Institute of Organic Training & Advice

Results of Organic Research: Technical Leaflet 8

Managing phosphorus dynamics in organic rotations

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Introduction

Organic farmers and growers need to ensure adequate availability of phosphate (P) from the soil in order to support the metabolic, energy transport processes essential to plant growth and also for optimum functioning of soil organisms, such as nitrogen fixing rhizobia. In relation to managing P dynamics in rotations, organic producers' principal aims are to:

1) optimise the utilisation of whatever P is in the soil, and,

2) maximise P recycling within the farm through the careful use of own manures and minimising P losses.

Widespread experience in organic farming systems in the UK indicates that soil P indices are often low or very low, when measured by current routine methods of soil analysis, yet at the same time yield levels are satisfactory and show no indication of limitation due to P deficiency. Developing appropriate management of P in organic rotations requires a good understanding of the complex plant-soil interactions which control P dynamics in soils and the efficiency of P supply from added crop residues, manures or brought-in fertilising materials. In an effort to improve understanding of P supply in organic farming systems there have been a number of research projects undertaken in which P dynamics have been investigated in detail. This Technical Leaflet draws on that research and in particular the P-Link project which used pot and on-farm rotation trials to investigate the ability of a range of 'P solubilising' crops and varieties to improve the spatial and temporal efficiency of P use in organic systems.

Form and amounts of P in soils

There is often a lot of P present in soil, but very little of it is in forms which can be used easily or immediately by plants. The total P content of soil varies greatly, ranging from around 500 to 2,500 kg per ha. In comparison, often less than 10 g per ha of P is in the soil solution as soluble orthophosphates ($H_2PO_4^-$, HPO_4^{2-}) at any one time; it is these forms which are plant available. However, this pool is regularly replenished – cereals take up 12-16 kg P per ha and root crops 17-25 kg P per ha over the growing season.

Phosphorus reserves in soil are found as both strongly adsorbed (and insoluble) inorganic forms and in complex organic forms (White, 1995) (see **Figure 1,** overleaf). The balance between these different forms depends on soil texture, mineralogy and organic matter contents. Information about the inherent reserves of P in a particular location can be determined from knowledge of the parent material or soil series for UK soils.

If soil P reserves are large the annual release of P may be sufficient to met the demands of many crops. Regular inputs of P fertiliser or manure in farming systems tend to increase soil P reserves as only 15-25% of applied P fertilisers are usually taken up by crops in the first year after application and the remainder are adsorbed by soil minerals and released only very slowly.

This Technical Leaflet is one of a series of leaflets for farmers and growers which summarise practical recommendations arising out of research. It draws on the results of the Defra funded P-Link project led by the Scottish Agricultural College and it is produced in collaboration with the Institute of Organic Training and Advice.

Other Leaflets in the series produced under this project and the Defra funded PACA Res project include: Phosphate Management Using Green Manures, Composting, Dairy Cow Nutrition, Financial Management, Nutrient Budgeting and Beef & Sheep Nutrition. For further information go to the IOTA website www.organicadvice.org.uk/research_results.htm

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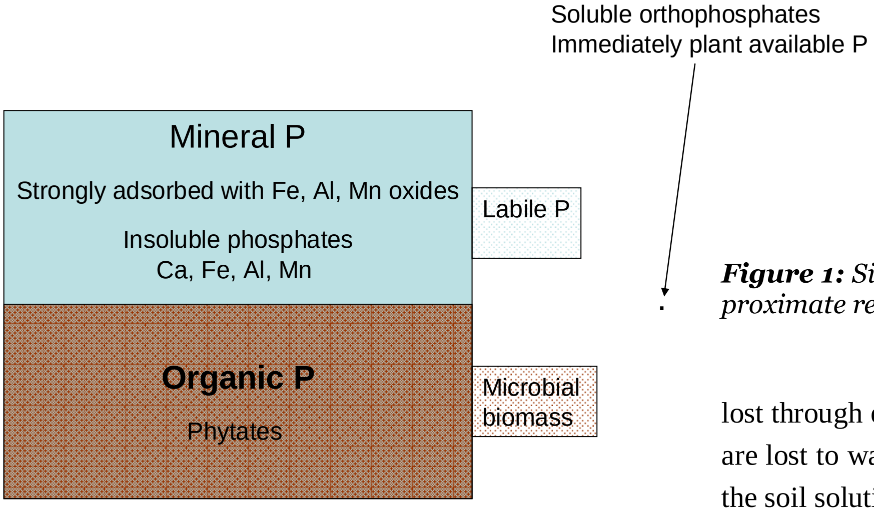


