

Agronomic management options for phosphorus in Australian dryland organic and low-input cropping systems

A. M. McNeill^{A,C} and C. M. Penfold^B

^ASoil & Land Systems, School of Earth and Environmental Sciences, The University of Adelaide, Glen Osmond, SA 5064, Australia.

^BAgronomy and Animal Sciences, School of Agriculture, Food and Wine, The University of Adelaide, Roseworthy Campus, SA 5371, Australia.

^CCorresponding author. Email: ann.mcneill@adelaide.edu.au

Abstract. Maintenance of available phosphorus (P) is a problem faced by both conventional and organic systems but it is exacerbated in the latter given that manufactured inorganic sources of P fertiliser are not permitted under the International Federation of Organic Agriculture Movements certification guidelines. The focus of this paper is a discussion of potential agronomic strategies to assist in sustainable management of the soil P resource in organic and low-input broadacre farming systems within the Australian rain-fed cereal–livestock belt. The paper considers three broad strategies for agronomic management of P in this context and draws on reported research from overseas and within Australia. An analysis of the current knowledge suggests that the option most likely to ensure that soluble P is not a limitation in the system is the importation of allowable inputs that contain P from off-farm, although for much of the Australian cereal–livestock belt the immediate issue may be access to economically viable sources. Research targeted at quantifying the economic and biological benefits to the whole-farm system associated with the adoption of these practices is required. Improving the P-use efficiency of the system by incorporating species into rotation or intercropping systems that are able to use P from less soluble sources has been a successful strategy in parts of the world with climate similar to much of the Australian cereal–sheep belt, and deserves further research effort in Australia. Agronomic management to maximise quantity and quality of pasture and crop plant residues undoubtedly builds labile soil organic matter and facilitates P cycling, but the strategy may be of limited benefit in low-rainfall areas that do not have the capacity to produce large biomass inputs. Evidence that organic or low-input systems naturally increase the numbers and diversity of soil organisms is sparse and published studies from Australian systems suggest that P nutrition is not enhanced. However, seed and soil microbial inoculants to facilitate improved P uptake have been developed and are currently being field tested in Australia. Progress in selection and breeding for cereal genotypes that are more P efficient and other plant genotypes that can use less labile P sources, is gaining momentum but still remains a long-term prospect, and may involve genetic modification which will not be acceptable for organic systems.

Introduction

Prevailing agricultural trade and economic policies have inexorably been driving Australian farmers towards more intensive cropping systems that rely heavily on inputs such as pesticides, fossil fuels, and fertilisers. Concurrently, there is increasing global awareness that food production is depleting large quantities of nutrients including phosphorus (P) from soil reserves worldwide (Sheldrick *et al.* 2002), apart from some countries in western Europe, Japan, and Korea that have large mixed farming systems. Paradoxically, however, the use of P fertiliser in excess of plant demands has resulted in significant environmental problems in many countries (Sharpley *et al.* 2005). Furthermore, phosphate rock (PR), the main raw material used in production of practically all P fertilisers, is a finite, non-renewable resource and known reserves are likely to be considerably depleted by 2100 (Stewart *et al.* 2005).

Australian dryland farming systems evolved in relation to relatively low productivity per unit area on a world scale, due mostly to infertile soils and low rainfall (Freebairn *et al.* 2006).

Thus, 15 years ago, ‘ley farming’ systems in southern and western Australia were typically an intimate association of crop and animal enterprises on the same farm (Perry 1992). These were low-input/low-output systems characterised by cycles of fertility exploitation by crops and fertility restoration using legume-based pastures. The systems were driven by relatively minor inputs of superphosphate fertiliser in either phase of the rotation (Puckridge and French 1983). In contrast, the northern agricultural region, based on higher fertility soils, evolved primarily under continuous cropping, although there have been suggestions to increase the role of legume-based leys (Dalal *et al.* 1995) in response to declining soil condition (Dalal and Mayer 1986), including P fertility (Dalal 1997).

As a reaction to the intensification of farming systems, some farmers have opted to retain low-input systems (Howden *et al.* 2004) or have explored the option of organic farming (Cornish 2009, this issue) in which manufactured soluble P inputs are disallowed (IFOAM 2005). Both approaches require agronomic management that improves access to less labile sources of soil P

stored either as soil organic matter or chemically 'fixed' by minerals. Although many Australian soils are inherently infertile, these reserves of less labile soil P on conventional farms or those newly converted to an organic system may be considerable as a result of superphosphate use for almost a century. This is because only about half the P added in superphosphate is eventually taken up by crops and pastures (and not all of this is exported in products), the rest being added to the stocks of less labile soil P (Bünemann *et al.* 2006).

There has been relatively little reported research in Australia into the agronomic management and nutritional aspects of broadacre organic farming systems (Penfold *et al.* 1995; Deria *et al.* 1996; Kitchen *et al.* 2003; Ryan *et al.* 2004; Evans 2005), although there is far more information published for organic cropping systems in other parts of the world such as Europe (Tagmann *et al.* 2001; Vestberg *et al.* 2002; Wiermann *et al.* 2002; Kirchmann and Ryan 2004) and Canada (Entz *et al.* 1998). Overall, the work has highlighted that, in common with other low-input systems, the maintenance of plant-available P is a major limitation. The problem is particularly extreme in stockless systems without access to manure and in mixed farming systems practised on inherently infertile soils, as is the case for much of Australia (Penfold 2000).

This paper discusses potential options available to organic and low-input farmers for managing P (Fig. 1), with particular reference to farming systems-based approaches. Future directions for research are highlighted. The paper focusses on the rain-fed cereal–livestock belt across southern Australia, which produces

~80% of Australia's grain, typically on mixed farms. The climate and soils of this belt present unique challenges for the agronomic management of P in general, and for organic management in particular, and these are briefly outlined. Three broad strategies for agronomic management of P in Australian broadacre organic farming systems are considered (Fig. 1). These strategies include: (i) potential approaches for maximising the P-use efficiency of crops and pasture species in the system; (ii) practices for increasing soil P cycling to facilitate release and synchronous uptake of plant-available P; and (iii) importation from off-farm of allowable inputs that contain P.

Climate and soils of Australian rain-fed broadacre agriculture

The extent of the Australian cereal–livestock belt and its climatic extremes has been well described (Nix 1975; Dalal and Chan 2001; Freebairn *et al.* 2006). Key features of Australian farming systems relate to the unusual nature of the rainfall, in particular the low annual averages, high variability, and long dry or wet periods (Freebairn *et al.* 2006), as well as the wide range of soil types. The predominant soil types are Chromosols and Sodosols in the southern regions, Vertosols in southern Queensland and northern New South Wales (NSW), and Kandosols in Western Australia (McGarity 1975). There are also significant areas of Ferrosols, Kurosols, Podosols, and Dermosols (Isbell 1996). Australian soils in the cereal–livestock belt are inherently low in soil organic carbon (C, ranging between 0.5 and 2%), as determined by the fixed factors of climate, depth, stoniness, mineralogy, and texture (Ingram and Fernandes 2001). Australia, with some of the oldest, most weathered soils of the world, generally has soil P levels which are low by world standards. The P content of Australian soils on average is 0.03%, compared with 0.04–0.10% for American soils and 0.05% for English soils (Gourley 1989). Soils in Australia, which are exceptions to this, are the Vertosols of northern NSW and Queensland, and some Ferrosols and immature volcanic soils of Victoria (Leeper and Uren 1993). Soils with moderate to extreme alkalinity or acidity are common throughout a large proportion of the cereal–livestock belt (McKenzie *et al.* 2004) and have a capacity to immobilise P into insoluble compounds. The recent National Land and Water Resources Audit of soil plant-available P status in Australia estimated that 64% of the total agricultural land area had less than 30 mg/kg plant-available P/ha (tested using the Colwell soil P test) and that 35% could be considered as marginal for plant requirements with less than 20 mg/kg of plant-available P. Exports of P for the period 1992–96 for all agricultural land uses were low, largely less than 10 kg/ha. There is growing interest in organic or low-input farming systems across all these diverse climatic and soil types (Cornish 2009, this issue). For example, in terms of the development of low-input systems, it is claimed that the practice of pasture cropping now has ~2000 practitioners across Australia (Howden *et al.* 2004).

