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Improving the sustainability of phosphorus use in arable farming – ‘Targeted P’

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1.2 Abbreviations

AHDB	Agricultural and Horticultural Development Board
ALTA	Arable long term average. Weather data were taken for only those grid square in the MORECS database where a majority of the land was arable. These were predominantly in the east and south of England and Scotland.
ASPR	Apparent Soil Phosphate Requirement: the quantity (kg ha^{-1}) of phosphate determined by subtracting offtake from inputs, associated with a change in soil test P (mg L^{-1}).
CV	Coefficient of variation
DAP	Di-ammonium phosphate
DHP	dissolved hydrolysable P (TDP-MRP)
DM	Dry Matter
EU	European Union
GS	Growth stage
Labile P	The P that is immediately able to contribute to plant uptake.
MAP	Mono-ammonium phosphate
MRP	Molybdate reactive P
N	Nitrogen
P	Phosphorus: To minimise confusion P is usually expressed on an elemental basis throughout this review. P can be converted to P_2O_5 by multiplying by 2.29.
Pi	Inorganic P
P_2O_5	Phosphate; the form of phosphorus used to define the nutrient content of fertilisers. 2.29 kg P_2O_5 = 1 kg P
PP	Particulate P (TP-TDP); P attached to soil, i.e. unfilterable material
PR	Phosphate rock
P offtake	'Crop P removal' is calculated using harvested weight and P composition.
P uptake	'Total P uptake' exceeds 'P offtake' due to P in haulm or straw and chaff.
SD	Standard Deviation
Soil P	Extractable soil P concentrations are typically quoted as mg kg^{-1} (research) or mg L^{-1} (advisory) and while not exactly equivalent (depending on bulk density) they are commonly considered as being interchangeable. Soil extractable P concentrations are sometimes converted to an area or volume equivalent basis, such as kg / ha / sample depth. This is particularly helpful when calculating long-term trends in P balances and when comparing with fertiliser applications or crop removal.
SRP	Soluble reactive P
SS	Suspended sediment
SSP	Suspended sediment P (PP/SS).
STP	Soil Test phosphorus refers to the various soil extraction and analysis procedures used for advisory purposes.
TDP	Total dissolved P
t ha^{-1}	tonnes per hectare

TGW	Thousand Grain Weight
TP	Total soil P
TSP	Triple super phosphate
WFD	Water Framework Directive
WP	Work Package

Abstract

A collaborative project conducted from 2010 to 2015 involved 17 partners from government, industry and academia. It explored technologies to support a more efficient and sustainable strategy for phosphorus (P) use on UK arable land, dubbed 'feed the crop, not the soil'. Through (i) a review, (ii) experiments on crop performance and P run-off, both in pots and the field, and (iii) modelling, the project explored how the farming industry might make the transition to this new approach.

Fifty years ago the current strategy for P use (as set out in the Fertiliser Manual, RB209; Defra, 2010) replaced an even less efficient one of relying entirely on fresh P fertilisers to support crop production. Soil tests for available P (STP) were then introduced so that fertiliser applications could be adjusted according to the estimated P supplying capacity of each soil. However, this 'soil P storage' approach is now becoming increasingly costly, amid concerns over finite and affordable global phosphate supplies. Also, the now-large reserves of P in most UK soils have become a significant cause of inland and coastal eutrophication, so threatening the achievement of good ecological status under the EU Water Framework Directive.

Two field studies, and a meta-analysis of published data, showed direct positive relationships between soil P (by Olsen's method) and dissolved P in surface runoff and drain-flow; these indicated that reducing STP from 25 to 10 mg kg^{-1} could help substantially in achieving the challenging target concentrations set for P in UK water bodies under the Water Framework Directive. Along with environmental benefits, large economic savings could also be made if the 80% of UK arable land now at P Index 2 (or more) were run down to P Index 1. However, reducing soil P levels will be incompatible with enhancing crop yield levels until (i) fertiliser P efficiencies can be markedly improved, and (ii) crop P sufficiency can be monitored more certainly than just with STP.

Ten field experiments on English or Scottish sites with low STP showed crop capture of soil-derived P to average 80% of estimated crop requirements (range: 42% to >100%) with no fertiliser applied. However, crop responses to fresh triple superphosphate (TSP) broadcast and incorporated in the seedbed were generally very small, as judged by the difference method, with extra P in the initial crop averaging only 4% of the P applied. The best way of enhancing initial recovery of fertiliser P was to use struvite (with slower P release than TSP) and place it close to the seed, but best initial recoveries of P were still less than 10%.

Experiments in pots showed the potential of P seed dressings and/or foliar sprays to supply P directly to crop plants, as well as the potential of struvite granules to act as a slow-release P

fertiliser. However, two further field experiments at Ropsley (Lincs.), where soils ranged from P Index 0, failed to detect any positive responses to small amounts of seed-dressed P or foliar P, even though crops responded by ~2 t ha^{-1} grain as soil P increased to Index 2. The exact fates and mechanisms of seed-dressed and leaf-applied P now need to be investigated in the field.

A new mathematical model, devised to simulate P transfers between fertiliser, soil, root and shoot, and crop yield effects, demonstrated high sensitivity of outcomes to the P buffering capacity (= fixation capacity) of the soil. However, disappointingly, AVAIL®-treatment of TSP to reduce soil fixation of added P, showed no consistent benefits either in pots or in the field.

It is concluded that the current strategy for P use (of 'feeding the soil to feed the crop') should be maintained for the time being, but that strong environmental imperatives should drive further intensive research into 'feeding the crop, not the soil', and a transition to this new strategy should be planned. Four 'P run-down sites' were established for this purpose. STP monitoring of these sites over 5-6 seasons demonstrated scope for arable farms to exploit soil-stored P whilst testing for more efficient P nutrition approaches, but uncertainties in determination and interpretation of STP were also shown. It is recommended that industry initiatives to improve P fertilising efficiencies should be monitored through careful routine use of STP, augmented by additional routine analysis of crop P. Critical P contents of harvested biomass (e.g. grain) are proposed to support researchers and farmers in their quest for new practices and products that will improve the sustainability of P use in future arable farming.

2. Report Synthesis & Recommendations

In this project we researched ideas for improving the sustainability of phosphorus (P) use in arable farming. A possible new philosophy was proposed of 'feeding the crop, not the soil' in relation to P nutrition of arable crops. Its adoption in the UK would depend on developing new or improved technologies for 'targeting' P applications more precisely for improved efficiency of use and relying less on soil available P.

This section (2) outlines headline results, messages for practitioners, key uncertainties and priority areas for further research. More details of the background and hypotheses are provided in Section 3 and in a bespoke review (Edwards *et al*., 2015), then each work-package is described in Sections 4 to 7 (and associated publications), whilst the last Section (8) discusses how P use in UK arable agriculture might best evolve in future.

2.1 The problem and key hypotheses

- Fertilisers account for by far the largest part (~80%) of mined phosphate rock (PR) of which there are finite global supplies, held by only a few countries (de Ridder *et al*., 2012). Sustainability and security of PR supply are thus of significant concern for inter-generational well-being.
- P is a life-essential element whose use in fertilisers supports the economic viability of agriculture, ensures the functioning of farming systems, supports the security of food and bioenergy supplies, as well as influencing human nutrition and health. However, the national and global use of P is highly inefficient. Typically amounts of P actually consumed in food or used in other products equate to only a quarter to a third of the P that is mined (Penuelas *et al.*, 2013; Withers *et al.*, 2015a).
- Unrecovered fertiliser P is stored in the soil, in living biomass (plants and animals) or is lost to rivers and then oceans where it causes environmental degradation, principally through eutrophication. A recent study of P use in the EU-27 showed that 40% of total P inputs ends up in the soil, and 17% of total P inputs are lost to water each year (van Dijk *et al*., 2016). In the UK, the Office for National Statistics has estimated that water resources contribute £39.5 billion to the UK economy (ONS, 2015) and eutrophication greatly degrades these services. Phosphorus is the main cause (63% of cases) of waterbodies failing to achieve good ecological status, and new lower standards for P in freshwaters have been introduced to combat eutrophication (EA, 2015; UKTAG, 2012, 2012). This is likely to lead in the near future to introduction of some regulatory controls relating to inorganic or organic fertiliser management, livestock management, and soil management.

In 2015 the government consulted on new basic rules for farmers to tackle diffuse water pollution from agriculture in England, with a focus on phosphorus.

- The comprehensive review prepared through this project (Edwards *et al.*, 2015) detailed the strong environmental drivers for a new philosophy of P nutrition in the UK and Europe, and also some feasible economic benefits. We summarised the aims of the new philosophy as being to: 'feed the crop, not the soil' (Withers *et al.*, 2014).
- The review indicated significant potential for existing and / or new technologies to target P applications for more immediate crop uptake, rather than with the current philosophy of broadcasting simple P fertilisers on the soil, sufficient to maintain a large soil store of fixed P that, by gradual desorption, provides sufficient available soil P throughout crop uptake to avoid any inhibition of growth or yield (Figure 2.1).

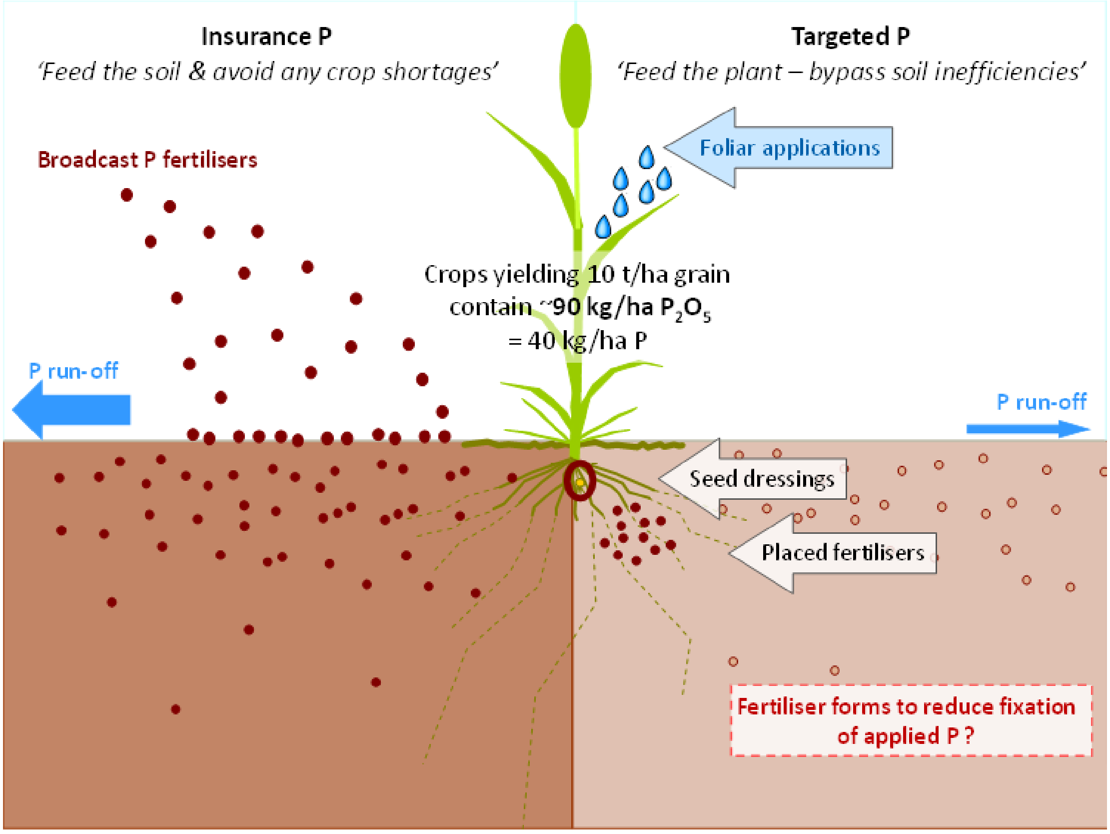

Figure 2.1. Schematic diagram suggesting the components of a more sustainable approach to P management of arable land in the UK ('Targeted P'; right) compared to current strategies ('Insurance P'; left). The targeted approach would use less fertiliser, be more economic, enable lower soil P, and reduce eutrophication risk.

- The review also suggested that the store of fixed soil P might be used for crop nutrition, if sufficiently efficient P fertilisers were available to meet any shortfalls from crop P demand.
- In reviewing approaches to the estimation of fertiliser P recovery it was concluded that soil P supplies and fertiliser P recovery should be estimated separately. Thus:

$$\text{Fertiliser P recovery (\%)} = \frac{\text{crop P demand (CPD) – soil P supply (SPS)}}{\text{Fertiliser P applied}}$$

- It was predicted that running down soil P to Index 1 would significantly reduce P emissions from agriculture to water bodies, and lead to gradual improvements in water quality.

2.2 Key Findings

- Two studies showed direct positive relationships between soil Olsen-P and dissolved P in both surface runoff and drain-flow. A meta-analysis of published data found the same trend and suggested that reducing soil Olsen-P from 25 to 10 mg kg^{-1} could help UK water bodies substantially in achieving the challenging target P concentrations set under the Water Framework Directive (WFD; ca. <30 µg L^{-1} soluble reactive phosphorus, SRP).
- At ten sites where Olsen-P indicated that soil P supplies would be low (P index 0 or 1 in England, L or VL in Scotland) crops were nevertheless able to capture a large proportion (median: 84%; range: 42% to >100%) of their P requirements from residual P in the soil.
- All of four additional sites set up in 2010 to 'run-down' STP from Index 2 to Index 1, by omitting any P applications, showed substantial seasonal variations in soil P (analysed by Olsen's method) and no certain decline in STP. Soil analysis also proved a poor predictor of SPS (P acquired by unfertilised crops) in the seven English response experiments and at all three sites with more acidic soils in Scotland there was no indication that Morgan's method was any better.
- In ten experiments, crop responses to fresh P amounts up to 120 kg ha^{-1} (NB 1 kg P = 2.29 kg P_2O_5) applied just before crop establishment were small; early crop growth was increased on average by 6% (significant in 4 of the 10 cases), and harvested produce increased by 3% on average (also significant in 4 cases). Yield responses to TSP broadcast before crop establishment were economically beneficial (even discounting any residual benefits for succeeding crops) for all three barley crops and two of three potato crops, but not for the two wheat or two oilseed rape crops.
- In all ten response experiments, P fertilisers of all forms were singularly inefficient at increasing crop P; P recoveries by the fertilised crops averaged only 4%. Total crop recoveries of fertiliser P, including by succeeding crops, were inferred from experiments at Ropsley (Lincs.), and research elsewhere to reach approximately 10% on average.
- The most effective means of physically targeting fertiliser P was found to be through fertiliser placement, but this only increased the yield response to P of barley and potatoes, not of winter wheat or winter OSR.

- The best way of enhancing recovery of fertiliser P was to use struvite (a slightly soluble P compound recovered from wastewater) instead of TSP and place it close to the seed, but best recoveries were still <10%. Placement of struvite proved significantly better than placement of TSP at just one of the ten sites (with potatoes).
- In the ten field-response experiments, AVAIL®-treated TSP seldom gave different yields from TSP alone (yield increased at one site and decreased at another), but responses to less soluble struvite P were often slightly better than TSP.
- A simulated 30 minute rain-storm soon after fertiliser application caused 25% loss of fertiliser P by run-off from TSP-based products, but struvite caused no effect on run-off P, whether soluble or particulate.
- The two field experiments at Ropsley, where a range of soil P was established from Index 0 to 2, failed to detect positive responses to small amounts of seed-dressed or foliar P, even though grain yields responded by ~2 t ha^{-1} to increasing soil P.
- However, experiments in pots confirmed the potential of P seed dressings and/or foliar sprays to supply P directly to crops, as well as the potential of struvite granules as a slow-release P fertiliser. Specific responses were as follows:
  - P seed dressings stimulated rapid root production of seedlings and appeared to enhance capture of soil-derived P, such that efficiency of the seed-applied P was enhanced.
  - Foliar P was taken up through stomata, and rapid rates of P distribution from leaves indicted scope to increase foliar P application rates. The combination of foliar P applications with P-dressed seed looked promising.
  - Use of struvite as a slow-release fertiliser showed reduced early growth responses compared to conventional P forms, but showed potential to release P far later into the growing season, at the peak of plant demand. Enhanced P release from struvite was also observed in the presence of organic acids exuded by crops.
  - Seed inoculation with *Bacillus amyloliquefaciens* FZB42 stimulated root growth, but reduced P-uptake capacity in low-P environments.
- A new mathematical model, devised to simulate P transfers between fertiliser, soil, root and shoot, and to predict crop yield effects, suggested that outcomes should be very sensitive to soil buffer power (the relationship between available and non-available soil P). Model runs predicted that applying P near the root zone (i.e. placement) could cause a 4% increase to plant P uptake over broadcasting P.

2.3 Messages for Industry and Policy

- This project has raised important questions about the current approach to P use on UK arable land, and after its wide-ranging research, most of those questions still appear valid. Along with ongoing changes in the industry, these questions now prompt the need to resolve a new improved approach to P use, and feasible means of transition. We propose that this process should be debated between key stakeholders in the efficiency of P use, possibly through a bespoke conference.
- The main form of P fertiliser used by arable farms in the UK (TSP) is highly water-soluble but its solubility has little value to arable crops since P fertilisers are largely used just to build soil P reserves and, on soils with low P status, equivalent crop responses can be obtained by less soluble fertilisers (such as struvite) and with lower environmental damage.
- Phosphorus (P) is an essential nutrient for maximising food production but also drives aquatic eutrophication. A transition to lower soil P fertility (i.e. P index 1) will deliver significant environmental gain in reducing background P concentrations in runoff, lower the eutrophication risk from agriculture and meeting the P standards required achieving good ecological status in UK freshwaters.
- As exemplified when large P amounts were applied to an Index 0 soil at Ropsley (Lincolnshire) the fate of the vast majority of the fertiliser P (>90%) was to build up inherent soil P levels, but (as judged by soil P analysis) only ~20% of this becomes available for subsequent crops, and only 10% can be accounted for in extra crop P uptake, so under the current philosophy for P use large quantities of residual fertiliser P need to accumulate to provide sufficient available P for crop growth. Dependence of crop production on this soil P store, necessitates an investment costing 1-2%[1] of the value of cereal production, just in lost interest.
- National statistics indicate that about 80% of arable land is at P Index 2 or more and that most farms are seeking to exploit their soil P stores; the literature provides ample evidence that continued cropping and P offtake serve to deplete soil P over time to the extent that crops become P deficient (e.g. Withers *et al*., 1994). However unexpectedly, on four sites with soils at Index 2, zero fertiliser P use for six years did not cause this P status to be depleted.
- Even in experiments on soils of low P status, crops gained far more of their P requirements from inherent soil P reserves than from fresh fertiliser.

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[1] *Depending on prices and interest rates: Example assumptions are £0.65/kg fertiliser P_2O_5 x 15 mg/L soil P (the difference between mid-Index 2 and mid-Index 0) x 40 kg P_2O_5 /ha/mg/L (apparent P_2O_5 requirement to build up soil P) x 3% interest / year supporting 8 t grain / ha / year valued @ £110 / tonne = 1.3%.*

- Crops being grown on low P soils should probably be fertilised annually (rather than rotationally) because, although crop responses to fresh P were small, about half of the crops grown on low P soils here showed worthwhile yield responses to fresh fertiliser P (applied to the seedbeds). Residual effects (on yields of succeeding crops) of these fresh P applications would probably have made all these fresh P applications worthwhile.
- Placement was the best means of improving the efficiency of soil-applied P fertilisers; effects here were sufficient to encourage greater adoption of modern placement technology, even though they were not large.
- Incidental losses of P in runoff due to rain soon after TSP application can be large (25%) and fresh TSP fertiliser should be incorporated before rainfall. Risks of incidental losses of P after fertiliser application could be greatly reduced or eliminated by use of less soluble P products (such as struvite) instead of TSP.
- Soil P analysis provided a crude but worthwhile guide to soil's P-supplying status. Soil tests did not prove sufficiently accurate or precise to provide good certainty in whether a crop would become P deficient, or in whether a crop would respond to fresh P applications. Whilst continuing to use soil P analysis, growers need to take significant precautions to mitigate against the causes of variations such as were seen at the run-down sites.
- There is good UK evidence to support adoption of routine crop P analysis to augment soil P analysis. Measurement errors for crop P are less than for soil P., and a 'critical' P content in whole shoot biomass can be specified for most UK crop species as approximately 0.25%. Although P analysis of harvested produce is likely to prove easier, more telling and useful than analysis of growing crops, standards for interpretation of harvested biomass P contents need to be properly resolved for UK crops. At present the best estimate of 'critical' P content in grain or tuber dry matter is 0.32% (or 0.4% in oilseeds), as indicated by overseas literature.
- Crop P analysis should be considered as a strategic tool to support soil P analysis rather than to support tactical use of fertiliser P. The small amounts of extra crop P uptake achievable from fresh fertiliser P applications largely increased biomass growth rather than tissue P concentrations. Thus it must be concluded that fresh P fertilisers such as were tested here, could not fully alleviate P deficiencies.
- Soil P analysis is best regarded as one risk indicator within a farm's broader P management approach; this approach could also usefully incorporate:-
  - Annual P analysis of leaf tissues and harvested crop produce. These will have the dual purpose of monitoring for crop deficiencies and monitoring crop P removals.
  - Routine recording of yields and P contents of harvested materials for each managed land unit.

  - P_2O_5 accounting; maintaining a continuous log of P_2O_5 additions in fertilisers, manures or other amendments from which crop offtakes in all removed produce, such as grain and straw, are subtracted to give an estimated P_2O_5 balance for each managed land unit, whether field or soil zone.

- Given that cumulative crop responses to fertiliser P are generally sufficient to pay for their use, even with the inefficiencies of dependence on soil P storage, any transition from high to low soil P fertility will need to be driven in part by environmental concerns transferred from end-users and governments; price and fertiliser supply issues simply do not have sufficient force or immediacy.
- The keys to this transition will be availability of more efficient fertilising techniques and improved ways of monitoring the soil P supplies to crops, such that growers become confident of avoiding crop P deficiencies.
- In most world regions, soil storage of P in quantities sufficient to sustain uninhibited crop growth is not feasible because P fertilisers are unavailable or too expensive. Thus there is a large commercial opportunity for industry to find better ways of satisfying crop P requirements on a global scale.

2.4 Project Achievements and Highlights

- This project developed a new way of viewing P nutrition, which is particularly relevant to the management of soil P; this recognises effects on crops of inherent soil P supplies as distinct from effects of fresh fertiliser P. This approach can be summarised algebraically as:

$$\text{Fertiliser P required} = \frac{\text{crop P demand (CPD)} - \text{soil P supply (SPS)}}{\text{Fertiliser P recovery (\%)}}$$

  and its value was demonstrated through its application here to the analysis of data from a wide range of P response and P targeting experiments.
- This new approach enabled a clear demonstration of the gross inefficiencies of soil-applied P fertilisers, as currently used, and the potential environmental benefits in reduced eutrophication risk from agriculture.
- A real role for crop P analysis was revealed, which has potential to reduce risks of crop P deficiencies whilst managing the run-down of soil P fertility.
- A combination of research in controlled environments and the field was able to demonstrate that altering the chemistry of soil-applied P fertilisers could marginally improve their

efficiency as fertilisers whilst markedly reducing the risk of incidental P in runoff after fertiliser applications.

- The project supported the establishment of a new simulation model to help understand daily dynamics of crop P nutrition.
- Research in controlled environments showed the feasibility of targeting P applications, either by seed dressings or foliar sprays, so that some of the gross inefficiencies of soil-applied P fertilisers are by-passed.

2.5 Challenges and Uncertainties

- In seeking to test new products and application methods for crop P nutrition, this research was frustrated by the difficulties of identifying good uniform arable field sites with low soil P supplies. Most of the sites selected eventually provided relatively large soil P supplies, and a few of the sites demonstrated significant background variability that may have masked differences between the techniques being tested. Nevertheless statistically significant responses in one or more measurements were detected at all sites.
- The challenge of finding good sites strongly underlines the importance of maintaining all four ‘Run-Down’ sites for as long as possible. These are unique sites for understanding soil P buffering dynamics of legacy soil P and assessing the economic impact of omitting P fertiliser on farms, and will provide a much more effective test-bed for improvement of crop P nutrition into the future.
- Some of the difficulties of site selection are now being turned to advantage in new large scale experiments (with tramline sized plots) being conducted in AHDB Research Project 2160004 ‘Cost-Effective Phosphorus’. Intra-field variability in soil P is being used with perpendicular tramlines so that interactions between treatments and soil P can be tested.
- Mimicking current commercial fertiliser placement machinery was not easy or perfect; availability of plot-scale fertiliser placement machine proved vital in the second and third potato experiments. However, the new large-scale trials in AHDB Project 2160004 are enabling experimentation with modern commercial machinery on grain crops.
- Experiences with use of STP revealed many causes of uncertainty which can now provide guidance for STP use in a commercial context. Whilst all users of soil P analysis must come to realise its significant inherent uncertainties, these should <u>not</u> justify its disuse! Rather, good STP use should be moderated by:

  - Religiously standardising all sampling conditions (including previous crop, sampling month, sampler, sample positions, sampling depth, lab. choice, etc.).

  - Taking and considering results from many samples together, and repeating analyses showing large contrasts or surprises. i.e. sampling should be organised in 'campaigns', whole farms or even several adjacent farms being sampled, analysed and interpreted together (in any case this will be convenient where a sampling agency is employed).
  - Using spatial variation in soil P changes to determine location-specific Apparent Soil Phosphate Requirements (ASPRs; Alison *et al*., 2016), and using these (rather than national standards) to estimate how best to balance P offtakes.
  - Augmenting soil analysis with crop analysis (see above).
- Whilst none of the 'P targeting' approaches tested here produced effects that would enable UK arable producers to change any time soon from partly or fully relying on an accumulated soil P store, some pointers here and in the literature indicated the feasibility of a future approach that should prove more environmentally and economically sustainable. This thus remains a future challenge, and could include a combination of:
  - Reduced crop P storage e.g. by breeding for reduced phytate formation (Burnett *et al*., 1997; Rose *et al*. 2012; 2013a; 2013b)
  - Seed dressings to replace seed P storage (e.g. Nadeem *et al*., 2012)
  - Development of fertiliser P forms with available P inhibited chemically or physically from soil fixation and with improved immediate recovery, possibly involving combination with other products causing local acidification (e.g. ammoniacal nitrogen),
  - Banded or placed application of organic or inorganic P fertilisers
  - Slow-release fertilisers containing re-cycled P (such as struvite)
  - Enhanced arbuscular mycorrhizal associations (Zhu & Smith, 2001).
  - Enhanced rhizosphere acidifying capacity, through enhanced excretion of organic acids (Jones, 1998).

  Note that the development and implementation of such a strategy would diminish the reliance of P nutrition on soil P analysis, and increase reliance on crop P analysis.

- Economic on-farm benefits of adopting more efficient techniques may be limited because they will bring just a one-off benefit whilst soil P stores are being exploited, albeit that this may take many years in some cases. Once a smaller soil P store has been established, crop P demands would still require similar amounts of fertiliser P to be applied as are now, even if fertiliser P recovery became as good as with nitrogen (say 60%). However, if the strong environmental drivers can be brought to bear, e.g. via public pressures focussed by supermarkets and government regulation, and if the global market for more efficient P fertilisers is recognised, commercial investments in appropriate R&D should become adequate to bring effective new solutions.

2.6 Requirements for Further Research

a. The vital importance of finding more efficient, reliable and sustainable ways of ‘feeding the crop, not the soil’ and positive results with pot-grown plants (Section 4) show that further more intensive research is merited into techniques for improving crop recovery of fresh P applications. There appears to be scope for innovations across a broad range of technologies including machinery for placement, chemistry to inhibit soil sorption, foliar P stabilisation and absorption and both micro- and macro-germplasm to improve uptake and reduce P demands.

b. The four ‘run-down’ sites established here to support development of more efficient systems of crop P nutrition, must be funded and monitored for the long term. The behaviours of crops and soils at these sites need to be monitored more closely so that the effects of any new ‘P-efficient’ technologies (be they physical, chemical or biological), can be validated and evaluated as quickly and robustly as possible.

c. The dynamics of crop P nutrition are evidently complex, with farming, fertiliser, soil, root, and shoot processes all interacting (Lynch *et al*., 1997; Greenwood *et al.*, 2001). Our attempt to model some of these interactions focussed on the short term (daily to season long) timescale, and addressed soil, root and leaf aspects. The industry would evidently benefit from being able to resolve the multi-season, multi-soil-type, multi-fertiliser, multi-species interactions that our empirical evidence indicates are governing optimal P nutrition in UK arable conditions. Consideration should now be given to the choice and design of model that could best provide such support through a review of extant models.

d. Empirical evidence of field crops with which a useful model must be reconciled includes contrasting rooting patterns (and arbuscular mycorrhizal associations), metabolic strategies of different crop species for acquiring soil P, P sorption properties of different soil types, plant P storage strategies (e.g. inorganic P storage in vacuoles, and deposition of phytate in vegetative and generative tissues) of different species, and effects of contrasting rainfall and solar radiation on crop growth, yield potential and soil conditions.

e. Proposals for use of routine crop P analysis (as well as STP) to monitor P use on arable land need to be supported by more evidence. Critical P contents of harvested biomass need to be determined from any data or samples remaining from the Critical P Project (Knight *et al*., 2014). Additionally there is a need for a wide ranging survey of crop P concentrations in the UK, both of leaves from growing crops, and of harvested produce, so the prevalence and patterns of crop P deficiency can be revealed. An initial approach would be to collate existing data from agricultural chemistry labs. However, a more structured survey should also test for the likely influences of soil type, organic matter, pH and P analysis, rotations and crop species, organic and inorganic P applications.

Subsequent sections of this report introduce the project (3) and provide detailed descriptions of the Project work (4 to 7), and the last Section (8) provides our current assessment of issues affecting future use of P in UK arable agriculture.

3. Introduction to the project and its hypotheses

This section summarises the problems that this project sought to address, provides some background to the solutions that were explored, and sets out the hypotheses and aims underlying the project.

3.1 The problem

Phosphorus (P) is a life-essential element whose use in fertilisers affects all farming systems, food production, national nutrition and bioenergy supplies, human health and the economic viability of agriculture. However, the national and global use of P is very inefficient. Typically amounts of P actually consumed in food or used in a wide range of other products account for only about a quarter to a third of the P that is mined (Penuelas *et al.*, 2013; Withers *et al.*, 2015a). The remaining unused P is stored in the soil, in living biomass (plants and animals) or is lost to the oceans.

Numerous mass balance studies recently completed for different countries have highlighted the unsustainability of current P use both in terms of a high dependency on imports of PR (or its manufactured derivatives) for future food and bioenergy security, and a high degree of wastage due to the unbalanced recycling of manure P to land, the limited recovery of unused P in waste and the considerable losses of P to the coastal zone (Choudhury *et al.*, 2014). For Europe alone, and assuming inorganic manufactured P costs of €2 per kg P, total P losses to water and to landfill represented 42% of annual P usage and have a potential value of over €1.5 billion (Withers *et al.* 2015b).

There is now global consensus on the need for more sustainable use of P. While there is on-going debate on exactly how much global PR reserve we have left (Edixhoven *et al.* 2013; Ulrich *et al.* 2013), there is no disputing that PR is a finite resource and that its cost to producers will only increase in the future (Elser *et al.*, 2014). Reserves of phosphate rock (PR) are held in mineable quantities in only a few countries (Cordell *et al.*, 2009), and their continuing depletion, plus the degradation of water quality and loss of aquatic biodiversity, are seen principally to result from production of food (Elser & Bennett, 2011; Cordell *et al.*, 2014). The EU has recently placed PR on its list of critical raw materials because of concerns over the potential availability and affordability of PR-based fertilisers in the future (EC, 2014). A future shortage of P could threaten national food security, and bioenergy production (Neset *et al.*, 2014). With these increasing concerns, and with more volatile PR prices in recent years (Elser *et al.*, 2014), the current approach to P fertiliser use appears unsustainable (de Ridder *et al.*, 2012).

The environmental damage (eutrophication) from unused and lost P is widespread and costly, affecting ecosystem diversity, human health, well-being and prosperity (Smil 2000; Smith & Schindler 2009). In the UK the estimated annual economic damage from eutrophication has been estimated at between £75-114 million (Pretty *et al.*, 2003), and in the USA it has been estimated at $2.2 billion (Dodds *et al.* 2009). There are also emerging concerns over the links between high P diets, high blood serum P and a range of human health problems including calcium homeostasis, kidney function, cardiovascular disease, ageing and cancer (Ellam and Chico 2012; Shroff 2013). The gross inefficiency of P use, and the resulting environmental and potential human health problems, will only become worse as a growing urbanizing global population demands more food, bioenergy and clean water, and changes to our climate will likely further exacerbate P losses and the eutrophication of our water resources.

There are therefore pressing economic, environmental, human health and resource justifications for increasing the sustainability of P use.

3.2 Possible solutions

3.2.1 **European blueprint**

In Europe, a 5R strategy has been proposed to improve the stewardship of P and to act as a blueprint for national and global P sustainability:

- Realign P inputs more precisely to maximise efficiency,
- Reduce P losses to the oceans,
- Recycle more P in bioresources,
- Recover and reuse P from wastes and
- Redefine P requirements in the food chain (Withers *et al.* 2015b).

This transition towards greater P sustainability will require a paradigm shift in current philosophies of nutrient management and attitudes towards food and bioenergy production (Gomiero *et al.* 2011; Withers *et al.* 2014; Jarvie *et al.* 2015). Agriculture is by far the biggest user of P with over 80% of mined PR required for the manufacture of inorganic P fertilisers. Whilst inorganic P fertilisers have been a cornerstone of the success of the green revolution in both developed and emerging economies, their past and current patterns of use have directly contributed to the global environmental and resource issues now faced by society. Imports of inorganic P fertilisers match surpluses of P in agricultural systems surprisingly closely and these surpluses are continually accumulating in agricultural soils (Withers *et al.*, 2014). This is because the majority of P in crops is fed to animals, animals excrete 70-80% of the P in their diet and the resulting amounts of manure P produced cannot be evenly distributed back to cropping areas due to their bulk, and the geographical disconnect between arable and grassland farming systems. Past excesses of fertiliser use and uneven recycling of manure P have led to widespread excess accumulation of soil total P and STP (Toth *et al.*, 2014). For example in England and Wales, over 40% of agricultural soils are above the recommended critical level of STP required for optimal crop production (PAAG, 2014). Soil P accumulation from past P inputs (termed 'legacy soil P') is the dominant source of diffuse P loss to water and is now considered to be a major reason why eutrophied waterbodies are not responding to current P input restrictions (Sharpley *et al.*, 2013). A radical rethink is therefore required on the current approach to P fertiliser inputs and how the very large store of soil legacy P can be re-used as an integral part of decisions on fertiliser needs (Rowe *et al.*, 2015).

3.2.2 **United Kingdom developments**

3.2.2.1 Current strategy

The current approach to P management in the UK was introduced in the 1960s in England and Wales and replaced one that had predominated through the early 20th century, which assumed that any P 'fixed' by the soil was irretrievable by crops, hence cropping was considered to rely entirely on use of large fresh P applications. Since the 1960s guidelines have been based on the 'Critical P' approach, following the development of the Olsen method of soil analysis to estimate potential soil P availability for a crop. At that time soil analysis data were grouped into Indices to indicate likely response of a crop to applied P fertiliser.

The 'critical P' approach depends on available P being released from the large store of fixed P in the topsoil (and sometimes distributed deeper in subsoil) rather than relying on fresh applications of fertiliser and/or manure to provide the P requirements of each crop. Thus the main aim is to maintain a level of available soil P (the Critical level) which allows a crop to achieve its optimum yield, i.e. a level to achieve 95-98% of maximum crop yield in a high proportion of seasons and cropping circumstances (Johnston *et al.*, 2014). Soil test P (STP) analysis based mostly[2] on the 'Olsen' method (Olsen *et al.*, 1954) is used to assess 'available' P, with a recommendation to maintain a concentration of between 16 and 25 mg L^{-1} (Index 2) for optimum yield of arable crops and grass (Defra, 2010). Thus most arable farms undertake regular soil analysis to monitor STP concentrations. Olsen-P accounts for only approximately 15% of the total legacy P that accumulates in soils through a replacement strategy (Johnston *et al.*, 2014) and regular analysis is needed in case a farm's P management leads to a fall in 'available' P over time, in which case additional fertiliser may be required. Similarly, where the

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[2] For other approaches to soil analysis see Withers *et al.* (2015).

replacement strategy leads to an increase in STP, fertiliser may be reduced below crop offtake levels.

Although typically less than 20% (and often <10%) of applied fertiliser P is used by crops in the season of application, the critical P approach has been presented as highly efficient (once the critical STP level has been achieved) since inputs and offtakes are usually matched (Syers *et al.*, 2008). However this analysis fails to recognise the contribution to crop uptake of naturally weathered soil P (Edwards *et al*., 2015), and the dependence on a large investment in legacy soil P; Withers *et al.* (2001) estimated that UK soils had accumulated over 1000 kg ha^{-1} P amounting to 12 million tonnes of P since the 1930’s. Additionally, the idea of ‘balanced’ P crop nutrition fails to recognise that crops export large amounts of P that are commonly not recycled.

3.2.2.2 An Alternative Strategy

To meet aspirations for sustainability, an alternative approach is clearly required to maximise the efficiency of P in the food chain, to fully utilise the stores of legacy soil P and to make economic, environmental and PR resource gains. This project developed a ‘Targeted P approach’ as an alternative to the ‘Critical P approach’ which entailed exploring the feasibility of farming on soils at P Index 1 rather than P Index 2.

The Targeted P approach aims to maximise the direct crop recovery of any applied P, and hypothesises that dependence on stored soil P could be reduced, and might even be eliminated ultimately. The approach aspires to fertiliser systems (products plus practices) that reliably achieve improved recovery of fresh P by the crop. It also embraces the philosophy that some depletion of total and available soil P reserves is environmentally desirable, especially where current soil P levels greatly exceed the ‘critical’ level. Reducing the store of legacy soil P would help UK farmers meet the requirements of the EU Water Framework Directive (WFD), which requires that all water bodies should achieve either high or good ecological status by 2021 or 2027.

Although previously considered to be fixed and unavailable to plants, a considerable proportion of the store of legacy soil P not assessed by Olsen has been shown to become plant-available (Blake *et al.*, 2003; Rowe *et al.*, 2015). Release of this store of legacy soil P depends on lowering STP below current ‘insurance’ levels, so that P can diffuse out. In addition, many plant species have innate mechanisms for mobilising less available and recalcitrant forms of inorganic and organic P; for example by exuding labile carbon for increased microbial activity, organic acids and anions for mobilising inorganic P and enzymes (phytase and phosphatase) to mineralise organic bound P (Richardson *et al.*, 2009). These innate mechanisms have been made redundant, and are consequently under-expressed in modern arable crops, by restricting plant breeding programmes to P-rich sites and by advocating nutrient management strategies that aim to ensure a plentiful supply of P in the soil (Withers *et al.*, 2014).

The Targeted P approach envisages that as soil P runs down and as crop uptake from fresh P applications becomes more reliable, crops will rely less on the store of soil available P; thus soil monitoring will become less essential. However, with a smaller proportion of crop P requirements coming from the soil in the longer term, the efficiency of any fertiliser P will need to be reliably high, so high recovery with reliability is a vital challenge of the targeting approach.

3.3 Project Hypotheses, Aims and Objectives

The overall aim of the project was 'to develop profitable and sustainable farming systems that maximise the efficiency of utilization of soil- and applied-P by arable crops and minimise negative impacts on the wider environment'. To achieve this aim, the project addressed address two key hypotheses:

1. Modification of fertiliser P-release patterns, better targeting of P inputs to meet crop P demand and more selective crop/soil management will improve the utilization-efficiency of soil- and applied-P by arable crops, allowing them to be grown on soils of lower P fertility without sacrificing farm profitability.
2. The adoption of novel soil and fertiliser management strategies on soils lower in P will reduce emissions in land runoff of P from applied fertilisers and soil stocks and lessen the wider negative environmental impacts of arable farming.

Thus the project had two main objectives:

1. To develop novel targeted fertiliser technologies and soil-P acquisition strategies that would enable arable crops to be grown on soils having a lower P status without sacrificing crop yield, crop quality or farm profits.
2. To determine whether adoption of novel soil and fertiliser strategies on low-P soils would enable reduction in P inputs, reduce emissions of P from land to water and lessen the wider negative environmental impacts of arable farming

These were addressed through five specific research objectives:

1. To investigate alternative approaches to improve the efficiency of P use by arable crops.
2. To optimise sustainable fertiliser strategies through mathematical mechanistic modelling
3. To quantify the effects of novel fertiliser technologies and soil P acquisition strategies on crop yield, crop quality and farm profits

4. To quantify the effects of novel fertiliser technologies and soil P acquisition strategies on the transport of P in land runoff and on potential eutrophication impacts
5. To quantify the wider economic and environmental impacts of techniques to improve sustainability of P use on arable farms

Each specific research objective was the subject of a bespoke Work Package (WP), and these are described in the subsequent Sections of this report.

4. Scoping alternative mechanisms for more efficient P use (WP1)

4.1 Introduction

The essential roles of P in plant growth are in forming the macro-molecules involved in plant metabolism ranging from nucleic acids to phospholipids. Concentrations of P in amply fertilised whole-plant tissues are of the order of 0.3% in the dry matter (DM); thus an annual crop producing say 10 t ha^{-1} of biomass must acquire ca. 30 kg ha^{-1} P during growth. Due to its low mobility in soil, P availability to plants is often limited, with corresponding constraints upon growth and yield. Deficiency symptoms in a range of agricultural crops generally appear when tissue concentrations are below 0.2% (in the DM). Low P availability can also negatively affect root growth (Drew, 1975) with concurrent consequences for the acquisition of water and other nutrients (Takahashi and Anwar, 2007). Agriculture commonly compensates for this naturally low soil P supply by applying manufactured inorganic P fertilisers and organic livestock and other manures.

Conventional P-fertiliser strategies aim to maintain high levels of plant-available P in soil to ensure that P does not become limiting throughout crop growth and development (Tunney *et al.*, 1997; Moody, 2007; Valkama *et al.*, 2011). This commonly entails initially over-supplying P to build-up a recommended level of soil available P (i.e. defined for the majority of crops as P Index 2, 16-25 mg Olsen-P L^{-1}, Defra, 2010) and then the subsequent maintenance of this ‘critical’ soil P level by matching predicted plant P-offtake in applications of soluble inorganic P fertiliser (Syers *et al.*, 2008). However, due in part to P fixation processes in the soil, and partly to the ability of crop plants to acquire native and residual soil P, less than a third (and often < 10%) of the applied fertiliser P each year is typically acquired by the current season’s crop (Sharpley, 1987; Baligar *et al.*, 2001; McKenzie *et al.*, 2003). The remainder is immobilised in the soil by sorption processes (Stutter *et al.*, 2012), and a portion lost to the environment each year through leaching and run-off causing widespread eutrophication of inland and coastal waters and threats to human health (Withers *et al.*, 2001; Smith and Schindler, 2009). Whilst PR prices remained low, this inefficiency was not a significant cost for agriculture, but has turned out be a huge cost to the environment (Dodds *et al.*, 2009)

It is also becoming increasingly clear that the reserves of phosphate rock (PR) from which inorganic fertilisers are derived will not last indefinitely, but are a finite natural resource which is held in mineable quantities in only a few countries (Cordell *et al.*, 2009). The EU has recently placed PR on its list of critical raw materials because of concerns over the potential availability and affordability of PR-based fertilisers in the future (EC, 2014). A future shortage of P could threaten national food security, and bioenergy production. With these increasing concerns over food, energy and water security and as PR prices have become more volatile in recent years (Elser *et al.*, 2014), the current approach to P fertiliser use appears to be unsustainable. This WP investigated various means of targeting P applications to improve the efficiency of P use, whereby smaller quantities of P might be used to more closely match crop demands (Simpson *et al.*, 2011; Withers *et al.*, 2014).

A diverse range of approaches was considered, including foliar P fertilisation with phosphate solutions; seed dressing with potassium phosphate or the bacterium *Bacillus amyloliquefaciens* FZB42, soil application of the slow-release recycled P source struvite, and coating of soil applied triple super phosphate (TSP) or di-ammonium phosphate (DAP) granules with the AVAIL® maleic-itaconic co-polymer. These novel commercial approaches have been advocated to improve P use efficiency and/or crop yield, but there is little evidence to support their use and a general lack of understanding of the mechanisms involved. Experiments were conducted in glasshouses or controlled conditions using spring wheat, and all approaches were compared to soil application of readily soluble P fertilisers either as TSP or DAP in order to evaluate their viability as potential alternative P-fertilisation methods in commercial agricultural systems.

4.1.1 **Foliar P and inorganic P seed dressings**

The temporal flexibility of foliar P application relative to incorporating or placing fertiliser P in the soil at the time of sowing enables P to be more accurately matched to the plant's increasing demand for P later in the growing season (Sutton *et al.*, 1983; Allison *et al.*, 2002). Foliar applied P is thought to enter the leaf through direct stomatal penetration, and depending on plant water status, atmospheric conditions and light intensity, is potentially rapid (Noack *et al.*, 2010). The formulation of any foliar P product (especially pH, counter ion identity, and adjuvant content) also has a major impact on its rate of uptake into the plant, with the key goals being to increase P uptake rates into the leaf by potentially reducing the ionic strength of the solution and increasing the amount of time the ion is in solution and in contact with the leaf (Bouma, 1969; Koontz & Biddulph, 1957; Fernández & Brown, 2013). Difficulties in applying sufficient foliar P to satisfy plant demand mean that all crop species are limited in the amount that can be applied in one dose without scorching the leaf. In addition, applying enough P at early growth stages to maximise a crop's yield potential is not possible using only foliar fertilisation as low ground cover during early growth leads to a large proportion any foliar-targeted P falling on the soil surface (Noack *et al.*, 2010). Thus our experiments tested combined foliar applications with seed dressings of P prior to sowing. Seed dressings provide P very close to the developing root system so should maximise the efficiency of uptake into the plant. However, depending on seed size, the seed surface can only be coated with limited quantities of P, meaning that seed treatments alone may not always be beneficial to final yields (Peltonen-Sainio *et al.*, 2006; Peske *et al.*, 2009; Valluru *et al.*, 2010). Greater success has been found by combining seed treatment with other, more substantial, P application methods. In this way, the application to the seed surface may disproportionately reduce the plant's requirement for additional P-fertiliser and so significantly improves the overall efficiency of use (Sekiya and Yano, 2009).