***Figure 1:** Size of key pools of P in soil showing approximate relative amounts.*

The living part of the soil organic matter also forms an important pool of P. In arable soils about 3% of P is in the soil microbial biomass, because of the increased soil organic matter and microbial activity this can increase to 24% in grassland soils (Brookes *et al.*, 1984).

Dynamics and cycling of P in soil

Inputs of P in rain are very small, however, there is some deposition in dust, particularly in dry weather but this usually amounts to less than 0.3 kg per ha per year (White, 1995). Because top soil is usually relatively high in P, losses of soil by wind or water erosion can lead to significant losses of P from soils. 26% of phosphate in rivers has been estimated to be of agricultural origin; this enters watercourses bound to soil particles lost through erosion (Defra 2008). Smaller amounts of P are lost to water through leaching, as the amount of P in the soil solution is usually very small.

Providing adequate levels of P for plant growth depends on both microbial activity to convert (mineralise) organic P forms and on chemical transformations within the soil. Both these processes replenish the small pool of P in the soil solution as it is emptied by plant uptake. These two parts of the P cycle in soil, which both control P availability for plants, barely interact (**Figure 2,** below left). 80-90% of all soil processes result from the interaction of soil organisms and soil organic matter. Soil organic matter is the main food resource for soil organisms as most rely on decomposition of the complex organic materials to obtain energy. In natural ecosystems, soil organisms are highly competitive with higher plants for available P. The breakdown of organic P (mainly found as phytates) depends on the presence of extracellular phytase enzymes which mineralise the phytates – these enzymes have many biological sources. Many micro-organisms (bacteria and fungi) are therefore able to mineralise organic P. Some soil micro-organisms also excrete organic acids which are able to attack insoluble calcium (Ca) phosphates in the soil, bind the Ca and hence release the P.

Mineralisation of soil organic P is seen across a range of environmental conditions and soil types; however these processes are most effective at near neutral pH. Up to 8 kg P per ha has been measured as released by mineralisation where old grassland is ploughed out or where large amounts of farmyard manure (FYM) are used (Brookes *et al.*, 1984). Increased biological activity stimulated by the regular return of crop residues, and the addition of composts or manures will therefore increase the amounts of P cycling in the organic half of the soil P cycle.