Challenges for agronomic management of P

In a recent treatise (Bundy *et al.* 2005) on the agronomic management of P in conventional systems, three major challenges were identified. These were: (i) to predict the need

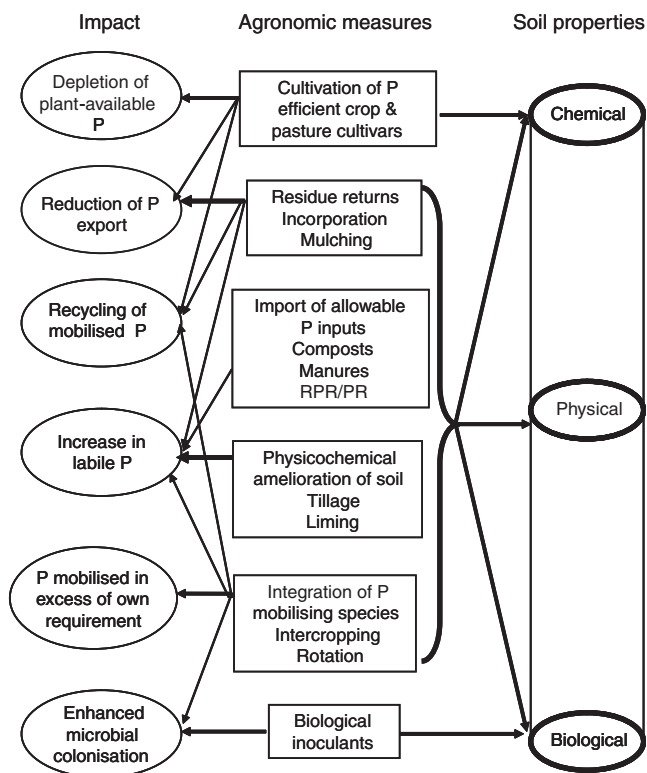


Fig. 1. Effects of agronomic measures on P availability to crops and pastures via changes in soil properties and subsequent effects on the farming system P cycle (modified from Horst *et al.* 2001).

for, and the amount of, supplemental P; (ii) to efficiently use available sources of P to meet this need; and (iii) to manage the agricultural system to minimise environmentally damaging P losses. Although an over-supply of available P is less of an issue for the relatively low-input Australian broadacre cereal–livestock belt, the other two challenges, i.e. predicting P requirements and efficiently using available sources of P, are extremely pertinent. Solutions addressing the latter should include the development of management techniques that can give crops access to the large amounts of residual or immobilised fertiliser P in Australian soils. The challenges are exacerbated for organic farming systems where the input of inorganic manufactured fertilisers is not allowed, and where (as referred to by Cornish 2009, this issue) significant problems (poor seedling vigour, weed competition, reduced N₂ fixation) can result from insufficient levels of plant-available P, particularly during the critical early growth stage (Grant *et al.* 2001). These problems ultimately reduce crop and pasture yields and compromise economic sustainability.

Where a farmer converts from conventional to organic methods, it may be possible to crop for a period without addition of external P inputs, but the question arises as to how long this can continue before yield reductions due to P deficiency occur and more importantly, given current technologies for assessing soil P status, whether the system can be managed to a specified critical threshold for soil P availability in order to prevent P deficiency occurring. Assessing critical thresholds for soil P availability is not a simple task, due to the complex chemical reactions that occur with both inorganic and organic P forms in soils. Indeed, there is still much debate regarding the ability of various soil P tests to accurately predict plant uptake and yield response for conventional systems, particularly in Australia (Holford 1997; Saggar *et al.* 1999; Burkitt *et al.* 2006; Moody 2007). Several studies have suggested that soil P availability dynamics in systems that receive predominantly organic P amendments may differ from conventional systems (Oberson *et al.* 1993; Motavalli and Miles 2002). Thus, developing criteria for assessing P availability in organic systems will require further research into soil tests that acknowledge the unique properties of the system (Waldon *et al.* 1998).

Options for maximising P-use efficiency by crops and pastures

Utilisation of species or genotypes with high dry matter productivity or grain yield per unit of P uptake

P-use efficiency by crops or pastures in simple terms can be defined as the amount of shoot biomass per unit of P present in the plant. It represents the integration of plant P uptake from soil and P translocation within the plant, processes that are both extremely complex (Holford 1997; Bucher 2007). Agronomic selection for P-use efficiency has largely been based on selection for increased shoot dry matter (DM) productivity or grain yield per unit of fertiliser P applied. Using this selection criterion, modern semi-dwarf cereal genotypes have been selected as more P-use efficient than older, taller genotypes. However, without P analysis of grain and stubble, it is unclear whether this is due to enhanced uptake or internal utilisation efficiency (Batten 1992). Recent field research into the yield of wheat under rain-fed conditions on acid and calcareous soils in Mexico concluded that P-uptake

efficiency was more important under low P situations and P utilisation efficiency under high P conditions (Manske *et al.* 2000, 2001), thus highlighting the importance of considering genotype × environment interactions in breeding programs.

Traditionally, pasture grass species are considered more efficient than pasture legume species at acquiring and using P, both on an individual plant basis and under competition in a mixed sward (Biddiscombe *et al.* 1969; Ozanne *et al.* 1969, 1976; Caradus 1980). Some years ago, Australian researchers showed that stylo was more efficient under low P conditions than white clover (Chisholm and Blair 1988a) and the suggestion was made that knowledge of the incorporation of P into major biochemical plant pools (particularly phospholipids) would provide a better basis for determining comparative P efficiency of pasture species (Chisholm and Blair 1988b, 1988c). Later work further identified that some scope existed for selection for P efficiency within white clover accessions, particularly those under P stress (Godwin and Blair 1991). Further studies using red clover, white clover, Italian ryegrass, and phalaris highlighted that temporal differences in ontogenetic development across species also influenced assessment of P efficiency (Kemp and Blair 1991, 1994). For example, early development of greater root dry weight in the grass species, linked to greater seed size and faster relative root growth rate, resulted in superior shoot DM production at lower fertiliser P rates relative to the clovers.

The P efficiency (PE) ratio, expressed in terms of grain yield per unit of P in the plant shoot (Table 1), attempts to describe the utilisation of P that a plant extracts from soil and fertiliser sources to produce grain. PE ratios reported for field-grown plants in dryland farming systems vary widely from 250 to 565 kg grain/kg P in shoots (Batten 1992). Significant differences in this P efficiency ratio exist between some genotypes at the same harvest index (Batten 1986; Batten and Khan 1987), suggesting that it should be possible to select for this type of efficiency without compromising high harvest index and yield. Potential selection for cultivars that are inherently more P efficient (i.e. produce more DM per unit of plant P) will be reliant on the presence of genetic diversity for P-use efficiency within a genus and the identification of traits for improved P-use efficiency that can be expressed in the selection environment (Manske *et al.* 2001). Over the years, Australian plant breeders may have unconsciously been selecting wheat genotypes for PE in yield trials where the applied phosphate fertiliser has been less than what the crop requires to produce optimum yield (Batten 1992). More than 20 years ago, selection pressure for PE was imposed consciously in the American tropics where, under low-input technology, wheats were selected to produce economic yields (80% of the maximum in that environment) on acid, infertile soils (Sanchez and Salinas 1981). Screening germplasm for shoot biomass or harvestable product in low P conditions may provide the best estimate of productivity in low P soils. However, before germplasm can be categorised as P efficient or P inefficient, it is important to identify that the superior performance in low P conditions is definitely related to a specific mechanism enhancing P uptake or utilisation rather than some other superior metabolic activity such as phytohormone production, photosynthetic rate, or adenosine triphosphate production (Gourley *et al.* 1993).

Table 1. Reported ranges for several P efficiency factors obtained for wheat and other cereals from semi-arid regions grown under field or glasshouse conditions at different rates of P fertiliser (inorganic unless stated otherwise)

Location	Experiment type and duration	Fertiliser P rates	No. of cultivars ^A	P efficiency factor/s ^B	Range of values		Source
					Low/no P	High P	
Australia	Glasshouse	Control, low	20	PE	50–200 g/g	110–715 g/g	Batten (1986)
Australia	Field (3 years), maturity	2, 4, 6, 8, 16, 18 kg/ha	23	PE (year 1) PE (year 2) PE (year 3)	543 g/g 394 g/g 457 g/g	504 g/g 330 g/g 334 g/g	Batten and Khan (1987)
Australia	Glasshouse, maturity	2, 40 kg/ha	23	PE PHI RE	107–396 g/g 15–63% 5–10.6 mg/g	46–292 g/g 14–67% 9.7–21.1 mg/g	Jones <i>et al.</i> (1989)
Australia	Field, maturity	2, 10, 40, 80 kg/ha	9	PE PHI	162–356 g/g 40–85%	182–294 g/g 70–85%	Jones <i>et al.</i> (1992)
Australia	Glasshouse, maturity	2, 40 kg/ha	3	PE PHI RE PUE (root)	381–403 g/g 80–84% 9.6–19.4 mg/g 5–9.7 mg/g	257–294 g/g 76–84% 10.1–34.1 mg/g 6.5–18 mg/g	Jones <i>et al.</i> (1992)
Unknown	Glasshouse, maturity	12, 60 mg/kg	2	PE		150–490 g/g	Horst <i>et al.</i> (1993)
Mexico	Field (3 years), maturity	0, 35 kg/ha	42, 30, 22	PUPE	5.2–9.7 kg/ha	8–10.8 kg/ha	Manske <i>et al.</i> (2000)
Mexico	Field (2 years), maturity	0, 35 kg/ha	38	PUTE	315–480 kg/ha	274–396 kg/ha	Manske <i>et al.</i> (2001)
Australia	Outdoor tanks (sand/solution culture), 35–41 days	20, 50, 350 µM P as KH ₂ PO ₄	96 wheat, 8 triticale, 2 rye	PUSE	600–3900 mg/mg	Not reported	Osborne and Rengel (2002c)
Australia	Glasshouse, 35–37 days	26, 339 mg P/kg as FePO ₄	99 wheat, 8 triticale, 4 rye	PUSE PUPE	425–1076 mg/mg 41–105 mg/g	149–350 mg/mg 31–50 mg/g	Osborne and Rengel (2002a)
Australia	Glasshouse, 35 days	20 mg P/kg as phytate or KH ₂ PO ₄ , 100 mg P/kg as phytate	20	PAE _{phytate} PAE _{KH₂PO₄}	18–22 mg/mg Not reported	40–43 mg/mg 287–326 mg/mg	Osborne and Rengel (2002b)
Turkey	Glasshouse, 49 days	0, 40, 80 mg/kg	20	P content EI	0.8–8.03 mg/pot 1.14–3.87	4.42–25.2 mg/pot	Karaman and Sahin (2004)
China	Glasshouse, maturity	10, 40 mg/kg	20	PUE PHI	197–304 g/g 56–75%	160–220 g/g 55–81%	Wang <i>et al.</i> (2005)
Turkey	Glasshouse, 39 days	20, 80 mg/kg	73	P efficiency		47–79%	Ozturk <i>et al.</i> (2005)
Australia	Glasshouse, 21, 35 days	0, 700 kg/ha for Ferrosol; 0, 100 kg/ha for Kandosol	15	P efficiency PUE (root); Ferrosol Kandosol	Ferrosol: 5–16%; 2.1–3.0 mg/g 3.3–4.5 mg/g	Kandosol: 11–29% 10.4–15.2 mg/g 13.6–23.9 mg/g	Liao <i>et al.</i> (2008)