4.1.2 **Struvite**

Struvite is produced as a by-product of wastewater treatment, where controlled struvite precipitation can be triggered in specialised reactors by manipulation of the sludge digestion process (Baur, 2009). Struvite is a low solubility slow-release P-fertiliser, which means that it provides P-inputs far later in the crop growing season than more soluble P sources. This is potentially more in harmony with crop demand which is far higher during the later stages of plant development (Veneklaas *et al.*, 2012). Previous experimental evidence has shown that struvite, despite its well-known low solubility in water, can be at least as effective as mineral P sources when used as the sole P fertiliser, especially in acid soils (Antonini *et al.*, 2012; Massey *et al.*, 2009; Degryse *et al.*, 2016). However, these have largely been "end-point" studies with results collected only at grain harvest, which have not assessed the potential pitfalls of using struvite as the sole P fertiliser on P uptake in the crucial early stages of plant growth and establishment *(Grant et al.*, 2001; Brenchley 1929; Boatwright & Viets 1966; Green *et al.*, 1973). The study here aimed to assess the impacts of struvite fertilisation at both the early growth stages that are crucial in crop development, and also at the endpoint of final yield.

4.1.3 **Bacterial seed dressings**

B. amyloliquefaciens FZB42 is a plant growth-promoting bacterium that has been demonstrated to promote the growth of colonised roots (Fan *et al.* 2011). This strain has been shown to produce large quantities of auxin, with increases in auxin production following the addition of the amino acid tryptophan (a source of carbon (C)) to the culture media (Idris *et al.*, 2007). The study here aimed to assess the nature of the biological interaction between *B. amyloliquefaciens* FZB42 and the wheat (*Triticum aestivium*) root system, with the hypothesis that any effects of *B. amyloliquefaciens* FZB42 colonisation on root uptake rates of inorganic P (Pi) would be dependent upon the soil Pi concentration. As the primary mode of *B. amyloliquefaciens* FZB42-root interaction observed previously was auxin production (Idris *et al.*, 2007), this interaction was investigated here by analysing the effects of exogenous auxin application upon both root Pi-related gene expression, and root exudation of organic C.

4.1.4 AVAIL®

The maleic-itaconic co-polymer AVAIL® is designed for use as a coating for conventional soil applied phosphate fertilisers, where it competes for adsorption sites on soil particles, and counter ions which immobilise added inorganic P by forming insoluble precipitates with phosphate. This is meant to ensure that the fertiliser phosphate in the immediate vicinity of the fertiliser granule is protected from immobilisation by the soil, and so remains available for plant uptake (Sanders *et al.*, 2012). The use of this polymer has been demonstrated to alter the proportions of insoluble P forms in soil, and in some soil conditions has proved very effective at increasing yields (Sanders *et al.*, 2012). This study aims to investigate whether AVAIL® can promote P-uptake in spring wheat on low-P soils under controlled conditions, and whether high calcium (Ca) levels play a role in AVAIL® effectiveness.

4.1.5 Summary

The overall objectives of this WP was to provide mechanistic understanding of the above approaches through detailed experimental work under controlled laboratory and glasshouse conditions and to help inform field and modelling work in the rest of the project. In particular, this work aimed to answer the following questions:

- Do seed dressings of P increase early vigour at a comparable rate to banded TSP/DAP?
- How effective is foliar P at entering the plant and how mobile is it once it has entered?
- Does the combination of seed dressing and foliar P provide a comparable level of P uptake to conventional TSP/DAP application but at greater efficiencies?
- Does seed treatment with *B. amyloliquefaciens* FZB42 enhance early root growth and P uptake in live soil and how is this effect produced?
- How do crop P uptake rates vary when using slow release fertiliser such as struvite compared to using a readily soluble P fertiliser when considered over both an initial establishment period of 36 days, and over an entire growing season?
- Can treatment with AVAIL® increase the recovery rate of applied highly soluble inorganic P-fertilisers such as TSP and DAP?

4.2 Materials and methods

As far as was possible, the experimental conditions were similar across all the individual studies testing the different alternative P application approaches. Choice of whether TSP or DAP was used as the positive control depended on the availability of materials at the time and for the purposes of these experiments are considered interchangeable in terms of their ability to supply P into solution.

4.2.1 **Plant growth conditions**

Three seeds of *Triticum aestivum* (spring wheat) were planted in either 8 cm diameter, 6.5 cm deep pots filled with 300 g sandy loam soil (21, 30 and 36 day experiments, or to grain yield for one set of seed/foliar experiments), or for the long-term experiment (90 days) to mature grain yield in 11 cm diameter 30 cm deep drainpipes filled to the top with 3 kg of the same sandy loam soil. This soil (from Abergwyngregyn, UK) had a low Olsen P concentration of 12-15 mg L^{-1} which provided a P-limiting environment for plant growth according to current recommendation systems used in England and Wales (Defra, 2010). To help understand the effectiveness of seed dressing plus foliar sprays, and the mechanism of action of the bioinnoculant *B. amyloliquefaciens* FZB42, additional high P soils (32-35 mg L^{-1} Olsen-P) from Abergwyngregyn or Thonock, UK were also collected to compare with treatment effects produced in the low P soil. Where soil based fertilisers were used, these were placed 2.5 cm (300 g pots) or 5 cm (3 kg pots) beneath the seed. The mass of each of soil based fertiliser (or mixtures of fertilisers) applied per pot was adjusted according to the pot surface area to produce a recommended constant rate of P fertilisation equivalent to 35 kg P ha^{-1} (80 kg ha^{-1} P_2O_5). In experiments involving seed treatments, dressings containing either potassium phosphate (OMEX Agriculture Ltd., Lincoln, UK), or a KCl control, and were applied directly to the seed coat using a micropipette such that each seed was coated with 3.45 µmol K and the P-treated seeds were also dosed with 1, 2, 3 or 4 µmol P $seed^{-1}$ as required.

At crop emergence, the excess seedlings were removed to leave only the largest seedling in each pot. The pots were kept in a heated greenhouse with artificial lighting set to produce an air temperature of 20^{o}C and a minimum of 16 hours of day length. Soil water holding capacity was measured gravimetrically, and the pots were watered thrice weekly by filling saucers at the bottom of the drainpipes for the long-term experiments or by maintaining the soil at 80 % of water holding capacity for the short-term experiments. To ensure that P was the only limiting macronutrient, the equivalent of 60 kg ha^{-1} N (as 1 M NH_4NO_3 solution) and 60 kg ha^{-1} K_2O (as 1 M KCl solution) were applied to each pot at seedling emergence. For the long-term experiment, an additional 60 kg ha^{-1} N was also applied at the stem extension growth stage as per current recommendations (Defra, 2010). Micronutrients were supplied in a weekly application of 10 ml of a solution containing: 5 mM $CaCl_2$; 2 mM $MgSO_4$; 765 nM $ZnSO_4$; 320 nM $CuSO_4$; 46.3 µM H_3BO_3; Na_2MoO_4 497 µM; 9.14 µM $MnCl_2$ and 38.7 µM Fe.EDTA (all Sigma Aldrich, Poole, UK).

Foliar P was applied at Zadoks' growth stages GS13 (three leaf), GS31 (stem extension) and GS39 (flag leaf) (Zadoks *et al.*, 1974). These applications were pipetted onto the leaves of each plant using a micro-pipette, and manually spread such that they covered as much leaf as possible. Equal quantities were applied to the top and bottom of the leaf, and applications were made in the morning so that there was a minimum of 8 h of photosynthetic light directly afterwards to maximise initial uptake rate. Treatments were either the ammonium phosphate solution described above (OMEX Agriculture Ltd., Lincoln, UK) for the P treatments or an NH_4Cl solution control for all other plants to ensure equal application of foliar NH_4^+, both mixed with 0.1% v/v of the adjuvant IA-500 (Interagro, Braintree, UK). Each dose consisted of 70 µmol N plant^{-1} and for the P treatments 46.3 µmol P plant^{-1}.

At harvest, the whole plant was extracted from the pot, the seed removed and weighed (if applicable), and then the root system washed in deionised water to remove any soil particles. All plant tissue was then dried at 85 °C overnight, weighed, and dry-ashed (550 °C, 16 h). The residue was dissolved in 0.5 M HCl and the P content was determined (Murphy and Riley, 1962). Any remaining struvite granules (if applicable) were extracted from the soil, air-dried, any adhering soil particles brushed off, and re-weighed at the end of each experiment. There were no discernible TSP or DAP granules remaining at the end of any of the short or long-term experimental periods.

4.2.2 Fertiliser Sources

Struvite granules commercially distributed under the trade name Crystal Green® were provided by Ostara Nutrient Recovery Technologies Inc. The granules contain >99% struvite ($NH_4MgPO_4{\cdot}6H_2O$) equivalent to 12% P (28 % P_2O_5). Triple Super Phosphate (TSP) and di-ammonium phosphate (DAP) granules both uncoated, and coated with 0.25 % v/m of the AVAIL® polymer were provided by Speciality Fertiliser Products. Ammonium phosphate foliar spray and potassium phosphate seed dressings were provided by Omex Agriculture. The ammonium phosphate solution was manufactured as a polyphosphate / phosphate mix, however testing prior to commencing the experiments several months later, using the ascorbate / molybdate blue method of Murphy and Riley (1962), showed that upon delivery 100% of the P content was accounted for by orthophosphate. Baccilus amyloliquefaciens FZB42 cultures were sourced from the Bacillus Stock Center.

4.2.3 Foliar P entry/mobility

To track the entry and mobility of foliar-applied P, phosphate solutions were labelled with the P radioisotope ^{33}P. Wheat seedlings were grown in the same growing conditions as above, but with no seed dressing. Once they had three leaves (GS13) they were laid horizontally with one leaf affixed to a clean bench surface using electrical tape. A 16 mm^2 square was then marked out using petroleum jelly on either the underside or the top leaf surface. 3 µl of ammonium phosphate solution (6.62 M P, OMEX Agriculture Ltd., Lincoln, UK) labelled with 22.2 MBq ml$^-$

^{1} ^{33}P (American Radiolabeled Chemicals Inc., St Louis, MO, USA) was then applied to the leaf surface, either mixed with 0.1% v/v of the adjuvant IA-500 (Interagro, Braintree, UK) or without, and left for 16 h with artificial illumination (light intensity = 260 µmol m^{-2} s^{-1} PAR representative of a cloudy day in the UK summer). Experiments to assess the impact of daylight were conducted in the same manner, but all treatments had 0.1% v/v IA-500 and dark treatments were covered to eliminate the presence of light. After 16 h, the seedlings were dried at 80 °C and the ^{33}P distribution in the plant imaged using a Cyclone Plus phosphor imaging system (Perkin Elmer, Waltham, MA, USA) with an exposure time of 15 min. The dried plants were then dry-ashed (550 °C, 16 h), the residue dissolved in 0.5 M HCl and the ^{33}P content of the resulting solution quantified using a Wallac 1404 scintillation counter (Wallac EGandG, Milton Keynes, UK) after mixing with Scintisafe scintillation fluid (Fisher Scientific, Loughborough, UK).

4.2.4 **qPCR on wheat phosphate transporters**

Quantitative RT-PCR (reverse transcription-polymerase chain reaction) to determine the relative expression levels of phosphate transporters, and starvation induced genes, in spring wheat roots was carried out on mRNA extracted from root tissue grown untreated, in the presence of *Bacillus amyloliquefaciens* FZB42, or in the presence of exogenous auxin (Indole acetic acid, IAA). This experiment is described in detail in Talboys *et al.* (2014).

4.3 Results

4.3.1 **Seed dressing with phosphate**

Seed dressing with 2, 3 and 4 µmol P per seed showed significant benefits in total P uptake by 25 days (of 59 - 108 %) over control plants that had received no P addition (Figure 4.1A). For the 3 and 4 µmol P dosages there was no significant difference in P uptake compared with plants grown in soil to which 885 µmol P (80 kg ha^{-1} P_2O_5) had been added (placed) in the form of TSP or DAP. Seed dressing with 1, 3 and 4 µmol P seed^{-1} also produced significantly greater total lateral root length (by 52 - 79 %) over no-P controls (Figure 4.1B).

All four seed treatment doses produced lateral root lengths that did not differ significantly from the soil TSP/DAP treatments (they ranged from 14 % to 28 % lower than the average of the TSP and DAP treatments). For seminal root lengths, the soil DAP/TSP treatments produced significant increases over the controls, but were not different to the seed-dressed plants. As a consequence of the much lower doses per plant of the seed dressing than the soil application treatments, the rate of recovery of applied P was much greater in the seed treatments; but it did not show a linear response with dose: 90% for 1 µmol, 207 % for 2 µmol, 252 % for 3 µmol and 185% for 4 µmol (compared with 1.23 % for TSP and 1.16 % for DAP).

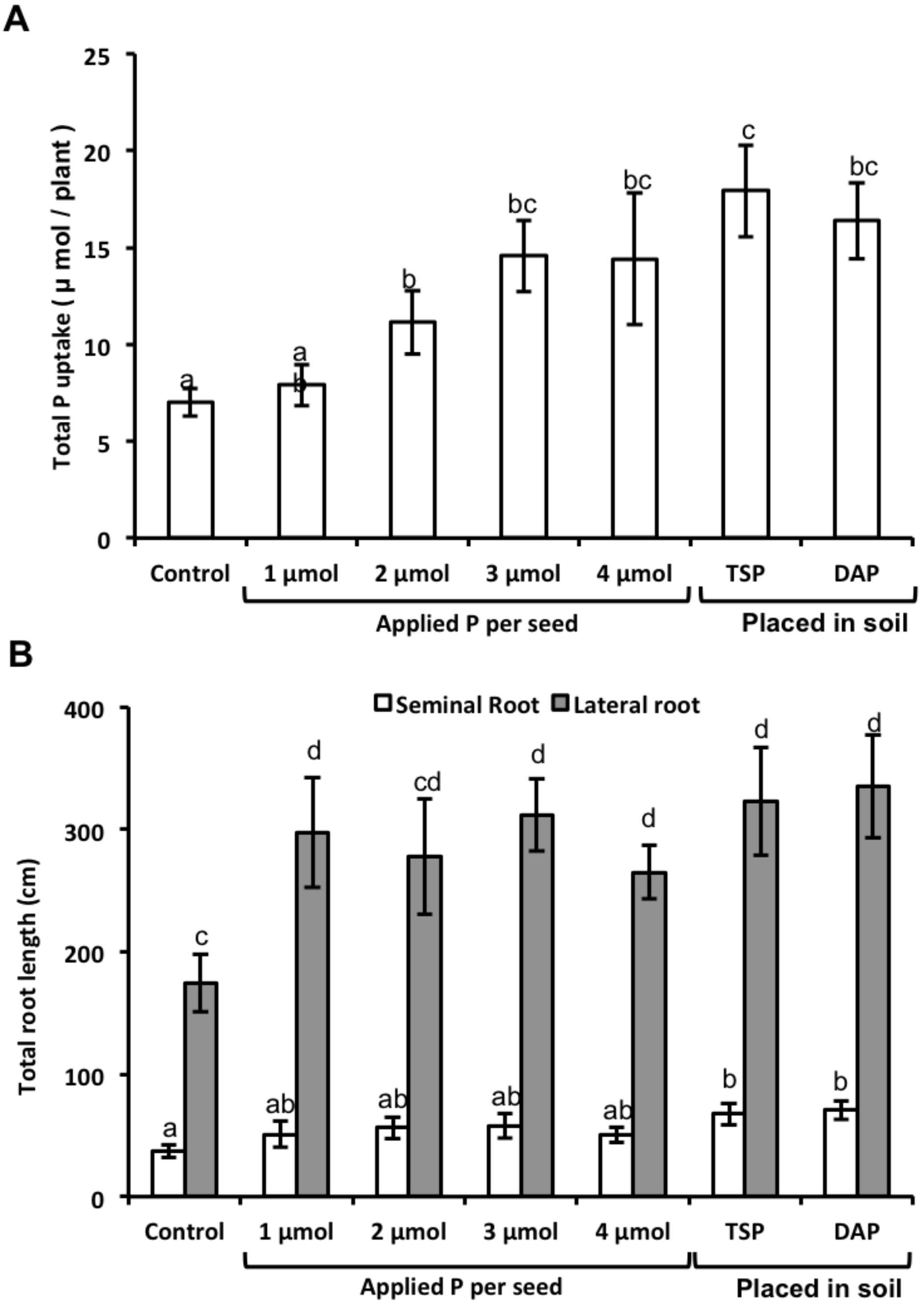

Figure 4.1. Micro-molar seed dressings enhance root production and P uptake. A: Total P acquired per plant (n = 4 for each treatment, except 4 µmol seed dressings where n = 3). B: Total length of each root class per plant, after 25 days when using seed dressings or placed soil-applied fertilisers alongside untreated controls. Placed fertiliser treatments equated to 885 µmol per plant. Different lower case letters mark values significantly different from each other using Student’s t-test (p <0.05). Error bars are standard errors of the mean (SEM).

4.3.2 **Foliar phosphate**

Application of the foliar phosphate solution with 0.1 % of the adjuvant IA-500 resulted in a significant increase (by 151 %) in the rate at which P was capable of entering the plant through the top surface of the leaf for plants grown for 16 hours in the light. There was, however, no significant difference in entry rate of P applied to the leaf underside when using IA-500, although P uptake was twice as high than when P was applied to the leaf top surface. Illumination of seedlings with 260 μmol m^{-2} s^{-1} PAR for 16 h, following application of foliar P formulations incorporating the adjuvant IA-500 (0.1 %) to the leaf underside, significantly increased both the uptake of P through the leaf surface into the whole plant over the 16 hours, and the mobilisation of the applied P within the plant, compared with seedlings incubated in the dark (Figure 4.2).

4.3.3 **Combining seed dressing and foliar applications of phosphate**

To test the effect of combined seed dressing and foliar sprays, pot experiments were conducted in both a low P soil and a high P soil. In a pot trial with the low P soil using a small soil volume (10 cm diameter, 10 cm deep pots) grain yields and P uptakes for the treatments using soil applied P (TSP) or seed dressing combined with 3 foliar applications or 3 foliar applications combined were significantly greater than the nil-P controls (Figure 4.3A and B). Applications of foliar P at a single growth stage produced no significant increases in P uptake or grain yield over the no-P controls. In pot experiments with the high P soil in which the wheat plants were grown to grain yield maturity in 11 cm diameter and 30 cm deep pots, the use of readily soluble, soil-applied P-fertiliser (TSP) at a rate of 80 kg ha^{-1} P_2O_5 produced significant increases (by ≥ 79 %) in total plant P uptake over the no-P addition controls (Figure 4.4 A). An increase in P-uptake (of 104% compared to the nil control) was also observed when dressings of 3 μmol P $seed^{-1}$ were combined with 3 foliar applications of 46.3 μmol $plant^{-1}$ (7 μl per plant); this treatment also produced uptake rates not significantly different from the soil applied P treatment in terms of applied P (Figure 4.4A). In this experiment grain yield was not significantly different in any treatments to the untreated controls (Figure 4.4B). In both experiments the recovery rate of P in the whole plant as a percentage of the amount of applied P was much greater in both the treatments with three foliar P applications alone and with seed dressing combined with the three foliar applications over the soil applied P treatments (Figure 4.3 and Figure 4.4).

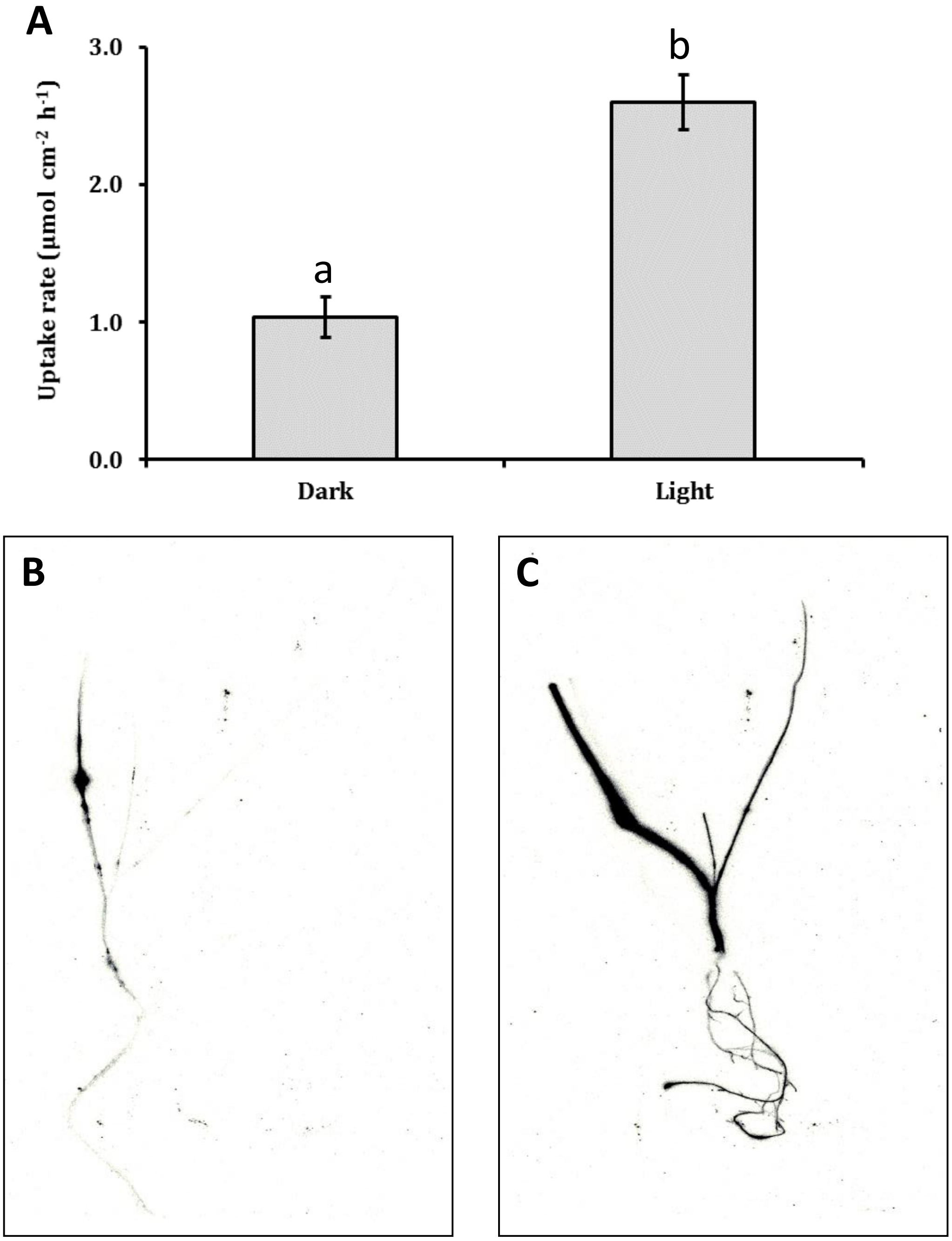

Figure 4.2. The impact of photosynthetic light upon the uptake rate of foliar P. Phospho-images of whole seedlings displaying the mobility of $^{33}PO_4$ following its application to a 16 mm^2 area on bottom of the leaf over 16 hours in either photosynthetic light (A) or darkness (B). Scale bars are 2 cm. C Average uptakes rates for the treatments depicted in A and B, with n = 3 for each treatment, lower case letters mark values significantly different from each other using Student's t-test ($p < 0.05$). Error bars are standard errors of the mean (SEM).

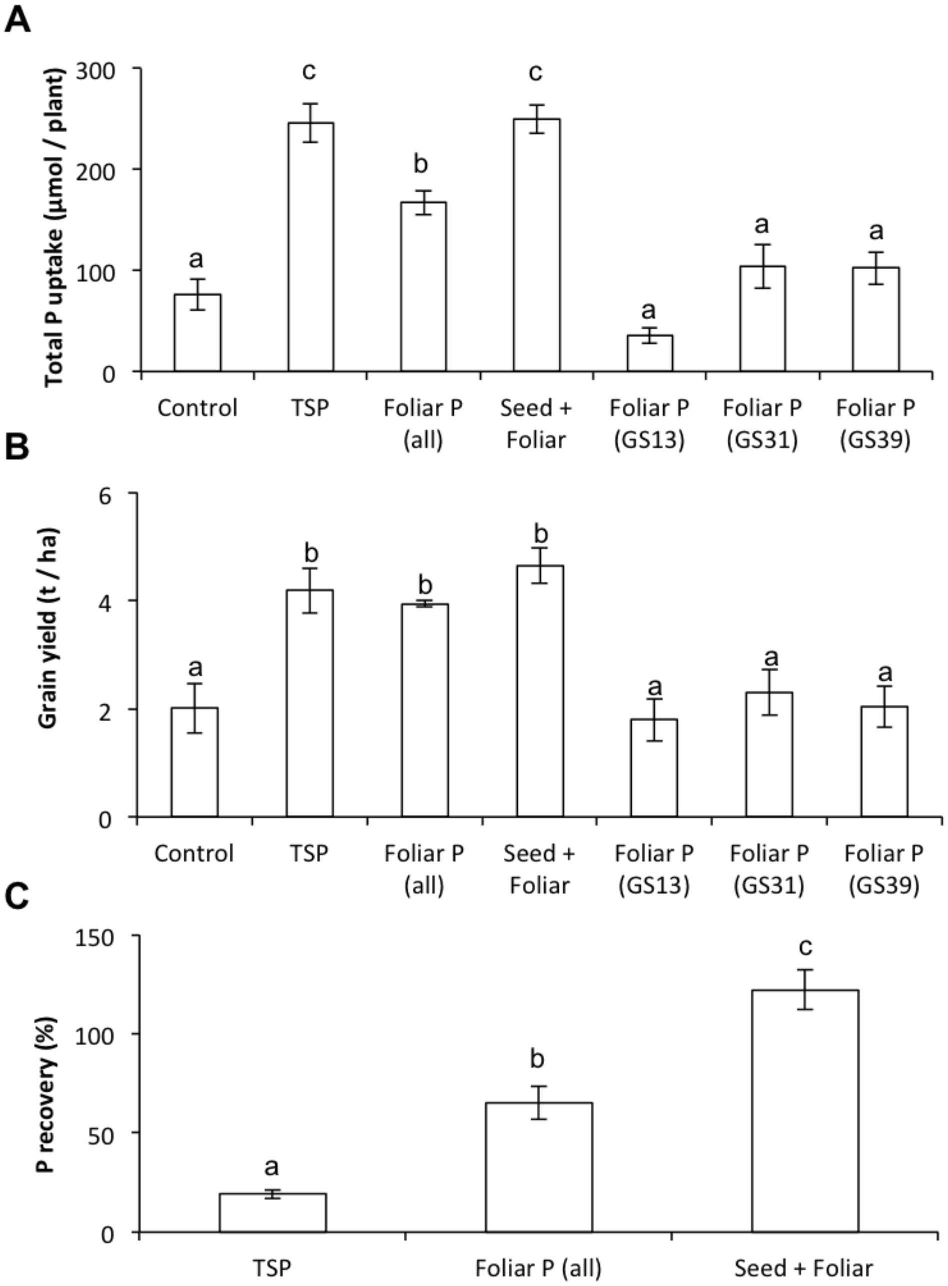

Figure 4.3. Foliar P-application alongside seed dressing can produce comparable outputs to soil fertilisation with greater P recovery rates. ***A*** *Total P content of wheat plants grown to yield in 500g soil with P-fertilisation regimes of untreated controls alongside : placed TSP (885 µmol P per plant); single or triple applications of foliar P (46.3 µmol P per plant per application); and seed dressings (3 µmol P per plant) combined with three foliar applications (46.3 µmol P per plant per application).* ***B*** *grain yields scaled to T/ha for the treatments depicted in A.* ***C*** *P recovery rates of the treatments that produced significant differences to the control values in A. For A, B and C n = 3-4 for each treatment, lower case letters mark values significantly different from each other using Student's t-test (p < 0.05), and error bars are standard errors of the mean (SEM).*

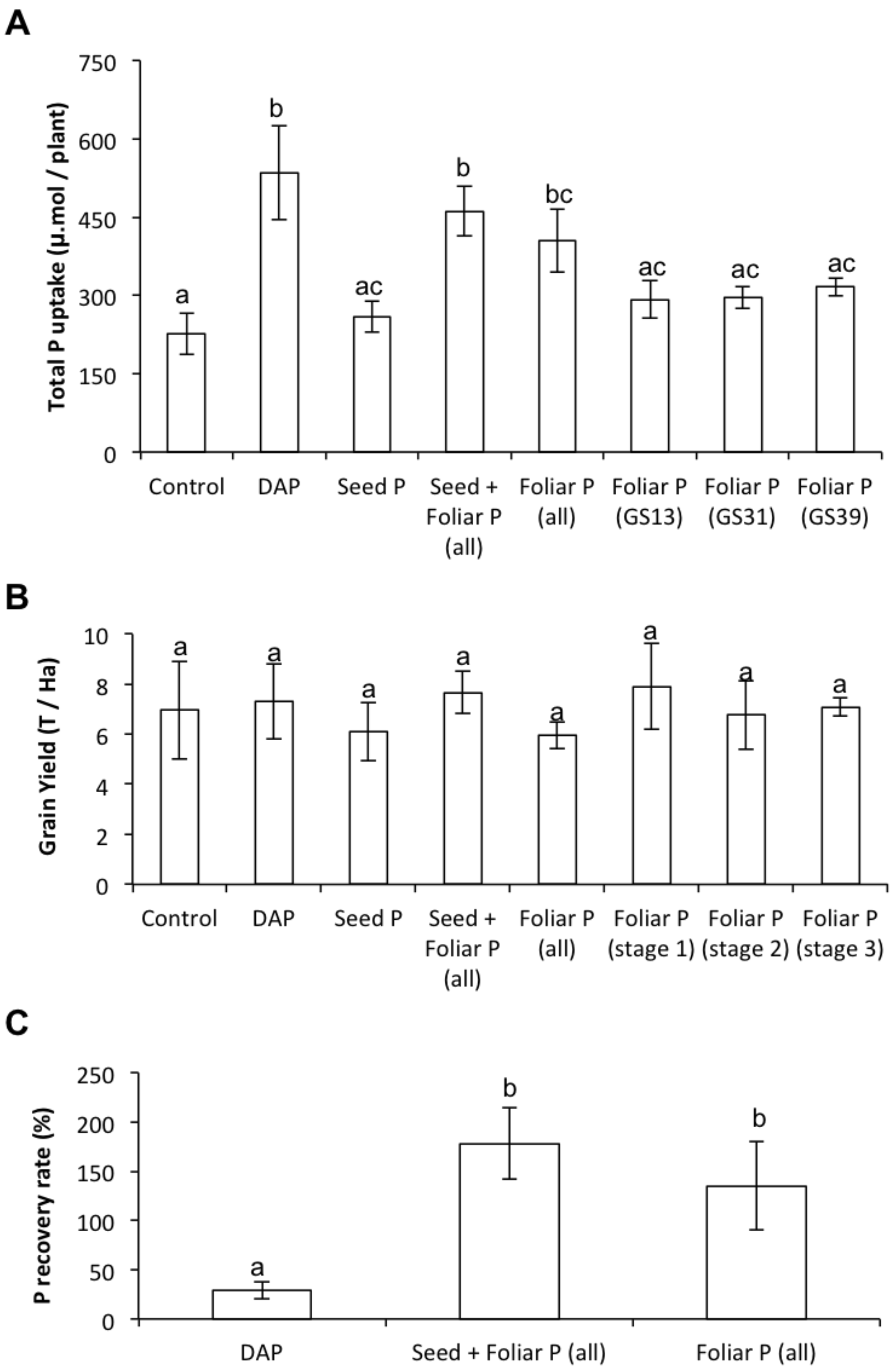

Figure 4.4. Foliar P-application alongside seed dressing can produce comparable outputs to soil fertilisation with greater P recovery rates. ***A*** *Total P content of wheat plants receiving either placed TSP (885 µmol P per plant); single or triple applications of foliar P (46.3 µmol P per application); seed dressings (3 µmol P) combined with three foliar applications,* ***B*** *grain yields scaled to t/ha for the treatments depicted in A.* ***C*** *P recovery rates of the treatments that produced significant differences to the control values in A. For A, B and C n = 3-4 for each treatment, lower case letters mark values significantly different from each other using Student’s t-test ($p < 0.05$), and error bars are standard errors of the mean (SEM).*

4.3.4 Seed treatment with *Bacillus amyloliquefaciens* FZB42

After 21 days growth in the experimental conditions described above, the application of *B. amyloliquefaciens* FZB42 as a seed dressing stimulated *T. aestivium* root production in live soil in both low and high Pi concentration (Figure 4.5).

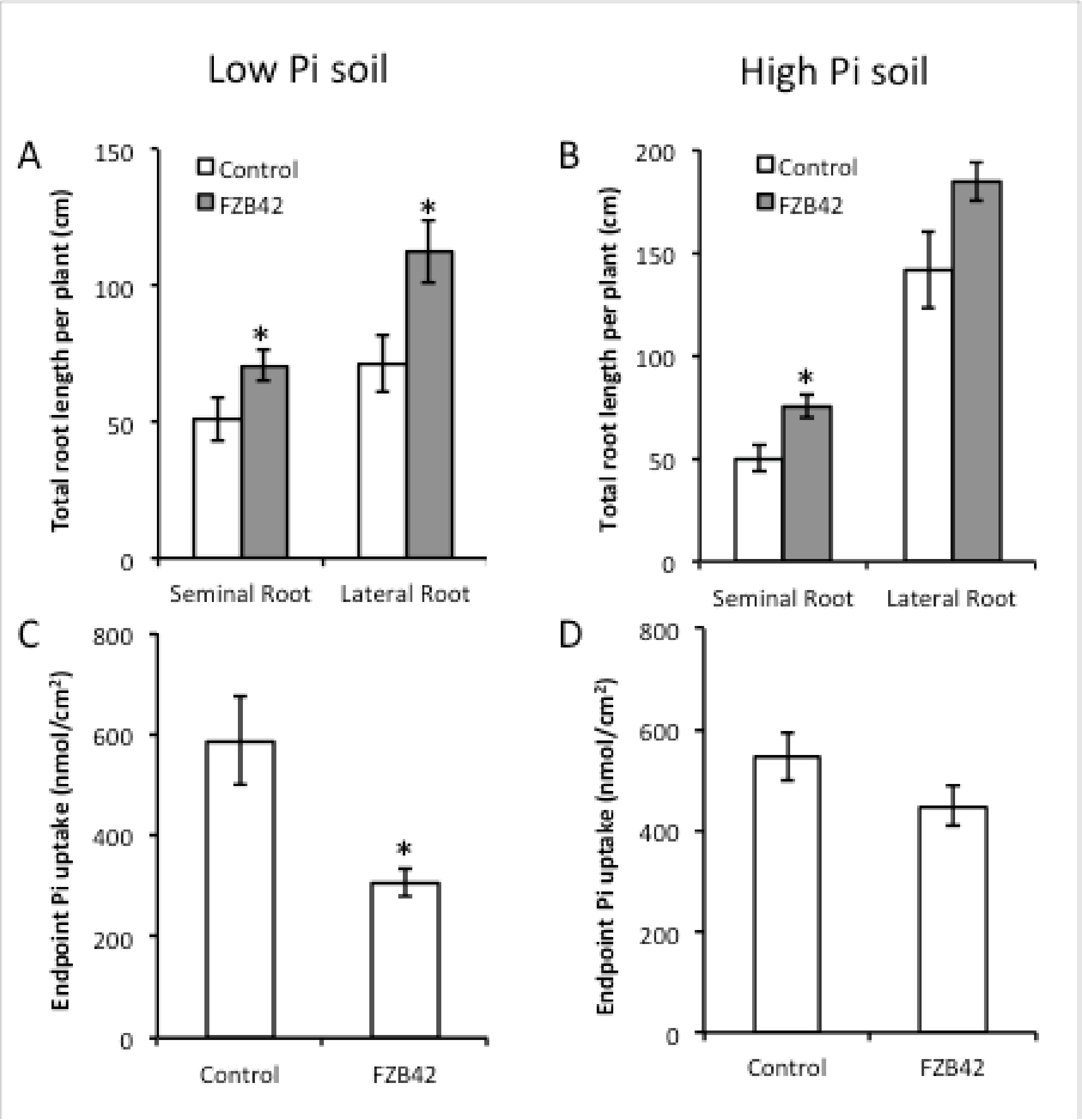

Figure 4.5. Seed dressing with Bacillus amyloliquefaciens B. amyloliquefaciens *FZB42 stimulates increased root production but reduced Pi uptake per root surface area in low Pi soils but not high Pi soils. A - B Total length of each root class per plant for three-week-old plants seed dressed at sowing with either* B. amyloliquefaciens *FZB42 or LB media as the untreated control and grown in either low Pi (A) or high Pi soil (B). C - D The total plant Pi content of the treatments in A and B, expressed as total Pi acquired after three weeks per root surface area. For A - D, n > 23 for each treatment, and * marks values significantly different from the untreated control values using Student's t-test (p < 0.05). Error bars are standard errors of the mean (SEM).*

B. amyloliquefaciens FZB42 treatment in low Pi soil resulted in significant increases in the length of the seminal root (by 39.1 %) and first order lateral root (by 51.0 %) per plant (Figure 4.5A), and length of the seminal root per plant was increased (by 50.9 %) in high Pi soil (Figure 4.5B). However, the average total Pi uptake per plant after three weeks growth was not significantly different in the *B. amyloliquefaciens* FZB42 treatment from the un-inoculated controls in both low- and high-Pi soils. However, when expressed on a per unit root surface area basis, total Pi uptake by *B. amyloliquefaciens* FZB42 treated root systems grown in low Pi soils was significantly less effective at acquiring Pi than un-inoculated controls (Figure 4.5C), whilst there was no difference in P uptake on high Pi soils (Figure 4.5D).

The relative expression of genes encoding individual cellular Pi transporters was also assayed. Of the six Pi transporters tested, a significant reduction was found in the relative expression of Ta*PHT1.8* and Ta*PHT1.10*, in both the *B. amyloliquefaciens* FZB42 and exogenous auxin application (IAA) treatments relative to the control (Figure 4.6A). Of the five Pi-associated genes tested, only *PAP15* showed any significant difference in expression under *B. amyloliquefaciens* FZB42 treatment relative to the control, with its expression increasing more than two fold over untreated controls (Figure 4.6 B). The expression of none these genes was significantly affected by the IAA treatment (Figure 4.6B).

4.3.5 **Struvite**

In 36 day experiments with spring wheat, plants grown in 300g of P Index 1 soil had significantly less total uptake of P when using struvite than with the readily soluble P fertiliser DAP (Figure 4.7). However, struvite was equally effective as a P source when buckwheat was grown. Buckwheat is known to produce organic acids to help mobilise soil P whereas spring wheat does not exude organic acids. Another short-term experiment using mixes of struvite and DAP similarly showed that struvite applied alone reduced P uptake relative to the DAP only treatment (Figure 4.8). However, the mixes of struvite and DAP overcame this short-term deficit in P supply and gave similar P uptake values to DAP alone (Figure 4.8).

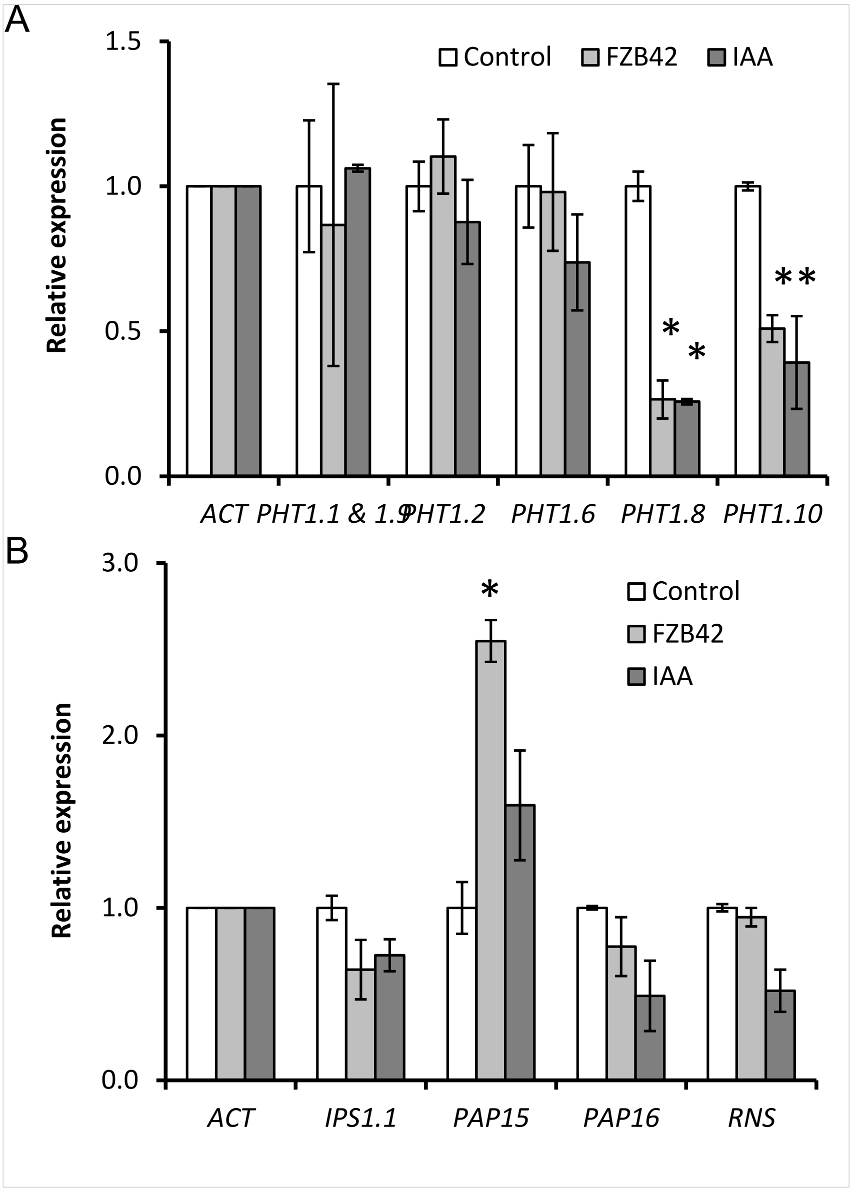

Figure 4.6. Baccilus amyloliquefaciens FZB42 *treatment effects on expression of root Pi transporters, and genes involved in internal Pi metabolism.* ***A*** *Relative expression of* Triticum aestivium PHT1 *genes, in roots, standardised to actin (ACT) controls. The experimental treatments were: innoculation with* Baccillus amyloliquefaciens FZB42, growth *in 1 µM IAA and untreated controls.* ***B*** *Relative expression of* Triticum aestivium *Pi metabolism genes in roots, standardised to actin (ACT) controls with the same treatments as in A. For A and B n = 3 for each treatment, error bars are SEM, and * marks values significantly different from the untreated control value (p<0.05).*

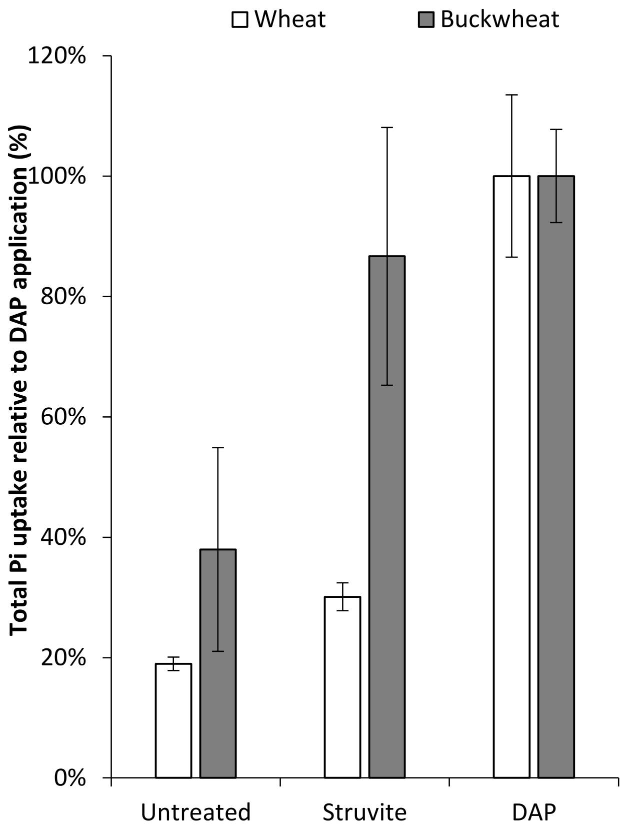

*Figure 4.7. Struvite proves less effective in providing P for early crop growth of wheat (*Triticum aestivum*), but struvite P release is enhanced when growing buckwheat (*Fagopyrum esculentum*) in a 30-day pot experiment in low-P sandy soil; P was applied at 17.6mg P pot^{-1} (35 kg P ha^{-1}).*

In a long-term pot experiment, use of struvite produced very similar rates of total P uptake (Figure 4.9A) and grain yield (Figure 4.9B) per plant to those obtained with use of TSP as the P fertiliser. However the number of mature grain heads produced was significantly increased ($p < 0.05$) when TSP was applied (control = 4.6 heads plant^{-1}, struvite 4.8 heads plant^{-1}, TSP 5.6 heads plant^{-1}). The rate of recovery in the plants of the P dissolved from the struvite fertiliser granules, minus untreated control P contents, was 175% greater than for the P released by the dissolution of the TSP granules (which had been added at the same P application rate per pot) (Figure 4.9C). Any residue from the applied TSP granules could not be identified from the bulk soil as so has been assumed for these purposes to be completely dissolved. There were also sizeable quantities of undissolved struvite after harvest in the long-term (to grain yield) pot experiments (ranging from 65.6% to 82.3 % of the initial mass).