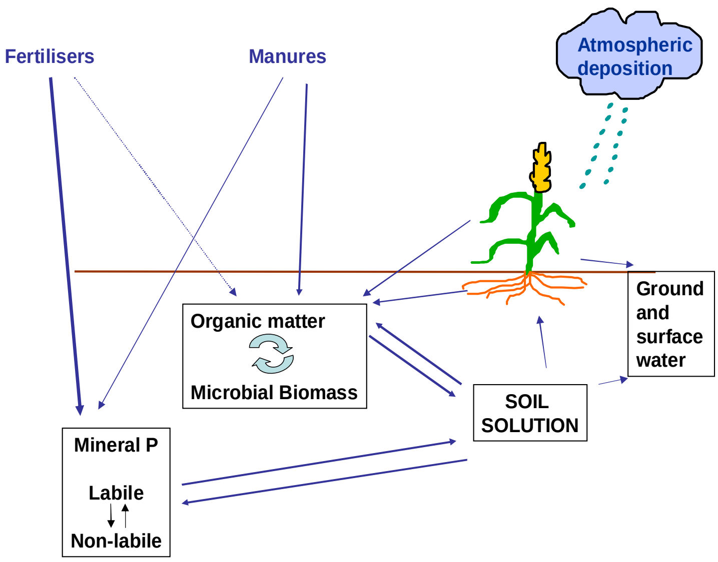
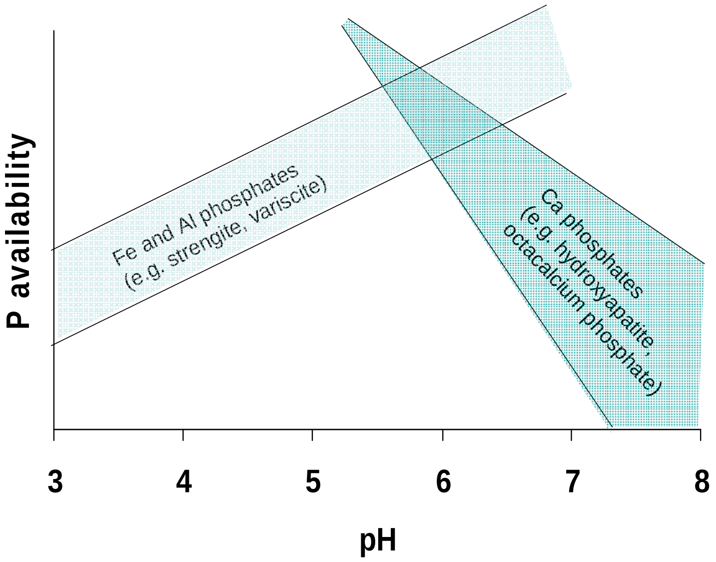


***Figure 2:** Schematic diagram of the soil P cycle*

It is important to recognise that none of the methods used in routine analysis of P availability in soil include determination of organic forms of P. The routine chemical extraction techniques used measure labile P in mineral forms together with the soil solution P. The P available to plants through cycling of organic P is not measured by these techniques. Hence the organic half of the soil P cycle is invisible when routine soil analysis is considered alone.

Complex interacting chemical equilibria control the mineral half of the soil P cycle. Phosphate is sorbed by ligand exchange by Al and Fe oxides (sesquioxides) in soils and also on to clay surfaces by hydroxy-Al polymers; on these surfaces the phosphate is held in an exchangeable form and can be released in the presence of competitive anions. It is this "labile" P that is largely targeted by routine measurements of P availability in soil.

Phosphate sorbed on soil surfaces as described above can become occluded in these materials, though the mechanisms are not always clear, so that it becomes non-labile and unavailable for plant uptake. Many of these bonds are most stable under acid conditions with increasing P availability as pH increases. Crystalline Fe and Al minerals such as strengite (Fe) and variscite (Al) are only stable in very acid conditions – but in acid soils, amorphous Al and Fe phosphates can form. Phosphates locked up in salts with Fe and Al become more available as pH increases **(Figure 3,** below).



Alternating aerobic/ anaerobic conditions, such as occur with seasonal waterlogging, can also lead to alternating precipitation and dissolution of hydroxyl-Fe – P compounds.

Above pH 6.5, and where there is Ca in the soil solution, insoluble calcium salts are precipitated, such as octacalcium phosphate and hydroxyapatite **(Figure 3).** Phosphates locked up in salts with Ca therefore become more available as pH decreases.

Consequently as both mechanisms usually occur simultaneously in UK soils, the availability of P is usually considered to be greatest between pH 6 and 7. This pH range also favours optimum biological activity.

Interactions between plant roots and soil – natural manipulation of P availability

Because of the P sorption capacity of soils, phosphate only moves very slowly by diffusion in soils. Consequently the root length and distribution in soil is critically important in determining how effectively plants can use soil P. The more roots spread through the soil volume, the more P that a plant will be able to "see". Hence ensuring that root growth is not impeded by compaction and maintaining good soil structure is critical for optimising availability of P to crops (**Figure 4**, overleaf).