^AWheat unless specified otherwise.

^BPE, P efficiency ratio (also called PUTE or PUE): P utilisation efficiency = grain yield/shoot P uptake (g/g or kg/ha); PHI, P harvest index = grain P content/shoot P uptake × 100 (%); RE, root efficiency ratio = shoot P uptake/root dry wt (mg/g); PUE(root), root P uptake efficiency = P uptake/root dry wt (mg/g); PUPE, P uptake efficiency = shoot P uptake/P supplied in soil plus fertiliser (kg/ha or mg/g); PUSE, P utilisation efficiency = shoot dry wt/shoot P uptake (mg/mg); PAE, P acquisition efficiency = shoot P uptake/P supplied (mg/mg); EI, efficiency index = dry matter yield²/total P content; P efficiency = shoot dry matter (low P)/shoot dry matter (high P) × 100 (%).

There appears to be a growing consensus that sufficient genotypic variation of PE within cereals exists to warrant breeding efforts (Table 1). Indeed, a comprehensive Australian study that screened over 100 cereal genotypes demonstrated a wide variation in soluble P-uptake efficiency (Osborne and Rengel 2002c) as well as in the capacity to use less soluble forms of P such as phytate and iron phosphate (Osborne and Rengel 2002a, 2002b). Rye and triticale appeared more efficient

than wheat in taking up and using P at low rates of P supply, and in ability to use less soluble forms of P (Table 1). Whether these genotypic differences in P exploitation could be used in the design of more sustainable P management for organic or low-input farming systems requires investigation at the field level. However, many of the studies have been undertaken in artificial media even though the results of screens using such methods may sometimes be poorly correlated with those using

soil (Hayes *et al.* 2004). Nevertheless, screening undertaken on soils (Table 1) has also resulted in genotypic differences in P-use efficiency being recorded for wheat germplasm in Turkey (Karaman and Sahin 2004) and China (Wang *et al.* 2005). Australian work using soils-based screening for PE (Table 1) has also concluded that there is germplasm in Australian wheat genotypes that may be valuable for breeding (Liao *et al.* 2004), although these researchers emphasise that breeding for P-uptake efficiency would only be feasible provided the trait is heritable and controlled by relatively few genes. There has been substantial progress, following the screening of 30 rice genotypes from Asia, South America, and Africa, in transferring a quantitative trait locus (QTL) for P uptake from a traditional landrace into a modern variety with a high harvest index. Field trials in a soil with high P fixing capacity demonstrated that the modified variety produced triple the yield of the modern variety under low P availability and 1.5 times under high P availability. These results are very encouraging but work on mapping QTLs for P traits in wheat is still in its infancy (Su *et al.* 2006) and it is likely to be more than a decade before wheat varieties will be developed and available for use by Australian growers.

The need for selecting and breeding more P-efficient crops is certainly receiving increasing attention worldwide (Lynch 1998) because removal of less P per unit of biomass produced leads to conservation of P resources in the system. Paradoxically, Australian wheat grains can currently be considered to be contributing to such P conservation in that they contain less P than grains from North America or the United Kingdom (Batten 1994). This is probably due to the semiarid nature of the environment that often precludes uptake of P after anthesis (Batten and Khan 1987), although low soil P availability is a major contributing factor in low-input systems.

There are also other reasons for seeking genotypes that achieve high yields of grain with low concentrations of P, such as the negative association between loaf volume and high grain P and the positive correlation between low grain P and lower concentrations of the anti-nutritional factor phytic acid (Batten 1992). Nevertheless, high grain P may be an advantage for organic crops if seed is going to be kept for sowing on-farm, a factor which needs to be considered in overall management of P in the farming system. High seed P (up to 0.37% for wheat and 0.79% for medic) has been positively associated in Western Australia (WA) with seedling vigour and significantly higher final DM production, both in the presence and absence of P fertiliser application (Bolland and Baker 1988; De Marco 1990), and also with higher wheat and lupin yields (Paynter 1992). Work in north-eastern Victoria also showed that wheat seeds with a P content at the lower end of the range 0.21–0.35% produced less early DM than wheat from seed considered high in P, although in this case there was no final effect on grain yield (Burnett *et al.* 1997). Similarly, studies on subterranean clover in WA also showed that the rate and percentage of seedling emergence and subsequent rate of leaf emergence are increased by high P concentrations (0.75% as opposed to 0.48%) in the seed (Thomson and Bolger 1993). In South Australia (SA), mean grain P concentration for wheat grown on organic farms across high- and low-rainfall areas was 0.25% compared with 0.34% on conventional farms (Kitchen 2001). Given the lower P concentration of the organic grain it seems likely that grain P

deficiency may reduce early growth and subsequently reduce yield in SA. Indeed, a study at Roseworthy, SA, attributed reduced yields in organic and biodynamic systems to weed issues (Penfold *et al.* 1995), which may well have been exacerbated by a lack of competitive seedling growth in the crops. Another study in southern New South Wales (Ryan *et al.* 2004) also reported significantly higher grain P concentrations from conventional farms (0.30–0.38%) than from those under organic management (0.28–0.31%). One option for organic farmers, if their own seed is known to have low P concentrations, is to obtain high-P seed externally if they are permitted within the certification standards.

Utilisation of species with ability to use more P from the soil

In most soils, the diffusion of P to the root is the main limiting factor for P acquisition rather than the rate of root P uptake (Jungk and Claassen 1997), so that there is generally a zone of P depletion immediately surrounding the root. Thus, to use more P from the soil a plant either needs to explore larger soil volumes to obtain available P or needs to be able to acquire P from less available forms in the depletion zone. Many plants are known to have specific root morphologies that allow them to obtain more available P than others, whereas some plants have physiological mechanisms that can mobilise less available soil P pools including insoluble inorganic forms and organic matter (Lynch and Ho 2005; Shenoy and Kalagudi 2005). These two options are discussed further in the following sections.

Root system architecture and morphology

Plant root architecture and morphology are important for maximising P uptake because root systems that have higher ratios of surface area to volume, such as those with long fine roots and abundant root hairs, will more effectively explore a larger volume of soil. Furthermore, the smaller radius of fine roots and root hairs causes a slower decline in P concentration at the root/hair surface, enabling a higher rate of P influx to be maintained, which may also contribute to greater P uptake. Therefore, this enhances opportunities for P transport via soil–root contact through growing species or genotypes with greater lateral root formation (Blair and Godwin 1991; Gahoonia *et al.* 1999; Manske *et al.* 2000), longer root hairs (Gahoonia and Nielsen 1997, 2004b), or reduced root diameter (Fohse *et al.* 1991) to allow greater potential for increased P acquisition by plants. Cultivars of beans have been identified that allocate resources into shallow root production, thus more effectively foraging topsoil and having greater P uptake than other cultivars (Lynch and Brown 2001; Liu *et al.* 2005). Of course, shallow rooting traits may not be so desirable in semiarid environments given the need to extract water from depth at certain times of the season, and that surface drying will reduce P uptake from this zone.

Agronomic evaluation of the influence of cultivar and species differences in root system morphology on P uptake has largely focussed on pot studies (Gahoonia and Nielsen 1996; Krasilnikoff *et al.* 2003). Field studies have been undertaken on barley in Europe, demonstrating the efficacy of root traits such as root hair length for increased plant P uptake (Gahoonia *et al.* 1999, 2000),

as well as for sustaining high grain yields under low P conditions (Gahoonia and Nielsen 2004a), although the relationships for wheat were reported as being less clear (Gahoonia *et al.* 1999). These European studies suggest that genetic modification could be used for upgrading PE in barley genotypes, although the time frame is long-term. Such developments, for barley and other crops, would potentially benefit low-input farming systems in Australia, but are not a viable option for organic systems because genetically modified crops are not permitted under the current certification scheme.