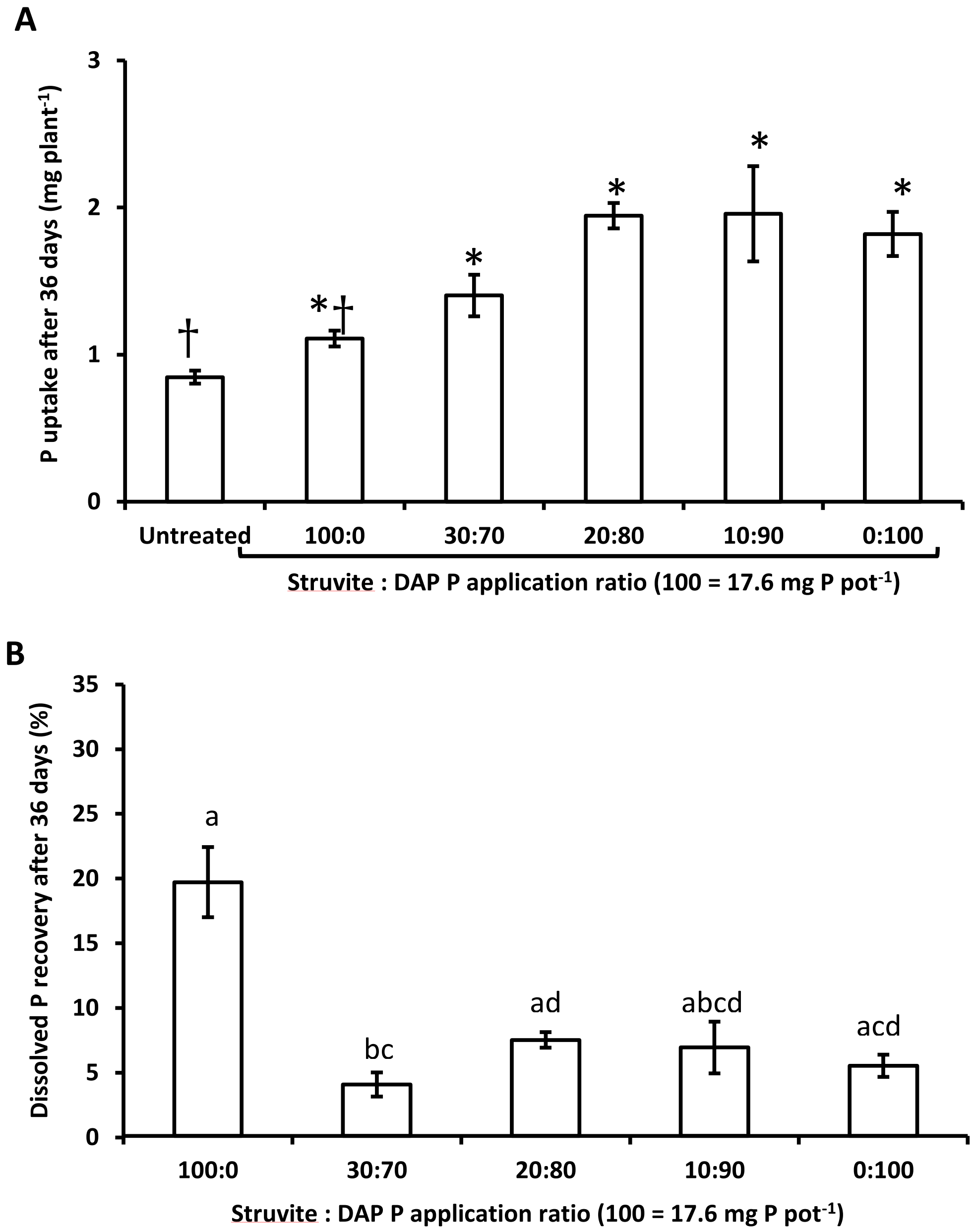

Figure 4.8. Applying struvite together with DAP allows the maintenance of early P uptake, whilst increasing P recovery in Triticum aestivum *receiving 17.6 mg P pot^{-1} (35 kg P ha^{-1}) in the form of struvite and/or DAP alongside untreated controls.* ***A*** *The total P uptake resulting from each treatment, asterisks mark pot trial values that are significantly different from the untreated negative controls, and daggers mark those that are significantly different from the 100% DAP (0:80) positive control using Student's t-test ($p < 0.05$).* ***B*** *The recovery rate of P that had dissolved from the fertiliser granules at the end point of the experiment. Different letters denote pot experiment values significantly different from each other using Student's t-test ($p < 0.05$, $n \geq 3$). Error bars are standard errors of the mean (SEM).*

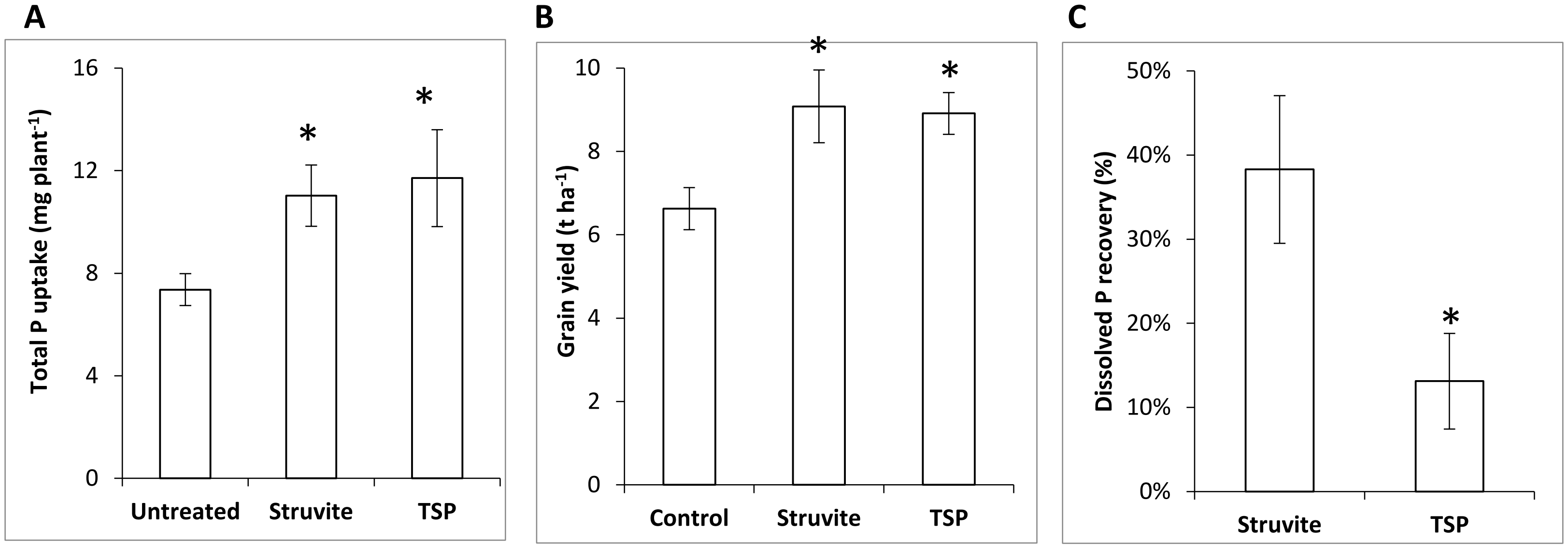

Figure 4.9. Struvite produces similar yield and P uptake of Triticum aestivum *to readily soluble P sources, with gains in crop P recovery rate in a 90-day growth experiment. P was applied at 33.3 mg P pot^{-1} (35 kg P ha^{-1}) in the form of struvite or TSP alongside untreated controls.* ***A*** *The total P uptake resulting from each treatment, expressed in µmol plant^{-1}.* ***B*** *The grain yield, scaled up to t ha^{-1}, of each treatment.* ***C*** *The dissolved P fertiliser recovery in the harvested plants (calculated as described in Materials and Methods). In A and B, asterisks mark values that are significantly different from the untreated negative controls, and in C they mark values significantly different from the TSP positive control using student's t-test ($p < 0.05$). Error bars are standard errors of the mean.*

4.3.6 AVAIL®

After 21 days growth in the experimental conditions described above, the use of AVAIL® coating on TSP and DAP fertiliser granules had a significant positive impact upon the P-uptake per plant when compared to both their no-polymer and no-fertiliser controls (Figure 4.10a). This impact was however not observed in experiments where plants were grown to grain yield (90 days) where both grain yield and P uptake were not significantly different between AVAIL® -coated TSP and uncoated TSP treatments (Figure 4.10b and c).

4.4 Discussion

4.4.1 Foliar fertilisation and seed dressing

The study provided evidence that the use of an adjuvant in foliar P formulations causes an increase in P uptake following application to the upper leaf surface, confirming the value of this well-established method for improving uptake rates into the leaf (Holloway, 1994; Noack *et al.*, 2010). In line with previous studies (Schönherr, 2006) the applied P was able to penetrate the upper leaf surface, and especially the lower leaf surface, even without amendment with an adjuvant. This foliar entry can be largely attributed to the presence of stomata on both sides of *T. aestivum* leaves. Trichomes are a significant barrier to leaf surface penetration, reducing the contact area of droplets with the leaf surface (Brewer *et al.*, 1991). Given the stomata are found on both sides of *T. aestivium* leaves, the increased uptake rates on the lower side of the leaf that we observed can be attributed to *T. aestivum* leaves having a lower density of trichomes here compared with the upper surface (Fernández *et al.*, 2014).

The important role of stomatal conductance in transfer of foliar-applied P into the plant can also be inferred from the positive effect of growing the plants in photosynthetic light (compared with the dark); stomata are known to open in response to light (Dietrich, 2001). Growing plants in photosynthetic light also increased the mobility of the foliar-applied P within the plant, which is likely to be linked to the increased flux of organic compounds into the phloem observed during active photosynthesis (Giaquinta, 1978). P could be carried into the phloem this way either via increased esterification of applied P or through simple mass flow delivering the P to the vicinity of vascular tissues.

To maximise P uptake from foliar applications it may be necessary to involve electrostatic spraying technologies so as to ensure even deposition on both abaxial and adaxial leaf surfaces (Maski & Durairaj, 2010).

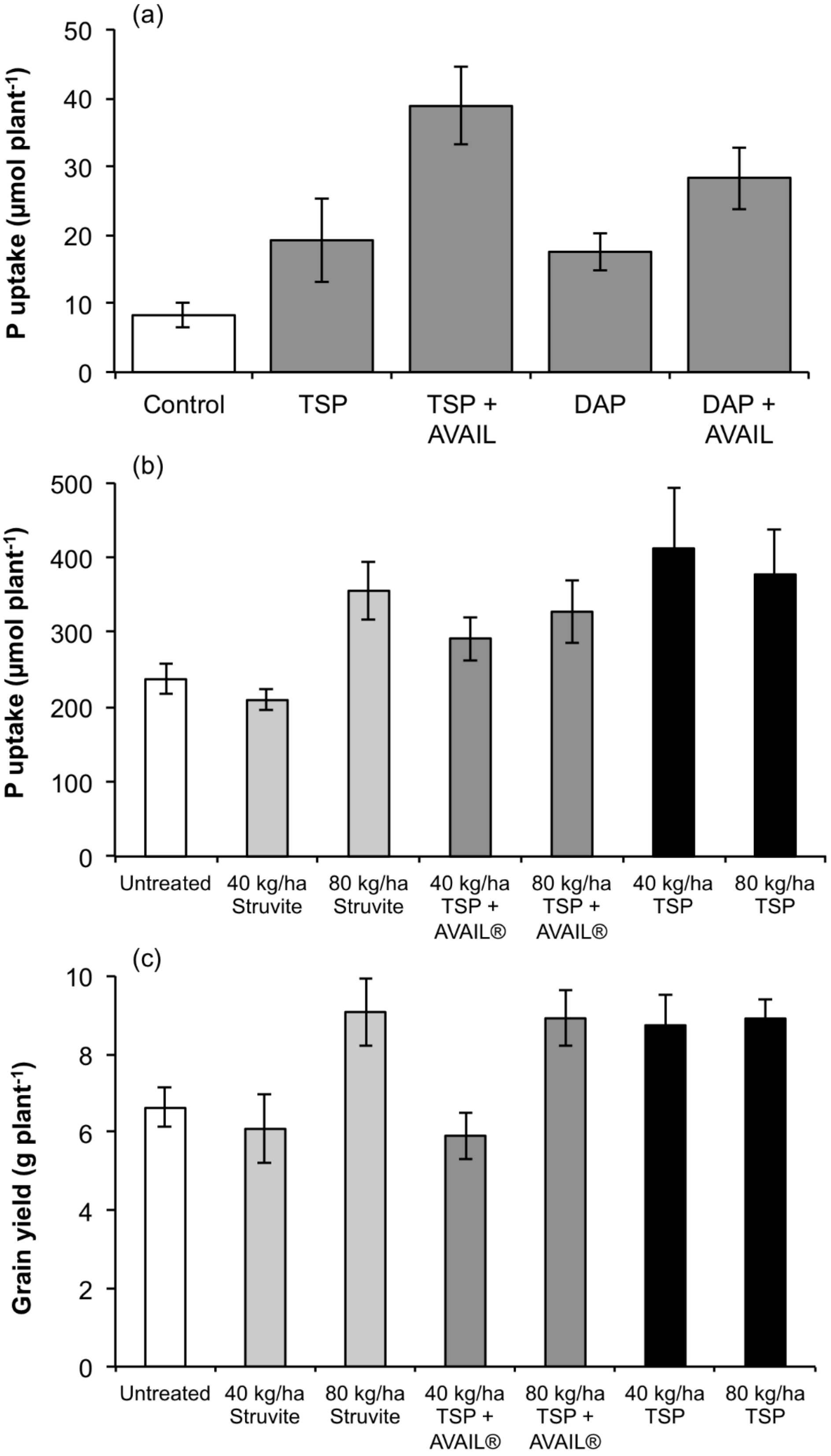

Figure 4.10. The effect of the Avail polymer on (a) total P uptake by spring wheat after 21 days, (b) total P uptake in spring wheat at harvest and (c) grain yield at harvest in relation to TSP and DAP without the polymer.

It is unclear whether the increased P mobilisation from the leaf enhances the rate of P entry into the leaf tissue through maintaining a stronger concentration gradient, or vice versa. Nonetheless, given that foliar scorch has been attributed to high nutrient imbalance in the area of foliar fertiliser application (Marschner, 1995), high mobilisation rates of foliar P from the leaf may enable higher dosage applications.

Application of P as a seed dressing at any of the doses used in our experiment increased lateral root production to a similar extent as did its application in the soil at ≥ 221 times the dose rate. However, seed application did not have the same magnitude of benefit to that of soil application in seminal root growth (though the difference between the two methods of application was not significant). The enhancement of lateral root growth is likely to be particularly important in enabling the exploitation of reserves of P and other mineral nutrients in a larger soil volume (Zhu and Lynch, 2004). This benefit is likely to be especially important for uptake of P because of its low mobility in the soil and, given that the increase in P uptake over the controls is greater than the quantity applied as a seed dressing, a high proportion of P taken up by the plants in the experiment is likely to have come from soil reserves. However it is possible that some of the seed dressing P from the two seeds per pot removed in the thinning process subsequent to emergence will have remained in the soil to be acquired by the remaining plant used in the experiments. This however remains considerably less applied P than in the soil fertiliser applications. These effects of enhanced early root production, and concurrent enhancements in P uptake are consistent with the findings of previous studies (Sekiya and Yano, 2009; Valluru *et al.*, 2010), and point to seed dressing being a valuable tool in increasing P-fertiliser use efficiency.

The combination of a P seed dressing and three subsequent foliar applications resulted in high rates of P uptake (equivalent to those achieved with much larger doses of soil applied fertiliser) in both pot experiments. The added advantage of combining seed with foliar application was, however, not consistent between the two experiments. An advantage of this combined application over foliar application alone was clear when plants were grown in a smaller soil volume (500 g per plant) with low intrinsic P reserves. However, when plants were grown in a larger soil volume with a much higher P concentration (3 kg) the combined seed and foliar application was better than the seed-only application but did not lead to a significantly greater P uptake than the foliar-only treatment. When *T. aestivum* seedlings are grown under severe P stress, they have been shown to have a markedly reduced ability to acquire P from foliar applications (Fernández *et al.*, 2014). This could possibly explain our results, where seed dressing P was required to maintain the plants’ ability to take up foliar-applied P when grown in small soil volumes, but in larger soil volumes P supply was maintained by the greater soil P reserves regardless of seed treatment.

4.4.2 Bacillus amyloliquefaciens FZB42

This study presents new experimental data demonstrating the complex nature of plant-microbial interactions in the rhizosphere. *B. amyloliquefaciens* FZB42, like a large proportion of rhizosphere microbes, secretes auxin as a component of its interaction with the plant (Idris *et al.*, 2007). The results of the present study demonstrate that exogenous auxin application to the *T. aestivium* root system, whilst capable of stimulating an increase in root production, also reduced root Pi uptake rate per unit root surface area from low Pi soils.

Root Pi uptake is mediated by Phosphate Transporter (PHT) proteins which are phosphate : H^+ symporters that use electrochemical gradients to drive Pi and proton symport into the plant (Pao *et al.*, 1998). In *T. aestivium* the Ta*PHT* gene family is proposed to encode a group of closely related high affinity phosphate transporter proteins whose expression in root tissue has been shown to be increased (Ta*PHT1.1 & 1.9, 1.2, 1.8, 1.10*) or unchanged (Ta*PHT1.6*) in response to decreased root Pi supply (Teng *et al.*, 2013; Davies *et al.*, 2002). Ta*PHT1.1 & 1.9, 1.2* and *1.10* expression has conversely been shown to be reduced in response to low P supply under field conditions, but this has been attributed to the effects of high levels of mycorrhizal colonisation (Teng *et al.*, 2013). Given that Ta*PHT1.8* and Ta*PHT1.10* have previously been identified as having significantly up-regulated expression in roots growing in low Pi environments (Teng *et al.*, 2013), the lower Pi uptake rates displayed by *B. amyloliquefaciens* FZB42 treated plants in low Pi conditions in the present study (Figure 4.1D, Figure 4.2A) could be explained by the *B. amyloliquefaciens* FZB42 treatment reducing Ta*PHT1.8* and Ta*PHT1.10* expression. The *B. amyloliquefaciens* FZB42 treatment effect upon Ta*PHT1.8* and Ta*PHT1.10* expression was also mimicked by the exogenous IAA application, which strongly implies that this is at least in part an auxin mediated process, and so an intrinsic component of the *B. amyloliquefaciens* FZB42-root interaction. We therefore propose that auxin production by *B. amyloliquefaciens* FZB42 lowered root Ta*PHT1.8* and Ta*PHT1.10* expression, directly resulting in the depressed plant Pi uptake levels observed in the pot experiments. It is possible that this effect enables auxin producing rhizobacteria to better compete for localised P in low P soils; auxin application has previously been shown to perturb the expression pattern of *PHT* genes in *Arabidopsis* (Karthikeyan *et al.*, 2002), and microbial re-modelling of *PHT* expression has also been demonstrated using arbuscular mycorrhizal fungi (Christophersen *et al.*, 2009; Glassop *et al.*, 2005). Our results have implications for the use of auxins in future biotechnological applications. Specifically, the use of auxins, or auxin-producing micro-organisms, to stimulate root production should be carefully mapped to environmental P conditions to ensure optimal Pi uptake, plant growth and yield.

4.4.3 **Struvite**

The greater plant recovery rate of P applied in struvite compared with the readily soluble P fertilisers supports the theory that the slow rate of P release from struvite is closer to the development of the crop root system's capacity to take up P *(Massey et al.*, 2009). Dissolved fertiliser P that does become adsorbed to soil particle surfaces, or precipitated out by complexion with cations, may be bound with a sufficiently high binding energy to make it less available for plant uptake in the short term (Holford and Mattingly, 1975; Beauchemin *et al.*, 2003). Maximising the proportion of applied fertiliser P that enters the plant potentially reduces the need for the plant to expend energy mobilising this tightly bound soil P, allowing a re-allocation of photosynthate and nutrients to other facets of growth and development.

The results show that use of struvite alone produces lower rates of P uptake early in plant development than use of more readily soluble P fertilisers. This is a potential problem in agricultural systems, where initial establishment and early growth are dependent upon early P uptake, and correlate well with final crop yield (Grant *et al.*, 2001; Brenchley, 1929; Boatwright and Viets, 1966; Green *et al.*, 1973). Good early growth is also viewed by the agricultural industry as an insurance against problems such as adverse weather conditions, pests, or diseases which may occur later in the growing period. Vigorous early growth also provides quicker soil surface cover, and therefore is useful in the reduction of soil erosion which can be a significant driver of environmental problems (Pimentel *et al.*, 1995) and weed competition.

While in the pot experiments in controlled glasshouse conditions the yield of grain obtained from plants fertilised with struvite alone was the same as that for plants fertilised only with soluble P fertiliser, the plants grown with struvite had a visibly reduced number of reproductive shoots and grain heads in later growth stages. The number of grain heads has long been known to be both a very significant driver of final yield and is also determined at early growth stages (Brenchley, 1929), so this could be a disadvantage of use of struvite fertiliser alone in field conditions. It is possible that, in the pot experiment, early disadvantages for plant development of the slower release of P from struvite compared with more soluble P fertiliser, were subsequently compensated by a more sustained rate of P release from struvite which was better able to meet plant P demand later in the growing season. Although the re-distribution of P already taken up by the plants meets a significant proportion of P demand for grain-filling, P-uptake from the soil at later growth stages may still be required to augment this (Boatwright and Haas, 1961; Mohamed and Marshall, 1979; Grant *et al.*, 2001), and also to facilitate carbohydrate translocation into the ripening grain (Sutton *et al.*, 1983).

This study also attempted to couple the early P uptake levels of readily soluble DAP fertiliser with the slow release and high plant P recovery rates of struvite, by combining the benefits of both approaches through the use of mixtures of the two fertiliser types. At 36 days, only a minimal quantity of the applied struvite had dissolved (9 %, when applied alone at 35 kg P ha^{-1}), but a much greater proportion had dissolved in a struvite only set of replicates in the pot trial taken to mature grain yield (26 %). These data further confirm that struvite provides a source of late season P which may significantly enhance yield (Sutton *et al.*, 1983). In addition, the large quantities of undissolved struvite remaining after harvest could also provide a valuable resource of P for future growing seasons which is potentially a more readily plant available source of P than immobilised residual soil P.

4.4.4 **AVAIL®**

The application of AVAIL® to TSP or DAP granules provided significant benefits in P-acquisition in the 21 day experiments, yet these benefits did not result in increased grain yields or P uptakes at harvest (90 days). Any increased early P-uptake rate of P using AVAIL® did not translate into a significant increase in reproductive shoots (6.0 per plant) compared to using uncoated TSP (5.8 per plant), and therefore the conclusion must be drawn that in these conditions over the long term AVAIL® did not increase P uptake when compared with the controls.

4.5 Summary and Conclusions

This WP used standardised laboratory conditions to scope a number of innovative crop P-nutrition strategies, in order to ascertain both their potential effectiveness of fertilisation and the potential rate of their recovery by the growing crop. The AVAIL® co-polymer was used to coat conventional fertiliser granules such as TSP and DAP to increase the proportion of fertiliser P acquired by the plant by inhibiting soil P immobilisation. Struvite granules recovered from wastewater, used as a slow-release fertiliser, have the potential to release P far later into the growing season at the peak of plant demand compared to conventional fertilisers. A combination of foliar applications and seed dressings offers the potential for similar yields but with much greater P recovery rates; spray techniques would need to target adaxial leaf surfaces. Finally, *Bacillus amyloliquefaciens* FZB42 was shown to be a plant growth promoting bacterium, able to enhance root growth and development, but not necessarily with positive effects on plant P uptake.

Our results show that: AVAIL® allowed enhanced P-uptake in the first 21 days of growth over uncoated TSP/DAP use, but by 90 days these benefits were no longer present. Struvite use gave comparable yields to more soluble P-fertilisers, y*et al*lowed far slower establishment rates. A combination of struvite with more soluble fertilisers was effective in overcoming this early shortfall in P supply when using struvite alone. A combination of seed and foliar treatments allowed comparable rates of early P uptake, and endpoint yields with far greater rates of P-fertiliser recovery. *Bacillus amyloliquefaciens* FZB42 provided stimulation of root growth, but also re-modelled phosphate transporter expression, leading to a reduction in P-uptake capacity from low-P environments. The results therefore offer a number of potentially viable P-fertiliser strategies that, if deployed in the appropriate conditions, could provide greater P-fertiliser recovery rates than conventional fertiliser use whilst increasing yields.

5. Optimising fertiliser strategies through modelling crop P dynamics (WP2)

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5.1 Introduction

In order to improve P efficiency in farming, we have developed a whole crop mathematical model. The aim of the model is to estimate how best to use applied P to complement soil P and satisfy crop P requirements of wheat. We will first discuss previous agricultural models and then follow with details of our model and how it is novel.

5.1.1 **Previous models**

There are a number of existing models that claim to model the overall plant, and a number of these are accessible via the Virtual plant web. We will discuss the main ones briefly to outline the strengths and weaknesses.

ANIMO is agricultural nitrogen model developed in mid 1980s in Wageningen, Netherlands. It deals with process oriented simulation of nitrate leaching to ground water, N&P loads on surface water and greenhouse gas emissions, and is geared towards ex-ante evaluation of fertiliser policy. It is written in Fortran, but source code is not available; only the executable file can be downloaded. Thus, use is quite limited.

APSIM is an agricultural production systems simulation developed in CSIRO Australia to deal with plant water, N&P, soil pH, erosion and management issues. It enables uploading data to fit the model. The plant processes are not linked to show how genotypic differences lead to phenotypic changes. This package only works in Windows environment and requires long learning curve (with paid training courses) to use.

CENTURY is a compartmental model (i.e. it appears to be a non-spatial lumped model) for plant-soil nutrient (N, P and S) and carbon cycling model for grasslands, agricultural lands, forests and savannas. It is programmed in Fortran and C and is usable in Windows and Unix environment. However, the web page is not maintained so code does not appear to be available.

CropSyst is a model produced by Washington State University and it mainly deals with crop N and water uptake. Its unclear how much (if any) plant biology is included in this package. It is written in Pascal and C++ and it is not clear how it could be extended and combined with other packages. It relies heavily on data fitting and thus the predictive power outside the datasets used is limited. It is free to download.

DAISY is a modelling code produced by University of Copenhagen to describe soil-plant-atmosphere water and heat balance and it works on all platforms. The links to the underlying plant physiology are not transparent. It is not farmer/policy maker etc. friendly as it requires significant programming knowledge on the part of the user.

DNDC is a model developed by University of New Hampshire for denitrification and decomposition of carbon and nitrogen bio-geochemistry in agro-systems. It is very specialised and only for N.

CAPRI is an EU model for common agricultural policy for regionalised impact modelling. It is developed for the EU system, but does not include plant processes explicitly. Thus it is not useful for a basic (and we mean by that beyond policy maker/social) science community.

DSSAT is a decision support system for agrotechnology transfer. Its focus is on plant-environment interaction on average. How genotypic changes in plant are translated into phenotypic changes is not included, thus it is not useful for fundamental plant scientists. However, the platform is relatively easy to use for a person familiar with modelling.

SUNDIAL is developed by Rothamsted Research for simulation of nitrogen dynamics in arable land. This package relies heavily on the monitoring data and thus the predictions are not trust worthy outside the domain present in the training datasets. It is not a crop growth model since it requires estimates of the expected yield before it can make fertiliser recommendation, i.e., it is fertilizer focused rather than plant focused.

WAVE is developed by Université Catholique de Louvain to simulate transport and transformation of water and agrochemicals in the crop, soil and sub-soil environment. Thus it is soil focused and not plant focused. The code is in-house and not shared.

In summary, all the packages described above have plant-environment interaction focus with very little “plant biology” actually included in them. Thus, it is difficult to see how these could be used for plant breeding scenarios and climate scenarios that are outside the datasets used to train the models.

In addition to the packages mentioned above there is a stream of in-house models loosely fitting under the term “functional-structural architectural models” emerging from various different research groups across the world. The typical ones dealing with root nutrient uptake are: RootTyp, SimRoot, ROOTMAP, SPACSYS, R-SWMS and RootBox. All these models have been developed/emerged since ~2000 and aim to take into account the 3D architecture of plant roots, but none of them describe the root-soil interaction explicitly. Instead an ad-hoc averaging is introduced and errors inherent are not always investigated. The models dealing with above ground 3D plant architecture, capture of sunlight and wind are by Prunsinkiewicz Algorithmic Botany group at the University of Calgary (using L systems) and Andrieu group which produced ADEL-Wheat model that also uses L systems to simulate above ground development of wheat. All these 3D models are good first steps to deal with the geometry of the plant-environment interaction, but so far, no model integrates fully the plant-environment interaction with plant internal processes. Thus, the question how different phenotypic outcomes originate from the same genotype in differing environmental conditions can still not be fully answered.

5.1.2 **Our whole crop model**

We have developed a unique whole crop mathematical model with the aim to estimate how best to use applied P to complement soil P and satisfy crop P requirements of wheat.

The whole crop model consists of 4 main sub models:

- Soil P and water model;
- Root growth model;
- Plant vascular transport model;
- Plant leaf growth and photosynthesis model.

An outline of the whole crop model is shown in Figure 5.1 and a summary of the mechanisms in each model, together with the inputs and outputs of the model are given in Figure 5.2. We have combined a novel and well-tested spatial soil and root model with an adapted well known above ground leaf model to create our whole crop model. By including plant processes such as root growth and photosynthesis we have linked the above and below ground aspects of the plant to enable feedback effects. This allows us to estimate the P and water distributions in time and with depth as well as leaf mass and plant carbon use.

The main inputs to the model are environmental conditions and fertilizer application methods. The primary outputs are root mass, leaf mass, plant P uptake and amount of carbon as a function of time. Grain yield is calculated by considering stem and leaf P concentrations and/or by considering total plant P uptake. The model therefore enables ‘what-if’ scenarios by analysing differing P fertilizer strategies on grain yield for different environmental conditions.

In the following sections we will describe the details of each model, and the results and calibration of the whole crop model against field trial data obtained by ADAS and SRUC.

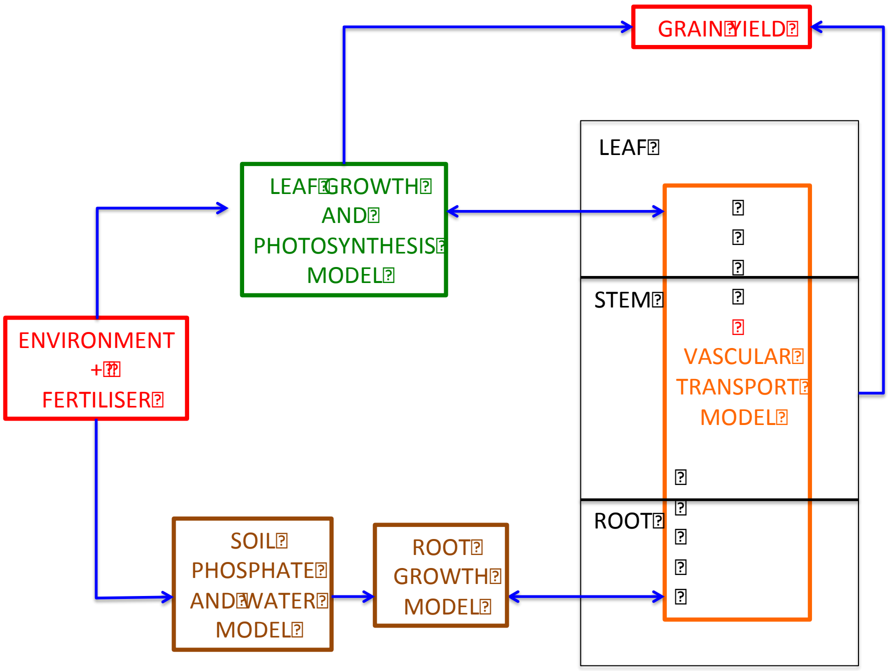


Figure 5.1. Schematic of the whole crop model.

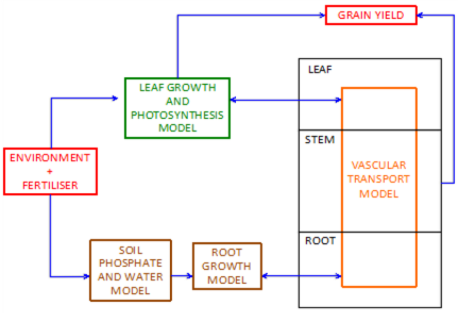
WHOLE CROP MODEL:

INPUTS:

- Soil buffer power
- Initial soil P profile
- Applied P amount and application method
- Cultivation method
- Weather data

OUTPUTS:

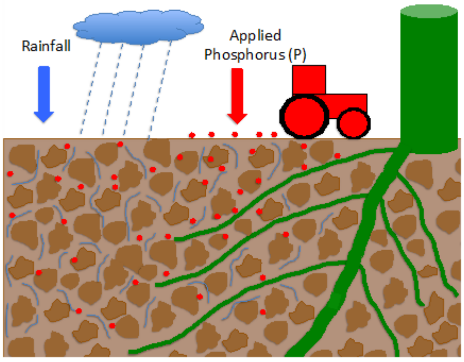
- P uptake by roots
- Root and leaf mass
- P and carbon amount in root, stem, and leaf
- Grain yield



ROOT MODEL:

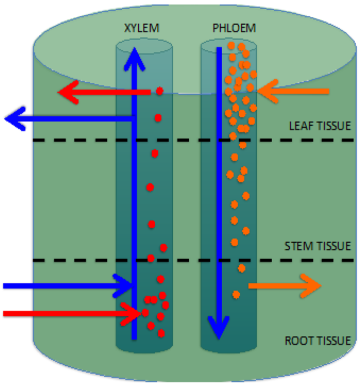
After **P** is applied, the model

1. Tracks the movement of **P** and **water** through the soil
2. Includes the binding reactions of **P** to soil particles
3. Calculates the depth-dependent uptake of **water** and **P** into a developing root system



VASCULAR TRANSPORT MODEL:

1. **Water** and **P** taken up from the soil enters the vascular tissue and travels up the plant
2. **Water** in the leaf exits to the air due to transpiration
3. **P** enters the leaf tissue to be used for leaf growth
4. **Sugars** produced from photosynthesis in the leaf enter the vascular tissue and travel down the plant
5. **Sugars** enter the root tissue to be used for root growth



LEAF MODEL:

1. **Water** in the leaf exits to the air due to transpiration
2. **P**, which has been transported in the vascular systems, enters the leaf tissue to be used in photosynthesis which then drives time-dependent leaf growth
3. **Sugars** produced from photosynthesis are used to make the leaf grow
4. **Sugars** also enter the vascular systems to travel to the roots

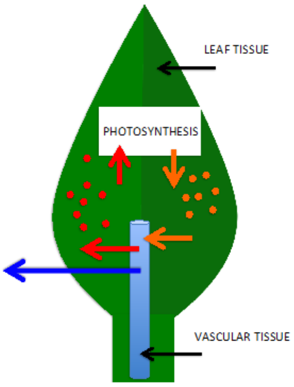


Figure 5.2. Summary of the processes of the individual components of the whole crop model.

5.2 Plant Growth Modelling and Plant P Uptake

This section describes the development and results of the vascular transport model and the leaf growth and photosynthesis model. Information on how grain yield is calculated is also given.

5.2.1 **Vascular transport model**

The aim of the vascular transport model is twofold. The primary aim is to connect the soil and root model (presented in the next section) to the leaf growth and photosynthesis model. P and water taken up by plant roots are derived from the soil and root models. They are then transported upwards for use in leaf growth, whilst photosynthates from the leaf model are transported towards the roots to enable their growth. The second aim of the vascular transport model is to improve understanding of the processes in vascular transport, specifically in wheat, to allow accurate modelling. This is necessary to ensure that errors are minimized before upscaling to field scale scenarios. Understanding of xylem and phloem transport is essential for understanding plant functioning and the optimal application of both soil and foliar- applied fertilisers may depend on the dynamics of vascular transport.

The vascular transport systems are responsible for the long distance transport of water, nutrients, and photosynthates around the plant. Water and nutrients such as P are transported in the xylem from the roots to the leaves, whilst photosynthates are transported in the phloem from the leaves to the roots. We have considered the flow in each system separately (Payvandi *et al.* 2014a and Payvandi *et al.* 2014b, respectively), and have also modelled the effect of coupling the xylem and phloem systems together (Payvandi *et al.* 2015, in preparation).

The transport mechanisms within the plant are very sensitive to environmental conditions, and hence they are modelled as being dependent on the interplay of differential pressures caused by varying environmental conditions. For example, the flow of water within the xylem is modelled as being dependent on the evapotranspiration within the stomata, and nutrients such as P are passively transported upwards within this transpiration stream. Flow in the phloem is modelling as being driven by the osmotic potential difference between leaf and roots, which is driven by photosynthate loading and unloading. Effects of gravity and varying leaf pressures (which reflects humidity) on flow in the xylem were investigated and, for certain parameter regimes, the flow of water could become multidirectional, which would inhibit nutrient transport to the leaves, and hence could be detrimental to plant growth. Seven different classes of flow were determined within xylem vessels, including root multidirectional flow (shown in Figure 5.3), which is similar to the hydraulic lift process observed in plants. In addition, environmental conditions required for positive unidirectional flow were found (Figure 5.3), these being optimal for nutrient transport from the roots to the leaves.

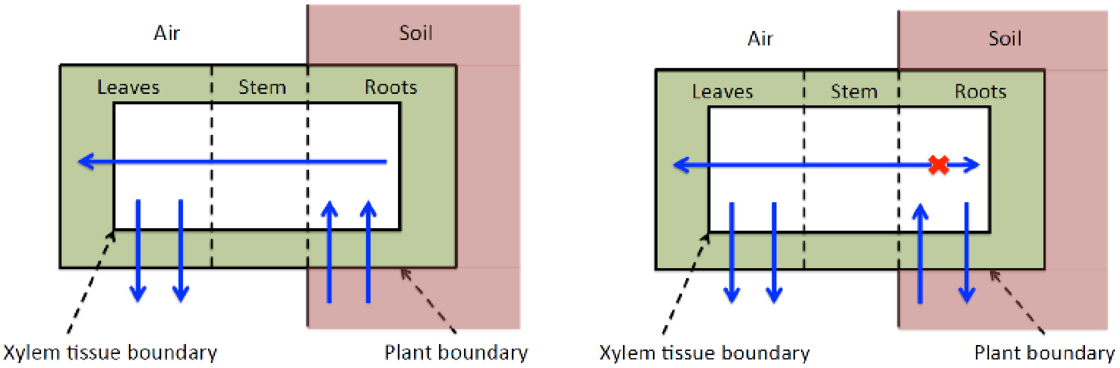


Figure 5.3. a) Positive unidirectional flow in the xylem, b) divergent root multidirectional flow in the xylem. The solid arrows indicate the direction of flow, and the cross indicates the point of divergence.

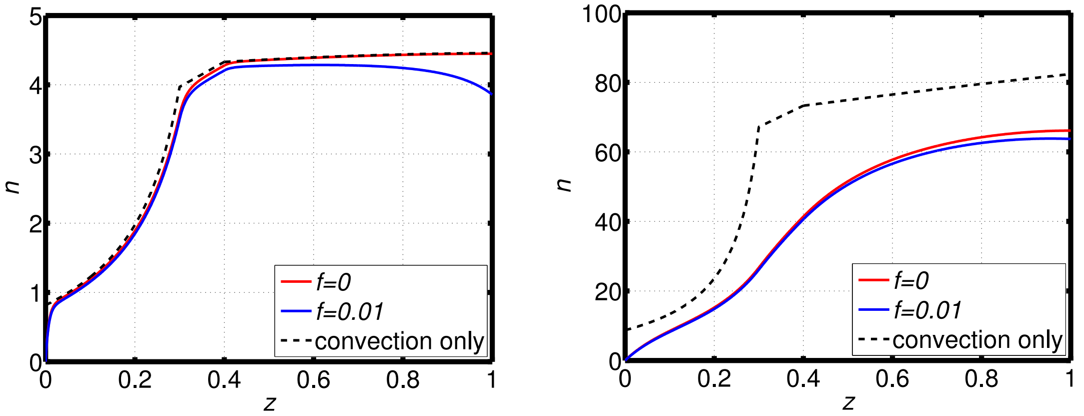


Figure 5.4. Profiles of nutrient concentration, n, with axial distance, z, where z=0 is the top of the plant, and z=1 is the bottom of the roots, for a) pressure external to the xylem, p_{ext}=-1, and b) p_{ext}=-0.35. The profiles show that, during the night, or at times of increased humidity (given by p_{ext}=-0.35), diffusion has a significant effect on nutrient transport and therefore nutrient transport cannot be modelled by a convection only approach. The amount of axial efflux of nutrient at the root tips due to meristematic growth is given by the parameter f.

Whilst vascular transport is not limiting in crop plants, accurate models are necessary to enable whole crop modelling. Diffusional transport of solutes/P within the vascular systems has generally been neglected in the literature since diffusion is small compared to convection in the main bulk flow. However, diffusion is significant near the vessel boundaries where the convective transport falls to zero, and during the night when the transpirational flow diminishes. In addition, the inclusion of diffusion permits the modelling of a root axial efflux of nutrient or photosynthate from the xylem and/or phloem, which may occur in response to the nutrient sink caused by meristematic tissue at the growing root tip. It was found in both the xylem and phloem that the effect of diffusion is significant and should not be neglected. In the xylem the effects of diffusion are especially pronounced if there is an axial efflux of nutrient, and at night when transpiration is minimal (shown in Figure 5.3). In the phloem, the magnitude of the effect is dependent on whether photosynthate unloading in the roots is active or passive.

5.2.2 Leaf growth and photosynthesis model

A model was developed to track the evolution of leaf mass, leaf carbon and leaf P with time. A leaf compartmental model was adapted from Thornley (1995) to allow inputs of spatially varying P and water transport profiles from the roots. In addition, photosynthesis was made dependent on the levels of P reaching the leaf to reflect the fact that P is necessary for leaf growth (Foyer & Spencer 1986, Wissuwa *et al*., 2005). Note that nitrogen levels were assumed to be non-limiting and therefore leaf growth was solely dependent on the P levels and other environmental conditions. P inputs can either be soil derived or leaf derived to allow the modelling of foliar application. Outputs of the model are leaf mass, and leaf carbon and leaf P. The leaf carbon can then be used as an input to the phloem in the vascular transport model, which can then drive root growth in the root model.

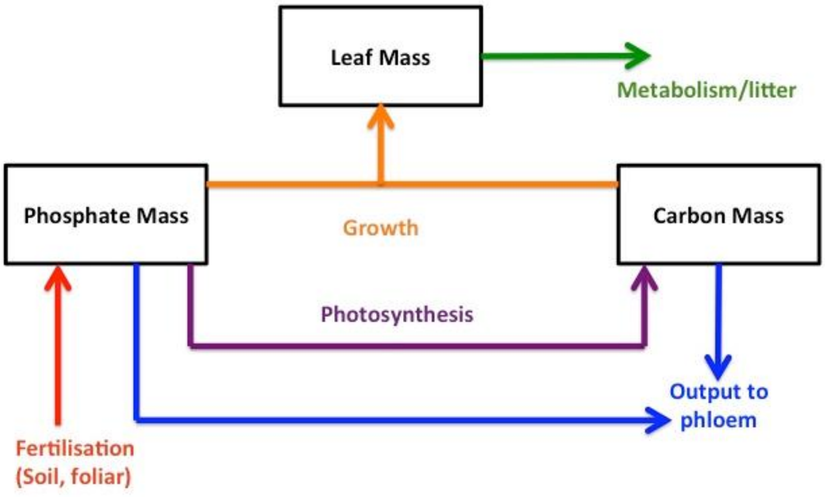


Figure 5.5. Schematic of the leaf compartmental model, adapted from Thornley including P-dependent photosynthesis.

Figure 5.5 shows a schematic of the leaf model. Leaf P mass increases due to applications of fertiliser, and decreases due to use in leaf growth, photosynthesis, and loss in the phloem. Leaf carbon mass increases due to photosynthesis, and decreases due to leaf growth and loss in the phloem. Leaf mass increases due to growth, and decreases due to metabolism and litter.

There are three key parameters which determine the dependency of leaf growth on P; f_p which represents the fraction of P used for leaf growth (L), k_p which represents the P to carbon (C) mass ratio for photosynthesis, and k_1 which represents the fraction of P used for photosynthesis. Initial estimates of the parameters were f_p=0.005 kg P kg^{-1} leaf DM (Thornley 1995), k_p=0.04 kg P kg^{-1} C (estimated from Targeted P review), and k_1=400 kg leaf DM kg^{-1} P (estimated from Targeted P review). Considering a constant rate of input of P from the roots, the change in leaf mass (L), P and C are plotted over time in Figure 5.6.

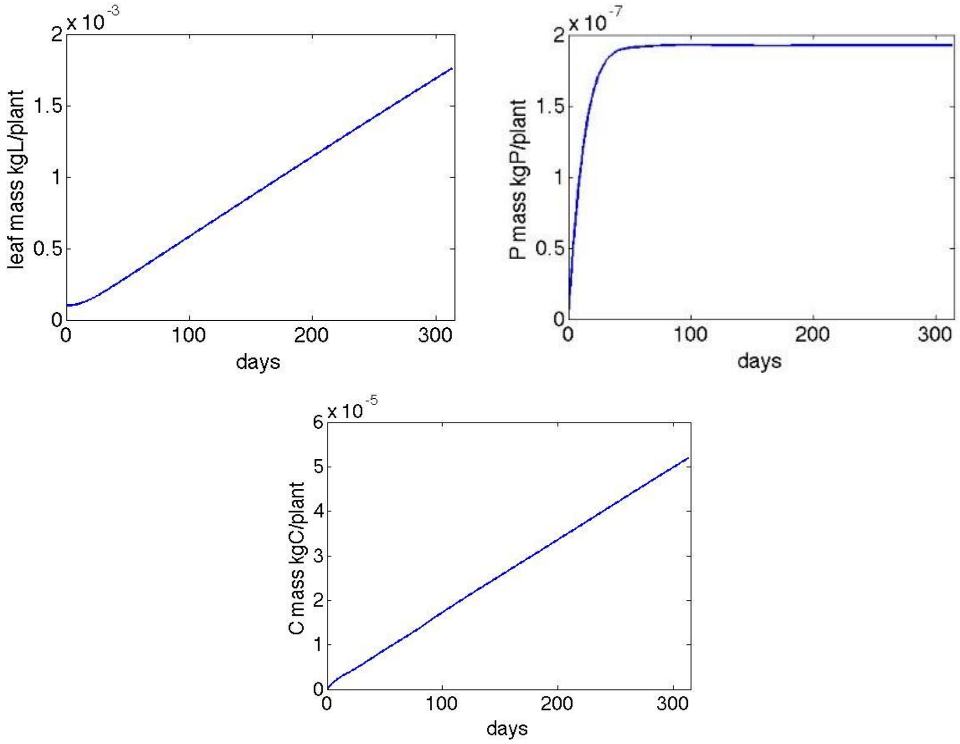


Figure 5.6. Dynamic output of the leaf growth model for constant P input and f_p=0.005 kgP/kgL , and k_p=0.04 kgP/kgC and k_1=400 kgL/kgP.

However, the model was particularly sensitive to f_p , k_p, and k_1 and, as an example, the dependency of the leaf model with varying fp is plotted in Figure 5.7. This sensitivity highlights the importance of obtaining good estimates of the parameters to ensure accurate predictions. In Section 5.5 (page 64), calibration of these parameters is discussed, using field trial data.

5.2.3 **Grain yield**

Once the root and leaf models are satisfactorily validated, grain yield can be calculated assuming that this is proportional to the overall P uptake calculated from the root model described below, since 70% of the P removed by a cereal goes into the grain (International Potash Institute, 2006).