The preparation of seedbeds with a tilth, and consequent network of pores, holding the right balance of air and water appropriate to the seed to be sown is a very critical step in crop production. Maintaining soil organic matter levels is also critical for facilitating seedbed preparation under a wider range of weather conditions and maintaining soil structure throughout the growing season.

Figure 3: *Schematic of relationship between P availability for mineral P and pH. The exact position of the lines depends on the presence of other compounds which also affect the activities of Ca, Fe and Al in soil solution (redrawn as a schematic from data in White 1995).*

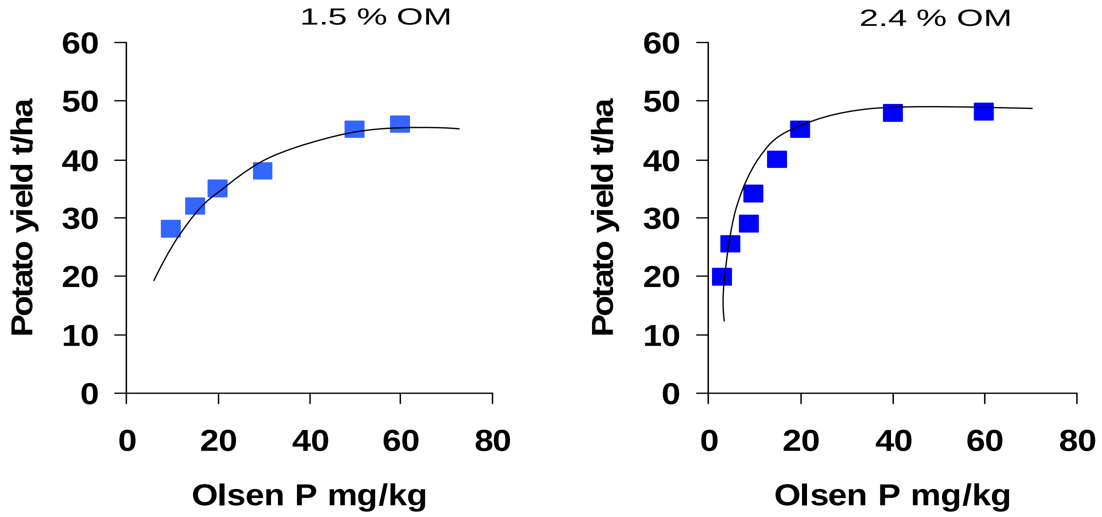


***Figure 4:** Response of potatoes in the field to available P (measured by Olsen P) on a silty clay loam soil, Agdell, Rothamsted. This soil at low organic matter contents is very poorly structured and it is thought that the main effect of OM was to improve rooting volume and hence access to P. This was confirmed when these soils were used in a glasshouse experiment, soils were first sieved and mixed with quartz sand to improve drainage. Rye grass yield on both soils (6 cuts) then gave a single exponential response curve to soil P with a critical point around 25 mg per kg as for the higher OM soil in the field.*

Plants are not just the passive recipients of the nutrients that the soil is able to supply. Plant roots are much more than the plant's drinking straws. The zone of soil in the immediate vicinity of the root (called the rhizosphere) is markedly different in its properties to the remainder of the soil as a result of the direct impacts of plants on the soil. It has been estimated that 10-44% of the total carbon fixed by the plant is released to the soil via the root (Bais *et al.*, 2006). An increased microbial population in the rhizosphere is supported by these carbon inputs from root exudation. Root exudates are composed of a range of carbon rich plant metabolites mixed together with ions, free oxygen and water; composition of root exudates varies from plant to plant (Raaijmakers *et al*., 2009). The amounts and composition of root exudates also modify the size and community structure of the microbial population in the rhizosphere.

Differences between species in rooting patterns and in the amount and timing of root exudates can lead to differences in plant P uptake on the same soil type (**Figure 5,** page 5). Shane and Lambers (2005) have shown that low soil P concentrations stimulate the development of specialist cluster roots by white lupin. These are major sites of organic acid and citrate excretion and consequently are able to mobilise calcium phosphates for plant uptake. Green manure species are largely selected for their impact as a disease break and/or with regard to nitrogen supply. However, evidence from the P-Link project suggests that it may also be possible to select crops and/or green manures which can have positive impacts for P cycling.

