kg ha^{-1} uncoated seed compared to 53 kg ha^{-1} in this pot experiment. For the Coat 10 treatment these workers had 68% w/w MCP per seed basis compared with 77% w/w this study. It is possible that this higher loading of MCP onto the seed may have reduced plant growth due to toxic amounts of P; however, Scott *et al.* observed rapid growth after emergence which compensated for the early damage by Coat 10 and no difference was observed between drilled and coated treatments 27 DAS. At the lower rates of coating in this study (5, 7.5 kg P ha^{-1}) any effect of sowing density would be lessened.

(c) *Soil water content*: The wetter conditions in this study (field capacity) compared to 75% w/w of field capacity (Scott *et al.*) could have resulted in a greater mobilisation of P away from the coated seed thus diluting the effect of coating. The higher moisture conditions could also increase initial uptake of P and consequently result in greater injury /toxicity to the seedlings.

(d) *Environmental conditions*: The study of Scott *et al.* (1991) was conducted in a growth chamber with 10°C/17°C 12 hour day length and a light intensity 312 μm m^{-2} s^{-1}, whereas the glasshouse temperatures in the current experiment ranged from 12° minimum to 20°C maximum with daylength approximately 11 hours and a light intensity mid-afternoon of approximately 1920 μmol m^{-2} s^{-1}. Light intensity and soil temperature both affect the ratio of shoots to roots (Marschner 1986). Decreasing light intensity increases shoot to root ratio due to competition for photosynthates and results in a greater dependence on the root system. At low P supply, this ratio was 0.86 for the experiment of Scott *et al.* compared with 0.66 for this study and at the highest P rate 1.25 compared with 0.66. For the experiment described by Scott *et al.*, a relatively small root system (due to lower soil temperature, light intensity and the choice of the variety) was supplying the larger shoot system with water and nutrients.

This smaller root system may account for the superior performance of P coated seed in that trial.

(e) *Varieties*: The studies were conducted using different semi-dwarf wheats, however Kite (Scott *et al.*) has Rht2 dwarfing genes compared with Banks (Rht1) Gale and King (1988), and consequently may produce a larger root mass/unit shoot during early seedling growth. Kite wheat however has been shown to be very efficient at growing at both low and high P supply Jones (1986) and is more tolerant of root diseases than Banks (Hollamby pers. comm.).

Pot Experiment 2:

This experiment was designed to investigate some of these differences in methodology. Under conditions of lower light intensity and controlled day length, plants in the Coat 5 treatment performed better than those in the Drill 5 for both varieties at both soil moisture contents. Kite had a larger root system and was more responsive to applied P than Banks. P-seed coating was more effective for Kite than Banks (Table 4.2). High moisture treatment resulted in more vigorous plant growth and seed coating was more advantageous under these conditions than at lower moisture content. There was no advantage of coating over drilled applications at 75%FC however at higher soil moisture, coating resulted in increased dry matter production and P concentration. Root dry weight was not different for coated or drilled treatments for either variety.

The light intensity day length comparison between the two studies was more difficult to investigate and was not attempted. Since in this second experiment seed coating was advantageous for both species and at both moisture regimes, it seems likely that the low light intensity and cooler temperatures are indeed a major factor.

It appears likely from these results that variety characteristics and responsiveness to applied P may affect the interpretation of the efficacy of P coatings.

Field experiments

Gunnedah:

Results from the second sampling indicated a trend towards seed coated treatments yielding more than drilled treatments at the same P rates. However the P response was not sustained through to grain yield. In fact, with a grain yield of 3.2 t ha^{-1} without applied P, the soil is clearly not very P deficient. Differentiating between small effects of coated and drilled treatments was therefore difficult. No conclusions could safely be drawn from this trial about the effects of P coated seeds on grain yield where the soil is more deficient.

Monarto:

The rates and form of P used for seed coating in this experiment had been previously shown to be safe for wheat grown under controlled conditions in a gleyed podzolic soil watered to field capacity (Ascher *et al*. 1987; Scott *et al*. 1987; Scott *et al*. 1991). We did not expect the damage during emergence to wheat seedlings with 3.5 kg P ha^{-1} when sown at the equivalent of 53 kg uncoated seed ha^{-1} in the field trial. However in this soil type (6% w/w clay) compared with the gleyed podzolic (10% w/w clay), without controlled moisture, emergence was reduced to 77% of the control by 3.5 kg P coated and to 68% by 8.2 kg P coated. Earlier workers (Carter 1969; Stevenson and Bates 1968; Ascher *et al*. 1989) have demonstrated that coarse textured sandy soils are more likely to exhibit fertiliser injury. Wheat has also been shown to be more susceptible to injury than either barley or oats (Ascher *et al*. 1987; Scott *et al*. 1987). The deleterious effect of coating on emergence of wheat in this experiment was large enough to mask any positive effects of coating. The trend towards coating being more effective for oats and barley than for wheat could be due, in part, to the

presence of the lemma and palea delaying emergence and allowing time for some of the soluble MCP to react with the surrounding soil (Scott 1989). This may reduce the fertiliser injury and allow the coating to be more effective.

In both field experiments P application resulted in a large growth response which had diminished by maturity. This is a common feature of field responses so that the importance of early P nutrition is dependent on environmental conditions during grain filling. For cereals this may translate to P seed coating significantly affecting grain yield only in years where root development is restricted and the root system is unable to extract P from the bulk of soil. Seed coating may increase P content, P uptake and dry matter in pot experiments but we have been unable to demonstrate advantages in grain yield in field experiments. If the P response had been greater at maturity the effects of seed coating may have been more apparent. This result emphasises the importance of choosing a site reliably responsive to P and demonstrates that depending on seasonal effects soil P testing may not be a reliable measurement.

These experiments have demonstrated a trend towards greater efficiency of fertiliser use by coating; P seed coating has the potential to be as, and even more, effective as conventional drilled applications of P. The limiting factor however, is the amount of fertiliser that can be coated on the seed without risking injury. The overriding factor of reduced emergence due to coating has highlighted that attention must be directed at preparation of formulations that are not injurious to germination under the wide range of conditions experienced in the field. Before P seed coating can be adopted for cropping systems attention must be paid to reducing the injury whilst still supplying the total plant requirements. A coating with a soluble P component and a less soluble P fraction may reduce injury yet still supply sufficient P for early growth. Species and varieties vary in requirement for P and tolerance to coating, this in turn affects the interpretation of efficacy.