Management that enables plant root systems to grow with less physical limitations and thus increases root exploration for P will be discussed in the section on tillage.

Uptake of P from less labile sources

There are several mechanisms that allow plants to gain access to poorly available inorganic and organic soil P fractions and thus increase the pool of soil P that contributes to plant P nutrition (Richardson *et al.* 2009, this issue). Briefly, these include release of protons or hydroxyl ions (Gahoonia and Nielsen 1992), organic acid anions (Gerke 2000 in Jemo *et al.* 2006), an increase in reduction capacity (Holford and Patrick 1979), and some rhizosphere phosphatase activity (Tarafdar and Claassen 1988). Such attributes are likely to be very important for plants in organic or low-input systems where the inputs of soluble P are low, whereas those of organic P may be relatively high. Excretion of these compounds tends to be greater in P-deficient systems (Hinsinger 2001) and so growing these species on many Australian soils should represent an opportunity to capitalise on these traits, although where there is a large amount of fixed P in soil then rhizosphere soil P dynamics will become an important factor in P availability and uptake (Hinsinger 2001).

Several crop species suitable for the Australian cereal–livestock belt are known to excrete P-solubilising compounds, including lupin (Gardner *et al.* 1983), pigeon pea (Ae *et al.* 1990), chickpea (Li *et al.* 2003a), lucerne, white clover, and cocksfoot (Li *et al.* 1997). Other species, such as medics, radish, and canola, have been shown to excrete P-solubilising substances under P-deficient conditions (Hedley *et al.* 1982; Lipton *et al.* 1987; Hoffland *et al.* 1992; Zhang *et al.* 1997) and might, therefore, be suited to systems where plant-available P is low. It has also been suggested that root exudates can play a role in P acquisition by cereals (Gahoonia *et al.* 2000). Furthermore, if P is mobilised by plants in excess of their own requirements then it may contribute to the P nutrition of other less P-efficient crops grown in rotation or intercropped in the farming system. Indeed, field experiments in the Cameroon on acidic, highly P-sorbing soils have shown rotational benefits of P-efficient cultivars of grain legumes (in this case, cowpea and soybean) for increasing yield and P uptake of a following maize crop. The authors suggested that this was partly due to the cycling of less soluble forms of P in soil via legume uptake and subsequent residue decomposition (Jemo *et al.* 2006), although unequivocal evidence for this was not presented. The nutritional benefits of legume–cereal rotations studied in Australia have mainly been attributed to nitrogen (N) and there has been little, if any, reference to P.

The potential value of species that excrete P-solubilising compounds has been demonstrated for several intercrop systems in pots (Table 2), as well as for rotations in pots, e.g. maize after lupins (Kamh *et al.* 2002). Reports from field experiments with intercropping in Australia are sparse (Table 2), although over 20 years ago, a beneficial effect on P uptake by wheat when grown with lupin was demonstrated (Gardner and Boundy 1983). More recently, field studies from north-western China (Table 2), on a calcareous soil, showed that

Table 2. Reported beneficial effects of P-mobilising species on dry matter, yield, and P uptake of intercrops

Location and duration of expt	Experiment details	Measured benefit	Source
Field, W. Aust.	Wheat sown at 85 kg/ha with white lupin sown at 60, 120, or 240 kg/ha	Wheat shoot P conc. increased from 0.13 to 0.16% as density of lupin increased	Gardner and Boundy (1983)
Field, W. Aust.	Sole wheat 85 kg/ha, sole lupin at 180 kg/ha, wheat/lupin intercrop at 85/135 kg/ha	Increase in shoot P conc. at harvest from 0.13% in sole wheat to 0.15% in intercrop	Gardner and Boundy (1983)
Field, China (maturity)	Maize/faba bean sole and intercrops adjusted to same densities. P rates 0 and 33 kg/ha. Microplots with zero, partial, or complete separation of roots	Grain yields (equiv. area basis) for intercropped maize and faba bean 8–33% more than sole maize and 24–64% more than sole faba bean. Total DM yields of intercrops higher than sole crops unless root systems entirely separated. P uptake of intercropped faba bean higher than sole faba bean at harvest for both P rates: 0 (2.58 v. 2.19 g/m ²), 33 (3.64 v. 2.33 g/m ²)	Li <i>et al.</i> (1999, 2003b)
Glasshouse, W. Aust. (49 days)	Wheat-chickpea intercrops with zero, partial or complete root separation. P as organic source (sodium phytate) or sparingly-soluble inorganic source (FePO ₄) at 60 mg P/kg	Independent of P form supplied P uptake (and biomass) of wheat in intercrop with no root separation greater than where roots completely separated (14.6 v. 9.6 mg P/compartiment for phytate; 13.2 v. 12.6 mg P/compartiment for FePO ₄)	Li <i>et al.</i> (2003a)
Glasshouse, S. Aust. (63 days)	P-inefficient wheat cv. Janz intercropped with P-efficient wheat cv. Goldmark or chickpea with zero, partial or complete root separation P as phytate or iron phosphate	Root contact between Janz and chickpea increased yield and P uptake of both crops	Wang <i>et al.</i> (2007)

total yield and grain yield of both species in a maize–faba bean intercropping system, were significantly higher than those of sole maize and faba bean on an equivalent area basis (Li *et al.* 1999). Furthermore, there was increased P uptake by both species in the intercropping system but not when the roots of the two species were kept separate (Table 2), suggesting that inter-specific facilitation for nutrient uptake had occurred below ground (Li *et al.* 2003b). Given these encouraging results for semiarid systems elsewhere in the world, it seems that some research efforts in Australia should be undertaken to seriously assess intercropping systems for particular environments in terms of yield and gross margin benefits, but also to understand the nutrient dynamics, including P cycling, in these systems. Organic farmers tend to use more complex rotational systems than conventional farmers (Cornish 2009, this issue) and are likely to be more willing to trial systems like intercropping. They also tend to have longer rotations, such as the pasture cropping mentioned above, which may facilitate the inclusion of less labile P sources into the biogeochemical cycle that can release plant-available P for crops grown in the shorter phases of the rotation between the longer pasture phases.

Promoting rapid P uptake and maximising the P uptake period

The importance of early-season P nutrition for maximising growth of crop and pasture species in dryland farming systems is well recognised (Batten *et al.* 1993; Grant *et al.* 2001). Seed inoculation with growth-promoting bacteria to encourage early seedling growth and enhance P uptake (Yadav and Tarafdar 2003) is an emerging technology and current investigations, under field conditions in Australia, are being undertaken within a joint venture between the Grains Research and Development Corporation and Philom Bios (S. Gleddie, pers. comm.). Detail concerning progress with identification and isolation of organisms suitable for soils of the cereal–livestock zone in Australia is discussed elsewhere in this issue by Harvey *et al.* (2009). It remains to be seen whether such a practice will be permissible in organic farming systems, although as long as genetically engineered organisms are not involved, it should be acceptable. The practice would be extremely effective if coupled with the standard approach adopted widely in conventional systems of early sowing in order to maximise length of time for crops or pastures to be able to take up P (Batten *et al.* 1993).

Enhancing soil biology

Although it is a central paradigm for organic agriculture that an active soil microbial community is vital for the functioning of the agro-ecosystem (Lampkin 1990), it appears from the literature that the evidence for greater soil biological activity and diversity in organic systems *v.* conventional systems is equivocal. Furthermore, it has to be remembered that not all microorganisms are beneficial in systems and that root pathogens can reduce the capacity for plants to take up P by pruning roots. There are reports of soil organism diversity, number, processes, and activities being larger in organic systems than in conventional systems (Fliessbach and Mäder 2000; Fliessbach *et al.* 2001; Peacock *et al.* 2001; Shannon *et al.* 2002). These observations are mainly attributable to input of

organic matter (i.e. provision of substrates) either by imported materials (such as manures or composts as discussed below in this review) or by longer pasture phases that increase soil C. Both these practices tend to sustain greater microbial activity, increase P mineralisation, and stimulate soil enzymes, including phosphatases (Goyal *et al.* 1993; Nguyen *et al.* 1995; Oberson *et al.* 2001; Oehl *et al.* 2004). In contrast there are other studies that report no consistent responses in the microbial status of soil managed under an organic regime (Yeates *et al.* 1997; Shannon *et al.* 2002), and in some cases a negative effect on microbial biomass has been reported, although there are no direct references to soil P dynamics in any of these. Conclusions may be confounded by the fact that the systems can often differ in more than one factor that affects microbial biomass, such as tillage (Lupwayi *et al.* 2001) and nutrient inputs (Graham *et al.* 2002). Thus, in one comparison it was suggested that N deficiency in the organic system may have limited microbial activity by reducing plant growth and rhizosphere C (Lützow and Ottow 1994), and in others, that the organisms appeared P limited (Parfitt *et al.* 2005). It should be noted that none of the studies mentioned here was undertaken for Australian systems with their unique climate and soils. Whilst these studies provide useful guidance there is a clear requirement for research in Australian systems to provide some unequivocal answers.