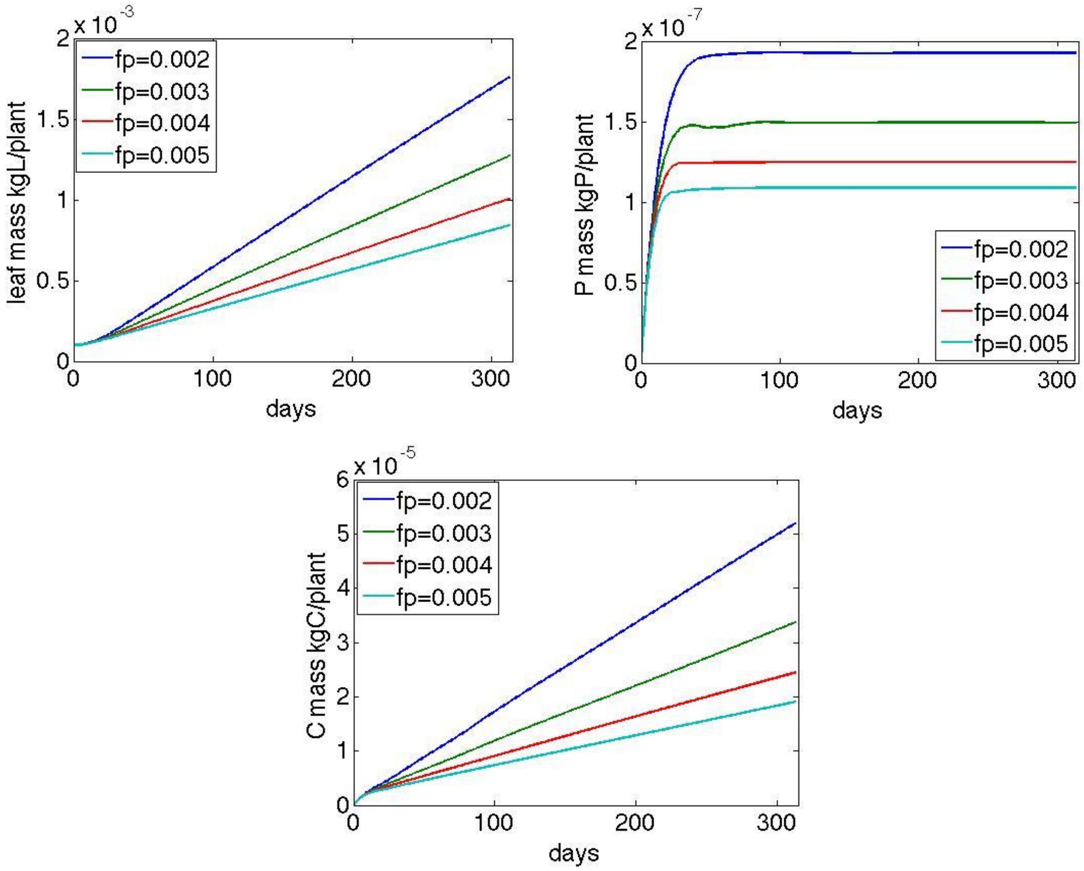


Figure 5.7. Dynamic output of the leaf growth model for constant P input for varying f_p. It can be seen for small changes in f_p, large variations occur in leaf mass (L), leaf P, and leaf carbon (C).

5.3 Soil-root Model

This section is taken from a paper to be submitted to Plant and Soil special edition (Heppell *et al.*, 2015).

This modelling work involves estimating the movement of P and water within the soil profile over time. The models of Roose and Fowler (2004) and Heppell *et al.* (2014b) are extended for the first time by adding the effect of climate, via surface water flux and xylem pressures as in Heppell *et al.* (2014a). This extension allows comparison of the model output, plant P uptake, against field study experimental data, for different environmental conditions. In addition, temperature-dependent root growth is incorporated so that the model can be applied to winter crops which show little or no growth at low temperatures.

The modelled estimates of plant P uptake (kg ha^{-1}) are compared against two sets of field trial data for barley. From this validation, the model is used to predict fertiliser and soil cultivation strategies which maximise plant P uptake. The strategies considered are shown in the flow diagram in Figure 5.8

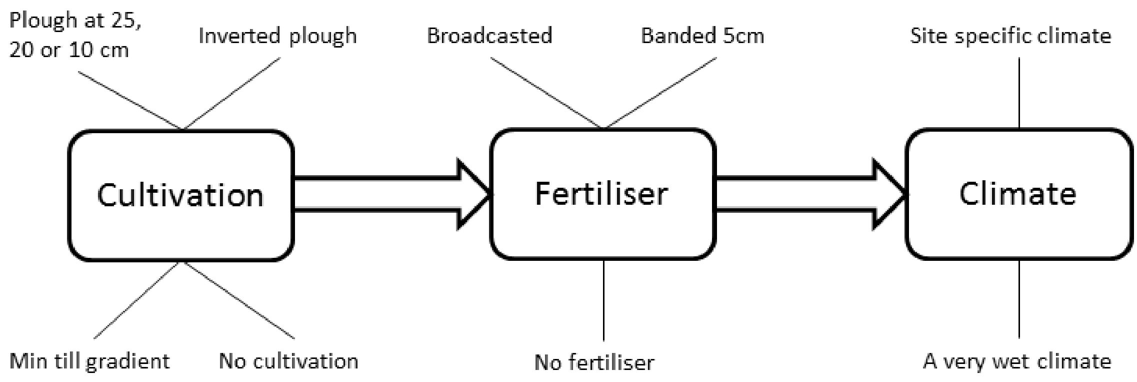


Figure 5.8. A set of scenarios to test the mathematical model; ploughing at 25, 20 or 10 cm, an inverted plough or using the reduced till gradient, top soil fertilisation, no fertilisation or fertiliser applied at 5 cm below and to the side of the seed, and finally using climate data with or without an additional constant heavy rainfall.

5.4 Coupled Plant Growth and Soil Model

The outline of the coupled model is shown in Figure 5.2. For initial testing and calibration, there is no consideration of storage of carbon and P in the stem tissues. Therefore the vascular transport model simplifies down to a direct connection between root model and the leaf model. The root model calculates P uptake, this P is passed to the leaf model to make the leaf grow by producing carbon in photosynthesis. Finally the carbon produced in the leaf is passed to the root model to amplify root growth thus creating a positive feedback loop. Total run time of the coupled model for each scenario is approximately 1 to 5 minutes, and calibration of the coupled model is discussed in the next Section.

5.5 Calibration of the Coupled Model against Field Trials

Calibration of the models were conducted using field trial data provided by ADAS and SRUC (see Section 6). Data sets were provided by SRUC and ADAS from two experiments:

- Spring barley at Balbathin, Aberdeenshire in 2011; data at GS31, GS45 and GS91;
- Winter barley at Stetchworth, Cambs. In 2012; data at GS39 and GS92.

5.5.1 **Root Model**

The model fits the winter barley data better at growth stage 39 (GS 39) compared with growth stage 92 (GS 92). At GS 39 the model predictions are within the error bars except for the scenario; 30 kg P/ha placed (Figure 5.9a). At GS 92 the model under predicts on all scenarios, but follows the trend of increasing plant P uptake values for increasing amounts of TSP applied (Figure 5.9b). The main reason for the under prediction stems from the unknown parameters, which include soil buffer power and the initial P profile in the soil. The initial P profile, at Index 1, is depleted before the end of harvest and the final total plant P uptake is therefore capped. This depletion effect is also seen when modelling the spring barley data (Figure 5.10), and in addition at GS31 the model fails to capture the effects between small and large amounts of TSP applied, fitting well at 0-20 kg/ha but not at 30-90 kg/ha (Figure 5.10a). In regards to the spring barley crop, GS31 is only a short time of 61 days and this is perhaps why little effects are seen between modelling different amounts of applied TSP. The amount of available P is unaffected by an additional supply as there is only a small root system generated by GS31. The plant P uptake estimate from the model, on average decreases from a constant P distribution to an exponentially decaying P distribution. There is a decrease of 4.7% (GS39) and 18.3% (GS 92) for winter barley, and -10.5% (GS 31), -12.3% (GS 45) and 5.0% (GS 91) for spring barley. The reason for a negative value (an increase in plant P uptake) for spring barley at GS31 and 45 is due to a small root system, and as a consequence the P deeper in the soil profile has yet to be utilised.

The model was used to simulate a range of fertiliser and soil cultivation strategies under wet and normal climate conditions at GS92 for an initial low P Olsen index soil (P1: 20 mg/l P ‘decay’; Figure 5.11a & b) and a high P Olsen index soil (P3: 60 mg/l P ‘decay’; Figure 5.11c & d). Instead of considering different amounts of applied fertiliser, six cultivation techniques are simulated (with soil mixing to 25, 20 and 10 cm, inverted plough, min till and no cultivation) along with three fertiliser P treatments (90 kg ha^{-1} placed, 90 kg ha^{-1} incorporated, and no fertiliser). At GS92 greatest plant P uptake is predicted to arise from plough inversion to 15 cm or placing 90 kg ha^{-1}; next-best P uptake was predicted from mixing the soil to 25 cm or placing 90 kg ha^{-1} P. Under a wet climate, plant P uptake values were predicted to increase across all fertiliser and soil cultivation strategies on average by 2%; the highest increase of 5% was seen from broadcasting P fertiliser. Increased water availability helped diffuse the top soil P and allowed more to be taken up by the plant from broadcast P fertiliser. As expected, in a high P index soil (P3) almost no response in plant P uptake was predicted from adding P fertiliser. For a low P index soil, plant P uptake appears limited due to a lack of available P and this results in little distinction between application techniques. Perhaps the simplistic implementation of the application techniques does not capture certain subtleties, such as changes in soil structure.

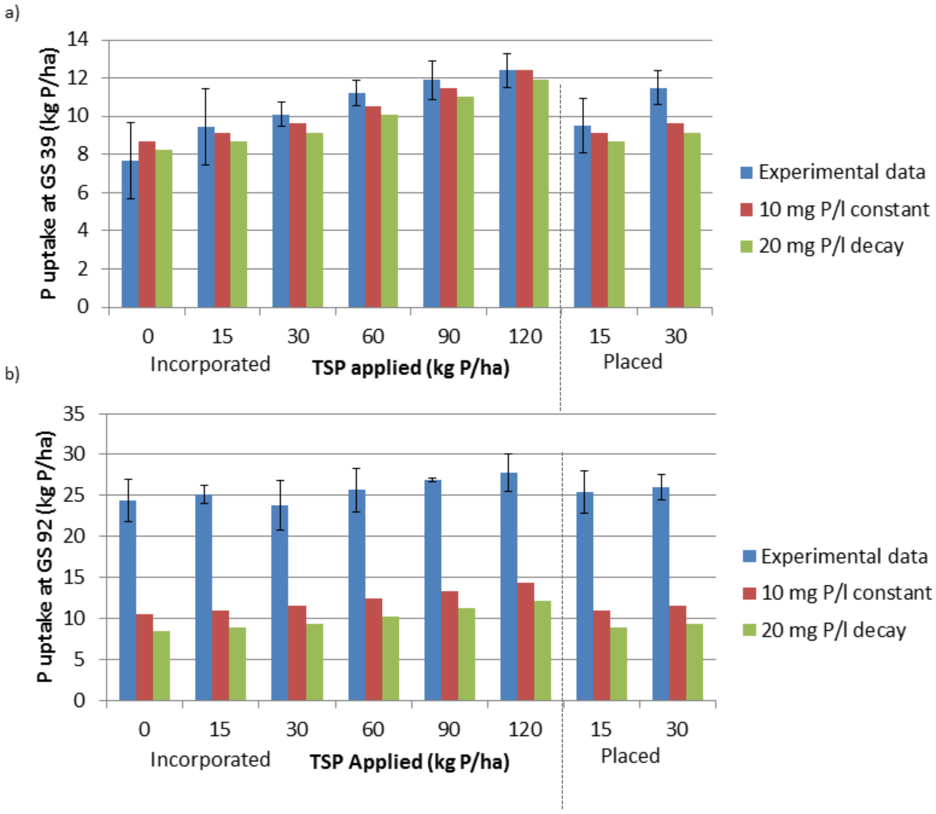


Figure 5.9. Experimental data and model predictions for winter barley at growth stages 39 (a) and 92 (b), for two modelled distributions for the initial P concentration, 10 mg P/l `at' and 20 mg P/l `decay'.

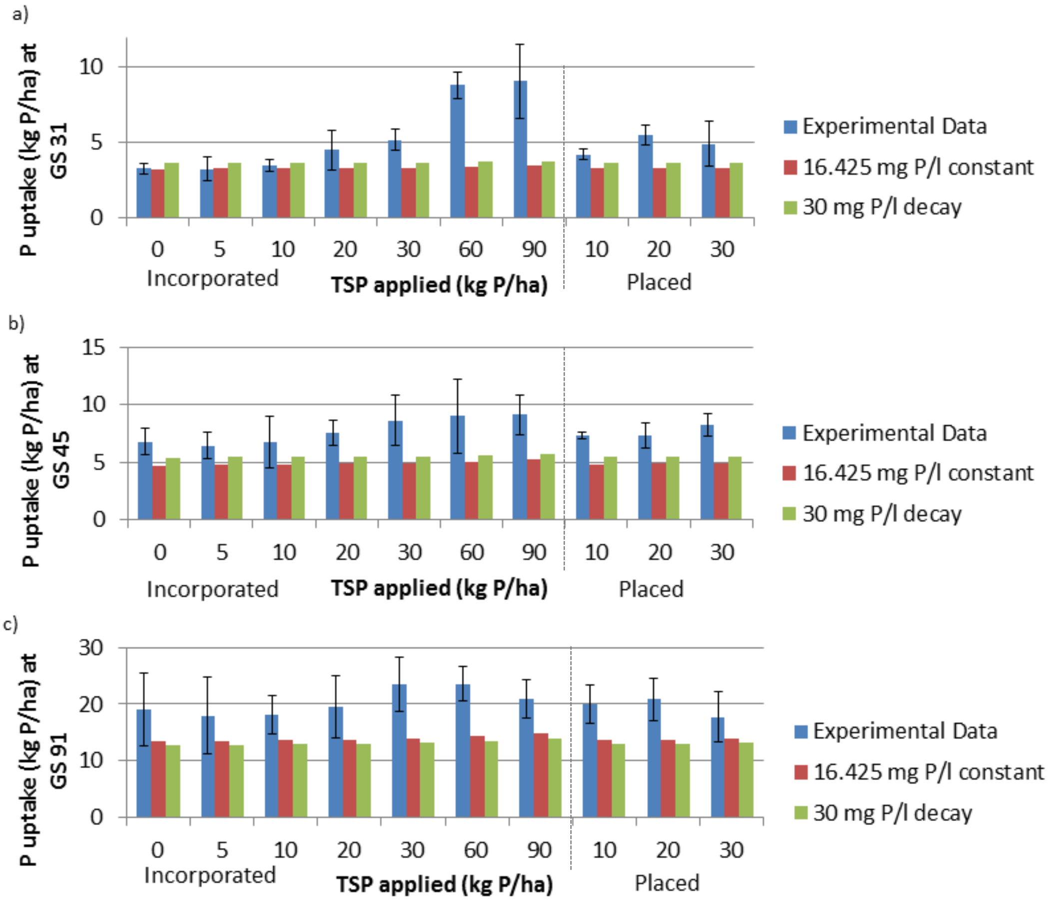


Figure 5.10. Experimental data and model predictions for spring barley at growth stages 31 (a), 45 (b) and 91 (c), for two modelled distributions for the initial P concentration, 16.425 mg P/l 'constant' and 30 mg P/l 'decay'.

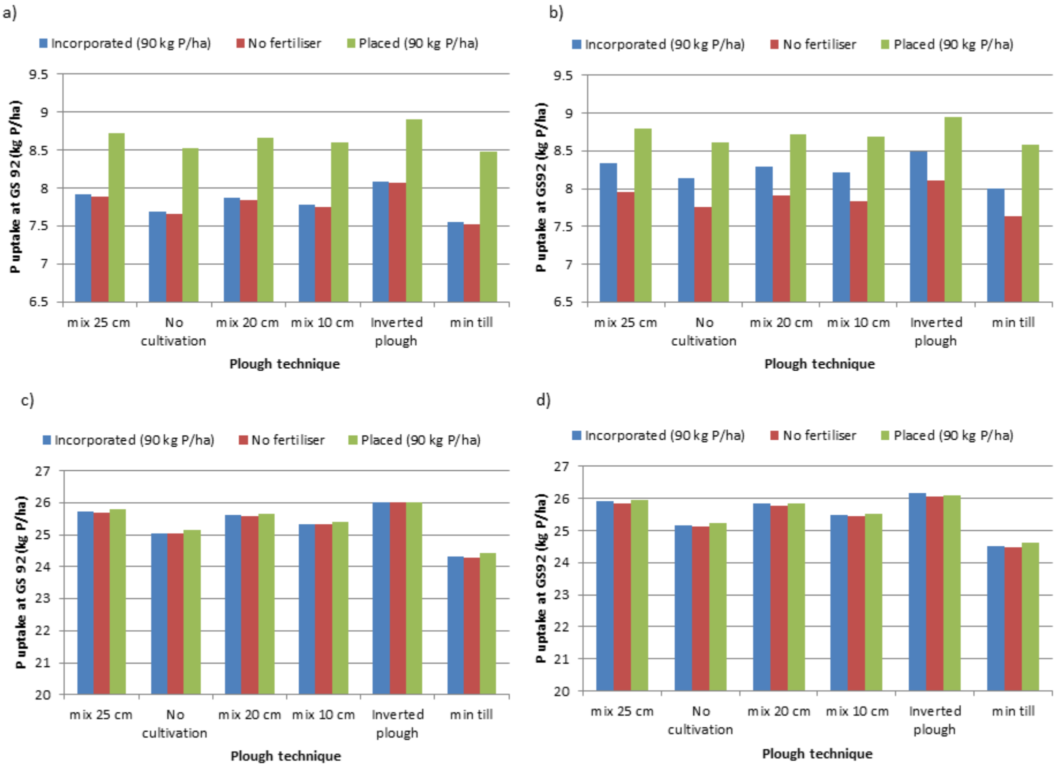


Figure 5.11. Model predictions for the set of scenarios described in Figure 3.8, for 6 cultivation strategies (mix at 25, 20 and 10 cm, no cultivation, inverted plough and min till) and 3 fertiliser placement options (90 kg P/ha incorporated (broadcast) or placed (banded) and no fertiliser), for a) and b) an initial P concentration of 20 mg P/l 'decay' (P1-low) for a normal and wet climate respectively, and c) and d) an initial P concentration of 60 mg P/l 'decay' (P3-high) for a normal and wet climate respectively.

In summary, applying P near the rooting zone (inverted plough and mixing at 25 cm while placing fertiliser) provides the best chance for maximising plant P uptake, and could result in a 4% increase to plant P uptake over doing nothing.

5.5.2 **Leaf Model**

To determine the values of f_p, k_p, and k_1, the model was optimized against field trial measurements of dry mass. Half of the data set was used for training the model, and the remaining half for testing the calibrated parameters. The spring barley data set was considered first, for which there were 10 scenarios per GS, and values found were f_p=0.0007, k_p=0.0001, k_1=100. Figure 5.12 shows the model predicted data compared to the experimental field trial data for these parameter values. The winter barley data set was then considered; this consisted of eight scenarios per GS, and values found were f_p=0.0001, k_p=0.0025, and k_1=500, as shown in Figure 5.13.

In Figure 5.12 the optimisation for spring barley appears to work well, since the resulting model predictions fall within the error bars of the field trial data. However, the optimisation for winter barley shown in Figure 5.13 does not work well at GS39. This is possibly due to the large variation in time scales, and also because time-dependent P uptake has not yet been included in the model (since the models are not yet coupled).

It was thought likely that temperature changes between the GS are important and should be included. Temperature dependence was therefore added into the model by including a nonlinear function with air temperature in the leaf growth term. Since temperature varies significantly with time, the addition of a temperature dependent function should allow the model to better accommodate the changes in dry mass across growth stages. This nonlinear function introduced two further parameters, making five parameters (f_p, k_p, k_1 , and two temperature parameters) to be optimised from eight data points; previously (without temperature variation) there were three parameters (f_p, k_p, and k_1). Optimising for the temperature-dependent leaf model we find f_p=0.0018, k_p=0.0001, and k_1=191, which gives the fit shown in Figure 5.14. This is a vast improvement on the fit in Figure 5.13, especially at GS39. The improvement is solely due to the inclusion of temperature dependence, which allows the model to vary more dynamically with time. This can be seen in Figure 5.15 which shows the variation of leaf mass with time in the case of a temperature independent model and a temperature dependent model. The inclusion of temperature-dependent leaf growth allows for a nonlinear variation of leaf mass with time, causing suppression of leaf growth during the autumns and winter months, and enhancement of leaf growth during the spring and summer months.

Note that, whilst the two additional parameters (resulting from the inclusion of temperature dependence) allow the model to better represent the variation in data, the confidence in the fit has reduced since we are fitting for a larger number of parameters with only 8 data points. In order to ensure more accurate and robust calibration, more data points are needed to confidently fit the 5 model parameters.

Calibration of the coupled model is discussed in the next section. Connecting the root model to the leaf model should improve the leaf model by providing a time and temperature dependent input of P to the leaf model.

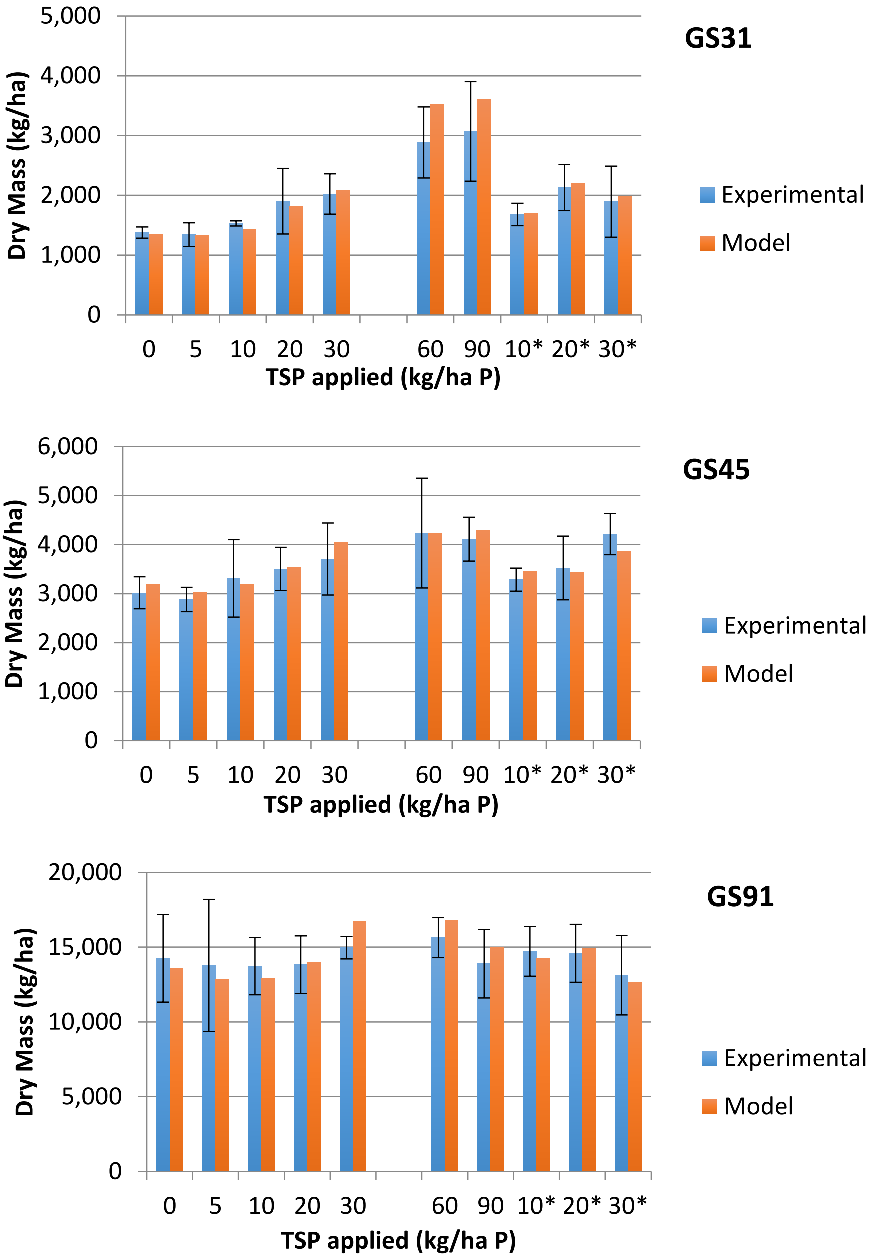


Figure 5.12. Experimental data and model predictions for spring barley above-ground biomass at GS31 (a), 45 (b) and 91 (c). The first 5 application rates, 0 to 30 kg ha^{-1} P TSP applied, are used for optimising the parameters, whereas the application rates 60 to 30 kg ha^{-1} P TSP applied are used to test the optimised parameters. Note that * refers to the fertiliser being placed in the soil rather than incorporated.*

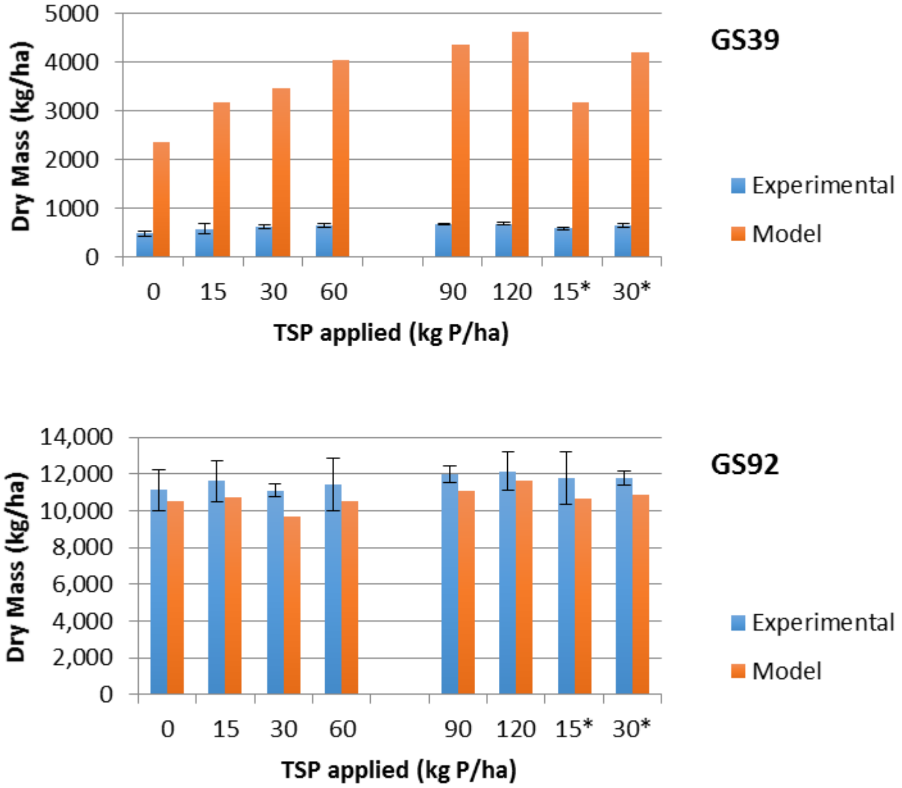


Figure 5.13. Experimental data and model predictions for winter barley above ground biomass at GS39 (a), 92 (b). The first 4 application rates, 0 to 60 kg ha^{-1} TSP P applied, are used for optimising the parameters, whereas the application rates 90 to 30 kg ha^{-1} TSP P applied are used to test the optimised parameters. Note that * refers to the fertiliser being placed in the soil rather than incorporated.*

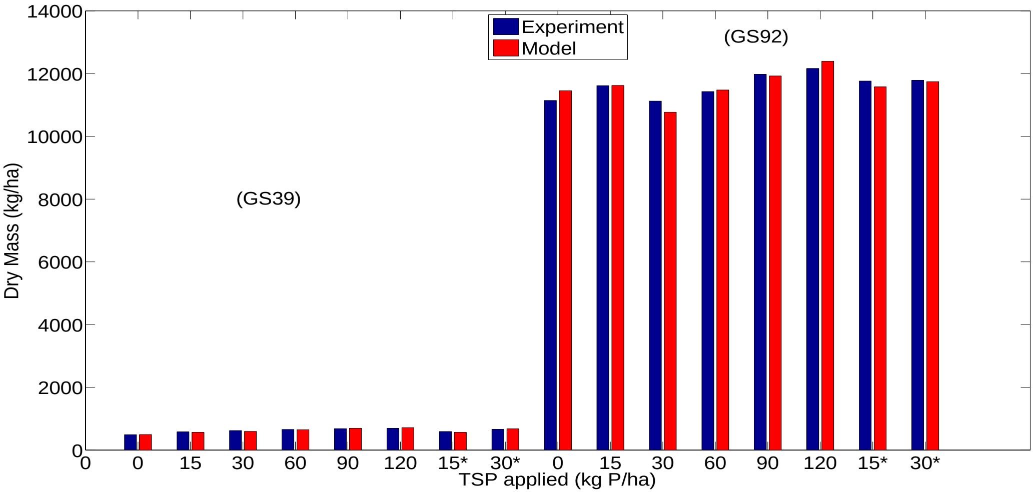


Figure 5.14. Experimental data and model predictions for winter barley above-ground biomass at GS39 (a), and GS92 (b) based on a model with temperature-dependent leaf growth. The first 4 application rates, 0 to 60 kg ha^{-1} TSP P applied, are used for optimising the parameters, whereas the application rates 90 to 30 kg ha^{-1} TSP P applied are used to test the optimised parameters. Note that * refers to the fertiliser being placed in the soil rather than incorporated.*

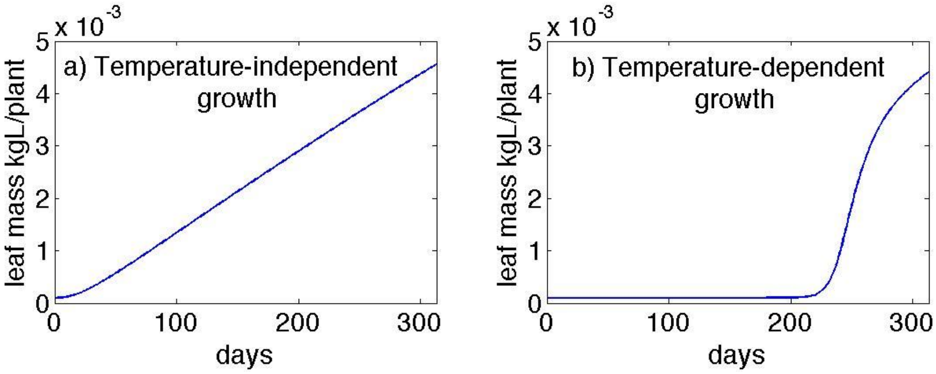


Figure 5.15. Modelled variation in leaf mass with time for the case of (a) Temperature-independent leaf growth, and (b) Temperature-dependent leaf growth. In both graphs, f_p=0.0018, k_p=0.0001, and k_1=191, In the case of temperature-dependent leaf growth, suppression of leaf growth can be seen for 0-200 days (autumn / winter months). Enhancement of leaf growth can be seen for 200-313 days (spring / summer months).

5.5.3 **Coupled Model**

To more accurately model the whole plant, an above ground model is added (leaf model), which tracks leaf growth and photosynthetic rates to estimate leaf carbon mass stored by the plant. With the addition of a leaf model, leaf carbon and leaf mass can be estimated during the crop life cycle. The role of leaf carbon is used in conjunction with temperature to set the root growth rate. As the two models are coupled they generate a feedback loop (in this case positive); an increase in plant P uptake from the roots increases carbon production via photosynthesis in the leaves, and vice versa. This new model (root and leaf) can be compared against the original root model and against field trial data.

The difference between the root and coupled model is first compared for the four main model outputs, main root length, plant P uptake, leaf mass and leaf carbon mass (Figure 5.16). The coupled model estimates much higher total amounts of all four outputs. The reason for the increase in the output values is due to the feedback effect, which promotes root growth, plant P uptake and leaf and leaf carbon mass. The shapes of the curves in Figure 5.16 for the coupled model are therefore non-linear (S-shaped).

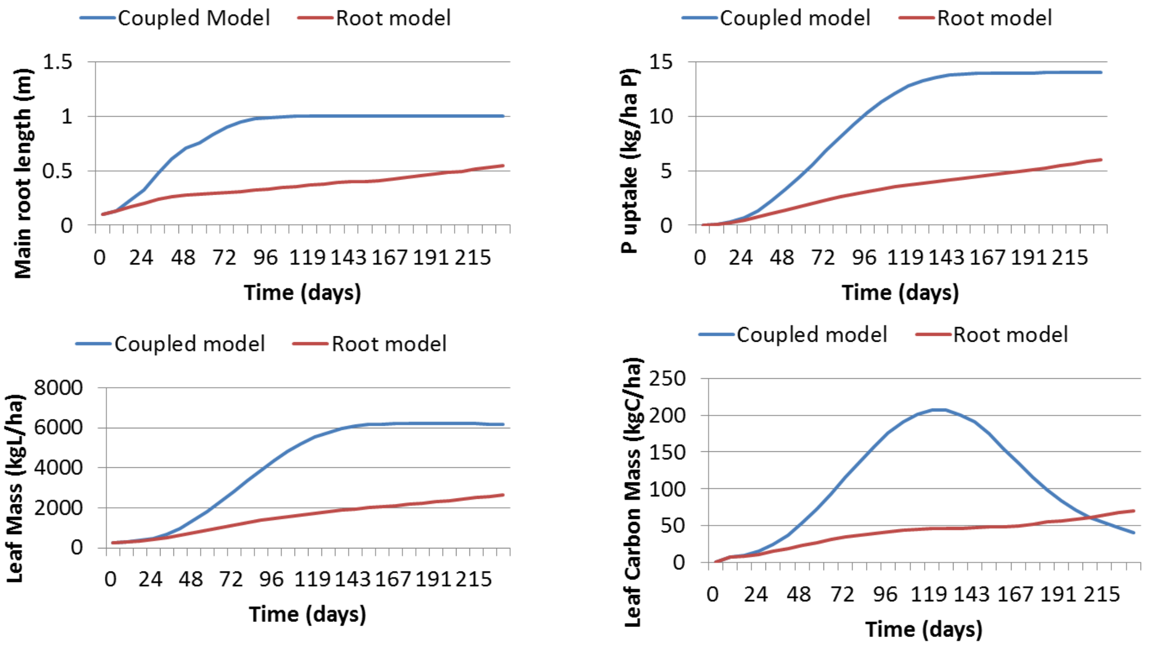


Figure 5.16. Comparison between the root and coupled model for four factors, a) main root length, b) P uptake, c) Leaf mass and d) Leaf Carbon mass.

The coupled model behaves similarly to the root model when comparing with the winter barley experimental data (Figure 5.17). There is a good fit at GS39, but the model under-predicts at GS92. Interestingly, the coupled model estimates a lower plant P uptake compared to the root model alone, when smaller amounts of fertiliser are added but estimates a higher plant P uptake when larger amounts of fertiliser are added. This could be due to the feedback effect increasing plant P uptake when applied P is at 60 kg P/ha or above and decreasing plant P uptake when applied P is below 60 kg P/ha.

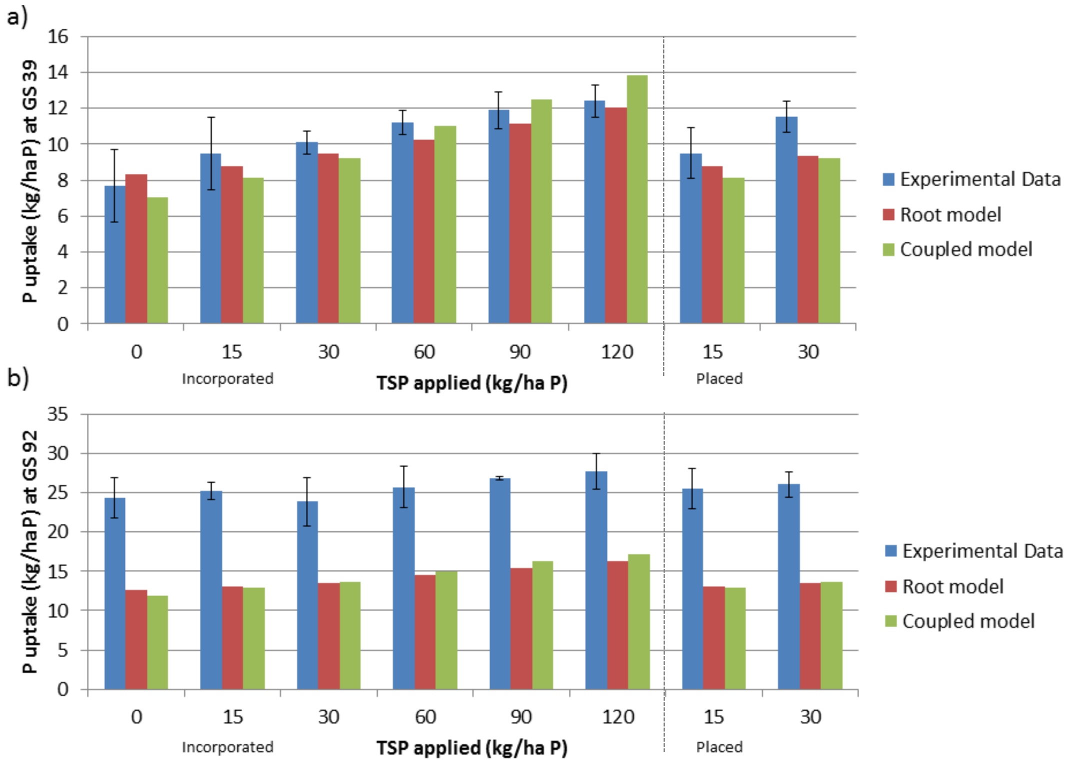


Figure 5.17. Experimental data and model predictions (root and coupled model) for winter barley at growth stages 39 (a) and 92 (b), for an initial P concentration, 20 mg P/l 'decay'.

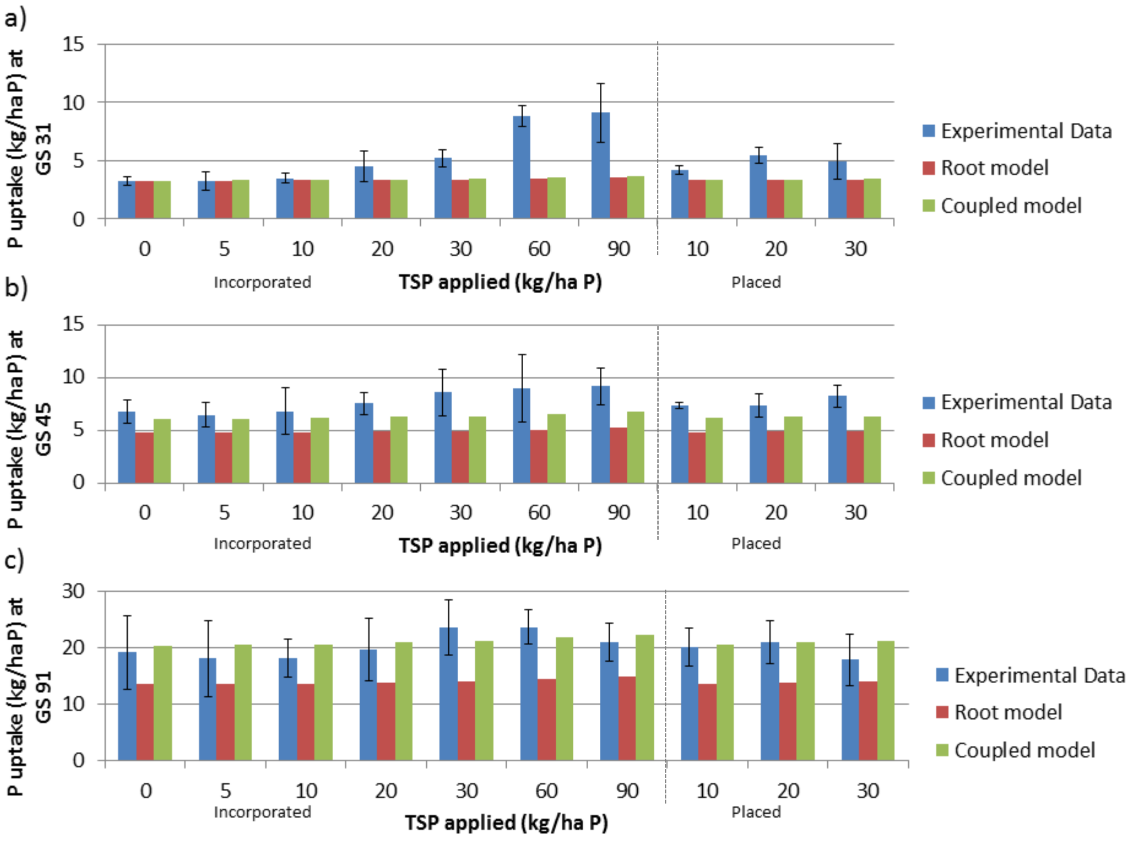


Figure 5.18. Experimental data and model predictions (root and coupled model) for spring barley at growth stages 31 (a), 45 (b) and 91 (c), with an initial soil P concentration of 16.4 mg P l^{-1}.

The coupled model still fails to capture the plant P uptake values at GS31 when adding 60 and 90 kg P/ha. As stated above, GS31 is only a short time after P application (61 days) and this is perhaps why little effects are seen between modelling different amounts of applied TSP. However the coupled model fits the spring barley experimental data much better than the root model, almost matching every data point, especially at GS91 (Figure 5.18).

5.6 Conclusions

A whole crop mathematical model has been developed in order to help improve efficiency of P use in arable farming. The model has been calibrated using field trial data from SRUC and ADAS for spring and winter barley respectively. Scenarios relevant to the aim of ‘Targeting P’ have been tested.

The whole crop model achieved good fits with the experimental data at early growth stages (GS31 & GS39), but poor fits at late growth stages (GS90 & GS91). The main reason for the poor fits could stem from having little information about the initial P distribution within the soil profile and / or from poor knowledge of P availability to the plant (related to soil buffer power). The soil buffer power value, a term used to describe the relationship between available and non-available P (in equilibrium), proved very sensitive within the model. The higher the soil buffer power the greater amount of P is bound in the soil and hence was unavailable.

It is concluded from the modelling work that applying P near the root zone ('placed' P) should provide the best chance for maximizing plant P uptake, and could result in a 4% increase to plant P uptake, compared to doing nothing.

In order to improve the calibration of the model and make model predictions more accurate, experimental site-specific data are needed with:

- More frequent observations across growth stages;
- More accurate determinations of soil buffer power;
- Initial distributions of soil P with depth in the profile;
- Initial water contents with depth in the soil profile;
- Detailed and local climate data.

5.7 Discussion

Field trial data used here generally had just one value for the soil buffer power despite there being evidence that values change within plots and even with depth (Bhadoria *et al.*, 1991). Therefore, to accurately model the available P within the soil, the soil buffer power value should be validated for site specific data. It appears likely that buffer power will significantly affect the optimal fertiliser and soil cultivation strategy. For example, for soils with a high buffer power, much of the applied P will be bound straight after P application and be non-available for plant uptake. Such soils provide a lower chance of achieving responses in plant P uptake.

Within some field sites there is little notion of how available P is distributed within the soil profile, with respect to depth. The idea that the majority of P added through fertilisers is recovered by the crop is partly true. However, from the modelling work presented here it can be concluded that the distribution of initial P within the soil profile significantly affects total plant P uptake. Section 5.4 showed that there was an increase in plant P uptake of 18.3% for winter barley (GS92), and 5.0% for spring barley (GS91) if a constant P distribution is compared to an exponential P distribution (decreasing with depth). The rate of decrease with depth (linear to exponential) differs from site to site for top-soils with similar P contents (Jobbágy & Jackson, 2001) and this could alter the optimal fertiliser strategy. Data concerning the state and distribution of P within soils is now becoming more valuable, as it can be used to enable savings on fertiliser costs (Yang *et al.*, 2013).

With the model fully operational, additional scenarios could be run to determine further optimal scenarios. One option could be to compare the effects of long term fertiliser using a variety of strategies such as RB209 recommendations, P placement in addition to replacement of offtake, P placement without replacement of offtake, only using recycled P forms, e.g. struvite, or zero P use (see Section 8).

5.8 Further publications

Aspects of the work described in this section have now been published in scientific journals; appropriate references are as follows:

- Heppell, J., Payvandi, S., Zygalakis, K., Smethurst, J., Fliege, J. & Roose, T. 2014a. Validation of a spatial-temporal soil water movement and plant water uptake model. Geotechnique 64: 526-539.
- Heppell, J., Talboys, P., Payvandi, S., Zygalakis, K.C., Fliege, Jörg, Withers, P.J.A., Jones, D.L. and Roose, Tiina (2014). How changing root system architecture can help tackle a reduction in soil phosphate (P) levels for better plant P acquisition. Plant, Cell & Environment 38, 118-128 (doi:10.1111/pce.12376)
- Heppell, J., Payvandi, S., Talboys, P., Zygalakis, K., Langton, D., Sylvester-Bradley, R., Edwards, A.C., Walker, R., Withers, P., Jones, D.L. & Roose, T. (2016). Use of a coupled soil-root-leaf model to optimise phosphate fertiliser use efficiency in barley. Plant and Soil doi:10.1007/s11104-016-2883-4 29 pages.
- Heppell, J., Payvandi, S., Talboys, P., Zygalakis, K.C., Fliege, Jörg, Langton, D., Sylvester-Bradley, R., Walker, R., Jones, D. L. and Roose, Tiina (2015). Modelling the optimal phosphate fertiliser and soil management strategy for crops. Plant and Soil doi:10.1007/s11104-015-2543-0 15 pages.
- Payvandi, Sevil, Daly, Keith R., Jones, David, Talboys, Peter, Zygalakis, K.C. and Roose, Tiina (2014). A mathematical model of water and nutrient transport in xylem vessels of a wheat plant. Bulletin of Mathematical Biology (doi:10.1007/s11538-013-9932-4)
- Keyes, S.D., Daly, K.R., Gostling, N.J., Jones, D.L., Talboys, P, Pinzer, B.R., Boardman, R., Sinclair, I., Marchant, A. & Roose, T. (2013). High resolution synchrotron imaging of wheat root hairs growing in soil and image based modelling of phosphate uptake. New Phytologist 198, 1-7 (doi:10.1111/nph.12294).