Because of low P concentrations in soil solutions, many plants have evolved further mechanisms to increase P uptake. The majority of plants are capable of forming mycorrhizal associations with various soil fungi. The most common is the arbuscular mycorrhizal (AM) association, which has been shown to have emerged very early in the evolution of land plants; only a very few crop species do not form such associations (Brassicae and Chenopodiaceae – including buckwheat). The AM association increases the effective root/soil contact area and increases the volume of soil from which P can be taken up hence AM fungi-plant associations play a very important role in improving P uptake. The ability of the fungi to dissolve otherwise unavailable sources of soil P therefore does not make an important contribution to the enhancement of P supply in AM fungi-plant associations, rather AM fungi-plant associations are able to use the available solution forms of P in the soil more effectively (Kucey *et al.*, 1989). AM associations also tend to increase water and micronutrient uptake by plants. AM associations are not usually formed where soluble soil P levels are high.

Maintaining P levels in soil

A target soil index of 2 (on the Olsen based scale) is recommended by Defra for arable, forage and grassland and index 3 for vegetables (Anon., 2010). The Defra funded project OF0114 concluded that in organic systems, soils with a P index of 1 may supply adequate P. This is because of the importance of the biological pools and processes in supplying P and the regular inputs of organic and relatively insoluble P sources, e.g. rock phosphate, which do not significantly enrich the available P pool but can contribute P over the long term.

There is no single right answer to the best P levels in soil for organic farming. But it is important to continue to monitor the P availability over time in the rotation through the combined use of soil analysis, plant analysis and nutrient budgeting, and to avoid downward trends.

Making the most of P inputs

If soil P levels are declining (indicated by both soil analysis and nutrient budgeting) or if the soil type is just inherently too low in P for the planned cropping, then organic farmers may supplement P supply through the use of brought-in manures (see Defra, 2002) or mineral rock phosphate (RP), such as Gafsa.

Rock phosphate

RP can have a variable composition but the most widely used RP in the UK is a calcium phosphate (apatite) which originates from sedimentary sources in North Africa (often known as Gafsa). Dissolution of RP depends on its reactivity, which is largely determined by its chemical composition, but also on soil moisture content, acidity and soil solution Ca and P concentrations. For Australia and New Zealand where RP is used widely, the optimum conditions for RP use are considered to be permanent pastures receiving adequate moisture (> 800 mm of rain evenly distributed through the year) and soil at less than pH 6 (Bolan *et al.*, 1990) However, there are indications from P-Link that RP remains effective even on higher pH soils.