There is a general perception that inorganic P uptake by plants occurs as a direct consequence of uptake from the soil by root cells. Although this is true, it is not the only mechanism of P uptake. In more than 90% of land plants, symbiotic associations are formed with mycorrhizal fungi (Schachtman *et al.* 1998) that allow plant access to soil P up to several centimetres away from the root via extraradical mycorrhizal hyphae (George *et al.* 1995). The contribution of mycorrhizal associations to efficient uptake of P by plants is very complex and a range of direct and less direct mechanisms have been suggested, including: increased physical exploration of the soil; increased P movement into mycorrhizal hyphae; modification of the root environment; efficient transfer of P to plant roots; increased storage of absorbed P; and efficient utilisation of P within the plant (Bolan 1991). Arbuscular mycorrhizal fungi (AMF) of the Phylum Glomeromycota (Schussler *et al.* 2001) are considered the most dominant in agricultural soils (Gosling *et al.* 2006). Recommendations for management of AMF for conventional systems in dryland agriculture include strategies to ensure effective and early colonisation (Abbott *et al.* 1995) to enhance P uptake at this important time. However, it is generally considered that many agricultural practices, such as tillage, biocides, and soluble fertilisers have had a negative effect on AMF associations (Gosling *et al.* 2006) and that agricultural soils are impoverished in AMF (Helgason *et al.* 1998; Menéndez *et al.* 2001). Furthermore, there has also been a suggestion that breeding programs may have further reduced the responsiveness of modern wheat cultivars to AMF (Zhu *et al.* 2001).

A 10-year study comparing four types of broadacre farming systems (organic, biodynamic, integrated, and conventional) in southern Australia reported that mycorrhizal colonisation of medic roots under the conventional system was significantly less than under the other systems (Penfold and Miyan 1998) although, due to an overriding influence of weeds, there was no

identified link with yield or P uptake. There have been other studies where the organic system had higher AMF colonisation potential and higher labile organic matter (OM) fractions, e.g. in the UK (Bending *et al.* 2000) and Switzerland (Mäder *et al.* 2000), but these do not necessarily translate into a more P-efficient system with regard to yields or P uptake. Despite the general finding that there are more AMF in the roots of plants growing on low P soil or in the absence of applied soluble P, the evidence in Australia strongly indicates that AMF, while perhaps contributing to crop uptake of P (Thompson 1990; Li *et al.* 2006) or zinc (Ryan and Angus 2003), do not directly contribute to yield increases in farming systems, whether organic or conventional, and may sometimes reduce crop growth and yield (Ryan *et al.* 2002, 2004, 2005).

Regarding other individual microorganisms in the system, a positive relationship between duration of organic farming and *Penicillium* abundance was detected by a Danish study (Elmholt 1996), but follow-up studies suggested that management factors such as high frequency of crop mixtures with legumes and grasses were an important determinant of this (Elmholt and Labouriau 2005). At three grassland sites in the UK, fungal-feeding nematodes were twice as abundant in organic as in conventional systems and are considered a robust indicator of changes in the management of the system (Yeates *et al.* 1997). Soil fauna will 'mix' nutrients through the soil profile, increasing the rate of breakdown of plant residues and thus causing nutrients such as P to be more rapidly, as well as spatially, available. A meta-analysis of data published before 2002 for biodiversity and abundance in organic agriculture showed that, in total, organisms were 50% more abundant in organic systems and that soil organisms responded positively to organic farming (Bengtsson *et al.* 2005). There is evidence from a Swiss long-term trial of increases in soil fauna (earthworms, carabids, spiders, staphilinids) under organic and biodynamic systems and significant increases in microbial diversity assessed using Biolog plates (Mäder *et al.* 2002). It was also noted that although P was less dissolved in the soil solution in the organic soils it had a faster flux between the matrix and the soil solution (Oberson *et al.* 1993), as well as via the microbial biomass (Oberson *et al.* 1996; Oehl *et al.* 2001), suggesting an important role of microbial processes in contributing to plant P supply. Both bacterial and fungal populations have been shown to be greater under organic management in many other studies (Fraser *et al.* 1988; Foissner 1992; Reganold *et al.* 1993; Zwart *et al.* 1994), although mainly for temperate climatic regions with relatively high rainfall compared with much of Australia.

Discrimination between farming systems in terms of broad taxonomic groups of soil organisms is hampered by the large spatial and temporal variation that occurs in distribution and activity of these groups and has led several workers to conclude that consistent long-term effects of organic farming on soil biology are difficult to confirm (Dick 1992; Ryan and Ash 1999; Parfitt *et al.* 2005). Nevertheless, there are those who believe that the tools are emerging to enable the effect of agronomic management on microbial diversity to be assessed, e.g. in relation to the suppression of soilborne diseases (van Elsas *et al.* 2002). Furthermore, tailoring inputs to feed soil microbes is far from being considered an agronomic strategy but as knowledge of soil microbial communities progresses it is suggested that more

precise rhizosphere management practices, enhancing soil and plant health and overall system productivity, could be developed (Welbaum *et al.* 2004). Recent work in Europe in conventional farming systems is showing some community structural changes in response to agricultural management such as rotation and P fertiliser (Bünemann *et al.* 2004). There is also evidence that 26 years of management practices favouring retention of soil organic matter (stubble retention, direct drill, and mulching pastures) have altered microbial community structure and the forms of organic P that accumulated at a long-term trial site in south-eastern Australia (Bünemann *et al.* 2008). Clearly, more work needs to be undertaken in elucidating the microbial dynamics that operate in systems with different OM inputs, and in understanding how these are manifested at the field scale in relation to P nutrition of crops and pastures.

Increasing the capacity for P cycling and release of available P

'Building' labile soil organic matter

A key approach, consistent with the ethos of organic farming, is to increase soil OM and thus increase soil organic P. In particular, if systems can be used that increase the labile or readily mineralisable fractions of OM, as suggested in one study (Vanlauwe *et al.* 2000b) where labile organic P in the form of particulate OM in soil increased following legumes that had been fertilised with PR, then these systems should directly improve supply of plant-available P. Indeed, in a follow-up study to the one just mentioned, increases in grain yield, total N, and total P uptake of a subsequent maize crop were demonstrated (Vanlauwe *et al.* 2000a). Organic matter can also indirectly assist the supply of available P by complexing iron (Fe) and aluminium (Al) and thus preventing the complexing of P, which also competes for sorption sites.

Research in tropical systems, including incubation studies (Kwambiah *et al.* 2003a, 2003b) and field studies (Nziguheba *et al.* 2000), has focussed on the relationships between plant residue quality factors such as total P, C:P ratio, and the release of plant-available P in soil. Studies indicate that increased microbial P and higher rates of organic P cycling (mineralisation) can occur with high-quality (low C:P ratio) inputs of OM. For example, in western Kenya, green-manure farming systems proved more effective in increasing P availability in an acidic, moderately P-sorbing clay loam soil than bare fallow or continuously cropped systems (Nziguheba *et al.* 1998). This effect was attributed to rapid release of soluble P forms in the green manure plant tissues and also rapid mineralisation of organic P forms into labile and moderately labile pools of P, resulting in increased microbial biomass P. Adequate C was critical to this occurring. Furthermore, there was an effect of the green manure in decreasing the P sorption capacity of the acidic soil. The addition of OM to calcareous soils increased extractable P mainly by influencing P insolubilisation rather than the adsorption process, and this effect was stronger at lower soil water contents (Braschi *et al.* 2003). Although there have been studies on organic P dynamics for intensive dairy pasture systems in Australia (Gourley *et al.* 2001; Burkitt *et al.* 2007) the potential for soil OM, added organic amendments, crop residues, and living biomass to supply P is relatively poorly understood for broadacre, low-input systems in the wheat/sheep belt. Recent

work (Bünemann *et al.* 2007) has shown that basal net P mineralisation rates for some soils from southern Australia, under optimal moisture conditions, are in the range 0.5–0.9 mg P/kg soil.day, which is relatively low by global standards but equates to 0.75–1.25 kg P/ha.day, rates sufficient for adequate P nutrition of most crops in southern Australia. Other incubation studies using the same soils have highlighted that dry–rewet events inherent in Australian systems are important for increasing the cycling of P from native OM (Nguyen and Marschner 2005), that the contribution of plant residue additions to the particulate OM fraction is also important for rapid release of available P (Ha *et al.* 2007), and that young plant material used in mulching or green manuring contributes to more rapid release and greater amounts of plant-available P in soil than mature residues (Ha *et al.* 2008).

Low available P in farming systems may affect N contribution from legumes in that if P is restricted, then N fixation may also be reduced (Ngululu 1993) and residues will be reduced in P. Furthermore, this may reduce N mineralisation: incubation studies on a clay loam from the Northern Territory using residues of cowpea and stylo with different P concentrations showed that mineralisation was reduced at lower P concentrations (Ngululu *et al.* 1997).