6. Alternative ways of using fertilisers to satisfy the phosphorus demands of arable crops (WP3)

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6.1 Introduction

The overall aim of this WP was to “*quantify the effects of novel fertiliser technologies and soil P acquisition strategies on crop yield, crop quality and farm profits”*. Current advice for arable crop rotations is to maintain soils at P Index 2 (16–25 mg L^{-1} Olsen P) (Defra, 2010), considered to indicate the level of plant-available soil P needed to achieve optimum yields of most arable crops grown in rotation, in most years. This is a strategy based on feeding the soil to feed the crop, since it relies on maintaining soil P reserves rather than on fresh applications of fertiliser P to meet the P demand of each crop. However, soil P reserves represent a significant financial investment by commercial farms, and recent research has shown high variability, from Index 0 to Index 4, in the soil P required for unrestricted yields (Johnston and Poulton, 2011, reporting 3 sites over 40 seasons; Knight *et al.*, 2013, reporting six sites over 3 seasons). Furthermore, maintaining elevated soil P levels represents a risk to the environment (see Section 7). A possible alternative and more sustainable strategy for P use in arable farming systems might be to maintain a lower background of soil P (e.g. Olsen P Index 1: 10-15 mg L^{-1} Olsen P), therefore tying up a smaller financial investment, but to supplement this with more targeted P applications and/or by fertilisers that are used more efficiently, and/or are from recycled resources.

Through preparing the literature review (Edwards *et al.*, 2015) at the outset of this project we concluded that the efficiencies of P fertilisers could be understood best if they were considered in the context of the two other key components of any ‘fertiliser requirement’, (i) crop demand: the quantity of nutrient taken up by the crop when it’s yield is unlimited by nutrient supply, and (ii) soil supply: the quantity of nutrient that the crop is able to acquire from the soil, without any nutrient additions. The approach taken to reporting the results of the experiments conducted in this WP is thus to examine first the evidence quantifying crop P demands, then to examine the evidence quantifying soil P supplies at each site, and lastly to quantify the efficiencies of P fertilisers, and the influences of fertiliser form and application method on them.

In algebraic terms:

$$\textit{Fertiliser P requirement (kg ha}^{-1}\textit{)} = \frac{\textit{(crop P demand, kg ha}^{-1}\textit{)} - \textit{(soil P supply, kg ha}^{-1}\textit{)}}{\textit{fertiliser P recovery (\%)}}$$

At present, fertiliser recommendations do not adopt this approach explicitly; they allude to crop P demands in terms of P offtakes, calculated as the product of tonnages of harvested produce (e.g. grain and straw, t ha^{-1}) and normal their P concentrations (e.g. kg P_2O_5 per tonne), and they treat soil test P (STP) as crudely representative of soil P supply (although not quantified in kg ha^{-1}). Thus recommendations differ according to crop type and yield level, and soil analysis, but they do not differ according to soil type; for instance there is no concept that soil or fertiliser P recoveries differ between soils. Except for the different ‘available’ P contents of organic materials, there is also no quantitative information in the current recommendations on fertiliser P recovery, or ‘efficiency’, for different soils and crops; there are just indications that potatoes, some field vegetables and forage maize have disproportionately large recommended amounts, and P placement or band spreading is suggested as appropriate for these crops.

Crop P demands: As explained by Edwards *et al.* (2015), although P is required for a number of essential metabolic functions in vegetative tissues, a majority of the P taken up by crops is actually used for storage in generative organs such as seeds, which might not rightly be deemed part of the crop’s essential requirements for maximising its productivity. P storage may also occur in vegetative tissues (Veneklaas *et al.*, 2012). It may therefore be misleading to consider the final P amounts taken up by crops as representative of their P ‘requirements’. Possibly crop P required for maximum productivity should be derived from the amounts of functional (photosynthetic, etc.) vegetative tissue associated with high yielding crops and the minimum P concentrations of these tissues when they are (just) maximally functional, for example Smith *et al.* (1985) suggest a requirement for 0.2% P during grain filling. Taking the benchmark wheat crop yielding 11 t ha^{-1} grain as described by Sylvester-Bradley *et al.* (2009), maximum non-grain biomass during its growth was 10 t ha^{-1}, so its crop P demand could be considered to be around 20 kg ha^{-1} rather than the 40 kg ha^{-1} that would be estimated as P offtake at harvest in RB209 (Defra 2010).

In this respect, it should be instructive to examine the way in which crop P concentration responds to *decreasing* P availability; if low P supplies reduce crop P concentration without diminishing crop growth, it may be assumed that a proportion of accumulated crop P was inessential for immediate growth i.e. some crop P represents 'storage', possibly unnecessary storage. In considering crop P demands, it may also prove useful to distinguish between P in living and dead tissues, to ascertain the extent to which P can be remobilised during senescence.

Unfortunately, sites chosen to have low crop P availability may have deficiencies in other aspects of conditions for crop growth which may constrain their yield potential well below 11 t ha^{-1}, for example the shallow soil depths of soils over chalk, so an alternative more direct approach to quantifying the crop P demands here will be simply to multiply the maximum grain yield achieved by the minimum crop P per tonne of grain. Thus it will be necessary to consider various ways of estimating crop P demand here.

Soil P supplies: Having defined soil P supply as the P taken up by the unfertilised crop, one clear interest in the experiments conducted here will be the extent to which the soil P supplies were predicted by the soil P analyses. However, low soil P was necessary to elicit crop responses, so to enable comparisons of the efficiencies of different fertiliser forms and practices. Thus the main criterion for selecting the experimental sites, apart from that the field should be planned to grow the right target crop, was that its analysis should show low topsoil P. No sites were selected with high soil P, so unfortunately there was a limited soil P range over which the predictive capacity of soil test P could be assessed. However, for the 'P Targeting' experiments (at Ropsley), TSP fertiliser was used to create a range of soil P levels. For the other 'Response' experiments, no specific preparations were made at the sites selected; the sites were intended to be representative of commercial arable fields in the UK. Note that the low topsoil P analyses sought here may have arisen from a variety of causes such as perennially low P additions as fertiliser or manure, high soil P fixation, previous reliance on P supplies from topsoil organic matter (which may not be reflected by soil P analysis), high crop P offtakes or reliance on subsoil P release. Thus the inherent ability of the chosen sites to satisfy crop P demands will be assessed before considering the efficiencies which were achieved by the different approaches to fertiliser use.

P fertiliser efficiencies: It is widely recognised that fertiliser P applied to soil tends to be rapidly immobilized by soil processes, especially when applied in highly water-soluble forms. To address the first part of the WP objective *to quantify the effects of novel fertiliser technologies*, two products that have shown the potential to increase fertiliser use efficiency were chosen for comparison with TSP, AVAIL® (a patented dicarboxylic acid polymer intended to reduce P fixation) and struvite (ammonium magnesium phosphate hexahydrate; $NH_4MgPO_4 \cdot 6H_2O$; recovered from waste water, and having a low water solubility). Previous field experiments have indicated that crop rooting systems, crop yields and efficiency of P uptake were improved by up to 15% when AVAIL® was used instead of water-soluble fertilisers (Sanders *et al.*, 2004). Also, previous experiments on struvite have shown that, although it has a very low water solubility, the availability of P to crops is equivalent to or better than that of water-soluble TSP (Johnston & Richards, 2003; HRI, 2008; Perez *et al.*, 2009; Cabeza *et al*., 2011). Consequently it appeared worthwhile to attempt a more thorough testing of both of these products across a range or crop and soil type conditions, to quantify their effectiveness under UK conditions, compared to TSP.

To address the second part of the objective of this WP "*to quantify soil P acquisition strategies"* and overcome soil P immobilisation, application methods that circumvented the soil and allowed more precise targeting of P (through placement or foliar applications) were tested in the same Response experiments. Placement of P close to the seed is a well-established technique used to improve responses to fertiliser P and achieve its better recovery, but its use on most English farms (not in Scotland) virtually ceased over recent decades to enable faster drilling rates; fertiliser P is now more typically broadcast, followed by soil-incorporation when the crop is sown, and seed drilling technology has much improved so placement is again feasible.

Placement of fertiliser P either with the seed, or as a concentrated band adjacent to or below the seed, has been shown to benefit early season root development, enhance P uptake and crop yield on low P status soils. For example it has been shown that annual fertiliser applications of 10 and 20 kg ha^{-1} P placed in the soil close to the seeds gave average increases in wheat yield and P uptake similar to broadcast applications of 40 kg ha^{-1} P (Wager *et al.,* 1986). Each experiment reported here compared fertiliser placement with broadcasting at two P rates, rates being set according to crop (15 and 30 kg ha^{-1} P for cereals and OSR; 40 and 80 kg ha^{-1} P for potatoes). These two methods and two rates were used with all three products – TSP, AVAIL® and struvite – in all combinations, to test for any telling or useful interactions.

As reviewed by Edwards *et al.* (2015), fertiliser P efficiency or recovery can be estimated in a number of different ways which require different interpretations. The approach adopted here is the 'difference method', which relates to the 'one off' effect of the fertiliser on P uptake by the crop which immediately follows its application. This 'P recovery' takes no account of any residual effects of the fertiliser on subsequent crops. It is thus estimated from the P taken up with fertiliser, minus the P taken up without fertiliser, divided by the total P applied in the fertiliser. Other than fertiliser form and placement, the series of Response experiments set up here was designed to address a significant number of factors with the potential to influence fertiliser efficiency, including crop type (autumn v spring sown), species, soil type and climate.

P Targeting: To further address the second part of the WP objective "*to quantify soil P acquisition strategies"* foliar P and P seed dressings were compared in two additional experiments at the long-term experimental site (at Ropsley, Lincolnshire) where a range of soil P levels (from Olsen P Index 0 to P Index 3) had been established; spring barley and winter wheat were chosen as test crops in the two test seasons. Foliar P applications are intended to provide a small amount of highly soluble (and therefore accessible) P to actively growing leaves, the hope being that foliar P applications might substitute for much larger applications of soil-applied P, as suggested by Allison *et al.* (2001). Previously, in the 1980s, ADAS tested whether phosphate sprays (providing some 2-3 kg ha^{-1} P) applied soon after tuber initiation could substitute for larger quantities of soil applied P and high soil P reserves adopted for on potato production. In this case the saving in soil-applied P was estimated to be 80-90%, depending on soil P index (discounting the reduced residual effects of soil-applied P). However, results in the 1980s were insufficiently consistent for the technique to be adopted generally.

Use of seed dressings has been advocated (see Edwards *et al*., 2015), based on similar arguments to those for use of foliar P, but favouring the more intimate contact between the added P and the seedling's developing root system. In addition to results in WP 1 (see Section 3), previous reports have shown that P seed dressings can enhance early growth, especially of herbage and fodder crops where the total above ground vegetation is periodically removed (e.g. Scott & Blair, 1988). However, responses have been more mixed with crops where final yields are largely determined at later stages of plant development (e.g. Peltonen-Sainio *et al.*, 2006).

Recently, phosphite fertilisation (including as seed dressings) has been proposed as an alternative to use of phosphate (López-Arredondo & Herrera-Estrella, 2012) despite there being some controversy about its effectiveness (Thao & Yamakawa, 2009). Thus the experiments at Ropsley were set up to test three types of seed dressing (phosphate, phosphite and Biomex, the latter being a preparation of a growth-promoting bacterium; Talboys *et al.*, 2014) and two foliar treatments (phosphate and phosphite) applied either during early or late tillering. In addition, a combined approach was tested, using a phosphate seed dressing followed by phosphate foliar sprays at either early or late tillering.

Given the difficulties in finding good experimental sites with low soil P (as for the 'P Response' experiments here), and the expected unrepresentative performance of soils that have just been *built up* to a level of soil P (as in the 'P targeting' experiments here), a third series of field experiments was set up, and is reported here, in which sites were established to assess the effects on fertiliser strategies and crop yields after *running down* soil P. The need for these preparations became evident through (i) the difficulties in finding commercial farms with suitable fields for the ‘P response’ experiments (with soils of low P status and fields of sufficient area), and (ii) the relatively equivocal results that can arise from fertiliser P response experiments conducted at only one level of soil P. Thus, in 2010, large scale field trials were established at four sites with contrasting soil types and adequate soil P levels (P Index 2); the expectation was that, assuming an Olsen soil P half-life of nine years (Johnston *et al.* 2016), if P applications were withheld from (four) large plots whilst another four received maintenance P dressings, sufficiently different soil P levels would be established after four years that P efficiency strategies could be tested on the same site at two different but representative levels of soil P. Additionally, since the effect of the P balance on the change in Olsen P can vary from soil to soil (Johnston *et al.* 2016), these experiments were expected to be useful in establishing a rate of change in Olsen P over a range of soil types and crop rotations, before allowing assessments of yield effects of reducing soil P.

Overall, the hypothesis being tested here is that application of more available P fertilisers, better targeting of P and improved acquisition of existing residual soil P reserves can reduce growing costs and the industry’s current dependence on elevated soil P-fertility. The field experiments undertaken to test this hypothesis were of three different designs, as follows:

- ‘P Response’ experiments: To test effects of two innovative fertiliser products (AVAIL® and struvite) compared with triple super phosphate (TSP) and to test methods of application (i.e. placement v broadcasting) on crop responses at sites with but different soil types and soil P Index 1.
- ‘P Targeting’ experiments: To test the effect of seed dressings (phosphate and phosphite) seed dressing and foliar P applications on crop yields over a range of soil P levels.
- ‘P Run down’ experiments: To prepare four sites for tests of technologies for improved P efficiency, and meanwhile to test rates of decline in soil P, and effects of reduced soil P on crop yield (i.e. after run down).

In Sections 6.2 to 6.4 these three sets of experiments will be described and discussed together.

6.2 Materials and Methods

6.2.1 **P Response Experiments**

6.2.1.1 Site choice and experimental design

Ten field experiments were conducted between harvest years 2011 and 2014 testing rates, application methods and types of P fertiliser for cereals (spring and winter barley, winter wheat), winter oilseed rape and potatoes under a range of site and environmental conditions. The 10 sites (Table 6.1) were chosen to have low soil P (P Index 0-1; 5-15 mg L^{-1} P by Olsen in England; very low or low by Modified Morgan's in Scotland), where freshly-applied P would be more critical to crop nutrition than at sites with greater levels of soil P.

Table 6.1. Cropping details for the P Response Experiment sites

Site	Crop	Variety	Harvest Year
Balbathin, near Inverurie, Aberdeenshire	Spring barley	Shuffle	2011
Hillhead of Barra, Aberdeenshire	Spring barley	Scout	2014
Stetchworth, Cambridgeshire	Winter barley	Winsome	2012
Gainsborough, Lincolnshire	Winter wheat	Gallant	2013
Terrington, Norfolk	Winter wheat	Gallant	2014
Jaywick, Essex	Oilseed rape	Compass	2014
Dunham on Trent, Nottinghamshire	Oilseed rape	Compass	2014
Tamworth, Staffordshire	Potatoes	Crisps4all	2012
Old Rayne, Aberdeenshire	Potatoes	Maris Peer	2012
Tamworth, Staffordshire	Potatoes	VR808	2014

At each site 64 (or 68 at Stetchworth) experimental plots (cereals & oilseeds: 24m x 4m; potatoes: 15m x 6 rows) were laid out and 16 treatments were allocated within each of 4 replicate blocks, giving a randomised block design. Each plot was split in half longitudinally and alternate halves were used respectively for quadrat sampling and combine harvesting.

6.2.1.2 Fertiliser treatments

The treatments tested in each experiment included all combinations of two application methods, three fertiliser types and two rates of fertiliser P. Fertiliser application methods were placement (at planting or drilling) or broadcasting (with incorporation) just prior to planting or drilling; fertiliser types were triple super phosphate (TSP), struvite, and AVAIL® +TSP; two rates of P were tested, depending on crop type (Table 6.2). Four additional P rates (applied as broadcast TSP) were tested to provide a curve of response to six rates of P using conventional practice (broadcast TSP with incorporation); these were 0, 15, 30, 60, 90 and 120 kg ha^{-1} for the cereals or oilseed rape and 0, 40, 80 and 160 kg ha^{-1} for potatoes. In addition, at the potato sites foliar P was tested as an addition to two of the TSP treatments (40 and 80 kg ha^{-1}); in each case foliar P was applied twice, at tuber initiation as 15 l/ha of ammonium phosphate solution (14%N w/v, 20%P w/v, as Folex from Omex, diluted in 200 l/ha water, giving 3.0 kg ha^{-1} P), and again three weeks later.

Table 6.2. Fertiliser treatments

Fertiliser type (& method)	**P rate (kg ha^{-1})**	
	for Cereals or OSR	***for Potatoes***
Untreated 'Control'	nil	nil
TSP (broadcast)	15	40
	30	80
	60	160
	90	
	120	
TSP (placed)	15	40
	30	80
Struvite (broadcast)	15	40
	30	80
Struvite (placed)	15	40
	30	80
AVAIL®+TSP (broadcast)	15	40
	30	80
AVAIL®+TSP (placed)	15	40
	30	80
Foliar + TSP (broadcast)		40 + 6 as foliar spray
		80 + 6 as foliar spray

Note: for the first experiment, at Balbathin, fertiliser application methods and fertiliser types were only compared at 10 kg ha^{-1} P and other P levels were 0, 5, 20, 30, 60 and 120 kg ha^{-1}. This experiment also included a foliar P treatment delivering a total of 6.6 kg ha^{-1} P in two sprays.

6.2.1.3 Site characterisation and management

Prior to drilling or planting each site was characterised by taking four bulked topsoil samples (0-150 mm), one from each block (Table 6.3). Soils were analysed by Olsen's method in England and Wales (MAFF, 1986) and by both Olsen's and Modified Morgan's (Foy *et al.*, 1997) methods in Scotland. All soil P concentrations are reported in mg L^{-1} after air-dried soils were sieved through 2 mm. Most of the selected sites had soil P within the target range of 5-15 mg L^{-1} (Olsen P Index 0 or 1) or 0-4.4 mg L^{-1} (Modified Morgan's very low, VL, or low, L), with the exception of the site at Dunham where soil P was 16 mg L^{-1} (Olsen P Index 2). Total soil P (MAFF, 1986) ranged from 357-1837 (mg kg^{-1}); soil types were predominately heavy – clay or clay loams (Table 6.3).

Table 6.3. Topsoil (0-150mm) characteristics at sites used for the P Response Experiments.

	Available P (mg L^{-1})[1]	[Soil P Index][2]	Total P (mg kg^{-1})	pH	Available K (mg L^{-1})	Available Mg (mg L^{-1})	Textural class	Sand (%)	Silt (%)	Clay (%)	NV (%)[3]	Organic C (%)
Barley (spring, S or winter, W)												
Balbathin (S)	2.1* (16)	L	1,050	6.0	158	143	Sandy loam	51	32	17	<0.1	2.88
Hillhead (S)	1.5* (17)	VL	1,070	6.3	368	90	Clay loam	50	24	26	<1	3.57
Stetchworth (W)	9	0	1,429	8.3	132	28	Clay	26	29	45	25.2	1.42
Winter wheat												
Gainsborough	14	1	758	7.9	113	63	Clay loam	44	38	19	5.9	1.80
Terrington	9	0	998	8.2	322	119	Clay	21	40	40	13	1.42
Winter oilseed rape												
Dunham	16	2	493	7.1	151	421	Clay loam	35	30	35	3.0	1.55
Jaywick	10	1	459	7.0	139	174	Clay loam	26	48	26	2.3	2.14
Potatoes												
Tamworth	13	1	357	5.6	218	63	Clay loam	43	31	26	1.7	1.12
Old Rayne	4.0* (27)	L	1,837	5.9	188	107	Clay loam	38	35	27	2.4	3.77
Tamworth	14	1	390	6.3	131	77	Clay loam	30	39	31	<1	0.89

[1] Available P measured using Olsen's P method except for sites in Scotland (indicated by *) where soil was measured using the Modified Morgan's method. Soil K and soil Mg were also determined by Modified Morgan's method in Scotland, and were very similar to results by the English method (MAFF, 1986).

[2] RB209 P Index 0-2; SAC status VL-L. Note: RB209 P index 0 can be considered comparable to SAC status VL and RB209 P index 1 comparable to SAC status L.

[3] Neutralising Value, $CaCO_3$ equivalent.

Previous crops, cultivation methods, and dates of fertiliser application, establishment (sowing or planting) and harvest are shown in Table 6.4. Fertiliser N rates and dates were according to current recommendations (Defra, 2010) for each site. Crops were examined during early growth for non-P nutrient deficiencies and signs of disease, and were treated accordingly.

Table 6.4. Details of crop management at each site. NA = not available.

Site	Crop	Cultiv'n method	Date P applied	[1] Date estab'd	Date N applied	[2] Date dessic.	Date harv'st
Balbathin11	S Barley	Plough	24.03	24.03	11.04	-	09.09
Hillhead 14	S Barley	Plough	09.04	09.04	9 & 30.04	-	29.09
Stetct'th 12	W Barley	Plough	30.09	30.09	9.3,5+30.4	-	02.08
Gainsbor 13	W Wheat	Non inv.	15.10	15.10	~15.03	-	02.09
Terr'ton 14	W Wheat	Non inv.	20.09	24.09	29.03	-	19.08
Jaywick 14	OSR	Non inv.	07.09	07.09	17 & 27.03	23.06	15.07
Dunham 14	OSR	Non inv.	29.08	29.08	7 & 23.03	17.06	21.07
Tamw'th 12	Potatoes	Plough	07.04	07.04	01.04	20.08	07.09
O Rayne 12	Potatoes	Plough	23.05	23.05	21.05	18.09	31.10
Tamw'th 14	Potatoes	Plough	29.04	29.04	21.04	25.08	11.09

[1] Date crop sown or, if potatoes, planted. [2] If relevant, date crop desiccated.

6.2.1.4 NDVI monitoring

Assessments of Normalised Difference Vegetation Index (NDVI) were made with a Crop Circle reflectometer (Holland Scientific) at all sites in 2014 (except Hillhead of Barra and Tamworth) at GS 21 for wheat and GS 1,8 for oilseed rape. NDVI may be used as a proxy for crop biomass, leaf area index, or crop nitrogen (N) content, with high values indicating large green areas and correspondingly large biomass amounts.

6.2.1.5 Crop sampling

Assessments of crop biomass, biomass P concentration and crop P uptake were undertaken at an intermediate growth stage (39, flag leaf visible, to 55, mid ear emergence) for cereals, 3,7 (first flower buds yellow) for oilseed rape and tuber initiation for potato crops. (Tuber initiation was defined as a swelling on the end of a stolon equal to at least twice the diameter of the shaft of the stolon). Also, in the initial experiment at Balbathin, quadrat samples were taken at both GS31 (first node detectable) and GS45 (booting), and at Hillhead they were only taken at GS31.

The crop was sampled from ground level from four randomly placed 0.25 m^2 quadrats per plot, weighed (fresh weight) and then dried (80°C for 24 hours) before being reweighed (dry weight). For the potato crop, emerged plants were counted for the two central rows of each plot and two representative plants per plot were selected for analysis; the number of initiated tubers was also counted. Sub-samples were taken for analysis of P concentration (MAFF, 1986).

Sap P samples were also taken by sampling sufficient plant material (300-400 g of whole plant or actively growing leaf), which was immediately placed in a cool box with ice packs before being delivered directly to the laboratory for analysis (Omex, 2016).

6.2.1.6 Harvest measurements

For cereal and oilseed rape crops 'grab samples' were taken immediately before harvest (or just prior to desiccation for oilseed rape). A representative sample (cereals *c*.50 tillers per plot, oilseed rape $8^{-1}0$ stems per plot) was cut at ground level, and samples were separated into fractions of ears (or pods for oilseed rape) and 'rest', weighed (fresh weight) and dried (80°C for 24 hours) before being reweighed (dry weight). Ear (or pod) samples were then threshed and the grain or seed was weighed, prior to dispatch to the lab for separate determination of P content in both fractions, grain or seed and 'rest'. Oilseed rape and cereal crops were harvested using a small plot combine, with grain weight, grain moisture, and plot dimensions being recorded. Paths were included in the plot widths.

Potato plots were machine-lifted and tubers were collected by hand from the middle two rows in the designated 'harvest area'. Defective tubers were grouped according to their disorder (e.g. green, deformed, mechanically damaged, pest attacked, diseased, cracked), before weighing. Sound tubers were collected and graded (>85 mm, 65-85 mm, 45-65 mm and <45 mm) and a weight for each grade was obtained. A sub-sample of tubers was chipped longitudinally and oven-dried at 100°C for 16 hours before being analysis for total P concentration (by acid digestion and ICP-OES).

6.2.1.7 Statistical analysis

Data from each site were subjected to three separate analyses of variance (ANOVA) using GenStat (VSN International Ltd) to test (i) whether all P treatments differed significantly from the control, (ii) whether there were statistically significant differences between the three P products, the two P application methods, or the two P rates, and whether there were any significant interactions between them, and (iii) whether there was a significant continuous response to increasing amounts of applied P (as broadcast TSP). For the latter P response analysis, an ANOVA with polynomial contrasts (linear and quadratic effects) was used to test for a significant linear response with P rate and also to test whether the response diminished significantly as P rate increased (i.e. as described by a quadratic function).

6.2.2 **P Targeting Experiments**

The long-term experiment site at Ropsley, Lincolnshire (Bhogal *et al.*, 1996; Hatley, 1999) was reinstated with a range of soil P levels. Then across these soil P levels spring barley (in 2013) and winter wheat (in 2014) crops were tested for their responses in P uptake and grain yield to P applications as seed dressings or foliar sprays or both.

6.2.2.1 Site preparation, characterisation & management

Prior to this experiment, topsoil (0-150mm) of the 162 plots of the long-term experiment at Ropsley were sampled to measure soil P (autumn 2010). Plot-specific amounts of TSP (up to 1,500 kg ha^{-1} P_2O_5) were then applied, split between August 2010 and April 2011, to create a range of soil P levels. Establishment of topsoil (0-150 mm) P levels was checked by sampling and analysing all plots (Olsen's method, by NRM Labs.) after harvest in 2011 and again after harvest in 2012. Then 99 plots were chosen for use in the two experiments harvested in 2013 and 2014 (Table 6.5), to provide soil P levels ranging from 5 mg L^{-1} (Olsen P Index 0) to 35 mg L^{-1} (Olsen P Index 3). Topsoils (0-150mm) of all tested plots were resampled after harvest in 2014 and P levels were analysed (by both NRM and Hill Court Farm Research Ltd.).

Table 6.5. Cropping details for the site at Ropsley, Lincs. Non-inversion tillage was used at this site in all seasons. The two P Targeting experiments were conducted in 2013 & 2014.

Harvest Year	Crop	Variety	Sowing Date	Date N applied	Harvest date
2011	Winter Wheat	Oakley	23 Sept	9 March	20 Aug
2012	Winter Wheat	Gallant	28 Sept	14 March	17 Aug
2013	Spring Barley	Quench	5 April	5 April	3 Sept
2014	Winter Wheat	Gallant	25 Sept	18 March	21 Aug

6.2.2.2 P Targeting Treatments

Seven seed dressing and foliar P treatments were tested on the spring barley and winter wheat crops, and compared with duplicate plots in each block of an untreated control (Table 6.6).

The seed dressings tested were phosphate, phosphite or Biomex, the P rate being <0.5 kg ha^{-1} in each case. Biomex (supplied by Omex Agriculture Ltd., Estuary Road, King's Lynn, Norfolk, PE30 2HH) is a product containing the beneficial bacteria *Bacillus amyloliquefaciens*, strain FZB42. The four foliar treatments were phosphite at early tillering (<0.5 kg ha^{-1} P), phosphate at early or late tillering (c.1.5 kg ha^{-1} P) and phosphate at early (c.1.5 kg ha^{-1} P) and repeated at late tillering (c.1.5 kg ha^{-1} P) plus phosphate seed dressing (Table 6.6).

Each treatment was tested at eleven soil P levels (P Index 0 to P Index 3, range: 5-35 mg L^{-1}) to assess whether treatment effects depended on soil P concentration. This was achieved by ranking all 99 plots within the experiment in order of soil P, and then dividing them into 11 classes of soil P. The nine targeting treatments (seven plus two controls) were then allocated randomly to the plots within each class.

Table 6.6. Experimental treatments at Ropsley

Treatment	**Product**	**Timing**	**P rate (kg ha^{-1})**
Untreated control			
Seed dressing	Biomex	With seed	<0.5
	Phosphite	With seed	<0.5
	Phosphate	With seed	<0.5
Foliar	Phosphite	Early tillering (31.5.13 GS23; 10.2.14 GS21*	<0.5
	Phosphate	Early tillering*	*c*.1.5
	Phosphate	Late tillering (14.6.13 GS32; 18.3.14 GS30)	*c*.1.5
Seed & foliar	Phosphate	Early & late tillering & seed dressing	*c*.3.5

* Note: for the winter wheat crop (harvest 2014) the early tillering foliar applications were delayed due to poor autumn crop growth in 2013 and were applied in early spring 2014.

6.2.2.3 Measurements

Assessments of crop biomass, P concentration and P offtake were undertaken at flag leaf emerged (GS39). The crop was sampled from ground level from four randomly placed 0.25 m^2 quadrats per plot, weighed (fresh weight) and then dried (80°C for 24 hours) before being reweighed (dry weight). Samples were sent to the laboratory to measure P concentration.

Canopy reflectance of all plots was measured on 2 July 2013 (GS59), and on 19th January (GS14) and 24th April (GS32) 2014.

‘Grab sampling’ was carried out immediately before harvest. Representative samples (*c*.50 tillers per plot) were cut at ground level. Samples were separated into grain and straw fractions, weighed (fresh weight) and then dried (80°C for 24 hours) before being reweighed (dry weight). Samples were then threshed and grain weighed prior to dispatch for separate determination of P content in the straw and grain fractions (MAFF, 1986).

The crop was harvested using a small plot combine, with grain weights, combine width and length recorded to enable yield calculation.

6.2.2.4 Statistical analysis

Regression analysis (with groups) was used in GenStat (VSN International Ltd) to model the relationship between the response variates (yield and P offtake) and the soil P level. The analysis fitted a sequence of models to determine (a) whether the response to increasing soil P diminished as soil P increased, and (b) whether the asymptotes and/or other response parameters were affected significantly by the targeting treatments.

6.2.3 P Run-Down Experiments

6.2.3.1 Site selection

Soil P run-down experiments were established at four sites in 2010 or 2011 (Table 6.7). Sites were chosen to have a starting Olsen P level of *c*.20 mg L^{-1} (mid P Index 2) and to represent a range of soil types and climatic conditions.

Table 6.7. Run-down site locations, soil types and initial soil P levels (all Index 2).

Site	Soil type	Initial soil sample date	Initial Soil P, mg L^{-1}
Boxworth, South Cambridgeshire	Clay loam	26 Nov 2010	24.0
Stetchworth, East Cambridgeshire	Sandy loam	16 Feb 2012	19.4
Weobley, Herefordshire	Silty clay loam	3 Mar 2011	16.4
Modbury, Devon	Silty clay loam[1]	24 Sept 2010	20.7

[1] The soil series at Modbury is Denbeigh, described as a silty clay loam over Devonian shale and slates, and is considered to be a P-fixing soil.

6.2.3.2 Experimental treatments & assessments

At each site eight large plots (c.0.5 ha) were established. Annual fertiliser P inputs were then estimated and broadcast as TSP before autumn cultivation for soil P maintenance on four of the plots, whilst the other four plots received no P-fertiliser inputs. All sites were cropped according to the on-farm rotation (Table 6.8). Plot-specific crop yields and P concentrations were not measured so, to estimate the crop P offtakes, average crop yields for each farm were multiplied by standard P concentrations from RB209 (Defra, 2010).

It was anticipated that soil P would decline to Index 1 (10-15 mg L^{-1}) on the 'run-down' plots at (at least) one of the sites before the end of the project. The intention was then to run an experiment on this site to test the most promising P fertiliser strategies (deduced from other Project results) for adoption at P Index 1, compared to the current 'RB209' approach of broadcasting TSP to provide more than enough to maintain soil P.

To assess the progress towards the target soil P indices [i.e. with 'maintenance' plots all at P Index 2 and 'run-down' plots all at P Index 1], soil samples were taken from each plot after harvest at the end of each growing season, and were subjected to Olsen's analysis (at the NRM labs.) for soil P.

Table 6.8 Crops grown in each harvest year, and mean rates of P applied as TSP to the 'maintenance' plots at the four Run-Down Experiments. WW, winter wheat; W OSR, winter oilseed rape; W Oats, winter oats; sp., spring.

Site	**2011**	**2012**	**2013**	**2014**	**2015**
S Cambs	W Cereal	WW	W OSR	WW	W Barley
E Cambs	-	Sp. Wheat	Sp. Barley	W Barley	Sugar Beet
Herefords	Linseed	Linseed	WW	WW	W OSR
Devon	W OSR	WW	W Oats	WW	W OSR
	P applied, kg ha^{-1}				
S Cambs	26	26	33	26	26
E Cambs	-	33	33	35	22
Herefords	39	13	48	39	22
Devon	22	28	33	39	22

6.3 Results

6.3.1 P Response Experiments

In reporting these ten experiments, the first consideration will concern how well the crops grew. Then, given that all treatments were applied before sowing, and that much the largest amounts of P were applied (broadcast) as TSP, we will use the broadcast TSP responses to show the extent of any responses to adding fertiliser P. This will then be followed by considering whether the responses to fertiliser P could be improved by using different forms of fertiliser, by placing rather than broadcasting the fertiliser, or whether some combination of these gave any synergistic effect. Regression analysis of crop attributes on rate of P applied was felt to provide the most robust test of the overall responsiveness of each crop to fertiliser P; thus formal comparison of the control (nil treatment) with all other treatments will only be discussed if this statistical analysis appeared to augment the above analyses e.g. by showing that the control plots were unrepresentatively variable.

The assessment of individual crop species will then be followed by a generalised assessment of data from all sites, across all crops, including economic indications of the most cost-effective methods for P fertiliser use.

6.3.1.1 Conditions for crop growth and production

The experiments took place at sites across England and Scotland over five growing seasons, so crops experienced marked contrasts in weather conditions (Table 6.9). Along with the variation in soils (Table 6.3), use of contrasting crop species and some tailoring of husbandry to suit crops to particular markets, the productivity of these crops was very varied (Table 6.10), as were the conditions in which the P fertiliser strategies were tested.

Excluding the second experiment at Ropsley, which is described subsequently (Section 6.3.2), all yields exceeded or were similar to the average UK farm yield for that crop in that particular season, but only three crops were particularly successful (at Balbathin, Stetchworth and Dunham); the modest yields generally arose because of the necessity of making some compromises about site choice in order to ensure that the soils had a low P status; low P status is commonly associated with other agronomic issues. Specific visible symptoms that indicated scope for greater yields were dryness after sowing at Balbathin, shallow soil and drill malfunction compromising establishment at Stetchworth, modest weed infestation and patchy drought caused by variable soil at Gainsborough, N deficiency at Terrington as evidenced by low grain N (%DM), some disease and uneven senescence in the wet summer of 2012 at Tamworth, and some disease again at Tamworth in 2014.

Thus the crops on which these experiments were conducted can be regarded as representative of average farm yield levels, but (assuming a crop's P demand is associated with its productivity) they will not apparently have generated particularly large demands for P. Note that UK national wheat yields in 2015 reached an all-time high of 8.8 t ha^{-1}, and new world record grain yields were achieved in England of 16.5 t ha^{-1} (Jones, 2015). Assuming that crop content of P was as suggested by Defra (2010), these yields would have required capture of 30 and 60 kg ha^{-1} crop P (grain plus straw) respectively.

Results from both winter wheat experiments should be treated with some caution as their yields and P offtakes may have been affected by low nitrogen and drought. Premature yellowing of leaves was noted in the Terrington experiment in June 2014, unrelated to any treatment. Analysis of grain samples after harvest confirmed N levels were low (mean 1.72 ±0.08%). At Gainsborough it was noted before harvest that the crop was showing signs of drought stress in patches relating to the soil texture. A score of green area (of flag, 2nd and 3rd leaves) was made on 24th July 2013 (from 0 = no green area to 100 = leaves all green) to test whether precision of the treatment comparisons could be improved by including this as a covariate in the statistical analysis. Note that covariance analysis is based on the assumption that the P treatments did not affect leaf senescence. Yields reported here are not adjusted for this covariate.

Table 6.9. Differences in monthly weather from the arable long term average (ALTA) for locations and growing seasons of the P Response and P Targeting Experiments. Data were taken from the MORECS database, and ALTA data were selected to represent the main arable area of the UK, 1984-2013.

Site & harvest year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
	Average temperature (°C, and % difference from ALTA**)**												**Mean**
Arable LTA	**10.5**	**6.9**	**4.7**	**4.2**	**4.3**	**6**	**8.1**	**11.1**	**13.8**	**16**	**15.9**	**13.1**	**9.5**
Balbathin 11	-11	-26	-49	-12	7	-7	12	-12	-15	-20	-19	-2	-13
Hillhead 14	-3	-23	26	5	12	10	1	-6	-3	-5	-20	-1	-3
Stetchw’th 12	-10	-6	2	-19	-33	-57	-9	-7	-1	13	8	4	-3
Gainsboro 13	-13	-6	-2	-17	-33	-62	-7	-4	-1	13	8	4	-4
Terrington 14	18	-10	23	29	42	22	22	13	7	9	-4	12	13
Jaywick 14	21	-4	36	50	56	35	33	14	11	16	1	18	18
Dunham 14	16	-10	32	29	42	23	23	11	9	11	-5	11	13
Tamworth 12	17	30	26	29	5	30	-20	2	-7	-8	-3	-7	4
Old Rayne 12	-2	28	-2	-2	26	33	-35	-23	-24	-20	-12	-12	-8
Tamworth 14	15	-9	38	29	35	18	20	5	7	8	-9	11	11
Ropsley 13	-12	-7	-2	-19	-30	-62	-9	-5	-1	13	7	4	-4
Ropsley 14	15	-10	32	26	35	22	23	10	9	11	-6	11	12
	Total solar radiation (TJ/ha, and % difference from ALTA**)**												**Total**
Arable LTA	**1.8**	**0.9**	**0.6**	**0.7**	**1.3**	**2.6**	**4.1**	**5.4**	**5.4**	**5.4**	**4.5**	**3.1**	**35.9**
Balbathin 11	-17	-22	-33	-14	-23	-8	12	4	-6	-11	-20	-10	-8
Hillhead 14	-28	-11	-33	-43	-15	4	-10	-7	-13	9	0	-13	-7
Stetchw’th 12	0	11	0	0	-8	-23	0	-2	-2	11	0	3	-1
Gainsboro 13	0	0	0	0	-8	-19	7	0	2	17	9	6	3
Terrington 14	0	22	17	14	8	15	-7	-7	4	15	7	-6	3
Jaywick 14	0	11	17	14	15	19	2	-2	6	11	7	0	15
Dunham 14	-6	11	0	0	8	15	-5	-7	2	15	7	-10	3
Tamworth 12	6	-11	0	14	-15	23	-12	2	-24	-7	-9	6	-5
Old Rayne 12	-17	-22	-33	-14	-15	15	-27	6	-24	-28	-16	-6	-14
Tamworth 14	-6	0	0	0	8	15	-2	-9	11	20	0	0	4
Ropsley 13	0	0	17	0	-8	-19	5	-2	-2	17	4	6	2
Ropsley 14	-6	11	17	14	8	19	-7	-6	2	15	4	-6	3
	Rainfall (mm, and % difference from ALTA**)**												**Total**
Arable LTA	**86**	**81**	**79**	**75**	**54**	**54**	**55**	**55**	**61**	**63**	**68**	**62**	**792**
Balbathin 11	-30	26	-38	-45	35	-4	-84	-18	38	-24	50	-13	-9
Hillhead 14	-2	-19	-8	73	61	-43	-16	-2	13	-6	156	-48	14
Stetchw’th 12	7	-10	16	-51	-44	-19	-49	-13	-66	-49	-29	-35	-26
Gainsboro 13	-22	6	28	-49	-46	4	-84	15	-34	-29	-31	-55	-23
Terrington 14	31	-46	-53	24	-15	-48	-53	85	-31	-16	60	-85	-11
Jaywick 14	45	-20	-3	37	48	-54	-56	62	-59	41	29	-71	8
Dunham 14	19	-51	-57	37	-7	-35	-53	78	-33	-48	13	-81	-18
Tamworth 12	-53	-58	-15	-33	-61	-67	115	-7	146	100	7	32	5
Old Rayne 12	-31	-53	-15	-29	-59	-80	135	-25	89	44	13	3	-3
Tamworth 14	49	-26	-8	89	61	-7	5	47	-5	10	46	-77	16
Ropsley 13	-19	11	39	-45	-37	-6	-78	13	-38	-16	-62	-60	-23
Ropsley 14	26	-54	-56	37	-24	-48	-60	85	-36	-44	28	-85	-18

Table 6.10. Crop performance in each experiment without and with P fertiliser compared to the average UK crop performance for that crop type in that year.

Site	**Year**	**Crop**	**Fitted yield – nil P**	**Fitted yield – max P**	**Av. UK yield for crop**	**Expt. yield**
			t ha^{-1}	*t ha^{-1}*	*t ha^{-1}*	*%UK av.*
Balbathin	2011	S Barley	6.9	7.6	5.4	141%
Hillhead	2014	S Barley	5.9	6.6	5.9	112%
Stetchworth	2012	W Barley	7.3	8.3	6.4	130%
Gainsborough	2013	W Wheat	6.7	7.7	7.4	104%
Terrington	2014	W Wheat	8.5	8.5	8.6	99%
Jaywick	2014	OSR	4.0	4.2	3.6	117%
Dunham	2014	OSR	5.1	5.1	3.6	142%
Tamworth	2012	Potatoes	46	45	37	122%
Old Rayne	2012	Potatoes	32	35	37	95%
Tamworth	2014	Potatoes	41	46	47	98%
Ropsley	2013	S Barley	4.7	6.5	5.7	116%
Ropsley	2014	W Wheat	3.0	4.3	8.6	50%

6.3.1.2 Performance without fertiliser P

One plot (or two plots at Stetchworth) per block received no fertiliser P. These plots commonly showed significant variability in crop performance. Hence the best estimate of soil P supply was taken as the intercept of the fitted regression of crop P offtake against all rates of P applied as broadcast TSP, including nil. These estimates were derived from 24 plots (or 16 for potatoes), hence were generally more precise, but none differed by more than 2 kg ha^{-1} P from the mean of the nil control plots (Table 6.11).

'Soil P' (without fertiliser P) uptake at harvest ranged from 11 kg ha^{-1} by potatoes at Old Rayne in 2012 to 30 kg ha^{-1} by oilseed rape at Dunham in 2014. All but two of the crops managed, without fertiliser P, to acquire more than 18 kg ha^{-1} P by harvest. Both crops taking up low P amounts (at Old Rayne and Balbathin) were grown within 15 miles of each other in Aberdeenshire, and both were spring sown crops, although the crops and the seasons were different: barley and potatoes in 2011 and 2012 respectively.

Analyses of P uptake during growth showed widely different patterns of P acquisition, ranging from 6-11% of final soil P uptake by tuber initiation in potatoes, to all of final soil P uptake by yellow bud stage (GS 3,7) in oilseed rape (102%) at Jaywick in 2014 or by flag leaf emerged stage (GS 39) in winter wheat (99%) at Terrington in 2014. Comparisons amongst the cereal crops or between the two oilseed rape crops show that, for the same species, patterns of uptake must have been quite different at the different sites, even within the same season. In general, even though soil analysis showed these sites to have relatively modest levels of soil-available P (Table 6.3), most crops managed to achieve substantial levels of P uptake without any fertiliser P applied (early mean 9.7 kg ha^{-1}; harvest mean 20.4 kg ha^{-1}), possibly sufficient to satisfy most of their essential requirements for P, as estimated in the Introduction above (Section 6.1).

Table 6.11. Estimates of **'soil P' uptake (kg ha^{-1})** during early growth stages (GS) and at harvest, without any fresh P applied. Means (and standard errors, SE) are taken from the analysis of the control against all other treatments, and the intercepts are taken from the fitted regression against rate of P applied as broadcast TSP.

Site-Year	**Early nil P uptake (kg ha^{-1})**				**Harvest nil P uptake (kg ha^{-1})**			
And growth stage at sampling (GS[1])	**Mean Control**		**Fitted intercept**		**Mean Control**		**Fitted intercept**	
	kg ha^{-1}	*SE*	*kg ha^{-1}*	*SE*	*kg ha^{-1}*	*SE*	*kg ha^{-1}*	*SE*
Balbathin-11 (31)	3.3	0.18	3.1	0.33				
Balbathin-11 (45)	6.8	0.56	6.8	0.49	12.0[3]	2.32	11.0[3]	1.04
Hillhead-14 (31)	7.8	0.89	8.1	0.60	18.6[3]	1.33	19.7[3]	0.93
Stetchworth-12 (39)	7.7	0.51	8.3	0.35	24.3	1.00	24.1	0.68
Gainsboro-13 (55)	15.1	0.65	15.4	0.60	24.8	0.97	22.8	1.17
Terrington-14 (39)	20.6	4.76	20.5	1.62	21.2	3.41	20.8	1.41
Jaywick-14 (3,7)	19.2	2.65	19.2	1.80	18.8	0.50	18.9	0.71
Dunham-14 (3,7)	14.1	1.49	13.7	1.07	28.0	2.82	29.7	1.53
Tamworth-12 (TI[2])	2.4	0.43	2.7	0.49	21.8[3]	2.54	23.5[3]	2.20
Old Rayne-12 (TI)	1.3	0.14	1.2	0.09	10.5[3]	0.52	10.6[3]	0.58
Tamworth-14 (TI)	1.3	0.14	1.4	0.12	23.5[3]	2.22	22.4[3]	1.56

[1] *Cereal growth stages are defined by Tottman et al. (1979); oilseed rape growth stages are defined by Sylvester-Bradley et al. (1984). GS3,7 is 'yellow bud' (just before flowering).*

[2] *Tuber initiation.*

[3] *Excluding straw P which was not measured for potatoes, or at Balbathin or Hillhead.*

6.3.1.3 Crop responses to increasing rates of broadcast TSP

Crop responses to TSP broadcast just before crop establishment were not large at any site; disappointingly, they were not statistically significant in some cases, and none of the significant responses was detectably non-linear or diminishing. Thus in Table 6.12 & Table 6.13 responses are just described by their slopes and intercepts. Interestingly, some crops responded more clearly in terms of biomass growth (Table 6.12) whilst others responded more clearly in terms of P concentration (Table 6.13). Responses for all crops are summarised in a 'dilution graph' (Figure 6.1); here the effects on crop P uptake or offtake (kg ha^{-1}) can be seen in relation to iso-uptake lines (grey) that are at intervals of 10 kg ha^{-1} P. No crop responded by more the 10 kg ha^{-1} P, even with the maximum amounts of P applied (120 or 160 kg ha^{-1}). Whether the increases in uptake were achieved by increasing P concentration, or by increasing biomass growth can be most easily seen in Figure 6.1 also. Only with oilseed rape at Jaywick in 2014 was there a significant response to broadcast TSP in both final biomass growth as well as in P concentration. Comparison of early values with harvested values shows how crop P concentrations were commonly diluted by biomass growth, and TSP effects on crop P concentrations diminished with time; only with the two oilseed rape crops which produced least biomass were effects on P concentration at harvest of any significance. Note that, as well as whole crop P, sap P was analysed during early growth at some sites (e.g. Hillhead) but showed no significant effects of applied P.