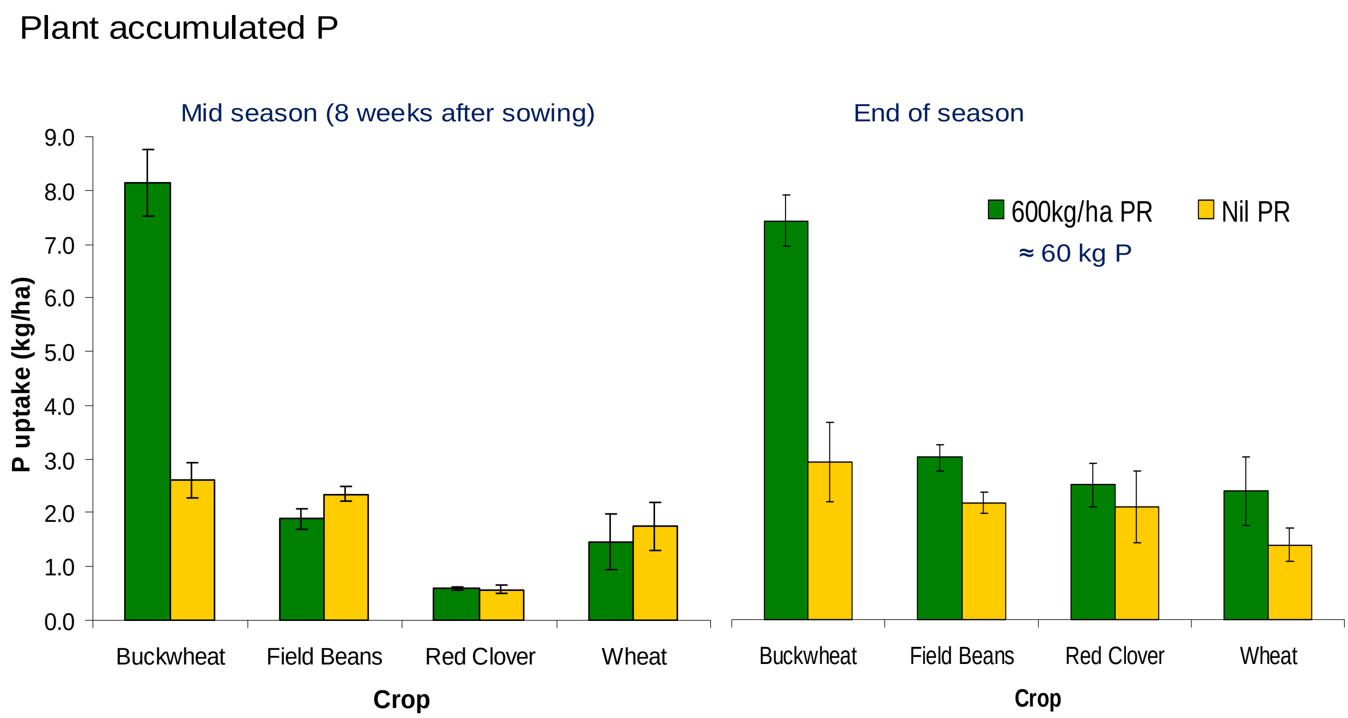


Figure 5: *Spring green manuring trial on a sandy soil with very low P status at Winshiel Farm carried out as part of the P-Link project. Crops were selected for their perceived ability to liberate P and use it effectively. If this were effective, it would transfer P from the mineral to the organic half of the soil P cycle when the green manures are subsequently incorporated.*

RP is relatively insoluble and hence only slowly available to the plant even under these optimum conditions, consequently an application of RP may be insufficient to meet the short term needs of demanding crops such as potatoes on a P deficient soil. Grinding of RP helps alleviate this problem especially if the source of the RP is classified as being of a low to moderate reactivity. However, availability remains relatively low. Very fine powders are also difficult to spread and may be re-prilled for sale.

However, it is important to realise that reactive RP does contain a small proportion of immediately available P (up to 1% of the P applied). If RP is applied to rapidly growing crops then this P will be crop available immediately following application – it is likely that application of RP outside the growing season and/or to fallow ground means that this P is fixed in soil and rendered unavailable for crop uptake. **Figure 5** also highlights that some crop species (here buckwheat) are able to liberate additional P from RP and use it effectively. Timing RP application within a rotation to a crop which can make best use of the RP and transfer it into the organic half of the soil P cycle may be an effective way of improving P use efficiency on a rotational basis.

Summary of practical recommendations

Interpreting soil analysis

- ♦ Routine analysis only measures the plant available P which is in a mineral form, including both that in the soil solution and that in a “pool” of phosphate from which phosphorus transfers readily to the soil solution.
- ♦ P in an organic form is not routinely measured by analysis.
- ♦ P index 1 may be acceptable for organic grassland and arable situations, but higher levels will be needed for intensive horticulture.
- ♦ Plant tissue analysis should be used where soil analysis indicates low P availability but yield seems unaffected, this will help to determine whether crops are limited by P availability
- ♦ Monitoring trends in soil P over a number of years is particularly important: it is more relevant to follow changes over time than have a snap shot at any one time.