The contribution of root organic matter *per se* to P cycling in the field has generally not been specifically studied, although by default the effects are integrated into outcomes from field studies. A 2002 field study on an acidic soil with high organic carbon (>3.0%) in Canada was used to specifically measure P mineralisation from root residues of several crops (peas, canola, and wheat). The authors concluded that root residues exhibited no tendency to immobilise P, although the rate of P mineralisation was less than with shoot materials (Soon and Arshad 2002). A study examining decomposition of mature canola shoot and root residues separately in a low-P status, alkaline Australian agricultural soil showed that plant-available P was significantly greater for the root residual material (S. Iqbal, pers. comm.). Further quantitative information of this type would enable better understanding of the contributions that the root systems of different crop and pasture species make to P cycling and of the relative importance in low-input organic systems. Incidentally, residues of mustard or rapeseed varieties high in glucosinolates (Morra and Kirkegaard 2002) could also potentially be used for increasing the suppression of soil-borne diseases and thus maintaining a healthy root system for P uptake. This appears to be possible without undue effects on beneficial soil organisms such as mycorrhizae. For example, a study on an alkaline silty clay loam soil in France reported no evidence of a negative effect of the incorporation of rapeseed residues on the colonisation of following crop (maize) roots by mycorrhizae (Pellerin *et al.* 2007). Similarly, in a study on Vertosols in south-eastern Australia there was no effect on AMF colonisation of wheat grown in rotation after brassica crops with different levels and types of root glucosinolates (Ryan *et al.* 2002).

Short and long phases of pastures in rotations

A large amount of research effort in Australia over the past 30 years has been devoted to understanding N cycling in rotations and far less has been dedicated to P, particularly in the southern and western regions. Work was conducted 20 years

ago in relation to P derived from mineralisation of OM residues on an alkaline sandy loam soil from the cereal–sheep belt in South Australia. These tracer studies showed that P from medic residues accumulated in wheat plant shoots, roots, and in soil microbial biomass in similar proportions (6.7, 7.0, and 8.1% of total P added), i.e. a total of 21.8% of the residue P became labile (McLaughlin and Alston 1986) in one season. Under field conditions, the amount of residue P incorporated into microbial biomass (22–28%) was even greater (McLaughlin *et al.* 1988b) and may be related to the fact that there was a rapid release of soluble P directly via autolysis of the residues upon initial wetting of the soil at the break of the season (McLaughlin *et al.* 1988c). Overall, this work highlighted the contribution that annual pastures in southern Australia can make to P cycling. Pastures, of course, require adequate available P for optimal growth and the use of allowable P inputs, to be discussed below in this paper, will be required in the system to sustain P benefits from medics to cereals.

Further work measured the relative uptake of P from fertiliser and medic plant residues in the field and showed that most of the P taken up by a wheat crop originated from historic soil sources, i.e. not sources from the immediate season's fertiliser or last year's residues (McLaughlin *et al.* 1988a). This underlines the fact that system P fertility is an integration of many years of inputs and that long-term P management strategies need to be evaluated to fully understand the sustainability of particular systems. Understanding the balance between plant-available P in soil and supply of P from organic residues is critical for organic systems that are likely to be operating without soluble P fertilisers.

The use of long phases of legume pastures will not only contribute to build-up of quality OM inputs from shoot and root residues (as mentioned above) but may also allow replenishment of labile P from the more 'slowly available' P reserves. It has also been suggested that perennial pastures are using P from deeper in the soil profile (Burkitt *et al.* 2007) and there is thus the potential for this P in plant residues to be released in the topsoil for the next phase. Although substantial evidence for this idea is lacking, further research on this is warranted.

Soil amelioration

In this section, we briefly consider issues associated with the maintenance of soil physico-chemical 'health' as they directly or indirectly relate to the supply of plant-available P: practices such as tillage, used by some organic growers to 'aerate' the soil and commonly used for weed control in organic systems, and addition of individual ameliorants, in particular lime, to address acidity issues.

Organic matter decomposition rates tend to be increased by tillage so there will be some mineralisation of organic P with tillage. It has been suggested that there are three main effects of tillage on nutrient availability (Robson and Taylor 1987): (i) temporarily altering the physical soil environment (aeration, bulk density, water availability), which affects the amount and distribution of roots within the soil profile; (ii) by mixing nutrients through the soil, availability can be either increased or decreased; and (iii) by negative effects on the soil fauna and AMF, although if a pathogen (such as rhizoctonia) is reduced then this will have a positive effect on root growth and P uptake.

Conventional tillage, practiced by most organic grain farmers, uses points providing full soil coverage, which mixes broadcast nutrients and surface OM within the tilled layer (~0–0.10 m). This should enhance P availability, at least while the temporary effect of tillage on soil strength persists. However, it should be noted that while organic systems have been shown to improve soil structure as determined from the parameters of increased soil OM, earthworm activity, water-stable micro-aggregates, and increased N mineralisation, these benefits did not reduce the susceptibility of the soil in the organic system to compaction from tillage, traffic, and grazing (Pulleman *et al.* 2003), which is likely to reduce P uptake from crop roots. The effects of organic farming on soil structure are not well reported, and published data in Australia are hard to find, suggesting that more research is warranted, in particular concerning the interactions with nutrient (P and N) uptake.

By comparison, direct drilling or no-tillage practices, which are used by many conventional farmers, using narrow points to create minimal disturbance, will leave immobile elements such as P (in a non-leaching environment) in the surface few centimetres (Cornish 1987). Thus, a zone of P-rich soil of low sorptivity is created at the surface (Costin and Williams 1983). In the cropping situation, soil moisture relationships will then become more important as the soil surface will have to be moist for the soil P to be available. Crop residue retention slows drying at the soil surface and this will prolong the availability of surface P, but stratification of P at the soil surface will likely require soil or fertiliser P further down the soil profile.

Researchers (Rehm *et al.* 2003) have highlighted the importance of root zone temperatures on soil P uptake, and the greater efficiency of banded fertiliser in cooler soil temperatures (10 cf. 25°C), where root access to the fertiliser is critical. They also investigated the effect of fertiliser placement (broadcast, banded with the seed) and tillage system (no-till, chisel plough, and mouldboard plough) on the growth of hard red spring wheat in Minnesota in the United States. The outcome from 5 site years of data showed that the effect of P rate on grain yield was consistent for all fertiliser placement options and was not affected by tillage system. In contrast, studies in Western Australia (Jarvis and Mason 1996) reported that broadcasting fertilisers is 50% less effective than drilling fertiliser with the seed or banding it below the seed where the soil is expected to remain moist for longer periods. However, other work in Australia has suggested that young wheat plants were unable to fully exploit banded P fertiliser because the roots were not sufficiently adapted to concentrated P sources, and that this effect was greater for direct-drilled crops (Cornish 1987).

A conundrum in nutrient management occurs in organic farming whereby the technology now exists via precision agriculture to very accurately place seed and fertiliser within defined spatial rows and depths, which could be advantageous for nutrient supply in organic systems. However, this technology is based around no-till systems, but as organic cropping systems chiefly use tillage for weed control, there is a need to redesign sowing machinery. Alternatively, the use of systems such as ridge tillage, which enables inter-row, in-crop weed control combined with precise seed and fertiliser placement on the ridge, may play a role in the wetter regions of Australia.

The addition of lime is usually made on acid soils to raise the soil pH and eliminate Al and manganese toxicities (Holford

1989). However, there are other secondary effects, which relate to the availability of P. These include increased solubilities of Al and Fe phosphates that increase the quantity of labile P, and increased precipitation of Al and Fe hydrous oxides, thereby decreasing their activities and enabling root penetration into acidic subsoils (McLaughlin and James 1991). Lime also increases negative charge or the electrostatic potential of the P absorbing surfaces, thereby reducing their affinity for P and increasing availability of organic phosphates (Costin and Williams 1982). Heavy dressings of lime on an acid sand in Tasmania were shown to decrease the leaching of P and increase the growth of subterranean clover (Paton and Loneragan 1960). Care needs to be taken to avoid over-liming because liming to pH > 6 is likely to have a negative effect on P availability because of the decreasing solubility of calcium (Ca) compounds, including phosphates, as pH increases (Fox 1979).

Importation of allowable and economically viable P inputs

Within the required standards for organic production in Australia there are mineral and organic options for P fertilisers. Reactive PR and PR are allowable mineral P inputs to organic systems, but their value has been questioned (Bolland and Gilkes 1990; Sale *et al.* 1997; Ryan *et al.* 2004). Several soil or climatic factors such as high P sorption capacity, low cation exchange capacity, high pH, low rainfall, low OM content, or low microbial activity (Vassilev and Vassileva 2003) may contribute to the reported lack of efficacy of these products. The scope for the cost-effective broadcast application of non-acidulated rock phosphate fertilisers is discussed elsewhere in this issue by Evans and Condon (2009).

Another allowable mineral input to organic systems is finely crushed or powdered rock. The application of silicate-based rock dusts at 10–20 t/ha increased yield in a German study (von Fragstein *et al.* 1988), but as the content of P in the base material was not included in the analytical data, it is assumed that the rock contained negligible amounts of this mineral. Studies using granite (silicate) rock dust on Western Australian soils ranging in pH from 4.69 to 5.2, found that the application of 2 t/ha of rock dust had no effect on yield, and an application of 20 t/ha reduced yields by 67% compared with the control (Bolland and Baker 2000). It was concluded that the product was an expensive input to farmers' operations and that it had no positive benefit on crop or pasture productivity.