After multiplying total biomass growth by P concentration to give total P uptake at harvest, only four of the ten crops responded significantly in P uptake to increasing broadcast applications of TSP. These results are presented in Table 6.14 as P ‘recoveries’ i.e. the slope of the regression of total crop P on P applied, expressed as a percentage, which gives ‘P recovery by difference’. Levels of P recovery were all very poor (<8%) and, given the levels of precision achievable in these field experiments, effects of broadcast TSP on crop P uptake could not be detected with confidence at every site.

Table 6.12. **Early biomass growth & final crop yield** (cereals @ 85% DM, OSR @ 91% DM, potatoes as harvested) as affected by fertiliser P rate, assessed by regressing data from all plots receiving broadcast TSP against the rates of P applied, from nil to 160 kg ha^{-1}, showing the intercept, the probability of an effect and, if significant, the variance accounted for (VAF) with its slope (kg biomass or 'yield' kg^{-1} P applied).

	Early crop biomass				**Final yield**			
Site-Year	*Intercpt t ha^{-1}*	*Prob.*	*VAF %*	*Slope*	*Intercpt t ha^{-1}*	*Prob.*	*VAF %*	*Slope*
Balb-11 (31)	1.38	<0.001	68	20.9				
Balb-11 (45)	3.10	0.001	32	14.2	6.99	0.205	~	~
Hillh-14 (31)	1.97	<0.001	54	8.2	5.90	0.005	29	6.6
Stetc-12 (39)	3.30	<0.001	55	10.4	7.25	<0.001	54	8.4
Gain-13 (55)	5.38	0.432	~	~	6.70	0.726	~	~
Terri-14 (39)	9.56	0.330	~	~	8.50	0.480	~	~
Jaywick-14	4.65	0.210	~	~	4.00	0.060	12	2.3
Dunham-14	3.55	0.510	~	~	5.14	0.886	~	~
Tamw'th-12	1.06	0.010	34	4.1	46.2	0.743	~	~
Old Rayn-12	0.48	0.400	~	~	32.2	0.199	~	~
Tamw'th-14	0.52	0.386	~	~	41.1	0.043	21	32

Table 6.13. **Crop P concentration during early growth and in harvested biomass** as affected by fertiliser P rate, assessed by regressing data from all plots receiving broadcast TSP against the rates of P applied, from nil to 160 kg ha^{-1}, showing the intercept (mg kg^{-1}), the probability of an effect and, if significant, the variance accounted for (VAF), and its slope (mg P / kg biomass / kg P applied / ha).

	Mean P concentration in early crop biomass with significant effects (slope) of fertiliser (mg P / kg biomass / kg P applied / ha)				**Mean P conc'n in harvested biomass$^{\#}$ and significant effects (slopes) of fertiliser (mg P / kg biomass / kg P applied / ha)**			
Site-Year	*Intercpt mg kg^{-1}*	*Slope Prob.*	*VAF %*	*Slope*	*Intercpt mg kg^{-1}*	*Slope Prob.*	*VAF %*	*Slope*
Balb-11 (31)	2,313	<0.001	47	8.9				
Balb-11 (45)	2,182	0.989	~	~	1,831	0.236	~	~
Hillh-14 (31)	4,100	0.137	~	~	3,922	0.891	~	~
Stetc-12 (39)	2,524	0.002	28	2.9	3,602	0.791	~	~
Gain-13 (55)	2,930	0.309	~	~	3,507	0.293	~	~
Terri-14 (39)	2,154	0.350	~	~	2,026	0.089	9	2.8
Jaywick-14	4,121	0.460	~	~	4,567	<0.001	44	13.2
Dunham-14	3,933	0.027	17	7.1	5,075	0.006	26	6.0
Tamw'th-12	2,682	<0.001	93	15.2	1,902	0.003	45	4.0
Old Rayn-12	2,582	0.682	~	~	1,806	0.108	~	~
Tamw'th-14	2,645	0.235	~	~	1,940	0.121	~	~

$^{\#}$ *excluding straw or haulm*

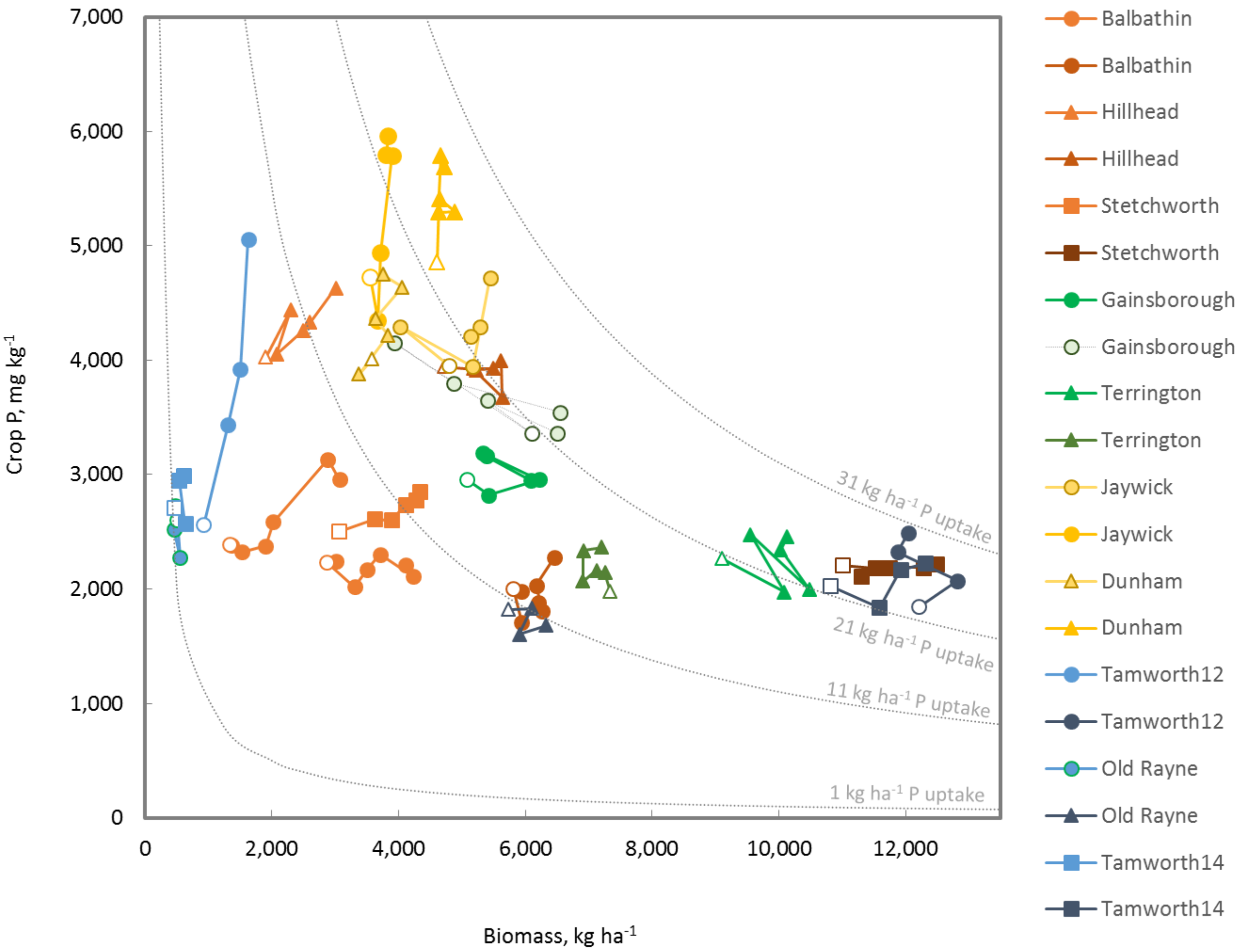

Figure 6.1. Crop P dilution graph, showing P concentrations (mg kg^{-1}) and biomass (kg ha^{-1}) during growth (above-ground crop; light colours) and at harvest (harvested grain or tubers; dark colours) in the ten response experiments described here (see legend for symbols) on barley (brown), wheat (green), oilseed rape (yellow) and potatoes (blue). Lines connect data from each site on a date, in order of increasing amounts of applied P from nil (open symbols) up to 120 (or 160 for potatoes) kg ha^{-1}. Iso-lines for crop P content (kg ha^{-1}) are shown in grey. Note that final harvest data at Gainsborough (dotted) were variable due to drought.

Seven of the ten experiments showed significant P recoveries during early growth, although these ranged from just 0.2% to 7.5% (Table 6.14). Also, there were only four significant responses in P uptake at harvest (Table 6.14), with spring barley at Hillhead in 2014, winter barley at Stetchworth in 2012, oilseed rape at Jaywick in 2014, and potatoes at Tamworth also in 2014; final recoveries were all less than 8%. Even the spring barley at Balbathin in 2011 and the potatoes at Old Rayne in 2014, which did not recover nearly as much ‘soil P’ as crops at the other sites (Table 6.11), did not respond significantly in their P uptake to the broadcast TSP applications. At Balbathin, there was a significant response during early growth, indicating 3-8% P recovery, but the data at harvest were not sufficiently precise to be able to say with confidence that TSP had made any difference to final P uptake. At Old Rayne, there was no evidence of any response to broadcast TSP, whether during early growth or at harvest, and whether in biomass, P concentration or total P uptake.

Given these small responses to broadcast TSP, maximum levels of P uptake by these crops were seldom much larger than levels of P uptake without any fertiliser P applied. The main interest in the following section is therefore whether different forms or methods of P fertiliser application might have improved the immediate responses of the crops for which additional P uptake was needed.

Table 6.14. **Early and final P uptake** as affected by fertiliser P rate, assessed by regressing data from all plots receiving broadcast TSP against the rates of P applied, from nil to 160 kg ha^{-1}. The probability (P) of an effect is shown and, if significant, the variance accounted for (VAF) by P rate, the slope of the effect (= 'recovery', expressed as a percentage) and its standard error (SE).

	Crop P recovery by difference during early growth (%)				**Crop P recovery by difference at harvest, including straw (%)**			
Site-Year	*P*	*VAF %*	*slope*	*SE*	*P*	*VAF %*	*slope*	*SE*
Balb-11 (31)	<0.001	78	7.5	0.77				
Balb-11 (45)	0.010	20	3.1	1.13	0.136	~	~	2.40[#]
Hillh-14 (31)	<0.001	50	4.3	0.91	0.176	~	~	1.41[#]
Stetc-12 (39)	<0.001	63	3.8	0.57	0.018	22	2.9	1.10
Gain-13 (55)	0.044	14	0.2	0.88	0.722	~	~	1.72
Terri-14 (39)	0.170	~	~	2.40	0.360	~	~	2.10
Jaywick-14	0.200	~	~	2.70	<0.001	69	7.6	1.06
Dunham-14	0.019	19	4.0	1.59	0.052	13	4.6	2.26
Tamworth-12	<0.001	75	3.6	0.50	0.112	~	~	2.40[#]
Old Rayne-12	0.743	~	~	0.10	0.722	~	~	0.63[#]
Tamworth-14	0.059	18	0.3	0.13	0.061	17	3.5	1.70[#]

[#] *excluding straw or haulm*

6.3.1.4 Effects of Forms and Methods of P fertiliser used

The difficulty of detecting effects of broadcast TSP, their small size, and the reasonable levels of precision achieved with most of the P response experiments here, raised some hope that it would be possible to detect improvements in responses to fertiliser P with either improved forms of fertiliser or with placement rather than broadcast distribution of fertiliser. Effects of fertiliser form on P uptake are examined first, followed by effects of method of application. Then crop performance at harvest will be described, as affected by both fertiliser form and application method. [Note the liquid and sprayed treatments tested at just Balbathin will be considered in Section 6.3.2.4.]

The form of fertiliser affected early P uptake significantly at four of the ten experiments (Table 6.15). However, the significant effects were small, and they were inconsistent between the sites. At Balbathin it was the AVAIL® treatment that improved uptake compared with other P forms, at Terrington and Dunham it was struvite that performed best, however at Tamworth in 2012 it was struvite that performed worst. Looking at all ten experiments there was no consistent overall pattern in results for the different products except that it is possible to surmise that struvite gave slightly better early P uptake than TSP or AVAIL® with the autumn-sown crops (wheat and oilseed rape).

Table 6.15. **Early crop P uptake (kg ha^{-1})** as affected by form and method of application of fertiliser P in ten experiments conducted in harvest seasons 2011 to 2014. The growth stage (GS) of sampling and probability of effects being real are shown together with the standard error of a difference (SED), and the probability of a real interaction between fertiliser form and method. Statistically significant or near-significant (<0.1) probabilities are shown in **bold**.

Crop	**Fertiliser Form (F)**					**Application Method (M)**				**FxM**
Site-Year & (GS)	***TSP***	***AV.***	***Stru.***	*SED*	*Prob.*	***B'cst***	***Plc'd***	*SED*	*Prob.*	*Prob.*
Barley, kg ha^{-1} P at GS31-45										
Balb-11 (31)	*3.9*	*4.8*	*3.7*	*0.35*	***0.017***	*3.7*	*4.5*	*0.29*	***0.008***	*NS*
Balb-11 (45)	*7.0*	*7.3*	*6.6*	*0.89*	*0.731*	*6.7*	*7.2*	*0.73*	*0.550*	*NS*
Hillh-14 (31)	*10.1*	*9.5*	*9.0*	*0.58*	*0.147*	*8.2*	*10.9*	*0.43*	**<.001**	*NS*
Stetc-12 (39)	*10.2*	*9.8*	*9.3*	*0.57*	*0.302*	*9.3*	*10.1*	*0.46*	***0.097***	*NS*
Wheat, kg ha^{-1} P at GS39-55										
Gain-13 (55)	16.2	16.2	17.7	*0.96*	*0.276*	16.2	17.2	*0.79*	*0.380*	*NS*
Terri-14 (39)	20.4	21.5	23.6	*1.33*	***0.061***	21.7	21.9	*1.09*	*0.892*	***0.034***
Oilseed Rape, kg ha^{-1} P at GS3,7										
Jaywick-14	17.3	16.8	19.0	*1.09*	*0.113*	18.4	17.0	*0.89*	*0.142*	***0.030***
Dunham-14	14.9	14.5	17.1	*1.34*	***0.022***	15.2	15.9	*1.10*	*0.353*	*NS*
Potatoes, kg ha^{-1} P at tuber-initiation										
Tamw'th-12	5.2	4.8	3.4	*0.60*	***0.013***	4.2	4.7	*0.49*	*0.297*	*NS*
Old Rayn-12	1.7	1.8	1.4	*0.21*	*0.197*	1.3	2.0	*0.17*	**<.001**	*NS*
Tamw'th-14	1.9	1.9	1.8	*0.21*	*0.758*	1.5	2.3	*0.16*	**<.001**	*NS*

The effect of fertiliser placement on early P uptake was just as small but was more consistent than the effect of fertiliser form (Table 6.15). In nine of the ten experiments average early P uptake with placement was greater than with broadcasting but the average overall effect of placement compared to broadcasting on crop P uptake was only +0.6 kg ha^{-1}! (Note that the amount of P applied was ~34 kg ha^{-1}, averaged over all treatments, so this only represents a small fraction.) At seven sites the effect of placement (or its interaction with P form) was statistically significant, although interestingly at two of these sites with autumn-sown crops

(Terrington & Jaywick; Table 6.16), placement only increased P uptake with struvite, and it tended to decrease P uptake with both TSP-based products.

Table 6.16. **Early P uptake (kg ha^{-1})** by winter wheat at Terrington and by oilseed rape at Jaywick in 2014, as affected by form and method of P application. The interaction between form and method of P application was statistically significant in both cases. Fitted P uptakes with nil P applied were 20.5 and 19.2 kg ha^{-1}. Mean P applied was 22.5 kg ha^{-1}.

	Winter wheat at Terrington		**Winter OSR at Jaywick**	
Product	*Incorporated*	*Placed*	*Incorporated*	*Placed*
TSP	21.8	19.0	18.7	15.8
Avail	22.0	21.0	18.5	15.2
Struvite	21.5	25.7	18.0	20.1
SED	*1.89*		*1.54*	

As already mentioned, fertiliser effects on P concentration were seldom large and tended to diminish as crops grew (Figure 6.1). Neither the different forms of P fertiliser nor their placement with the seed altered these effects, such that it was only with potatoes that there were any significant effects on P concentration in harvested biomass (Table 6.17), and these effects were small.

Table 6.17. **P concentration of harvested biomass (mg kg^{-1})** as affected by form and fertiliser P method application in ten experiments conducted in harvest seasons 2011 to 2014. The probability of effects being real is shown together with the SED, and the probability of a real interaction between fertiliser form and method. Statistically significant or near-significant (<0.1) probabilities are shown in **bold**.

Crop	**Fertiliser Form (F)**					**Application Method (M)**				**FxM**
Site & Year	***TSP***	***AV.***	***Stru.***	*SED*	*Prob.*	***B'cst***	***Plc'd***	*SED*	*Prob.*	*Prob.*
Barley										
Balbathin-11	1,783	1,892	2,176	183	0.120	1,933	1,968	150	0.817	0.694
Hillhead-14	3,939	3,679	3,883	85	0.011	3,882	3,786	69	0.177	0.385
Stetch'th-12	3,536	3,544	3,671	132	0.527	3,583	3,584	108	0.998	0.978
Winter wheat										
Gainsbro-13	3,485	3,483	3,392	156	0.780	3,434	3,473	127	0.773	0.642
Terringt'n-14	2,114	2,127	2,250	74	0.144	2,182	2,146	60	0.554	0.264
Oilseed rape										
Jaywick-14	4,718	4,903	4,991	155	0.213	4,847	4,894	126	0.717	0.037
Dunham-14	5,278	5,142	5,200	138	0.621	5,168	5,245	113	0.502	0.223
Potatoes										
Tamw'th-12	2,198	2,250	2,230	121	0.911	2,295	2,158	110	0.174	0.563
O Rayne-12	1,726	1,642	1,929	58	**<0.001**	1,779	1,753	47	0.589	0.751
Tamw'th-14	1,816	2,010	1,975	87	**0.073**	2,007	1,860	71	**0.045**	0.073

Notwithstanding this, there was substantial further P uptake (up to 16 kg ha^{-1} for cereals and oilseeds, and up to 22 kg ha^{-1} for potatoes) between the early crop sampling and final harvest at seven of the ten sites, and effects of fertiliser form on crop P uptake had become apparent with more consistency by harvest time (Table 6.18). In particular, struvite gave largest P offtakes at eight or nine of the ten sites and this difference was statistically significant at four of these. Only with the spring barley at Hillhead did struvite give a statistically significant *slightly smaller* P uptake compared to TSP. But overall struvite increased final crop P uptake by 1.4 kg ha^{-1} compared to TSP. (There were no significant interactions in final crop P uptake between form and method of P application).

By the time of harvest, the effects of placement on crop P uptake had rather diminished and none was still statistically significant, although final P uptake with placement was nevertheless still a little (~0.5 kg ha^{-1} on average) greater than with broadcasting at seven of the ten sites (Table 6.18). At Tamworth in 2012 P placement was achieved manually rather than with normal commercial machinery and this treatment was noted to inhibit growth and caused final P uptake to reduce by 2.5 kg ha^{-1}.

Table 6.18. **Crop P uptake at harvest (kg ha^{-1})** as affected by form and method of application of fertiliser P in ten experiments conducted in harvest seasons 2011 to 2014. The probability of effects being real is shown together with the SED, and the probability of a real interaction between fertiliser form and method. Statistically significant or near-significant (<0.1) probabilities are shown in **bold**. Results for Balbathin, Hillhead, and potato sites do not include straw or haulm P.

Crop	**Fertiliser Form (F)**					**Application Method (M)**				**FxM**
Site & Year	***TSP***	***AV.***	***Stru.***	*SED*	*Prob.*	***B'cst***	***Plc'd***	*SED*	*Prob.*	*Prob.*
Barley, kg ha^{-1} P in grain *(straw P not determined in Scotland)*										
Balbathin-11	*10.4*	*12.0*	*12.3*	*1.14*	*0.441*	*11.0*	*12.1*	*0.93*	*0.420*	*NS*
Hillhead-14	*21.6*	*19.8*	*20.1*	*0.43*	***<.001***	*20.2*	*20.8*	*0.35*	*0.121*	*NS*
Stetch'th-12	*24.8*	*25.1*	*25.0*	*0.79*	*0.951*	*24.6*	*25.3*	*0.64*	*0.264*	*NS*
Winter wheat, kg ha^{-1} in grain plus straw										
Gainsbro-13	24.1	23.7	25.7	*1.28*	*0.257*	24.4	24.5	*1.04*	*0.953*	*NS*
Terringt'n-14	21.0	20.9	22.5	*0.70*	***0.051***	21.7	21.3	*0.57*	*0.475*	*NS*
Oilseed rape, kg ha^{-1} P in seed plus straw										
Jaywick-14	20.2	21.6	22.2	*0.85*	***0.060***	21.7	20.9	*0.69*	*0.249*	*NS*
Dunham-14	30.9	31.1	32.0	*1.53*	*0.743*	31.1	31.6	*1.25*	*0.732*	*NS*
Potatoes, kg ha^{-1} P in ware yield										
Tamw'th-12	25.6	25.2	28.2	*1.95*	*0.274*	27.6	25.1	*1.59*	*0.132*	*NS*
O Rayne-12	10.9	10.3	12.7	*0.55*	***<.001***	11.0	11.7	*0.45*	*0.133*	*NS*
Tamw'th-14	22.6	24.1	25.6	*1.09*	***0.038***	23.9	24.3	*0.89*	*0.648*	*NS*

Overall there was a small effect of placement on early P recovery but this tended to be counteracted by reduced P uptake later so there was virtually no effect of placement on final P recovery. Also there were no statistically significant interactions in final P uptake between form and method of fertiliser application.

Turning from P uptake to effects of both form and method of application on final crop yields, both techniques caused significant effects (Table 6.19) but effects on yield did not necessarily relate to effects on P uptake. Struvite was not convincingly positive for yields of combinable crops; Balbathin gave a positive result, but the yields at Gainsborough were too variable be certain of an effect, and at Hillhead (the Scottish site with the least inherent soil P; Table 6.3) struvite gave significantly worse yields of spring barley than the TSP-based products. Struvite was only convincingly positive on potatoes, at Tamworth in 2012 by as much as 7 t ha^{-1}. AVAIL® tended to give lower yields at most sites than with just TSP but this decrease was only statistically significant with potatoes at Tamworth in 2014. The overall yield disadvantage of using AVAIL® was 2% and the overall advantage of struvite was 3%.

Table 6.19. **Harvested crop yields** as affected by form and method of application of fertiliser P in ten experiments conducted in harvest seasons from 2011 to 2014, with the probability of effects being real or there being a real interaction between fertiliser form (F) and method (M). Relevant SEDs are shown and near-significant (<0.1) probabilities are shown in **bold**.

Crop	**Fertiliser Form (F)**					**Application Method (M)**				**FxM**
Site & Year	***TSP***	***AV.***	***Stru.***	*SED*	*Prob.*	***B'cst***	***Plc'd***	*SED*	*Prob.*	*Prob.*
Barley, t ha^{-1} at 85% DM										
Balbathin-11	7.03	6.68	7.45	*0.256*	***0.028***	6.96	7.15	*0.209*	*0.380*	*NS*
Hillhead-14	6.54	6.34	6.05	*0.128*	***0.007***	6.10	6.52	*0.104*	***0.001***	*NS*
Stetch'th-12	7.66	7.63	7.42	*0.133*	*0.153*	7.42	7.72	*0.108*	***0.010***	*NS*
Winter wheat, t ha^{-1} at 85% DM										
Gainsbro-13	7.15	7.02	7.86	*0.583*	*0.310*	7.37	7.31	*0.476*	*0.904*	*NS*
Terringt'n-14	8.31	8.27	8.30	*0.113*	*0.933*	8.39	8.19	*0.092*	***0.040***	*NS*
Winter oilseed rape, t ha^{-1} at 91% DM										
Jaywick-14	4.00	3.93	4.06	*0.076*	*0.243*	4.08	3.92	*0.062*	***0.016***	*NS*
Dunham-14	5.14	5.23	5.10	*0.096*	*0.371*	5.17	5.13	*0.079*	*0.587*	*NS*
Potatoes, t ha^{-1} ware										
Tamw'th-12	32.9	32.3	39.7	*1.77*	***<.001***	36.6	33.4	*1.45*	***0.034***	***0.002***
O Rayne-12	24.5	24.7	25.3	*1.15*	*0.787*	23.7	26.0	*0.94*	***0.021***	*NS*
Tamw'th-14	42.4	38.7	43.1	*1.47*	***0.011***	39.7	43.1	*1.20*	***0.009***	*NS*

Placement gave significantly better yields than broadcasting at two barley sites and two potato sites but it gave slightly worse yields than broadcasting in the four autumn-sown wheat and OSR experiments, significantly so at one wheat (Terrington) and one OSR site (Jaywick). Both of these latter two were sites where early P uptake had been particularly successful anyway, and placement enhanced early P uptake further. The effects of placement on potatoes were up to 3 t ha^{-1} but placement by hand at Tamworth in 2012 did also decrease potato yield significantly. This arose principally because placement of TSP (rather than other forms) decreased yield significantly; there was a statistically significant interaction with fertiliser form here (There just remains a question as to whether placement might be slightly detrimental to yield where crops are predicted to be successful in acquiring ample P during early development. There is no indication here of how such detrimental effects might be caused, but in general, early P uptake would be most likely to arise where soil P levels are inherently high, soil conditions are conducive to good plant establishment and a highly soluble form of fertiliser P is used. Note that the Dunham site here had the greatest soil P level of all seven English sites (16 mg L^{-1}); however, the soil P level at Terrington was low (9 mg L^{-1}), yet this site still showed a negative effect of placement.

Table 6.20) such that yield was probably increased if struvite was placed. The yield decrease due to TSP placement was probably due to the manual method of placement used, as explained previously.

There just remains a question as to whether placement might be slightly detrimental to yield where crops are predicted to be successful in acquiring ample P during early development. There is no indication here of how such detrimental effects might be caused, but in general, early P uptake would be most likely to arise where soil P levels are inherently high, soil conditions are conducive to good plant establishment and a highly soluble form of fertiliser P is used. Note that the Dunham site here had the greatest soil P level of all seven English sites (16 mg L^{-1}); however, the soil P level at Terrington was low (9 mg L^{-1}), yet this site still showed a negative effect of placement.

Table 6.20. **Ware potato yield (t ha^{-1})** at Tamworth in 2012, as affected by form and method of application of fertiliser P.

Product	**Incorporated**	**Placed**
	t ha^{-1} ware	
TSP	38.3	27.5
AVAIL	33.0	31.6
Struvite	38.4	41.0
SED	*2.51*	

6.3.2 P Targeting Experiments

Description of the results from the Ropsley long-term site in Lincolnshire will consider first how successfully the topsoil P levels were built up by large applications of P_2O_5 as TSP in 2010-2011, then it will address the growing conditions over the two seasons of experimentation, and lastly it will assess whether effects of the 'targeted' P treatments could be detected.

6.3.2.1 The range and stability of soil P levels

Interpretation of soil P results from Ropsley must acknowledge that this site is generally not ploughed; crops are drilled after some cultivation, but the soil is not inverted. Hence the mixing of P fertiliser into the seedbed after its application may be limited and may not be uniformly distributed through the depth of soil sampling (0.15m). Nevertheless, cultivations and sampling depths have both been maintained constant at the site over the period of these experiments.

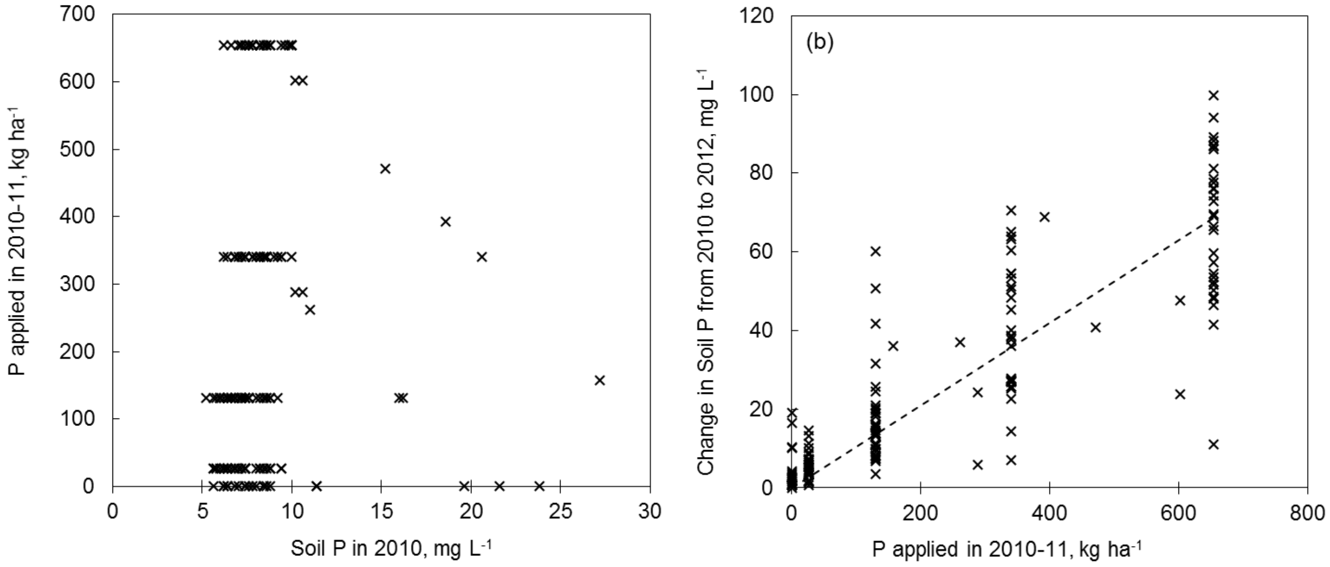

Figure 6.2. (a) Initial soil P status at Ropsley, Lincolnshire in 2010-11 with amounts of fertiliser P applied, and (b) the changes in soil P caused by these in 2012 when the P targeting experiments were established. The fitted line (dashed) has a slope of 0.105 (R^2=0.73); if considered to the sampled depth this equates to 21% of P applied.

In 2010, excluding 9 plots with high values (ranging from 15 to 27 mg L^{-1}, which will be called 'outliers' below), soil P analysis showed levels across all 162 plots at the Ropsley site ranging from 5 to 11 mg L^{-1} and averaging only 8 (median 7) mg L^{-1} (Figure 6.2a). Thus the soil of almost all plots had become seriously depleted of 'available' P over the ~15 year period since a range of soil P levels had been maintained by regular TSP applications (Hatley, 1999). The quantities of fertiliser P deemed necessary to build the range of soil P levels necessary for the first experiment in 2013 were 26, 131, 340 and 655 kg ha^{-1} (60, 300, 780 & 1,500 kg ha^{-1} P_2O_5). All, except three outlier plots, received some fertiliser at one of these rates. Ten plots, including most of the remaining outliers, received other intermediary rates of fertiliser.

By autumn 2011, there was a good relationship (R^2 0.67) between increases in soil P and amounts of P applied, and this relationship was maintained through to autumn 2012 (Figure 6.2b); on average soil P analyses in 2011 and 2012 showed soil P had increased by around 0.1 mg L^{-1} per kg ha^{-1} P applied, although average soil P levels in 2012 were about 10% less than those measured in 2011. Thus by autumn 2012 the plots were exhibiting a range of soil P levels from 5 to 107 mg L^{-1} (median 23 mg L^{-1}). From these 162 plots, a set of 99 was selected for the targeting experiments, having soil P ranging from 5 to 35 mg L^{-1} (median 15 mg L^{-1}). This set of 99 excluded all but one of the plots receiving the largest amount of fertiliser P because it was thought that their high soil P levels would mask any effects of the crop-targeting treatments. The unselected plots were not reanalysed for soil P subsequently but, in autumn 2014 after the experiments were complete, reanalysis of the 99 selected plots (with four plots excluded because they showed peculiarly large soil P) showed that the median soil P level had decreased over the two seasons by 1.1 mg L^{-1} to 13.7 mg L^{-1}, whilst the range was sustained (being 6 to 43 mg L^{-1}). [NB It is evident that plots with less soil P in 2012 tended to show increases by 2014, whilst larger values in 2012 showed decreases along with increased variability in 2014, so it is possible that soil analysis for the 2014 results was positively biased compared to the 2012 analysis, hence the 2014 results may mask a larger real decrease in soil P during the two experiments, since there is no evident reason why the low soil P values should increase during these experiments.]

Changes of 0.1 mg L^{-1} in soil P per kg^{-1} ha^{-1} P applied equate to about 24 kg^{-1} ha^{-1} P_2O_5 applied per 1 mg L^{-1} change in soil P; this compares with similar values deduced from a recent analysis of a commercial soil P database (Rollett *et al.*, 2016; median 21, inter-quartile range 15-26 kg^{-1} ha^{-1} per mg L^{-1}), and with a larger value (~40 kg^{-1} ha^{-1} P_2O_5 applied per 1 mg L^{-1} change in soil P) suggested in the Fertiliser Manual (Defra, 2010).

6.3.2.2 Establishment and crop growth

Barley established well in spring 2013. However, P deficiency symptoms appeared in patches and these appeared severe in some low P plots by 27 June (GS49). An attempt was made with NDVI scanning on 2 July (GS59) to quantify these symptoms; reflectance values were unusually small for this stage and red reflectance sometimes exceeded near infra-red reflectance, giving some negative values of NDVI, especially on plots low in soil P. The significant correlation with soil P (Table 6.21) indicates that red reflectance was probably associated with the P deficiency symptoms seen.

None of the relationships shown in Table 6.21 accounted for a large proportion of the variation because (i) the data related to individual plots, (ii) the soil P data were evidently imprecise (soil P in 2012 was on average 0.9 of values in 2011 but they only accounted for 45% of variation at the plot level), and (iii) the experiment was affected by variable waterlogging and weed infestations.

Table 6.21 Statistics relating to effects of soil P and targeted P treatments (seed-dressings or / and foliar-sprays) on performance of spring barley and winter wheat in experiments conducted in successive seasons on the long-term P experiment site at Ropsley in Lincolnshire.

Site & Variate	*Units*	**Inter-cept**	**Mean** (all plots)	**Soil P effect** *Prob.*	**Var. Acc. for** *%*	**Slope due to soil P** *per mg L^{-1}*	**Prod-uct effect** *Prob.*
Spring barley 2013							
NDVI	*ratio*	0.00	0.16	0.019	26	0.018	0.510
Biomass @ GS39	*t ha*$^{-1}$	3.7	5.1	<0.001	40	0.081	0.585
P in biomass @ GS39	*%*	0.13	0.15	0.003	8	0.0013	0.979
P uptake @ GS39	*kg ha*$^{-1}$	4.29	7.65	<0.001	33	0.20	0.803
Straw P @ harvest	*% DM*	0.04	0.04	0.175	NA	NA	0.797
Grain P @ harvest	*% DM*	0.20	0.22	0.01	6	0.0009	0.680
Grain P @ harvest	*kg ha*$^{-1}$	5.0	10.8	<0.001	24	0.525[1]	0.872
P uptake @ harvest	*kg ha*$^{-1}$	5.5	12.5	<0.001	22	0.654[1]	0.849
Biomass @ harvest	*t ha*$^{-1}$	5.08	9.35	<0.001	24	0.426[1]	0.892
Grain yield @ 85%DM	*t ha*$^{-1}$	4.65	5.78	<0.001	27	0.067[2]	0.570
Winter wheat 2014							
NDVI in January	*ratio*	0.20	0.22	<0.001	17	0.0034[1]	0.764
NDVI in March	*ratio*	0.17	0.20	<0.001	20	0.0017[1]	0.858
NDVI in April	*ratio*	0.26	0.41	<0.001	22[3]	0.0142[1]	0.043
Biomass @ GS39	*t ha*$^{-1}$	4.47	4.75	0.081	13[3]	0.033	0.007
P in biomass @ GS39	*%*	0.11	0.11	0.618	NA	NA	0.709
P uptake @ GS39	*kg ha*$^{-1}$	4.7	5.52	0.171	1	NA	0.119
Straw P @ harvest	*% DM*	0.02	0.02	0.018	6	0.000[1]	0.987
Grain P @ harvest	*% DM*	0.17	0.16	0.756	18[3]	NA	<0.001
Grain P @ harvest	*kg ha*$^{-1}$	0.9	6.1	<0.001	15	0.375[1]	0.715
P uptake @ harvest	*kg ha*$^{-1}$	1.3	6.5	<0.001	17	0.381[1]	0.725
Biomass @ harvest	*t ha*$^{-1}$	-1.26	6.18	<0.001	17	0.114[2]	0.742
Grain yield @ 85%DM	*t ha*$^{-1}$	1.03	3.58	<0.001	15	0.238[1]	0.923

[1] an additional quadratic term was also significant, but is ignored here.
[2] this is the linear slope. An exponential function fitted significantly better than a linear function.
[3] includes the significant effect of products.

However, soil P certainly did have major effects, including on crop P uptake at GS39 in 2013, mean values ranging from 5 to 11 kg ha^{-1} over the soil P range from 5 to 35 mg L^{-1}. This uptake was expressed mainly as extra biomass; P concentration of the biomass at GS39 was only slightly affected by soil P and P concentration was generally less than 0.2% even at 35 mg L^{-1} soil P. Only six of the 99 plots showed P concentrations exceeding 0.2%; these were spread across all levels of soil test P from 8 to 34 mg L^{-1}, but five of these were amongst plots receiving 340 kg ha^{-1} or more of fertiliser P in 2010-11.

After sowing in late September 2013, establishment of winter wheat in the second experiment was good, but plants appeared relatively small and pale by November with much leaf browning; visual scores of crop density and leaf colour did not significantly relate to soil P so the symptoms were probably due to waterlogging which particularly affected the NW section of the experiment. Fitted relationships between NDVI scans in January or March with soil P (measured in 2012) showed that the range of soil P was having small but significantly positive effects on crop growth (Table 6.21).

By April, infestations of blackgrass and wild oats had become severe, especially in areas with weak crop growth. The NDVI scan in April showed larger effects of soil P and also some small but significant effects of P targeting treatments (Table 6.21; Figure 6.3).

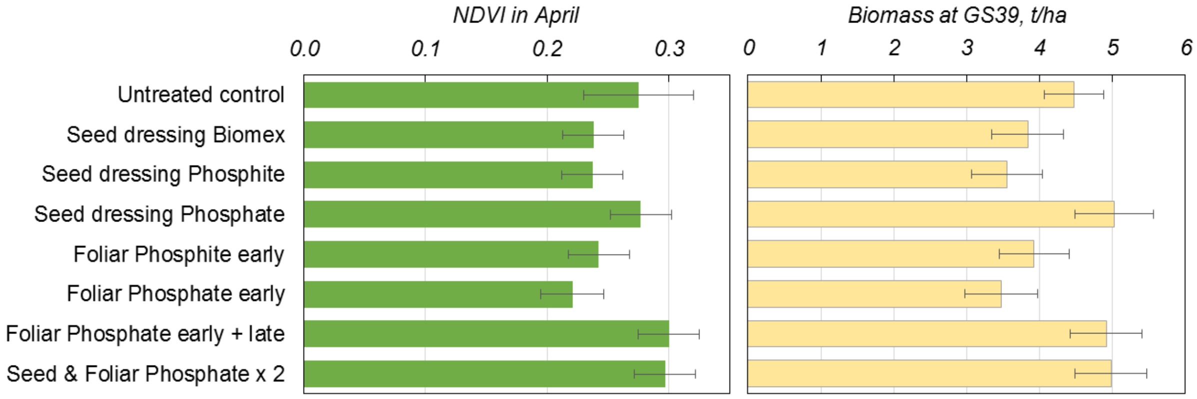

Figure 6.3. Effect of crop P targeting treatments at Ropsley in 2014 on NDVI of winter wheat in April and biomass at flag leaf emergence stage (GS39). Errors bars indicate 2 x SE.

Then, through the summer, growth was clearly poor and patchy, and was especially poor in the outer rows of many plots. Crop samples taken at GS39 showed overall P uptake was much less than in 2013 at 5 kg ha^{-1}, and there was hardly any effect of soil P on this; biomass was less than 5 t ha^{-1}, and its P content was very poor at 0.11%. There were some small effects of P targeting treatments (Table 6.21) which were in line with the effects seen in NDVI in April (Figure 6.3), but these were not large and arose as much through the early foliar phosphate spray reducing biomass compared to the control, as with increases in biomass associated with the late foliar phosphate spray. The phosphate sprays were not noted as affecting leaf condition, say through scorch.

Biomass P levels of 0.15% in 2013 and 0.11% in 2014 (Table 6.21) were so small that all plots must have been suffering from serious P deficiency throughout both experiments. There were significant responses to increasing soil P in all measures of crop biomass growth and in grain yield but, given that even the plots with >30 mg L^{-1} soil P were still showing biomass P concentrations at GS39 commensurate with deficiency, it is doubtful whether any plot tested in these experiments should be considered as having had an adequate supply of soil P for uninhibited growth, and the generally poor growth (and low grain yields; see below) must be partly attributed to P deficiency, even though (especially in 2014) there were clearly other contributory factors, such as weeds.

It appears that, even though Olsen's analysis both before and after the experiments showed levels of soil P which would normally be considered adequate for crop growth, quantities of P which the crops could acquire from the soil were clearly insufficient for the crop to respond in biomass as well as building tissue P to levels considered adequate for optimal tissue function.

6.3.2.3 Soil P effects on final P uptake and yield

By harvest in 2013 the spring barley plots showed a strong response to soil P with up to 19 kg ha^{-1} P being acquired at the higher levels of soil P compared to about 8 kg ha^{-1} with the lowest soil P levels. A high proportion of final P uptake (80-90%) was in the grain, and grain P concentrations generally just exceeded 0.2%, with a slight positive effect of soil P Table 6.21). However, the effect on P uptake was mainly expressed in terms of total biomass and harvested grain; these increased from about 7 to 11 t ha^{-1} and 4 to 6 t ha^{-1} (Table 6.21; Figure 6.4) respectively as soil P levels increased from less than 10 to more than 20 mg L^{-1}.

Final performance of the winter wheat crop in 2014 was poor, and markedly worse than the spring barley in the previous season (Figure 6.4); nevertheless there were strong effects of soil P. For example, although final P uptake was less than half of P uptake in 2013, as soil P increased from less than 10 to more than 20 mg L^{-1}, total P uptake increased from about 2 to 7 kg ha^{-1} and related well to the previous pattern of P uptake in 2013 ($R^2 = 45\%$), total biomass also increased from 4 to 8 t ha^{-1} in 2014, and grain yield increased from 2 to 4 t ha^{-1}.

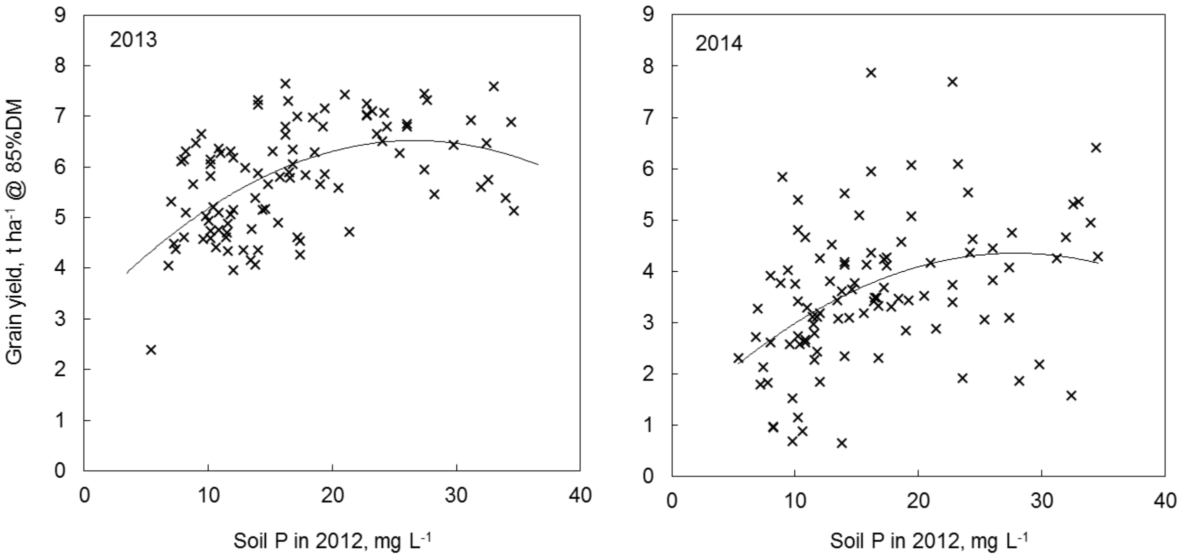

Figure 6.4. Relationship of grain yield in 2013 (spring barley) and 2014 (winter wheat) with soil P measured in 2012. The lines are quadratic fits (R^2 = 30% in 2013 and 17% in 2014) which give soil P optima of 26 and 27 mg L^{-1} respectively, assuming a soil 'requirement' of 20 kg P_2O_5 ha^{-1} mg^{-1} P L^{-1}, P_2O_5 costs £0.65 kg^{-1}, and the grain price is £110 t^{-1}. There were no significant effects of targeted fertiliser P products in either season.

6.3.2.4 Effects of plant-targeted P treatments

Given the small amounts of P applied in the Targeting treatments (Table 6.6), their uptake needed to be very efficient to affect P uptake, biomass growth or yield in these two relatively imprecise trials. The most precise variates showed coefficients of variation (CVs) of ~15% and most datasets showed CVs exceeding 20% in these experiments. Thus in the event, there were only a few instances where significant effects were detected (Table 6.21, right-hand column), and these appeared to arise through negative effects of Biomex and phosphite, rather than positive effects of phosphate seed dressings or foliar treatments (Figure 6.3).

The pattern of these negative effects was similar between the treatments, indicating that they did not arise through errors in measurements. No scorch effects were noted from foliar treatments, so, if the effects were real, it seems likely that both of these products may have caused some more subtle inhibition of growth. In 2014 the targeting treatments had no significant effects, except there were some slight and negative significant differences in grain P concentration (compared to the control); however, the maximum difference in grain P between two treatments was only 0.02%DM and the statistical significance of this test might have arisen by chance.

Thus overall the targeting treatments were unsuccessful in improving crop performance. Note that a two foliar spray treatment[3] providing a total of 6.6 kg ha^{-1} P was also tested on spring barley in the 'response' experiment at Balbathin in 2011, but without causing any significant effects on the crop.