Soil additions

- ♦ Rock phosphate, such as Gafsa is relatively slowly available to the plant, however even on alkaline soils useful amounts of P can be taken up.
- ♦ Availability of rock phosphate can be increased by the use of green manures.
- ♦ Apply RP to pasture or crops during the growing season in order to maximise P uptake.
- ♦ Imported manure is a useful source of P: e.g. 1.4 kg P_20_5 per tonne of cattle FYM, 0.4 kg P_20_5 per m^3 of diluted cattle slurry.
- ♦ Brought-in feed stuffs can also be a useful source of P: e.g. rapeseed meal 10 kg P_20_5 per tonne, 18% CP compound feed 3.6 kg P_20_5 per tonne.

Management of soil P

- ♦ Plant available P is maximised at soil pH 6 – 7.
- ♦ Availability of P from soil reserves to crops can be improved by:
  - ◊ Ensuring good soil structure in order to maximise root penetration.
  - ◊ Including in the rotation those crops and green manures which have the potential to solubilise P – Buckwheat is particularly effective
  - ◊ Increasing soil biological activity and hence mineralisation of organic P
  - ◊ Designing the rotation to optimise conditions for arbuscular mycorrhizal (AM) associations with crops by minimising fallows and ensuring host crops are present.

Key references

1. Research references

Anon (2010) Fertiliser Manual (RB209). 8th Edition. The Stationery Office, London. Available at: http://www.defra.gov.uk/foodfarm/landmanage/land-soil/nutrient/documents/rb209-rev-100609.pdf

Bais, H. P., Weir, T. L., Perry, L. G., Gilroy, S. and Vivanco, J. M. (2006). The role of root exudates in rhizosphere interactions with plants and other organisms. Annual Reviews in Plant Biology **57**: 234-266.

Brookes, P. C., Powlson, D. S. and Jenkinson, D. S. (1984). Phosphorus in the soil microbial biomass. Soil Biology and Biochemistry **16**: 169-175.

Defra project OF0114. Optimisation of phosphorus and potassium management within organic farming systems: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=9066

Defra (2008). Sustainable Farming and Food Strategy Indicator Data sheet: Nitrate and phosphate in Rivers. Available at: http://www.defra.gov.uk/evidence/statistics/foodfarm/general/indicators/documents/h4a.pdf

Kucey, R. M. N., Janzen, H. H. and Leggett, M. E. (1989). Microbially-mediated increases in plant – available phosphorus. Advances in Agronomy **42**: 199-228.

Raaijmakers, J. M., Paulitz, C. T., Steinberg, C., Alabouvette, C. and Moënne-Loccoz, Y. (2009). The rhizosphere: a playground and a battlefield for soil borne pathogens and beneficial microorganisms. Plant and Soil **321**: 341-361

Shane, M. W. and Lambers, H. (2005) Cluster roots: a curiosity in context. Plant and Soil **274:** 101-125

White R. E. (1995). Introduction to the Principles and Practice of Soil Science. 2nd Edition. Blackwell Science, UK.

2.Useful sources of further information

Organic Eprints: a searchable website for organic research throughout Europe www.orgprints.org

PACA Res Research Reviews:

The role, analysis and management of soil life and organic matter in soil health, crop nutrition and productivity: www.organicadvice.org.uk/papers/Res_review_16_soils.pdf

Laboratory mineral soil analysis and soil mineral management in organic farming: www.organicadvice.org.uk/papers/Res_review_15_soils.pdf

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Useful sources of further information (continued)

Compost: the effect on nutrients, soil health and crop quantity and quality: www.organicadvice.org.uk/papers/Res_review_3_compost.pdf

Nutrient budgets for organic farming:
www.organicadvice.org.uk/papers/Res_review_19_nutrient_budgets.pdf

Efficiency of soil and fertilizer phosphorus use. FAO Fertilizer and Plant Nutrition Bulletin 18 ISBN 978-92-5-105929-6 E:mail: publications-sales@fao.org

Defra (2002) "Managing manure on organic farms" Booklet 4 by ADAS and ORC Elm Farm available from http://www.defra.gov.uk/foodfarm/landmanage/land-soil/nutrient/documents/manure/livemanure4.pdf

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