The recycling of human wastes (biosolids) and use as fertiliser is not permitted in organic agriculture at this stage. However, there are data from conventional systems in Australia demonstrating that biosolids can supply P to support yields equivalent to that obtained with inorganic P fertiliser (Wegler-Beaton *et al.* 2003) and that biosolids have a residual nutrient value, including P (Pritchard *et al.* 2006), although this aspect needs to be managed to avoid potential losses and negative environmental effects (Bell *et al.* 2006). A complete life-cycle analysis of any production system to assess the environmental effects (Brentrup *et al.* 2004) should include the fate of biosolids and thus it seems likely that their use in organic systems may need to be considered in the future. However, this review will focus on a consideration of the potential for currently allowable organic input options, namely manures, composts, humic substances, and liquid products.

Manures

Australia, like New Zealand, has historically concentrated on developing extensive livestock systems. Large quantities of bulk manure to support nutrient supply in organic farming have, therefore, not traditionally been available (Condrón *et al.* 2000). This is in contrast to the European intensive farming systems for which housed or lot-fed animals are a feature. In the European system, nutrients surplus to animal requirements are cycled through the soil-plant system following manure or compost application. Direct applications of manures are common in Europe and the United States, but are restricted in their allowable application rates by their N-polluting potential. To prevent nitrate leaching to groundwaters, application is based on the crop's potential to use the applied N. Using this strategy, P is often applied in excess to crop requirements because the N:P ratio in manure is lower than in plant tissue (Edmeades 2003), leading to P build-up in soil and to increased environmental risks associated with elevated dissolved P concentrations in runoff waters (Chen *et al.* 2001; Schwartz and Dao 2005).

Concerns about pollution of groundwater are less in much of the cereal-livestock belt in Australia, perhaps apart from the deep sands in Western Australia. This is due to the extensive nature of most of the enterprises, the fact that they are often based on soils with low subsoil permeability, and rarely overlying fresh-water aquifers (Ball 2001). Thus, extensive low-input or organic farming systems in Australia represent an ideal sink for organic fertiliser products derived from livestock manures.

A review of the value of fertilisers in crop production using data from 14 long-term field trials in the United States and Europe concluded that nutrient inputs resulted in increases in crop production of 150–1000% (Edmeades 2003). When manure-based fertilisers were compared with conventional chemical fertilisers, the manured plots had higher OM contents and hence biological activity, but these did not always translate into higher yields. The manure application rates ranged from 4 to 35 t/ha.year and this appeared to be the overriding factor influencing soil organic matter.

Recent expansion of intensive pig and poultry industries in Australia has led to increased supplies of manure now being available for application to farmland. According to Australian Bureau of Statistics figures (ABARE 2006) there are $\sim 62 \times 10^6$ meat chickens in Australia, with 5.5 batches produced per year. Based on figures provided by S. Guerke (pers. comm.), this equates to an estimated 640 000 t of deep-litter chicken manure

produced per year, which at 2% P (Pittaway 2002a) and a 20 kg P/ha application rate, is sufficient to crop 640 000 ha. The pig industry in Australia comprises ~ 2.5 million animals. In terms of manure output of total P, this equates to ~ 8000 t/year, or, at an application rate of 20 kg P/ha, sufficient to cover 400 000 ha. If all this P could be recovered from these production systems alone, at the suggested application rates, it would be sufficient to cover 5.5% of Australia's 18.9 Mha of cereal-cropping land (ABARE 2006). Economic forces, which are discussed later in this paper, are critical in the utilisation of these products. Also integral to the wider utilisation of allowable organic inputs is the need for research to validate the short- and long-term nutrient value and cost effectiveness of these products (either as straight manure or as compost) in a range of applications and environments, as well as assessing perceived negative effects such as accumulation of metals to toxic levels (Merrington *et al.* 2003; Oliver *et al.* 2005; McLaughlin *et al.* 2006).

Composts

A recent communication from the European Communities Commission on Soil Protection (Favoino and Hogg 2008) emphasises the use of high-quality composted products for addressing global issues such as desertification, erosion, and maintenance of C in the soil. The role that compost and composting may have in mitigating greenhouse gas emissions through several effects is also noted; including increases in soil organic C and related sinks, improved uptake of nutrients, avoided energy uptake for the production of equivalent chemical fertilisers, and avoided release of nitrous oxide from chemical fertilisers even allowing for the release from organic amendments.

The organic certification standards (Monk and Dargusch 2006) state that manures must be composted before application to land from which food for human consumption will be produced in that year. Raw manures, however, can be applied to land in a ley period or for forage production. The use of composts as a principal form of nutrition (Table 3) is as old as agriculture (Balfour 1975; Subba Rao 1982b), and along with farmyard manures, they have been a mainstay of organic farming (Lampkin 1990). Composting of manures has associated costs (Eghball 2001) but also numerous benefits. These include weed and pathogen elimination, reduced odour and, importantly, volume reduction (Wiederholt *et al.* 2005) by up to 50% (Subba Rao 1982b; Lampkin 1990). Composting operations

Table 3. Chemical characteristics of materials suitable for co-composting
Modified from Pittaway (2002b)

	C:N ratio	% N	% P	% K	% Lignin	Bulk density (kg/m ³)	% Water (by wt)
Dairy manure	11–18	2.7–4	0.5	1.7–2.4	8.1	460–582	67–87
Feedlot manure	6–14	1.7–4	0.5–1.0	1.8–2.3	8.1	460–582	67–87
Pig manure	7–24	1.9–5.6	0.4–1.2	0.1–4.8	2.2	272	65–91
Pig litter	–	0.3–1.0	0.05–0.6	0.2–0.7	–	–	54–98
Poultry manure	2–24	1.6–10	1.1–2.3	1.7–2.2	3.4	263–563	22–75
Cotton trash	30	1.3	0.45	0.36	15	112	–
Peanut shells	–	0.8	0.15	0.5	23	–	–
Corn stalks	60–73	0.8	–	0.8	11	11	12
Wheat straw	100–150	0.3–0.5	0.15–0.26	0.6–1.02	7–18	20–131	4–12

generally rely on several aggressive turning operations to aerate and mix the material, but where nutrient conservation is important, less turning of the heap is preferred. Studies using cattle manure found that N and P losses were substantially less in a static than in a turned compost heap (Parkinson *et al.* 2004). Using static composting methods, the final N and P concentrations were up to 54 and 101% higher, respectively, than in the original manure, due to DM losses.

For the same nutrient concentration it is, therefore, less costly to transport the material from source to paddock and to spread it. In the Australian context, this is a vital consideration, as transport costs have historically been a major impediment to the more widespread utilisation of this product as a nutrient source (Penfold 2000).

Where P is the major limiting nutrient for crop production, then P-rich feedstock for compost production will be required (Table 3). Compost contains nutrients at levels dictated by the raw materials used in its production (Eghball 2001; Pittaway 2002a). Of the readily available manures, broiler chicken litter contains the highest amount of P at 1.1–2.3%, while pig manure contains much less at 0.4–1.2% (Table 3; Pittaway 2002b). Few broadacre studies of the response of crops and pastures to applications of these products have been reported for Australia. One study investigated the potential for rice- or wheat straw-based pig bedding to improve crop yield on a sodic soil in the Wimmera region of Victoria. Results showed that an application of wheat straw bedding at 20 t/ha increased wheat yields by 80%, canola by 215%, and field peas by 80% compared with an unfertilised control (Armstrong *et al.* 2000). In the following year, with no additional compost applied, canola yields at two experimental sites showed 223 and 700% increases over the application of urea and/or gypsum. These results suggest benefits from the bedding material beyond nutritional content, but they are unlikely to be realised at all sites. An investigation of the effect of di-ammonium phosphate (DAP), cattle feedlot manure, and compost on the yield and biomass production of winter wheat in a semi-arid environment of Texas, USA, found that P uptake was greater from the DAP, which produced more tillers, but the slowly available nutrition from the manure and compost over the length of the growing season generated similar grain yields (Willis and Stewart 1997). Composted bovine manure applied at 36 t/ha on a duplex soil in north-eastern Victoria, increased wheat grain yields by 28% and seed protein content by 13.5% (Slattery *et al.* 2002).

A major question is whether the application of compost is a financially viable approach to nutrient management. In the year from April 2007 to March 2008, the price of DAP has risen by 68% to \$1160/t from works in South Australia. Composted chicken manure prices have increased marginally to \$50/t, leading to a substantial increase in demand for this product. Based solely on P content and price, and present freight rates of \$2–30/km, a farm 600 km away could be supplied with chicken manure for the same cost as the purchase and transport of an equivalent amount of P as DAP, although this assumes equal availability of P in the two sources, which is not necessarily the case. Using the present (February 2009) price (Port Adelaide, SA) of DAP at \$900/t and urea at \$750/t, the value of N and P is \$1.63/unit of N and \$3.04/unit of P (Glendinning, 2000). Thus, the value of these elements in a tonne of chicken

manure based compost (2.0% P, 4.0% N) is \$65.20 for N and \$60.80 for P, a total of \$126/t, with no freight component included. The present cost of broiler compost in South Australia is ~\$60/t. Spreading costs another \$15/t, generating a total cost of \$75/t plus transport from the source of compost to the paddock. Providing reasonable economies of scale, compost could be freighted over 400 km and the price of the N & P components would still be cheaper than DAP fertiliser for a conventional farmer. While this is a substantial financial outlay for an organic farmer, in relative terms to conventional fertiliser prices it appears that compost may now be more competitively priced, at least in some regions of the Australian wheatbelt. However, more research is needed to determine how much of the total P (and other nutrients) content of these composts is plant available and the time-frame for release of that P, in order to validate economic comparisons with more soluble P fertilisers.