6.3.3 **P Run-Down Experiments**

Whilst they were not used to test targeted P treatments in this project, preparation of the four run-down sites for future research on P efficiency did provide soil P results relevant to soil P management. Mean soil P results for both the maintenance and the run-down treatments are shown for each site in *Figure 6.5*. There was significant annual variation in the soil P levels of both treatments at all sites, as was shown previously for two calcareous sites in the 1980s (Withers *et al.,* 1994). Differences in soil P between the treatments appeared to arise in the first season at the two western sites, whereas they appeared to arise more gradually at the two eastern sites. By harvest 2015 significant differences in soil P between maintenance and run-down treatments had developed at all sites, but in contrast to the previous study (Withers *et al.,* 1994) all plots at all sites were still at P Index 2 (16-25 mg L^{-1}) or more at this stage, treatment differences were relatively small in relation to the annual variation, and there were no clear patterns of soil P decrease due to the 'run-down' treatment at any site; i.e. treatment differences appeared arise more through soil P increasing in the maintenance treatment, rather than soil P decreasing in the run-down treatment. This was most clearly the case at Boxworth. Thus the decision was taken to delay the use of any of these sites (for testing P Targeting Strategies) until autumn 2016 at the earliest (and this would be undertaken under the separate 'Cost effective P' project: AHDB Research Project 2160004).

Once the run-down plots have decreased convincingly to Index 1, and there is sufficient and sustained evidence of a difference between run-down and maintenance plots, then two of the four run-down sites will be used to compare optimised fertiliser strategies involving combined Targeted P application methods in replicated field experiments. Treatment effects on crop P uptake during the growing season, final yield and grain quality will be compared with fertilised and unfertilised controls and P-use efficiencies will be calculated. These experiments will now be reported separately (under AHDB Research Project 2160004).

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[3] The crop had two applications in early May and mid-June of Folex P at 7 l/ha (11:47:0 w/v), delivering 3.29 kg ha^{-1} P each.

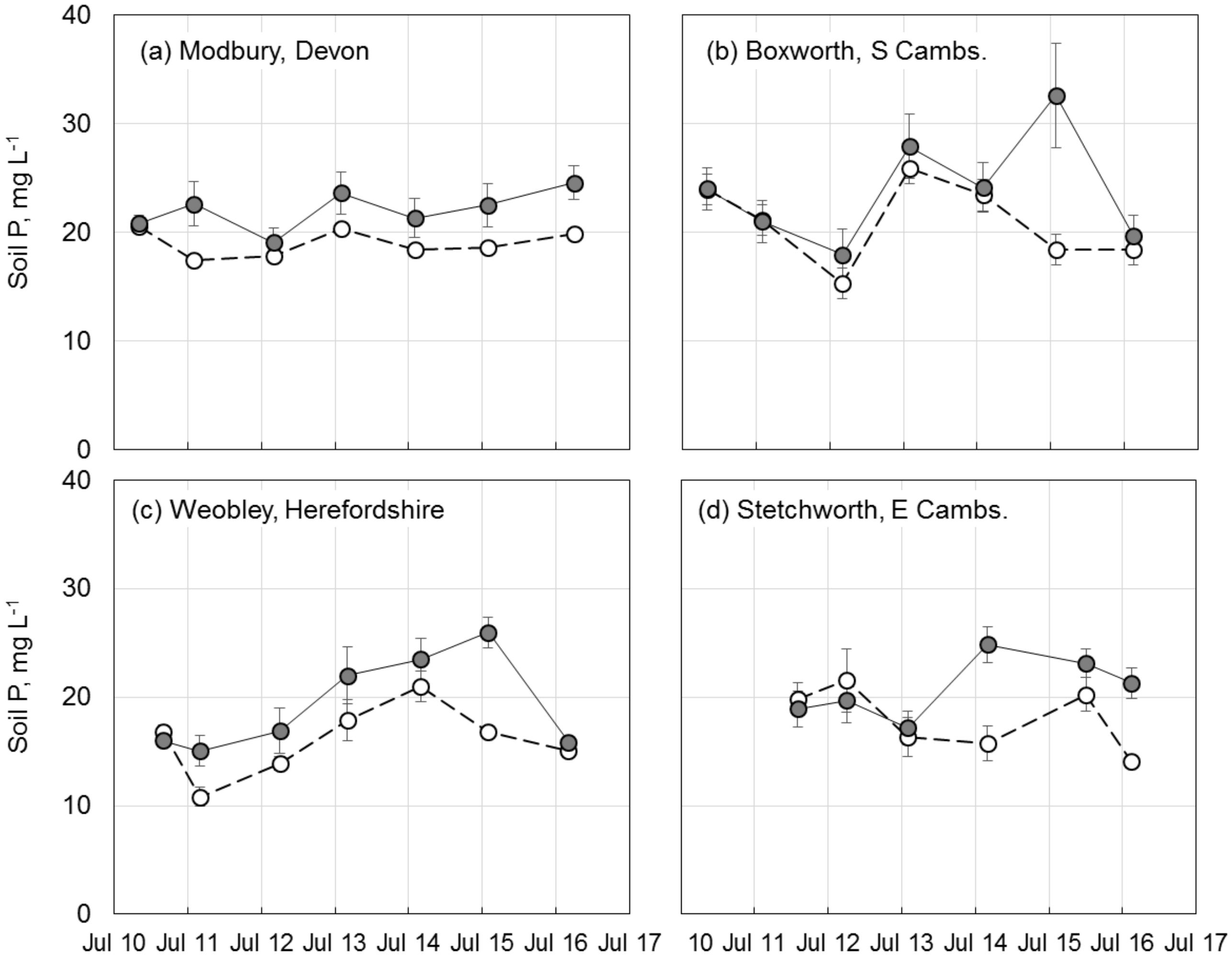

Figure 6.5. Development of differences in soil P between 'maintenance' (closed circles) and 'run-down' (open circles) treatments at four sites from 2010 to 2016. Both treatments were cropped annually; run-down treatments had no P applied. Error bars = 2 SEs.

6.4 Discussion

The main aim of the field experiments reported above was to test ideas for improving the effectiveness of 'fresh' fertiliser P applications i.e. increasing the immediate response of the crop for (or to) which they are applied. In introducing this work, we proposed that efficiencies of fresh P fertilisers need to be analysed and understood in terms of estimated 'gaps' between the total 'demands' of crops for P and the inherent 'supplies' of P from that stored in soils (without any 'fresh' fertiliser or manure being applied). Hence this discussion will first consider evidence relating to P demands and supplies, before considering attempts to improve P fertiliser efficiencies.

However, before entering into the discussion, it should be noted that this 'balance' or 'gap' approach to crop P nutrition, whilst being slightly more sophisticated than the current approach (in RB209; Defra, 2010) which does not directly address fertiliser efficiency, represents a gross simplification of the many processes and factors known to influence optimal crop nutrition. The 'gap' approach is nevertheless adopted here because it has proved useful in supporting the nutrition of crops with other nutrients, most notably nitrogen (Sylvester-Bradley, 2009; Sylvester-Bradley & Withers, 2012), particularly through providing a straightforward framework for separating the effects of crop, soil and fertiliser. However, as with nitrogen nutrition, it must be acknowledged that static estimates of both the demand and supply of P must grossly simplify the complex interacting dynamic processes that accompany the growth and nutritional responses of any crop. Of particular importance here are:

- Interchange between available and unavailable nutrient forms in soil,
- Effects of soil conditions, especially water content and temperature, on nutrient availability, and spatial heterogeneity of nutrient availability in soil, e.g. decreasing P with depth.
- Root extension and proliferation causing progressive crop exploration of soil.
- Responses of root growth and function to the spatial heterogeneity of nutrients in soil,
- Influences of root or microbial exudates on nutrient availability,
- Symbiotic effects of mycorrhizae on crop nutrient capture,
- Crop growth as affected by solar radiation, soil water content (hence rainfall) and temperature.
- Crop storage of nutrients, for example as inorganic ortho-phosphate in vacuoles of leaf tissues, or as phytates (*myo*-inositol hexakisphosphate, or $InsP_6$) in seeds and tubers.
- The progressive shift through crop development from formation of metabolic tissues with high P contents to formation of structural (e.g. cellulose and lignin) and storage (e.g. starch, oil, protein) compounds with low P contents.

Over and above the modelling work in this project (Section 5), many attempts have been made to model many of these factors and processes, incorporating their temporal, and sometimes also their spatial, inter-relationships in systems of algebraic formulae (e.g. Lynch *et al.*, 1997; Greenwood *et al.*, 2001a; 2001b; 2008). However, for various reasons, none of these has achieved a significant role in commercial crop production, so our analysis here favours use of simple concepts that can be easily communicated for use in the largely unautomated mental reasoning and decision-making processes of commercial farmers and other practitioners. Crude separation into (i) crop P demand, (ii) soil P supply and (iii) fertiliser P efficiency at least distinguishes the three main factors underlying any evaluation of fresh applications of P fertilisers.

6.4.1 **Crop P Demands**

Crop nutrients which are manipulable, such as P, need not constrain crop growth or productivity; rather, the limits to productivity (hence potential demands for nutrients) are generally set by availability of 'given' (unmanipulable) resources such as light energy and water, and by the ability of the particular genotype and the particular farming system to enable capture of these by the crop and convert them into harvestable biomass. P has many essential metabolic roles in support of processes effecting resource capture and conversion, but these are not sufficiently well quantified to enable confident estimation of a specific crop P demand for a specific genotype-by-environment combination. Demand is therefore best estimated empirically. Here we propose this should be done by:

i. Taking the maximum quantity of biomass that was produced in the experiment (derived from the statistics in Table 6.12), and
ii. Multiplying this biomass quantity by the 'critical' concentration of crop P (the minimum thought to be compatible with uninhibited crop growth, as discussed and summarised below).

However, in each case it was necessary also to:

iii. Check observed crop P concentrations (Table 6.13) against those reported in the literature for any indication that maximal crop growth at a site was generally limited by P supply, and
iv. In cases where it seems likely that the crop was generally (in all treatments) limited by P supply, deduce a potential biomass production from external evidence e.g. the farm yields of that crop in that region in that year (e.g. as reported nationally by Defra; Table 6.10).

There is an extensive literature specifying 'critical' shoot P concentrations in various crops. These were usefully summarised for the UK by Barraclough *et al.* (1999), and show some significant variability. However, Barraclough and co-workers conducted their own studies of the scope for monitoring P status of growing crops directly, by sampling shoots, leaves or petioles (unfortunately they did not include P contents of grain, seed or tubers), and they deduced best approaches to the definition of 'critical' P concentrations for both wheat and OSR in the UK (Barraclough *et al.*, 1999; Bollons & Barraclough, 1999; Major & Barraclough, 2001). As part of this work they showed that crops store P in shoot tissues (as inorganic ortho-phosphate) and they explored whether this P provided a more useful criterion for diagnosis of P status, beyond simple analysis of %P in shoot DM. They concluded that the best value indicating critical P status of wheat was 0.32% in DM of the youngest fully expanded leaf during stem extension (GS31-39), and the best for OSR was 0.45% P in DM of any expanded leaf taken from the middle of the canopy at the rosette stage, decreasing to 0.22% P at the yellow bud stage. P contents of whole shoots were less reliable than sampled leaves but, the ranges of critical P concentrations in DM in their whole shoot data are useful for comparison with results here (and for definition of crop P demands, below) and were 0.22% to 0.34% for wheat at GS39 and 0.21% to 0.28% for OSR just before flowering (GS3,3 to 3,7).

Bolland & Brennan (2005) reported similar critical P concentrations for barley in Australia (as well as for oats, triticale and lupin) as did Mazza *et al.* (2012) for ryegrass with >3 t ha^{-1} biomass in Brazil. As regards potatoes, recent studies in Argentina have been made to develop a 'P nutrition index' (Zamuner *et al.*, 2016), analogous to the N Nutrition Index widely used for N management in France and elsewhere (Lemaire *et al.*, 2008). Here it was deduced that critical shoot P concentrations (Pc; g kg^{-1} DM) could be summarised in terms of total crop DM (TDM, t ha^{-1}) by the expression

$$Pc = 3.919*TDM^{-0.304},$$

thus potato crops with five or more t ha^{-1} vegetative biomass would have critical P concentrations of 0.2 to 0.25%, similar to those of other crop species. Hence, when estimating crop P demands here, it seems that a summary value for critical P concentration in whole shoots (at the stage when yield formation starts) can be taken as ~0.25% for all crop species.

The critical P concentration can be multiplied by the concurrent biomass quantities to give P demands of crops just before their yield formation starts, and this can be taken to represent the P requirements for all the photosynthetic activity necessary to support yield formation, since (in determinate crops) no further vegetative or floral structures are formed after flowering. However, a full description of crop P demand must also address the P requirements of the generative organs that normally constitute the harvestable 'yield', and the extent to which vegetative P is redistributed to the generative organs (P harvest index).

Minimum or 'critical' P concentrations prove more difficult to specify here because a large proportion of the P in generative organs is stored in the form of phytate (Eklund, 1975; Phillippy *et al.*, 2004; Raboy, 2009) which is not essential for yield formation and does not add value to the saleable produce, except when it serves to support crop regeneration i.e. where it is to be used for 'seed' (whether a true seed or a vegetative propagule such as a 'seed' tuber) rather than for food, feed or fuel. It is not even certain that phytate adds value to seeds in normal arable conditions since seedling performance has not been found to differ significantly with seeds of different P contents (Burnett *et al.*, 1997; Rose *et al.*, 2012). However, it must be recognised that, with current commercial germplasm (unselected for low phytate), crops store some phytate even if they are P deficient, (e.g. Lickfett *et al.*, 1999; Figure 6.6). Thus it must be assumed here that the P in generative organs must include some phytate and that, for the time being, critical values must be determined empirically, rather than by inferring quantities according to their essential or inessential physiological functions.

Evidence of critical P concentrations in generative tissues is surprisingly sparse compared to evidence for vegetative tissues (or soil); Barraclough and co-workers did not study this in their work in the late 1990's and grain P concentrations were not measured in the recent AHDB work on critical soil P (Johnston & Poulton, 2011; Knight *et al.*, 2014). Probably the best evidence is that reported by Bolland & Brennan (2005) who derived mean diagnostic critical P values in Australia of 0.27% for oats (range 0.18–0.39%), 0.32% for barley (range 0.23–0.35%), and 0.22% for triticale (range 0.19–0.25%). For potato tubers, van der Zaag (1992) suggests a similar standard concentration of 0.3%, but the work of Lickfett *et al.* (1999) indicates a larger critical concentration of 0.4% for rapeseed (Figure 6.6). This work was in pots so may not relate well to field-grown crops, but it seems logical to expect a larger critical P concentration for oil-rich seeds than for starchy seeds, due to their greater energy density (Berry & Spink, 2006).

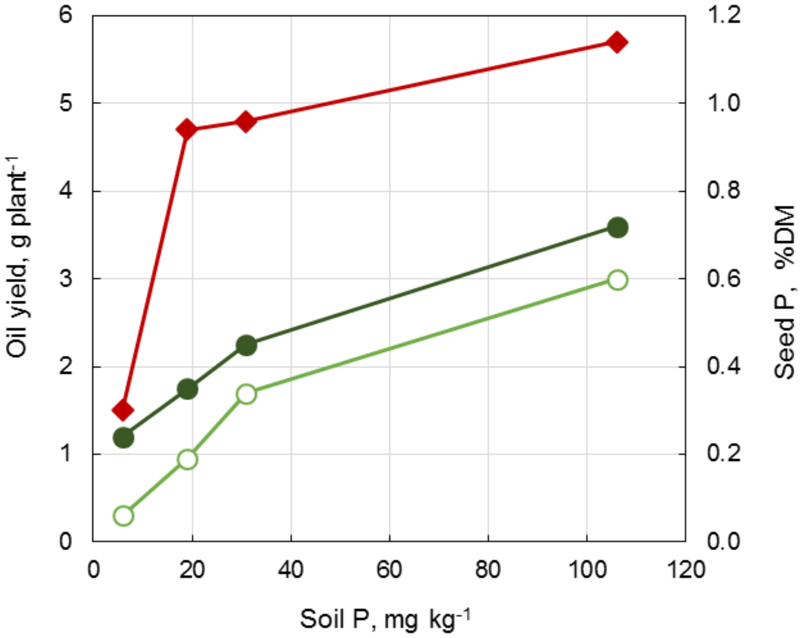

Figure 6.6. Effect of soil P, as affected by fertiliser P in a pot experiment, on oil yield (diamonds), seed P (closed circles) and seed phytate P (open circles) of oilseed rape (mean of two varieties, Bristol & Lirajet), after Lickfett et al. (1999). Oil yields at the top three P rates were not significantly different; all seed P values were significantly different.

Comparing these critical P concentrations with those observed in the ten Response experiments (Figure 6.7), five crops, including all of the potato crops, appeared to be deficient in P during their vegetative development (Figure 6.7a), and the same crops appeared to have been deficient in P during yield formation (Figure 6.7b). (Note that 0.25% P can be taken as the critical P concentration of vegetative biomass of all the species here, including potatoes. However, because the potato crops here were sampled early, when their total biomass was only 0.5-1.2 t ha^{-1}, the equation of Zamuner *et al.* (2016) predicts critical concentrations of 0.32-0.39% P in biomass.) It is possible that critical P concentrations in potato *tubers* from UK crops are substantially less than the norm of 0.3% quoted by van der Zaag (1992) but nevertheless it is difficult to imagine that critical P concentrations in potato tubers would be as low as 0.2%, so it seems likely that these three potato crops were P deficient throughout their growth.

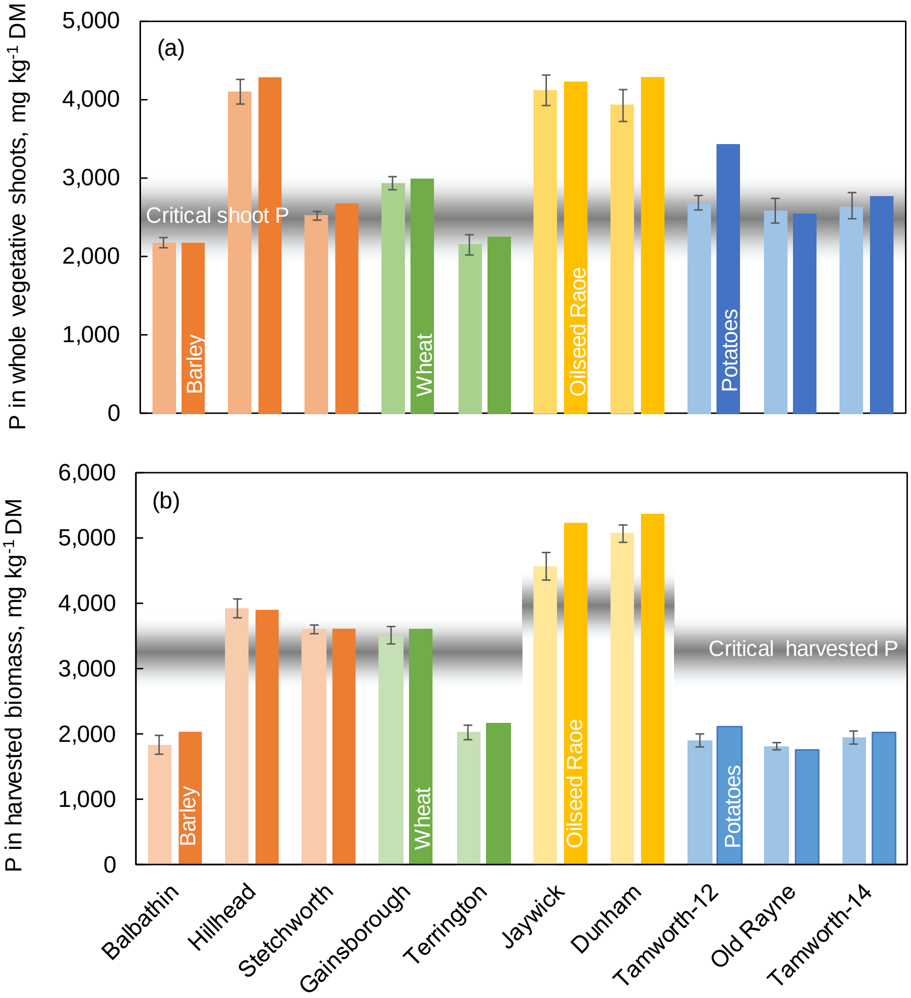

Figure 6.7. Comparison of crop P concentrations in the Response experiments (light colours, nil P applied; dark colours, with 50 kg ha^{-1} fresh broadcast P) with critical (a) crop or (b) harvested P concentrations (black horizontal bands) derived from the literature, showing the prevalence of P deficiencies, and small responses to fresh fertiliser P. The colour code is brown (barley), green (wheat), yellow (oilseed rape), and blue (potatoes).

Out of the ten cases tested in the Response Experiments here (Figure 6.7), crop P analysis would have provided helpful predictions of yield responses to fresh P in only one case, and it would have been misleading in two cases (Hillhead & Jaywick). However, due to the ineffectiveness of fresh P fertilisers and the small size of potential crop responses compared to experimental error, it was difficult to conclude whether crop P analysis would be helpful in the remaining seven cases. To illustrate, both crops grown at Ropsley were undoubtedly responsive to increasing soil P and crop analysis would have identified these deficiencies, but there was were no positive responses to targeted P treatments here.

At the levels of critical grain, seed and tuber P summarised here, quantities of P in these generative organs, expressed on a land area basis, would appear to substantially exceed quantities required to support canopy functions. If the critical P concentration in vegetative tissues is taken to be ~0.25% (as above), and that in generative tissues is taken as ~0.32% (and if straw or haulm P at harvest is 0.06%), the total amount of vegetative P will only exceed the total P in generative organs if the biomass harvest index is small (<0.3; Figure 6.8), which is rare in UK conditions and is normally associated with low crop yields (<3 t ha^{-1}) e.g. in drought-affected regions. Thus it seems that with higher yielding crops in the temperate UK, crop P demand should be defined largely as the product of potential yield and a critical P level in generative tissues; evidence here and in the literature shows that P Harvest Indices tend to be high (mean 83%; range 71-92%), due to almost complete redistribution of the vegetative P – straw or haulm P concentrations here tended to be of the order of 0.06% (range 0.039% to 0.080%), only about half of that assumed in the Fertiliser Manual (RB209; Defra, 2010).

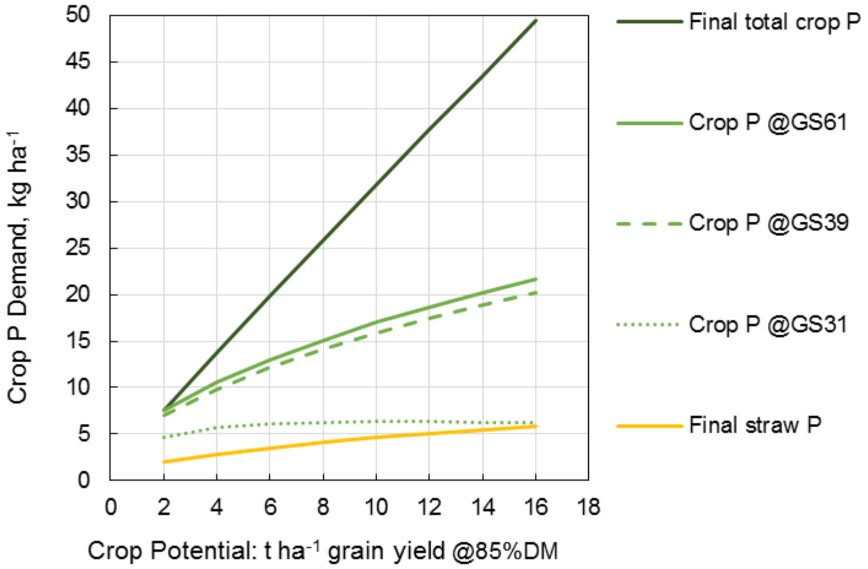

Figure 6.8. Predictions of how crop P demands of wheat relate to potential grain yields of up to 16 t ha^{-1} (the recent world record), with associated demands at intermediary growth stages (GS) and quantities of final straw P. Assumptions are explained in the text.

Based on these conclusions it is possible to calculate final and interim crop P demands for wheat, assuming [from a range of literature (Beed *et al.*, 2007; Sylvester-Bradley *et al.*, 2008; Clarke *et al.*, 2012) and recent summary data from the Yield Enhancement Network (Sylvester-Bradley & Kindred, 2014)] that:

- Harvest Index = 0.2485 + 0.12 * ln(potential yield, t ha^{-1})
- Redistribution of anthesis biomass to grain during grain-fill = 24%
- No non-grain biomass is formed after anthesis, and
- Intermediate biomass at GS31 and GS39 = 16% and 57 % respectively of that at GS61,

Results are shown in Figure 6.8. Given the near linear relationships of crop P demands over the range of yields normally applicable to UK conditions, can be summarised per tonne of yield, as follows:

Growth Stage (GS)	**Crop Demands according to potential grain yield**	
	***P**, kg tonne^{-1}*	***P_2O_5**, kg tonne^{-1}*
As stem extension starts (GS31)	0.7	1.6
At flag leaf emergence (GS39)	1.7	3.8
At anthesis (GS61)	1.8	4.1
At harvest (GS92)	3.2	7.3

Note that the demands increase markedly after flowering. At harvest they differ a little from the values used in the Fertiliser Manual (for cereals: 7.8 plus 1.2 kg t^{-1} P_2O_5, equivalent to 3.4 plus 0.5 kg t^{-1} P; Defra, 2010) because demands are based on critical P concentrations rather than overall average P concentrations, and because demands relate to all above-ground biomass rather than just the biomass removed at harvest.

From similar information about barley, oilseed rape and potatoes, similar predictions can be made of the crop P demands at each of the sites used for experiments here, with crop P demands (in relation to harvest grain, seed or total tubers) being 3.2 kg t^{-1} @ 85%DM, 4.7 kg t^{-1} @ 91%DM and 0.72 kg t^{-1} @ 21%DM respectively (as P_2O_5 these crop demands are 7.3, 10.7 and 1.6 kg t^{-1} respectively). Thus total crop P demands at each site can be tabulated in the next section and compared with the actual amounts of P acquired by the unfertilised crops – the soil P supplies – so revealing the ‘gaps’ in P supply and indicating the crops’ needs for fertiliser P.

6.4.2 **Soil P Supplies**

Soils' capacities to supply P is conventionally monitored by soil testing (soil test P; STP). There are multiple issues governing the use, accuracy, precision and value of STP which were discussed previously through this project by Edwards *et al.* (2015) and some of which are being considered in the current AHDB Project 216-0004. These include differing sorption properties, and subsoil reserves on different soils. It would need a much larger body of data than has been generated here to adequately validate STP as an indicator of soil P supplies, and hence fertiliser P requirements (e.g. Kuchenbuch & Buczko, 2011). However, it is relevant to note that annual monitoring of the run-down sites here (Figure 6.5) revealed some significant uncertainties that apply to commercial use of STP, where the recommendation is for unreplicated sampling (15 sub-samples, combined into one sample for analysis) within each field on a four year cycle (Defra, 2010). The results presented here are averages from separate composite samples taken from four adjacent replicate areas of only 0.5 ha within each field, so are more intensive than is advised commercially. Yet the average standard error of each determination for the run-down treatments was 1.66 mg L^{-1}, hence most of the differences between successive years across the sites (ranging up to 8.3 mg L^{-1}) can be regarded as statistically significant. Given that the lower and upper boundaries of soil P Index 1 differ by only 6 mg L^{-1}, the differences between successive samplings (average 3.3 mg L^{-1}) would often cause a change in soil P Index, and hence a change in fertiliser recommendation despite the expectation that soil P should be approximately in a steady state at these sites. Causes of the differences between successive samplings may include any or all of weather effects, rotational effects, sampling differences, and laboratory drift; all of these possibilities need to be mitigated if growers are to maintain confidence in routine use of STP.

The extent to which the run-down treatments at all four sites failed to show a reduced level of STP was surprising, considering the expectations from previous work (Johnston *et al.*, 2016), which in summary describe STP on unfertilised, cropped sites as having a half-life of nine years. Soil P did not appear to have run down convincingly at any of the four sites over the five years (Figure 6.5). The differences that developed between the two treatments at each site appear to have arisen more due to build-up of soil P in the maintenance treatments, than to run-down where crops received no added P. Nevertheless, it is clear from sites such as at Ropsley, that both STP and soil P capture by crops can become seriously depleted where P additions are withheld for a significant period of years. It therefore seems feasible, on the many farms where a negative P balance is currently being maintained (e.g. Edwards *et al.*, 2015), that both STP and soil P capture must decrease at some point; whether STP and soil P capture will change simultaneously or sequentially is important, because if soil P capture changes *before* STP, there is a significant risk that a large tranche of commercial arable crops will develop undiagnosed P deficiencies.

Recent summaries of >172,000 commercial soil P tests in the UK (PAAG, 2015) show very little evidence of significant changes (Figure 6.9) despite the predominance of negative soil P balances being maintained on UK arable farms (Edwards *et al.*, 2015). Given the difficulty in identifying sites which have contrasts in soil P and are also suitable for field experimentation, it should be emphasised that maintenance of these run-down sites is likely to prove extremely valuable, not only for developing and testing more efficient P use strategies, whether they be fertilisers, crop species, varieties, or management practices, but also, it may be worth considering closer monitoring of crop P concentrations and crop P offtakes at these sites so as to check whether or not decreases in crop performance *precede* decreases in STP, hence whether the arable industry risks being (or is) subject to undiagnosed deficiencies on fields where farms are intended to be run down soil P.

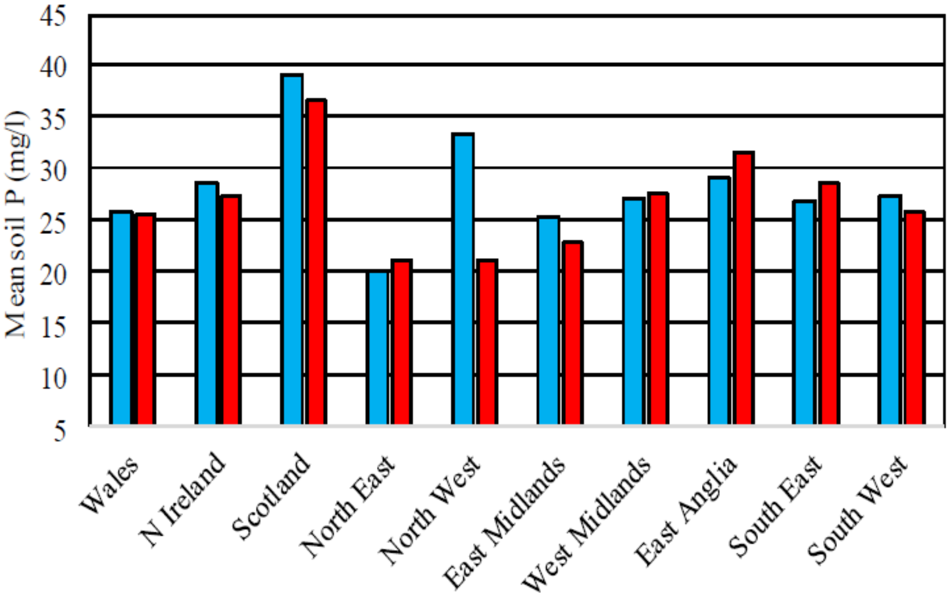

Figure 6.9. Recent average soil P levels as derived from 172,857 samples analysed in 2015 (red), compared to the average of similar samples analysed in 2009 (blue). Copied from PAAG (2015; their Fig. 4b).

STP can be validated for all the 'Response' and 'Targeting' experiments here with quantities of P acquired by each crop, without any fresh P applications (Figure 6.10). In general, quantities of soil-derived crop P exceeded 20 kg ha^{-1} in the English response experiments; it was only in the two 'Targeting' experiments at Ropsley, where the unfertilised plots had received no fertiliser P for many years, and in two of the three Scottish response experiments, that soil P capture was small (<12 kg ha^{-1}). The Olsen's method appeared to provide a reasonable way of predicting this for sites in England, but not for the Scottish sites where Olsen's method put all three sites into P Index 2 or 3.

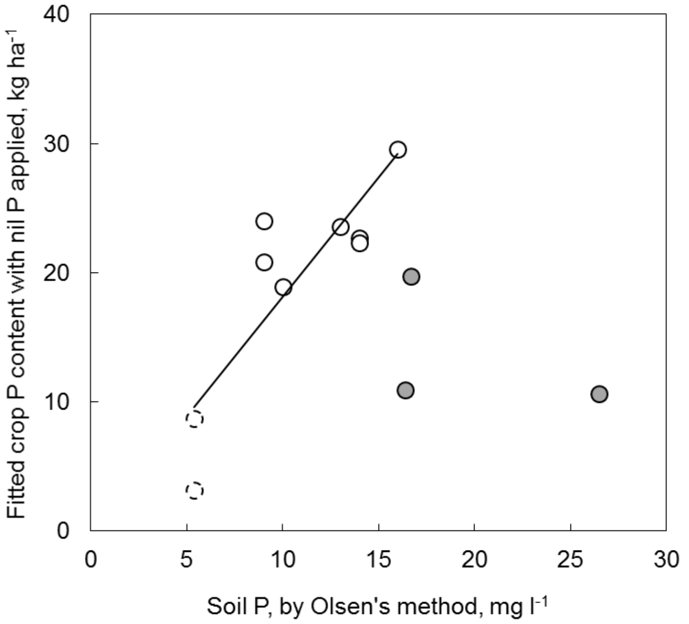

Figure 6.10. Relationship between soil P analysed by Olsen's method and total P content at harvest of crops with no fresh applied. Grey symbols are for Scottish sites. The regression line (y = 1.82x; R^2 = 0.74) applies to just the English sites, of which the two trials at Ropsley, Lincs. are shown by dashed circles.

Note that in Scotland, where soils tend to be more acidic (Table 6.3), use of Morgan's method for STP and its classification into soil P status by the Scottish advisory services (Sinclair *et al.*, 2015) predicted that these three sites would provide very low (VL) or low (L) soil P supplies. However, soil P capture at the Hillhead site was significantly larger (20 kg ha^{-1}) than at the other two Scottish sites, yet its soil was classed as VL, as against L at the other two sites.

Clearly any factor (other than P nutrition) which constrains crop growth to less than the potential set by availabilities of light energy and water may also constrain crop capture of soil P. Hence some degree of interdependence must be expected between soil P supply, as determined through nil P treatments, and crop P demand as determined from treatments with ample P supplies. Thus, whilst providing a good indication, nil P treatments do not necessarily provide the perfect measure of the soil's inherent capacity to supply P.

If the two 'Targeting' experiments at Ropsley are included (or excluded), on average the soils supplied 18 (20) kg ha^{-1} P for the crops grown at these sites compared to the average of 25 (26) kg ha^{-1} that the crops were estimated to 'demand' (Figure 6.11). Thus the average gap or shortfall in P supply was 8 (6) kg ha^{-1}. Only in the case of oilseed rape at Dunham in 2014 did the soil supply exceed the crop demand, and this was the only site with soil in Index 2 (just).

P supply shortfalls were greatest for the potato crops and least for the oilseed rape crops, although there were insufficient sites for the significance of this comparison to be tested. The shortfalls in P supply ranged from nil at Dunham to 15 kg ha^{-1} at Old Rayne in 2012 (across sites chosen to be at Index 1), and then to 24 kg ha^{-1} at Ropsley (in 2014), where the soil had received no P inputs for many years. The two sites amongst the 'response experiments' with the largest P shortfalls were Balbathin in 2011 (13 kg ha^{-1}) and Old Rayne in 2012 (15 kg ha^{-1}), both in Aberdeenshire; the English site with the greatest shortfall was with the potato crop at Tamworth in 2014 (11 kg ha^{-1}).

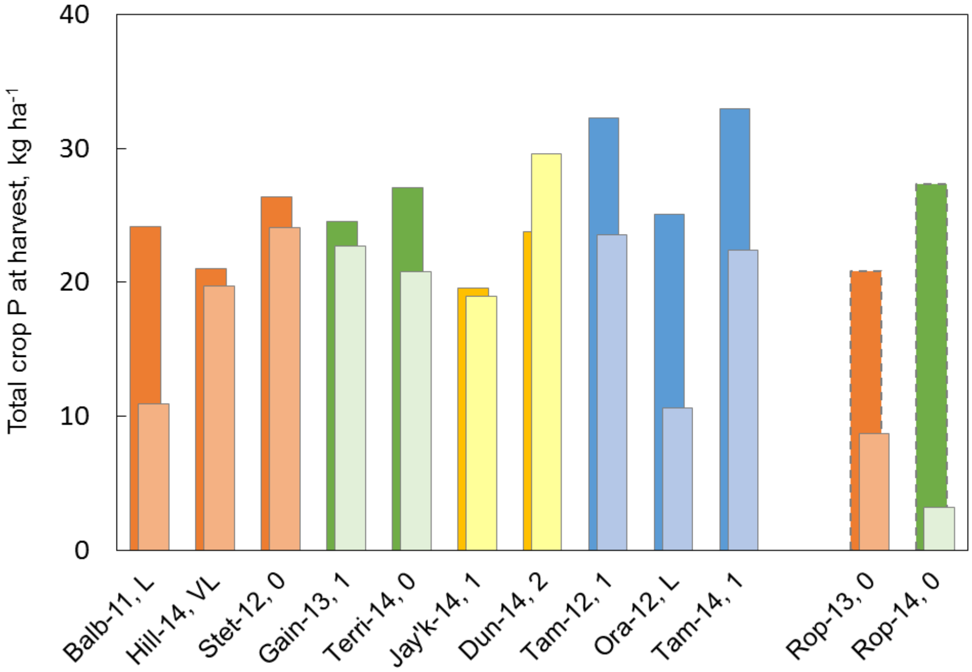

Figure 6.11. Gaps between soil P supplies (P uptake with nil P applied; light colours) with crop P demands (taken as the maximum fitted yield x 'critical' P content; dark colours) in the 12 Response and Targeting experiments described here on crops of barley (brown), wheat (green), oilseed rape (yellow), and potatoes (blue). Short site names, harvest years and soil P indices (Defra 2010; Sinclair et al., 2015) are shown. Note that no fresh P was applied at Ropsley so crop P demands are estimated from crop yields at optimal soil P levels.

Given the calculated shortfalls between crop P demands and soil P supplies at nine of the ten sites, fertiliser P requirements can be estimated, assuming that the recovery of fertiliser P can be predicted. Clearly if 10% of fertiliser P is recovered by the crop, these shortfalls will be satisfied by application of 10x the shortfall as fertiliser P, and any practice or product that increases this recovery will reduce the fertiliser P requirement and save cost. Figure 6.12 compares these estimated requirements with current recommendations, and shows little concurrence. This is not surprising since fertiliser recommendations have largely been devised to maintain the soil P store, rather than to elicit immediate crop responses. However, it is important to be able to predict crops for which immediate responses would occur, and would be profitable.

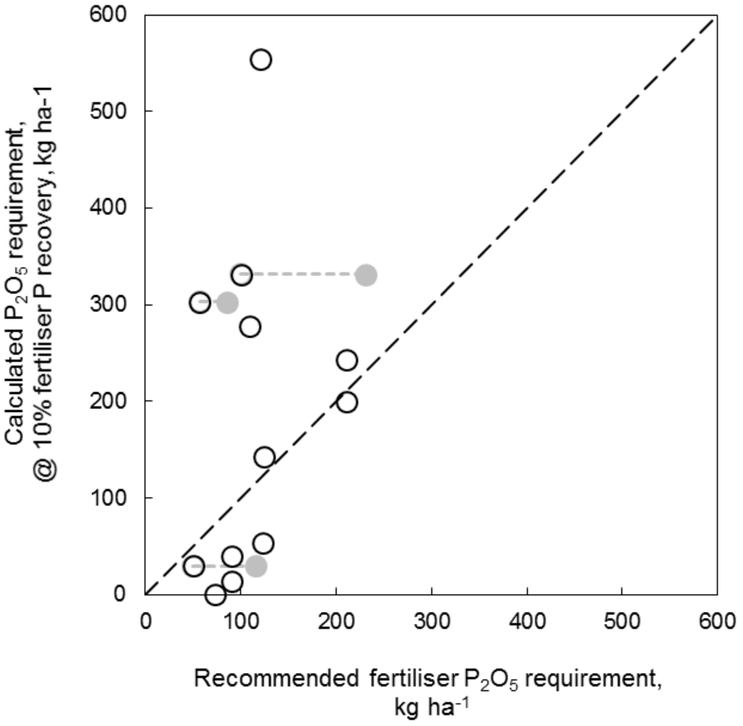

Figure 6.12. Relationship between fertiliser P_2O_5 requirements estimated from response of crop P content to applied P at each site and those prescribed in national recommendations for England (RB209; open circles) and Scotland (Sinclair et al., 2015; grey circles). The dashed line indicates equality (1:1).

The next sub-section (0) will therefore examine whether the sites with expected shortfalls in P supplies did respond to fresh fertiliser P, it will examine the recoveries of P achieved after broadcasting TSP, and consider the best means of maximising immediate recovery of fresh fertiliser P. The final sub-section (6.4.4) will then consider the profitability of fresh P use.

6.4.3 **Fertiliser P Recoveries, and their possible improvement**

Crop recovery of P from broadcast TSP, whether during early growth or at harvest (Table 6.14), was disappointingly small (with an average of only 4% and a maximum of 8%), inconsistent and difficult to detect with the conventional small plot experiments that were used here. Somewhat larger apparent recoveries were observed in the pot experiments (11% for struvite and 13% for TSP; Section 3). It was also disappointing that the effects of placement and of different products (AVAIL® and struvite) on crop P uptake were largely undetectable (Table 6.18). It is a salient demonstration of the sorption capacity of most UK soils that such a large proportion of highly water-soluble fertiliser (TSP >90%) or indeed insoluble fertiliser (struvite; Talboys *et al.*, 2016) was rendered beyond crop recovery within the two to eight months of crop growth after its application. No attempt was made to determine the proportion of the struvite granules that dissolved at these field sites, so low P recovery from struvite may partly have arisen from low struvite solubility (Talboys *et al.*, 2016) rather than soil sorption. Puzzlingly, although they were small effects, placement rather than broadcasting of fresh fertiliser P sometimes gave statistically significant negative effects on yield (e.g. at Terrington and Jaywick in 2014, and Tamworth 2012; Table 6.19); it seems unlikely that this would have been caused by a mechanical effect, especially on autumn sown combinable crops, so maybe there was an effect of localised acidity close to the roots, created by TSP dissolution?

The small P fertiliser effects that did occur appeared easier to detect when translated into biomass growth or grain (or other) yield (Table 6.12; Table 6.19) rather than when measured as P uptake. Probably this arises because of the difficulty in taking representative crop samples and / or undertaking precise crop P analyses (Table 6.13).

Of course the large unrecovered component of fresh P applications is expected to benefit succeeding crops. The best demonstration of this here was from the fertiliser treatments used to establish basic differences in soil P for the targeting experiments at Ropsley, where legacy effects (of broadcast TSP) were clearly apparent. Soil P analysis indicated 20-30% availability of P from TSP fertiliser 1-2 years after its application (Figure 6.2b), which compares with 12% assumed (and approximately achieved) by Knight *et al.* (2014) in setting up soil P differences in the Critical P Project. On the other hand, crop recovery from these applications averaged at only 1.5% and 1.0% in the second (2013) and third (2014) years after the fertiliser was applied (2010-11); this was even less than recoveries in most of the response experiments in the first year after P application (Table 6.14). The 2nd and 3rd year effects of P applications on grain yield at Ropsley were 3 and 6 kg grain kg^{-1} P applied in 2013 and 2014 respectively, similar to the immediate (1st year) responses in the response experiments (Table 6.12), so there may be a way that residual soil P is more effective in promoting crop growth than fresh P which has not yet equilibrated with soil processes.

Generalising from the results here it would seem that 4% of a fertiliser P application might be recovered in the first year, 2.5% in the second, 1.5% in the third and 1% in the fourth and fifth years; this adds to an overall apparent fertiliser P recovery by arable crops of the order of 10%, far from the complete recovery that has been claimed by using the balance method (see discussion in Section 7.1 of Edwards *et al.*, 2015). Part of the discrepancy is attributable to the 5 to 9 kg ha^{-1} P that crops can acquire in the prolonged absence of fertiliser P use (see discussion in Section 7.2 of Edwards *et al.*, 2015); the intercepts of ~5 kg ha^{-1} P in crop P uptakes at Ropsley are the best examples of inherent soil P supplies here (Table 6.21).

It should be noted that simple estimation of fertiliser P recoveries by difference is likely to give exaggerated results to some extent. The ‘added nitrogen interaction’ observed by Jenkinson *et al.* (1985) is likely to have an analogous ‘added P interaction’; i.e. fresh fertiliser P can be expected to encourage capture of inherent soil P, so increasing apparent fertiliser P recovery and under-estimating soil P supply. If the level of inherent soil P is small, then this effect is also likely to be small, and certainly, apparent fertiliser P recoveries estimated here lack any large values.

It would be expected that, if the poor recoveries of soil-applied fertiliser P are mainly attributable to rapid P sorption by soil, the P treatments that ‘by-passed the soil’ – seed dressings and foliar sprays – would have been at a large advantage here. The lack of measurable responses to these treatments (Section 6.3.2.4) is thus disappointing; especially after achieving positive results (with seed dressings) in the pot experiments (Section 3). However, given the concerns about imprecision in the trials and small amounts of P applied, it is suggested that further more intensive work is necessary on both seed and foliar treatments to deduce their potential in P nutrition of arable crops.

6.4.4 **Economic implications of immediate crop responses to fertiliser P**

It is by no means clear from the rather modest biological responses to fresh P described above, and the further small responses of successor crops to residual soil P as demonstrated in the Targeting experiments, whether the economics of using ‘fresh’ P fertilisers are positive in these experiments, and also whether any of the targeting practices might be considered economically worthwhile.

There are two possible approaches to the economic analysis of fertiliser P use, choice between which depends on one’s attitude to crop P nutrition. It may be that fertiliser P is used either:

1. To feed the crop, as espoused throughout this Project, to elicit a response in the first crop to be grown, and that residual benefits to subsequent crops can be treated as an added bonus,

or

2. To feed the soil, as currently advocated in the Fertiliser Manual (Defra, 2010), to maintain or increase the soil P store, with any response of the initial crop to the fresh P being treated as an added bonus.

Either way, it is necessary to consider both the initial and the residual effects of fertiliser P, but in the initial case the whole investment in fertiliser P is justified (or not) on the basis of the initial crop’s response, whereas the second philosophy incorporates a notion of investment in a soil

P store, so the economic analysis should incorporate a notion of interest lost on capital invested in the store. The latter approach was used by Knight *et al*. (2014) in their analysis of Critical Soil P experiments.

Choice between the two approaches would seem to depend on whether the fresh P effect is taken as likely or not, which in turn probably depends on the optimal level of soil P as determined by residual effects of fertiliser P. Hence proper resolution of a best-economic P management strategy will probably require a process of iterative optimisation. However, as an initial step, it will be instructive to explore the first approach above.