Phospho-compost

The fortification of compost with PR to increase the P content of the final product has the potential to significantly improve the cost effectiveness of compost application to P-deficient soils. This process is likely to enhance the value of PR by increasing P availability following soil application (Handreck 1986; Masih *et al.* 2004; Pareek *et al.* 2004). It is claimed that fortified compost provides a promising method for enhancing the solubility of PR and thereby improving its availability to plants (Zapata and Roy 2004), which would be particularly useful where organic farming is practised. Phospho-composting uses the organic acids and humic substances produced by the bacteria and fungi in a compost pile to release P from PR. It is also believed that the organic acids perform a chelating function on Ca, Fe, and Al (Zapata and Roy 2004).

Information on the agronomic efficacy of composted products is limited. One study (Singh and Amberger 1995) produced enriched compost (phospho compost) using low-grade rock P added to wheat straw to which molasses was applied to enhance microbial activity. Phosphate was added at the rate of 5% P₂O₅ (2.4% P). In a glasshouse experiment with soil of pH 7.65, they found that PR-enriched compost trebled the yield of ryegrass compared with the control at 14 weeks after sowing. This provided an equivalent yield to single superphosphate applied at the same rate of P as the enriched compost treatments.

Anaerobic digestion: energy from compost

While this paper is primarily focussed on agronomic management options for improving P nutrition in Australian broadacre organic and low-input farming systems, it is important also to consider the broader context of long-term sustainable food production systems. Compost application to broadacre farmland has been suggested as a practical and economically feasible means of addressing P nutrition. However, within the compost is embodied a considerable amount of energy in the form of C, which would normally become greenhouse gas, as 78–87% is evolved as carbon dioxide (CO₂) during the composting process and through mineralisation following land application (Martin and Haider 1976). To help address the issue of energy in sustainable production systems, it is suggested that raw material should first be composted in an anaerobic digester.

This process is described as the conversion, by primary colonisers, of OM into simple sugars. Secondary colonisers, mostly methane (CH₄) bacteria, then break down the organic acids into CH₄ and CO₂ (Subba Rao 1982a). The CH₄ can then be used within the animal production unit for heating or as a fuel for power generation. It is also possible to compress CH₄ to produce compressed natural gas or produce liquefied natural gas by cooling the CH₄ to -162°C. Both of these fuels would then be suitable for use in powering compost-turning equipment and trucks for distribution of the product.

The residue from the anaerobic digestion can then be used as a fertiliser, as it remains rich in N and P (Subba Rao 1982a). One study in Germany applied fresh manures, composted manures, digested manures, and N-amended digested manures to crops in an 8-year rotation (Möller *et al.* 2006) and concluded that there were no negative effects on nutrient availability following anaerobic digestion.

Pyrolysis has been proposed as an alternative to anaerobic digestion for energy and nutrient extraction from manures (Bridle and Pritchard 2004). The principal energy product generated by pyrolysis is oil and the sludge nutrients are recovered in the char. A study using sludge from a pilot plant in Western Australia confirmed that the P was plant-available but the N was insoluble (Bridle and Pritchard 2004). This process may also be a viable means of obtaining P for organic farming, either in its raw form or processed into a form which will enable passage through seeding machinery. Alternatively, it could be added to compost piles before fermentation, in the same way as PR.

Humic substances

Humic substances, described as an extraordinarily complex mix of organic compounds, which have not yet been isolated (McCarthy *et al.* 1990), are the relatively stable forms of OM. They can be considered to consist primarily of three fractions: humic acid, fulvic acid, and humin, classified according to their water solubility. Humic substances are important sources of N, P, and S in most agricultural soils and help prevent cation leaching due to their very high cation exchange capacity. Humic substances may be extracted from leonardites (oxidised lignite coal) or they can be applied as a component of compost.

An investigation of the effects of humic substances on plant growth found benefits particularly in root growth and the uptake of macronutrients, including P. The benefits in plant growth associated with the application of composted plant and animal residues, are believed to be due partly to the minerals contained within the products but also to the auxin-like activity in growth promotion. It was determined that 75 kg/ha of humic substances were required to increase their soil concentration by 100 mg/kg, but similar effects were possible by foliar application at rates 100 times lower, suggesting that foliar application had the most promise (Chen and Aviad 1990). The authors also suggested that the greatest benefit would most likely be found in arid and semi-arid soils of low OM contents and the best way to achieve this would be the application of compost containing a high level of the humic substances.

Humic substances can improve the availability of P in rock phosphates by causing the release of PO₄⁻ anions and Ca²⁺

cations (Mayhew 2004). This is due to their high total acidity, ability to complex and chelate the resulting solutions, and to stimulate microbial metabolism. As dry humates are particularly dusty materials to handle, in the USA they are now pelletised with rock phosphates and other nutrients as required, enabling them to be applied through seeding equipment in the crop row.

The problem of phosphate fixation in alkaline soils, whereby dicalcium and tricalcium phosphates are formed, is well known. Laboratory studies have suggested that there is potential in applying humic acid/phosphate-blend fertilisers to alkaline soils to maintain applied P availability for a longer period (Martinez *et al.* 1984). It was also suggested that humic acid from lignite could be effectively added to alkaline soils as a means of dissolving P from insoluble forms including tricalcium phosphate and fluorapatite.

Organic substance-based liquid fertilisers

This group of products includes those derived from seaweed, fish wastes, vegetable origin, or animal products and as such are suitable for use in organic production. Through combinations of plant-available nutrients and/or plant growth substances, they generally claim to increase plant yield and quality, improve nutrient-use efficiency, provide greater stress tolerance, and increase greater root growth and activity. An extensive review of these products used on cereals, root crops, legumes, pastures, and vegetables in New Zealand concluded that 'these products do not contain sufficient concentrations of plant nutrients, organic matter or plant growth substances to elicit increases in plant growth when applied as recommended'. While not investigating P solely, the review unequivocally reported that using the listed products would not compensate for inadequate levels of available soil P in any of the listed crops (Edmeades 2002).

Conclusions

This review of the potential options available to organic and low-input, broadacre rain-fed farming systems for agronomic management of plant-available P has highlighted that strategies such as selecting for plants that make more efficient use of the P taken up, or that can obtain more of the labile P in soil, represent useful agronomic tools in low-input or organic systems. However, while inherent variability within and between crop and pasture species in terms of grain or biomass produced per unit of P uptake has been known for many years, there has been little concerted effort to understand, or exploit, the benefit of these in farming systems. Progress in selection and breeding for cereal genotypes that are more P efficient is also gaining momentum but still remains a long-term prospect. Improving the P-use efficiency of the system by incorporating species into rotation or intercropping systems, which are able to obtain P from less soluble sources, has been a successful strategy under field conditions in parts of the world with climate similar to much of the Australian cereal-sheep belt, and deserves further research effort in Australia. However, it should be remembered that these latter two options may both involve genetic modification, which will not be acceptable for organic systems, but could benefit low-input systems. The use of soil amendments to obtain recalcitrant P is not dealt with in this review but is covered elsewhere in this issue.

The review suggests that agronomic management to maximise quantity and quality of pasture and crop residues undoubtedly builds labile soil organic matter and facilitates P cycling, but the strategy may be of limited benefit in low-rainfall areas that do not have the capacity to produce large biomass inputs. The use of different species, either in polyculture, companion cropping, or in rotational sequence, has demonstrated small but tangible benefits to P uptake and yield. Thus, innovative approaches to cropping and pastures may be required, including long pasture phases, pasture mixtures, green manuring of P-solubilising species, intercropping, and growing species previously not considered as suitable for economic (or other) reasons. Further research at the paddock scale is required to quantify the potential benefits of some of these alternative systems.

The review also concludes that there is sparse evidence demonstrating that numbers and diversity of soil organisms, such as vesicular arbuscular mycorrhiza or *Penicillium*, naturally increase in organic or low-input systems, and published field studies from Australian systems suggest that P nutrition is not enhanced. However, field testing of seed or soil microbial inoculants to facilitate improved P uptake is currently underway in Australia and the outcomes from this work will provide valuable information regarding options for microbially based management of P availability in low-input or organic systems.

Finally, the review recommends that the option most likely to ensure that labile P is not a limitation in the system is the importation of allowable inputs that contain P from off-farm. Furthermore, co-generation of energy associated with the processing of these potential inputs could contribute to overall sustainable development of the system. However, for much of the Australian cereal/livestock belt, the immediate issue may be access to economically viable sources, and research targeted at quantifying the economic and biological benefits to the whole-farm system associated with the adoption of these practices is required.

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