Taking the price of fertiliser P at £0.65 kg^{-1}, cereal grain at £115 t^{-1}, rape seed at £265 t^{-1} and potatoes at £150 t^{-1}, there were five economically beneficial yield responses to incorporation of broadcast TSP before establishment of the crops studied here: all three barley crops and two of the three potato crops (i.e. not Tamworth in 2012) responded profitably. Results indicate that the other five crops (both wheat crops, both oilseed rape crops and one potato crop) did not justify fresh P use. For the barley crops, the economic benefits of fresh P were marginal (mean+£0.20 kg^{-1}) whereas for potatoes they were larger (mean+£1.36 kg^{-1}).

Placement of fresh fertiliser P was also generally positive for barley and potatoes whilst being negative for wheat and oilseed rape (Figure 6.13). Thus the total economic benefits of placing 20-25 kg ha^{-1} P (~50 kg ha^{-1} P_2O_5) as fresh TSP (versus applying nil P) would have added £43 ha^{-1} to the gross margin of barley (averaging both winter and spring sown crops) and £333 ha^{-1} to the gross margin of potatoes, whilst being negative for wheat and oilseed rape (by an average of £34 ha^{-1}). Of course it is not certain whether these differences between crop species were real or just occurred by chance, but at least the greater benefits for potatoes support current advice in the Fertiliser Manual (Defra, 2010). The additional positive responses to fresh placed P of the barley crops are interesting; however, the statistically significant negative response to P placement by one wheat and one oilseed rape crop were puzzling, and require further investigation on a broader range of soils.

Given that an overall economic assessment of the value of different P fertiliser strategies involves a considerable number of factors including (i) the likelihood of a response to fresh P, (ii) the value and duration of residual effects on subsequent crops, (iii) which crop species are included within the rotation, (iv) prices for their produce and the price of fertiliser P, and (v) rates of interest, the resolution of an optimum strategy and the main considerations in arriving at this strategy on any particular farm are quite complex and involved. Thus these issues are addressed more thoroughly in Section 8 where broader considerations of environmental impacts and sustainability of fertiliser supply must also be included.

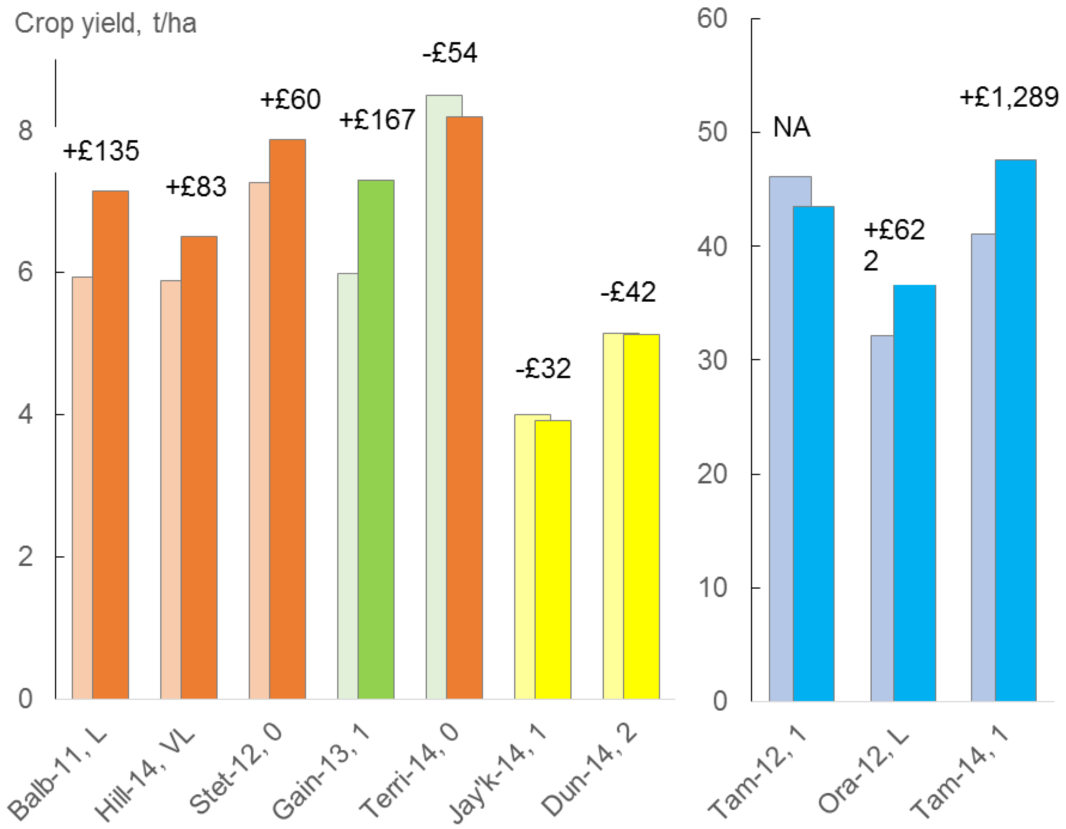

Figure 6.13. Effects of P placement (dark colours) at low soil P Indices [as indicated] compared to applying nil P (light colours), on crop yields and gross margins. Note: these calculations simply consider the additional yield achieved from placement and do not consider other costs associated with placement such as purchase of specialised machinery.

6.4.5 **Conclusions**

- Soils purposely chosen to have low P supplies (P Index 1 in England or L status in Scotland) supplied surprisingly large amounts of P (15-25 kg ha^{-1}) to arable crops and therefore in most cases their demands for additional P were relatively small.
- Nevertheless crops growing on these soils did respond positively to fresh applications of fertiliser P made just before sowing, particularly potatoes. Here, barley crops also responded, whilst winter wheat and oilseed rape did not.
- However, fresh fertiliser P was always used inefficiently, with the mean recovery (by difference) being 4%. Ultimate fertiliser P recoveries would have been larger if residual effects on succeeding crops had been measured (as exemplified by soil P build-up treatments in the Targeting Experiments) but overall P recoveries nevertheless would have been very poor, given that unfertilised soils provide P to crops (assumed to arise from mineralisation and weathering).

- Immediate responses to fertiliser P were enhanced, particularly with potatoes and barley, by placement of the fertiliser close to the seed and in some cases by using (less soluble) struvite rather than TSP. However, AVAIL® did not show consistent positive effects.
- The literature indicates that to maintain uninhibited growth and unaffected yields, crop P contents should exceed 0.25% in vegetative whole crop biomass and 0.32% in generative biomass.
- Fresh P applications seldom 'cured' P deficiencies (judged according to 'critical crop P' concentrations above), whether they were placed, broadcast or slow release, because their efficiencies were so poor.
- Given the relatively large uncertainties entailed in soil P analysis, crop P analysis should be considered for more routine use, taking these 'critical crop P' values as standards, against which growers can build confidence that their P management strategies are adequate.
- The recent tendency of arable farms to maintain negative soil P balances (with the intention of exploiting 'surplus' soil P storage), the increased use of organic P sources, and the poor capacity of P fertilisers to immediately correct P deficiencies indicate the need for a survey of P concentrations in harvested biomass of UK crops (grain, seed, tuber and root) to reveal the prevalence and patterns of P deficient arable crops in the UK, and to identify any other factors having effects on crop P concentrations.
- Annual P demands of most arable crops are dictated by their inherent tendency to store inorganic P in their vegetative tissues and phytate in their generative organs (up to 80% of total crop P). Development of genotypes with reduced phytate storage are likely to have reduced sensitivity to low soil P supplies, but developing these types has not been initiated and would take many years. Thus most current UK-grown arable crops with average or good yields must capture 25-35 kg ha^{-1} P to support uninhibited growth, and if theoretical potential yield levels are to be achieved (Berry *et al*., 2011; Allen *et al*., 2005), P requirements could be as much as 40 kg ha^{-1} for oilseed rape, 60 kg ha^{-1} for cereals, and 70 kg ha^{-1} for potatoes.
- It is difficult to monitor soil P sufficiency because of the poor repeatability and precision of soil P analyses, as evidenced by monitoring the 'Run-Down' sites established here. These difficulties could be reduced or even eliminated by monitoring crop P analysis, and ultimately by improving the immediate recovery of applied P.
- Although pot experiments indicated some promise from using P seed dressings or foliar sprays to by-pass P sorption processes in soil, positive effects of these techniques were not replicated in the field experiments reported here. Nevertheless, an intensive research effort is justified to achieve more efficient and reliable P delivery systems.

- Maintenance of several sites with contrasting levels of soil P will be crucial in the quest for more efficient P delivery systems and for genotypes with reduced P demands. Hence, despite slow development of soil P differences, the 'Run-Down' sites have acquired vital importance to the arable farming industry, so that it can defend itself from likely impacts of environmental failures caused by its current P management philosophy, as demonstrated in the next Section (7).

7. Environmental impacts of alternative approaches (WP4)

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7.1 Introduction

The continuing accumulation of surplus P in agricultural soils, and top-dressings of fertilisers and manures to the soil surface, pose a considerable risk of P loss to water causing eutrophication (Sharpley *et al.*, 1985a,b; Hooda *et al.*, 2001; Maguire *et al.*, 2005). Previous work in the UK has clearly demonstrated a positive link between soil P concentrations and P loss in run-off (e.g. Broadbalk plots, Heckrath *et al.*, 1995; Holbach plots, Withers *et al.*, 2009). Losses of P in runoff occur in both particulate form and in dissolved form, but as soil Olsen-P increases a greater proportion of this loss is in dissolved form and more bioavailable to aquatic biota (Reynolds and Davies, 2008; Withers *et al.*, 2009). The amount and rate of dissolved P release to run-off is determined by soil P sorption properties and the depth and time of soil-water contact. Losses of particulate P from soils will depend on the size of the particles transported during storm events and the extent to which these particles are enriched with P from previous fertilisation. Heckrath *et al.* (1995) found that soluble and total P in drain-flow from a clay soil increased sharply when soil Olsen-P concentrations exceeded about 60 mg kg^{-1} (P Index 4), subsequently referred to a change-point (Figure 7.1). These data suggest that if soils are kept at the agronomic optimum (P Index 2, 16-25 mg L^{-1}), they will not pose a risk to water quality and there will be no trade-off between sustainable intensification and the environment. However, concentrations of P in run-off at optimum soil P fertility levels may still pose a eutrophication risk because the concentrations of dissolved P required to limit algal growth in freshwaters are very low (30-35 µg soluble reactive P (SRP) L^{-1}, see review by Withers *et al.*, 2016). Maintaining soil Olsen-P at agronomically-optimum levels may therefore still greatly exceed the low national water standards for eutrophication control set under the Water Framework Directive (WFD), (UKTAG, 2010, 2014). Moreover, it is not known whether a lowering of the critical P concentration for arable crops from P Index 2 to P Index 1 would be beneficial in reducing the concentrations of P in land run-off so that the objectives of the WFD of reaching good ecological status can be achieved more rapidly.

Fresh applications of fertiliser invariably lead to elevated run-off P losses in addition to those derived from the soil. These losses have been termed 'incidental' (Haygarth & Jarvis, 1999), and arise due to inadequate contact time for an equilibration of P between the fertiliser and the soil. Consequently, incidental P losses are most commonly observed when P fertilisers and manures are applied to the land surface and it rains soon afterwards. Although generally small in relation to the amount of fertiliser P applied, incidental losses occur in rapid flow pathways (e.g. overland flow, drain flow), and are characterized by very high P concentrations, mostly in soluble P form (Hart *et al.*, 2001; Withers *et al.*, 2003).

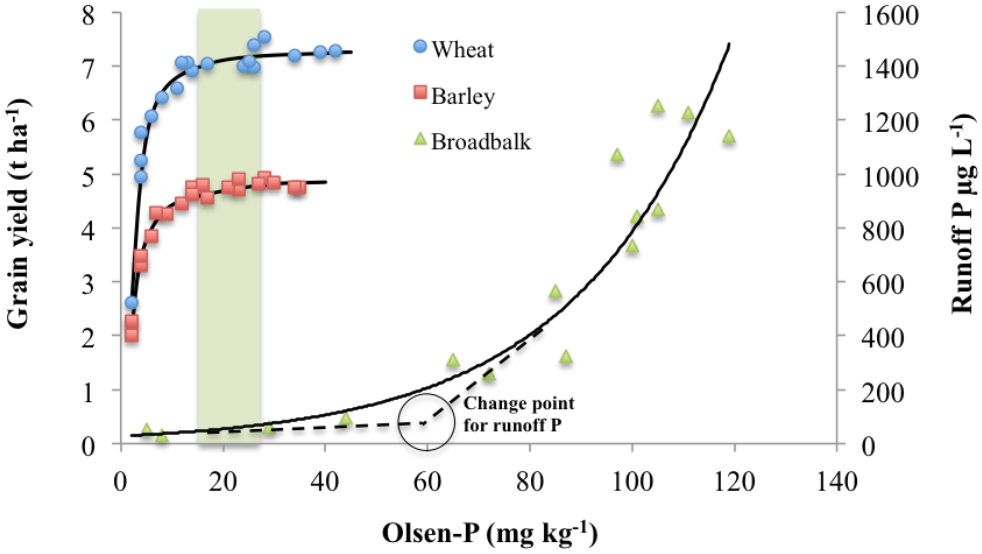

Figure 7.1. Data from Rothamsted showing that the Olsen-P concentrations required for optimum yield of wheat and barley on silty clay loam soils are well below the Olsen-P concentration at which P concentrations in drain-flow accelerates. The green shaded area represents the band of Olsen-P (Index 2) considered optimal for crop yield in the UK. The yield response data are taken from Poulton et al. (2013) and the runoff soluble reactive P (SRP) data are from Table 17 in Heckrath (1998). Reproduced from Withers et al., (2016).

The largest P concentrations in runoff most frequently occur in the first storm event after fertiliser application. The magnitude of the initial P release and overall loss is related to the type of fertiliser applied, the amount of P applied, soil wetness and how soon rainfall occurs after application as well as the P sorption properties of the soil. The P fertilisers that are applied to arable soils invariably have a very high water-soluble P component, which makes them very vulnerable to incidental P loss (Hart *et al.*, 2001; Withers *et al.*, 2001). Incidental P losses from manures depend on the amounts of water-soluble P they contain (Withers & Bailey, 2003; Kleinman *et al.*, 2004). The risk of generating run-off and subsequent loss of applied P is greater on heavy-textured soils which remain wetter for longer and have lower infiltration capacity, and where fertilisers are top-dressed instead of incorporated or placed to save time at drilling (Shore *et al.*, 2016). Incidental P losses in sub-surface run-off are generally much smaller than in overland flow due to the greater opportunity for P adsorption in the subsoil (Sims *et al.*, 1998; Withers *et al.*, 2003). Losses of P from high solubility fertilisers are very bioavailable and are taken up rapidly by aquatic biota. Use of more slowly-available P fertilisers with lower water-solubility, offer the potential advantage of reducing such incidental P losses and reducing eutrophication risk, whilst giving farmers more flexibility in the timing of when they can apply P fertilisers safely during the cropping year.

Here we tested the hypothesis that the adoption of novel soil and fertiliser management strategies will reduce P in run-off from applied fertilisers and soil stocks and lessen the wider negative environmental impacts of arable farming. Three field experimental sites were instrumented to monitor surface runoff and/or drain-flow during storm events, or under simulated rainfall, to:

- Quantify the impacts of soil P levels on P loss in surface and sub-surface run-off to establish if lowering soil P levels (from P Index 2/3 to Index 1) reduced losses of dissolved and particulate P from soils in land run-off.
- Measures 'incidental' losses of dissolved and particulate P in land run-off after the application of struvite (low water solubility) or AVAIL®+TSP (increased availability of soluble P) in comparison with triple super phosphate P fertiliser.

In addition, the potential dissolved and particulate P release from soils from previous experiments (Knight *et al.*, 2014), and from the Loddington catchment (Palmer-Felgate *et al.*, (2012) were assessed by the DESPRAL test developed by Withers *et al.* (2007). The results from Cockle Park, Kingsbridge and the DESPRAL analysis were then compared with other available data in the UK on the relationship between soil Olsen-P and runoff-P obtained under natural rainfall (Withers *et al.*, 2016).

7.2 Materials and Methods

Field experiments were carried out at three sites (that generated significant run-off) between 2010 and 2015 (Figure 7.2) to investigate effects of soil P and fertiliser-applied P on P in run-off as follows:

- Cockle Park (Northumbria) – effects on soil Olsen-P on P concentrations in drain-flow
- Kingsbridge (Devon) – effects on soil Olsen-P on P concentrations in overland flow
- Loddington (Leicestershire) – effects of conventional and novel fertilisers on P concentrations in overland flow

In addition, the DESPRAL test (Withers *et al.*, 2007) was used to determine the potential for dissolved and particulate P transfer in run-off on three further soils from the AHDB-funded critical P project (Knight *et al.*, 2014).

At Cockle Park and Kingsbridge, run-off was collected and quantified (volume and determination of P forms) from plots with different levels of soil P over a series of storm events. At Loddington, conventional and novel fertilisers were top dressed to plots at either P Index 2 or P Index 4. Shortly after fertiliser application, a portable rainfall simulator was used to mimic heavy rainfall. Run-off following rainfall simulation was collected and quantified (volume and determination of P forms).

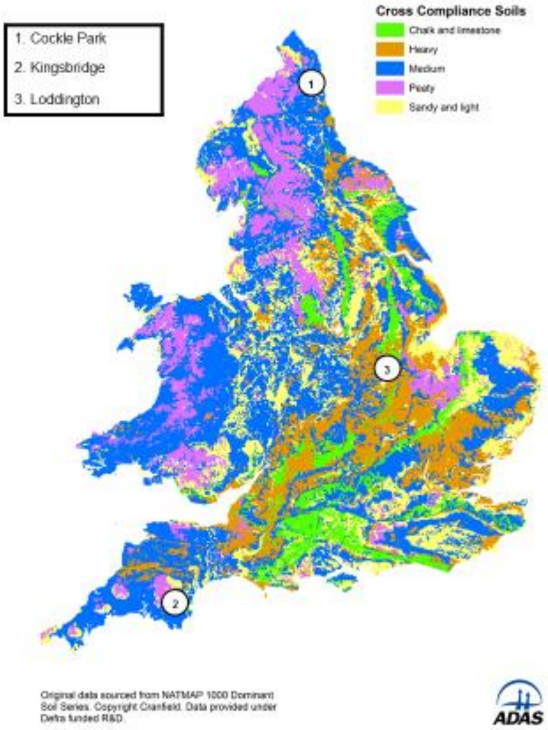

Figure 7.2. Experimental sites for P run-off assessments.

7.2.1 **P losses in surface drain-flow at Cockle Park, Northumbria**

Cockle Park is a Newcastle University farm located just north of Morpeth, Northumberland. The farm hosts an existing experimental facility for monitoring surface runoff and drain-flow. Soils at the site are uniform fine loam over clay (Dunkeswick Association) with a relatively permeable topsoil over a poorly structured, slowly permeable subsoil. Previous measurements at the site (Armstrong & Davies, 1984) have indicated an abrupt change in hydraulic conductivity from in excess of 100 mm per day in the topsoil to less than 2 mm per day at 40 cm depth. Below 60 cm hydraulic conductivity falls below 1 mm per day and for practical purposes the subsoil is impermeable below this depth.

Nine established and hydrologically-isolated (by polythene barriers at least 1 m deep) 0.25 ha plots (approximately 100 m x 25 m) at the site were monitored and sampled over two successive winters. Each plot had a main drain running the length of each plot, with 3 perpendicular lateral drains across the width of each plot, with gravel backfill to within 30 cm of the surface. In addition, the site was mole drained (perpendicular to the lateral drains) in 2009 at a depth of 0.5 m (2 m spacing, Figure 7.3). The drainage water (i.e. drain-flow) from each plot was drained into a concrete chamber, within a ditch running along the downslope (northern) boundary.

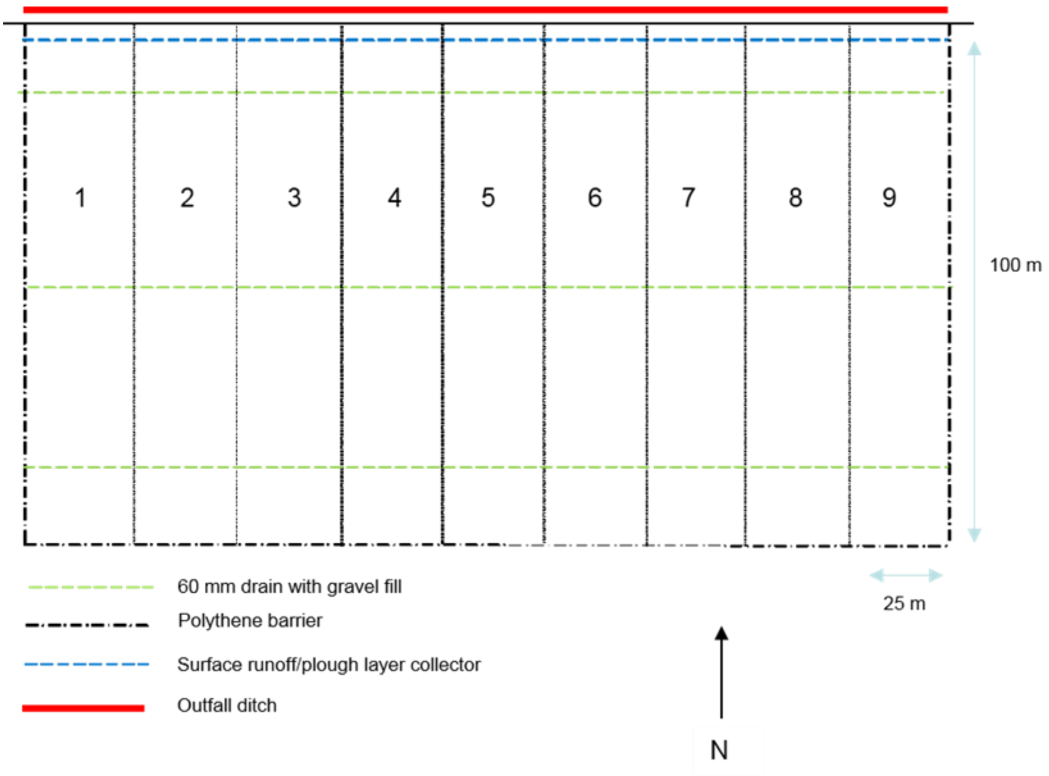

Figure 7.3. Plan of Cockle Park hydrologically isolated drainage plots

Each plot also had a combined surface run-off / plough layer collector (30 cm deep gravel filled trench), piped to the outfall chamber, although this flow pathway was not monitored for chemical composition. Flow was monitored using a "V" notch weir tank flow meter and head recorders (drain flow and surface run-off) and depth was continuously monitored telemetrically via a pressure transducer linked to an automatic pump sampler set up to take samples at specified intervals.

Soil P measurements in autumn 2010 showed that the site had low soil P (typically P Index 0) across nearly all plots. In order to establish the effect of soil P on run-off P, fertiliser P (TSP) was applied to create differential P indices over two cropping seasons, 2010-2011 and 2011-2012 (Table 7.1). Once different P levels had been established (and confirmed through subsequent soil sampling in spring 2012, Table 7.1) monitoring of P concentration in surface drain flow (total P (TP), total dissolved P (TDP), molybdate reactive P (MRP) and suspended sediment (SS)) was started in autumn 2012. To maintain plots at the target P levels TSP was incorporated into the seedbed of each plot annually at RB209 recommended ‘maintenance levels’ based on expected crop yield - 100 kg P per hectare (assuming a yield of 6 t ha^{-1}). Soils were reanalysed in spring 2013 and spring 2014 (Table 7.1).

Table 7.1 Soil P concentrations (0-15 cm depth) measured at Cockle Park in 2010 and during the runoff monitoring period 2012-2014.

	Soil P (mg L^{-1}) and [ADAS Index]			
Plot no	**2010**	**2012**	**2013**	**2014**
1	5 [0]	17 [2]	11 [1]	9 [0]
2	4 [0]	20 [2]	14 [1]	10 [1]
3	3 [0]	11 [1]	9 [0]	6 [0]
4	3 [0]	7 [0]	4 [0]	3 [0]
5	4 [0]	9 [0]	7 [0]	9 [0]
6	10 [1]	13 [1]	9 [0]	9 [0]
7	3 [0]	21 [2]	21 [2]	14 [1]
8	5 [0]	7 [0]	7 [0]	5 [0]
9	5 [0]	13 [1]	10 [1]	12 [1]

Both surface and sub-surface flow were monitored but only sub-surface (drain) flow was collected for suspended sediment (SS), total P (TP), total dissolved P (TDP) and molybdate-reactive P (MRP) analysis. Drain water sample collection during the overwinter drainage season (October to March) was structured according to drain flow volumes: samples were collected using an initial trigger of 1 mm to ensure capture of small events. A total of seven storm events capturing a range of flow events over the two winter drainage seasons that were monitored. Not all plots generated run-off for some storm events. Drainage water samples were collected using Aquamatic samplers controlled by data loggers. Twelve samples were taken at 30 minute intervals after each trigger (1 mm of drain flow) and four samples were selected from these for analysis. The samples to be analysed were selected to represent initiation of flow, peak flow and recession flow. Following run-off (for each of the four selected samples), filtered (using a 0.45 µm membrane filter) and unfiltered samples, from each plot, were sent for laboratory analysis (within 24 hours of collection) for MRP, TDP and TP analysis.

A sample of unfiltered run-off was also retained from each plot for the measurement of suspended sediments. P concentration data was used in conjunction with the record of discharge to calculate P losses on a plot by plot basis for each event.

The aim was to crop the site with winter wheat throughout the experimental period. However, the site was too wet to establish any crops in 2010, 2011 or 2012 and was left fallow. Winter wheat (variety: Scout) was sown in 2013 and harvested in 2014. 'Grab sampling' was carried out immediately before harvest in 2014. Representative samples of plants (*c*.50 tillers per plot) were cut at ground level. Samples were separated into ear and straw fractions, weighed (fresh weight) and then dried (80°C for 24 hours) before being reweighed (dry weight). Samples were then threshed and grain weighed prior to dispatch to the laboratory for separate determination of P content in the straw and grain fractions. The cereal crop was harvested using a small plot combine; combine width and plot lengths were recorded to enable yield calculation. Yields were very variable across the plots (<2 to >9 t ha^{-1}) due to differences in soil wetness and these masked any effect of Olsen-P level on crop performance; these data are therefore not presented here.

7.2.2 **P losses in surface run-off at Kingsbridge, Devon.**

At a site where sufficient surface run-off was generated under natural rainfall, run-off traps were established in six experimental plots (15 m x 3 m), representing a continuum of soil P levels from 9 mg L^{-1} (P Index 1) to 23 mg L^{-1} (P Index 2; Table 7.2). Plots were chosen to be as similar as possible in slope (11-15 %) and were all at right angles to the tramlines. The soils in all plots were Milford series: well drained fine loamy reddish soils over siltstone rock. There were no experimental treatments (the experiment tested the difference in run-off as a result of variations in soil P levels across the site identified by high resolution soil sampling by SOYL Ltd.) and plots were not replicated at each location. The run-off collected after each storm event was measured, sub-sampled and the P forms determined. In addition, an automatic sampler was deployed in a selected sample of events to quantify the pattern of P loss during a storm event, but these samplers failed to catch a complete storm hydrograph and are not presented.

Run-off volumes from seven individual storm events were measured using a tipping bucket linked to a data logger. A known proportion of the run-off was diverted to a collection tank for sampling for P. Prior to sampling, the depth of water in the collection tank was measured before the contents of the tank were agitated to ensure thorough mixing. Samples were taken from around one-third of the way between the water surface and the bottom of the tank. Following run-off collection filtered (using 0.45 µm membrane filter) and unfiltered samples, from each plot, were sent (within 24 hours of collection) for laboratory determination of MRP, TDP and

TP, respectively. A sample of unfiltered run-off was also retained from each plot for the measurement of suspended sediments. P concentration data was combined with the record of flow to calculate P losses on each plot area for each event. Data for plot Lower 2 are not presented as the P concentrations of the sampled fractions were consistently an order of magnitude higher than all of the other plots suggesting that this plot was potentially contaminated with P from another source.

Table 7.2 Soil P concentrations (0-15 cm) and slope for each monitoring area at Kingsbridge, Devon at the start of the monitoring period in October 2012.

Plot name	**Soil P (mg L^{-1})**	**Slope (%)**
Big Combe	9 [0]	11
Lower 3	11 [1]	15
Lower 2	13 [1]	15
Church 4	15 [1]	12
Church 6	21 [2]	12
Church 5	23 [2]	12

In addition, two storm events, with different intensities, were continuously monitored using ISCO samplers to provide an insight into storm patterns of P loss on soils with different levels of soil P. Regression analysis (with groups, groups being the individual plots) in GenStat (VSN International Ltd.) was used to model the relationship between the response variable (TP, TDP, MRP, DOP or PP) and the explanatory variable (time). The analysis fitted a sequence of models: 1) a single line, 2) parallel lines and 3) non-parallel lines to determine whether the intercepts and/or slopes of the lines were significantly different for each experimental treatment (group).

7.2.3 **P losses in surface run-off at Loddington, Leicestershire**

A field experiment was established at Loddington Farm in Leicestershire to compare the risk of incidental P loss in surface runoff following the application of conventional and novel fertilisers. The farm has previously been used to characterise P sources to water (Withers *et al.*, 2009; Jarvie *et al.*, 2010; Palmer-Felgate *et al.*, 2012) and evaluate the impact of mitigation options to reduce P loss (Quinton *et al.*, 2003). The soil at the experimental site is Denchworth series (Fe rich) derived from boulder clay and is under-drained. The site experiences regular run-off events transporting P-rich colloidal particles both to the drainage systems and in surface runoff.

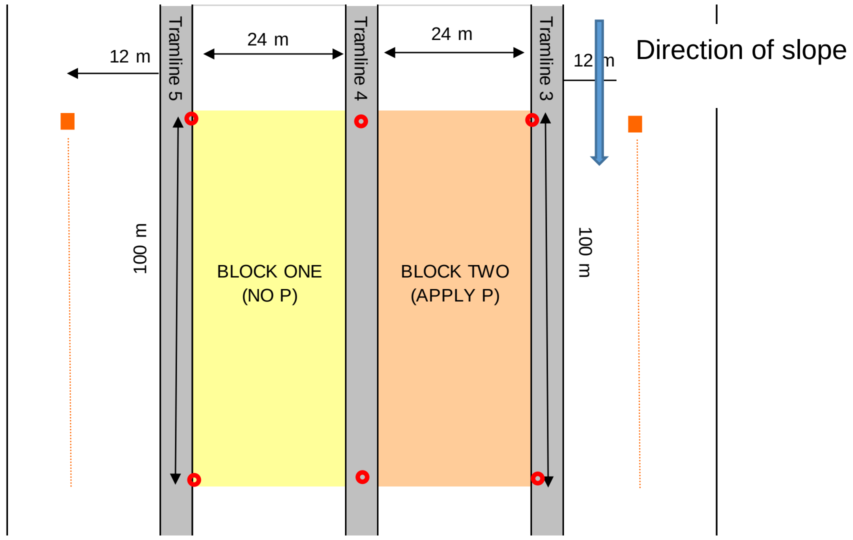

Figure 7.4. Plan of incidental run-off site: block 1 (P 17 mg L^{-1}) and block 2 (P 65 mg L^{-1}).

Prior to the measurement of runoff in autumn 2014, the cropping years 2011-12 and 2012-13 were used to create two 0.25 ha areas (blocks) with different soil P levels. The different soil P levels were created by applying additional amounts of TSP to one of the blocks (Figure 7.4). At the start of the run-off experiment, soil Olsen-P in Block 1 was 17 mg L^{-1} (low Index 2) and in Block 2 was 65 mg L^{-1} (P Index 4). The purpose of the different levels of soil P fertility was to determine whether runoff P concentrations elevated by fertiliser application might be reduced by sorption to the soil. Any sorption would be expected to be less on the high P soil. The two experimental areas were positioned in a sloping field sown to oilseed rape, in the direction of the tramlines (Figure 7.4) and had similar soil pH (7.0) and nutrient status (K, Mg).

Within each area, small bound plots were established to measure runoff after fertiliser application in November 2014. The run-off was measured from 0.5 m x 3 m plots within each block and the experimental treatments randomly allocated to each plot prior to rainfall simulation. The treatments compared top-dressings of TSP (46% P_2O_5), TSP+AVAIL® (46% P_2O_5) and struvite (28% P_2O_5) at a rate of 20 kg P ha^{-1} and there were 3 replicates of each treatment. Rainfall was simulated using a nozzle mounted on a frame at a height of 2.5 m. This was operated under a cover to avoid wind drift and to ensure that the simulated rainfall was directed to the plot areas. The simulator applied 'rainfall' (using mains water at 7 PSI sourced from the local farm at Loddington) to three plots simultaneously at a rate equivalent to a rainfall intensity of between 50 and 60 mm per hour (50 to 60 litres per hour on each 1.5 m^2 plot).

Each of the three plots was hydrologically isolated by metal dividers and runoff reaching the lower boundary of the plot was directed via a hose pipe into a 50 litre collection tank positioned downslope. The oilseed rape plants were then removed from the plot areas and the fertiliser treatments were applied one hour prior to starting the rainfall simulation. Rainfall simulation continued until run-off had been generated from each of the three plots for 30 minutes, after which the volume of run-off was measured. Three filtered (using a 0.45 µm membrane filter) and three unfiltered samples from each plot were sent (within 24 hours of collection) for laboratory determination of MRP, TDP and TP. A sample of unfiltered run-off was also retained from each plot for the measurement of suspended sediments. These measurements could be used to calculate dissolved hydrolysable P (DHP: TDP-MRP; organic P not immediately available for plant uptake), particulate P (PP: TP-TDP; P attached to soil, i.e. unfilterable material) and suspended sediment P (PP/SS).

7.2.4 **The DESPRAL test**

The DESPRAL test (an environmental soil test to de̲termine the potential for s̲ediment and P̲ transfer in r̲un-off from a̲gricultural l̲and, Withers *et al.,* 2007) was undertaken on soils from three of the AHDB Critical P sites (Peldon, Great Carlton and Caythorpe) in 2013. The test mimics the effect of a storm event on the distribution of dissolved and particulate P in dispersed particles <20 µm in size. These sized particles have been previously been shown to be the dominant form of P transported in sheet run-off.

Soil samples were taken from a minimum of 10 points within the plots to a depth of not less than 50 mm (50-80 mm) and bulked together to make one sample per plot. The soils were then allowed to air dry naturally, large clods were broken down by hand, organic debris removed and the sample was sieved through a 5.6 mm sieve. 20 g of sieved soil was then placed into a 1 litre measuring cylinder and 200 ml of water was slowly added before swirling the cylinder gently to wet the soil. Following a standing period of 1 hour the sample was diluted with water to 1 litre. The sample was then inverted at a regular frequency for exactly 1 minute before being placed on a bench for 280 seconds. Samples were taken from a depth of 10 cm below the surface and either sent to the laboratory for the measurement of TDP and TP, or transferred to a weighed dry dish (10 ml sample), dried overnight and reweighed to determine suspended solids content.

7.3 Results

7.3.1 **P loss in drain-flow at Cockle Park, Northumbria**

Average rainfall at the site is *c*.700 mm (Met office 1981-2010 mean data). In comparison, rainfall from August 2012 to July 2013 was 954 mm and from August 2013 to July 2014 was 688 mm. Annual water discharge through the field drains (November to April) averaged 53%

of incoming rainfall in 2012/13 and 38% of incoming rainfall in 2013/14. However, there was considerable variation in the amount of drainage between plots, as has been found in other similar studies monitoring sub-surface runoff (e.g. Hodgkinson *et al.*, 2002). The monitored storm events represented a range of different sized storms (2.7 – 9.4 mm) and exported highly variable amounts of P and SS (Table 7.3). Measured SRP, TDP and TP concentrations ranged from limits of detection (10 μg L^{-1}) up to 87, 186 and 1,848 μg L^{-1} respectively (Appendix 1). Sediment concentrations ranged from 22 – 3,437 mg L^{-1}.

Table 7.3 Measured losses of soluble reactive P (SRP), total dissolved P (TDP), total P (TP) and suspended sediment (SS) for seven storm events monitored in drain-flow at Cockle Park from 2012-2014 and in overland flow at Kingsbridge from 2012-2013.

Site *Storm event*	**Date**	**Runoff** *(mm)*	**SRP** *(g ha^{-1})*	**TDP** *(g ha^{-1})*	**TP** *(g ha^{-1})*	**SS** *(kg ha^{-1})*
Cockle Park						
1	07/12/2012	3.27	0.90	1.93	6.9	3.31
2	27/01/2013	9.37	2.06	2.17	2.7	2.95
3	17/03/2013	3.86	0.31	2.23	7.9	5.51
4	19/01/2014	5.29	1.53	5.04	19.1	23.13
5	25/01/2014	4.29	0.94	1.47	8.7	9.86
6	15/02/2014	7.90	1.79	4.56	21.9	19.02
7	01/04/2014	2.66	0.36	1.00	9.4	10.65
Kingsbridge						
1	14/12/2012	10.73	11.60	32.10	1804.0	1528.4
2	08/01/2013	2.88	1.01	2.03	115.2	297.6
3	18/01/2013	2.92	1.44	2.66	82.9	60.6
4	22/01/2013	8.59	2.40	2.61	176.5	166.6
5	07/03/2013	0.20	0.21	0.25	0.6	0.1
6	21/03/2013	6.12	4.76	8.80	175.2	68.9
7	22/03/2014	8.59	1.64	7.38	125.0	75.1

Averaged across all the seven events monitored, there were highly significant effects of soil Olsen-P on the flow-weighted concentrations of both SRP and TDP (Figure 7.5). Range and median concentrations of both SRP and TDP were noticeably increased at the highest Olsen-P value (21 mg L^{-1}), but there was only a small statistical advantage in fitting an exponential rather than a linear function to the data. Predicted concentrations of SRP and TDP at Olsen P concentrations of 10, 16 and 25 mg L^{-1} were 14, 29 and 51 μg L^{-1}, and 40, 64 and 100 μg L^{-1}, respectively. DHP dominated dissolved P forms (>50% of TDP) when Olsen-P fell below 19 mg L^{-1}. Lowering Olsen-P from 25 (top of Index 2) to 10 mg L^{-1} (bottom of Index 1) therefore reduced the flow-weighted SRP concentration by over 70% (37 μg L^{-1}), and TDP concentrations by 60% (60 μg L^{-1}). Over a total year, this would reduce SRP loads from 28.2 to 7.4 g ha^{-1} and TDP loads from 55 to 22 g ha^{-1} based on an average annual flow of 220 mm.

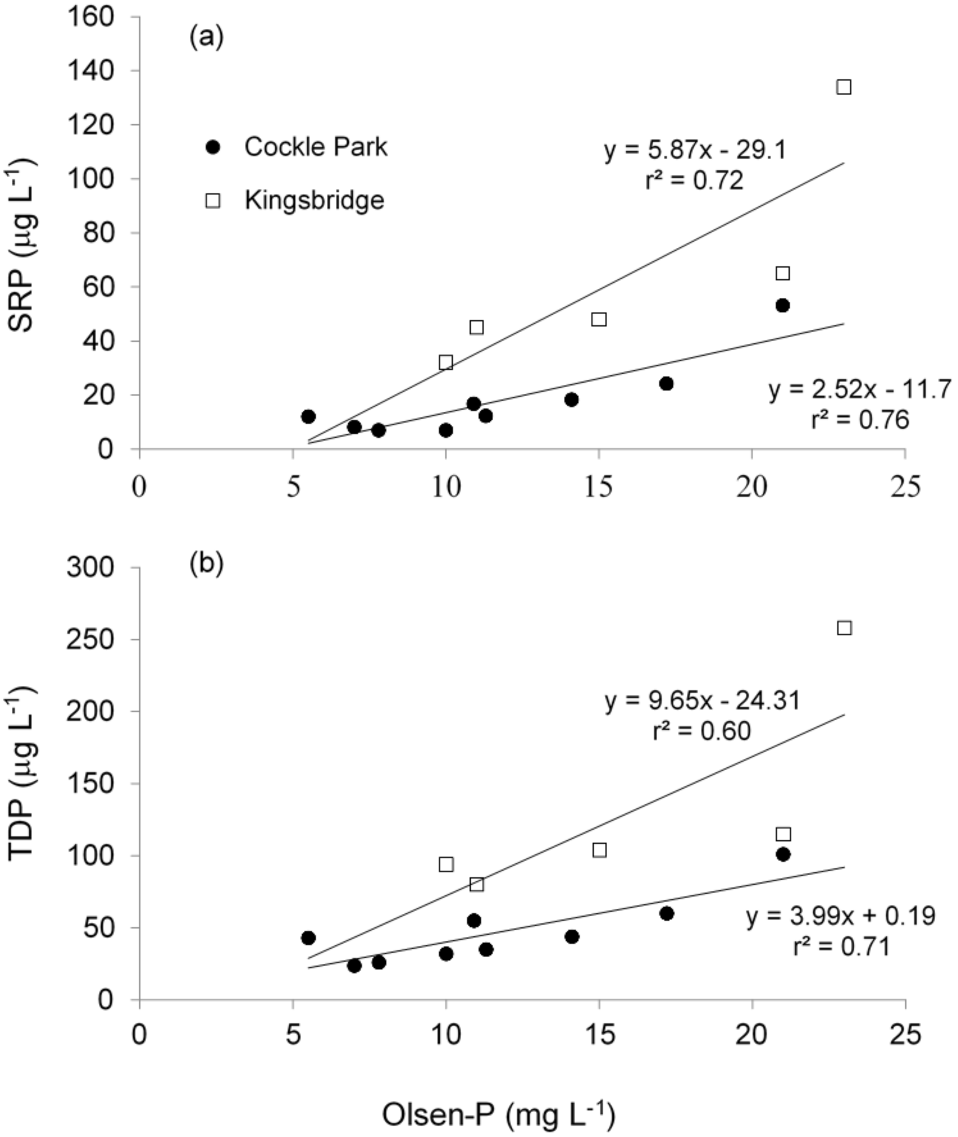

Figure 7.5. The relationship between soil Olsen-P concentration and flow-weighted concentrations of (a) soluble reactive P (SRP) and (b) total dissolved P (TDP) in sub-surface runoff through drains at a field site in Northumberland (Cockle Park), and surface runoff at a field site in Devon (Kingsbridge) England. Each data point represents the average flow-weighted concentration measured in 7 storm events at each site within the period December 2012 - April 2014. For Cockle Park, Olsen-P concentrations are the mean of 2012 and 2013. Equations and correlations coefficients (r^2) are shown.

There was no effect of soil Olsen-P on runoff flow-weighted TP concentrations (Figure 7.6), which were always dominated by particulate forms (mean 80% of TP) and averaged 268 μg L^{-1}. Total estimated annual TP load based on an average annual flow of 220 mm was 0.15 kg ha^{-}

^{1}. Sediment-P concentrations ranged from 619-1419 mg kg^{-1} and showed a positive linear relationship with Olsen-P (Figure 7.5). Lowering Olsen-P from 25 to 10 mg L^{-1} would reduce SS-P concentrations from 1,566 to 930 mg kg^{-1} based on this relationship.

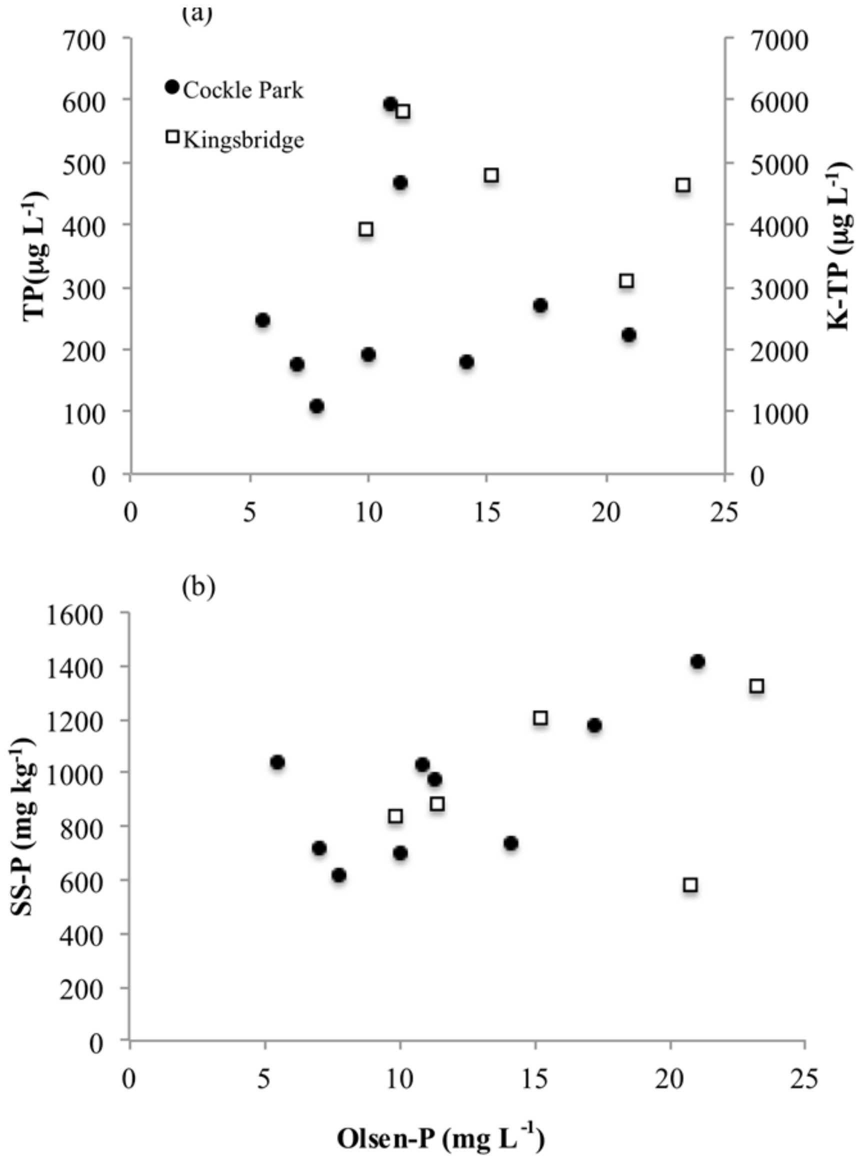

Figure 7.6. The relationship between soil Olsen-P concentration and flow-weighted concentrations of (a) total P (TP) and (b) sediment-P (SS-P) in sub-surface runoff through drains at a field site in Northumberland (Cockle Park, CP), and surface runoff at a field site in Devon (Kingsbridge, KB) England. Each data point represents the average flow-weighted concentration measured in 7 storm events at each site within the period December 2012 - April 2014. For Cockle Park, Olsen-P concentrations are the mean of 2012 and 2013.

7.3.2 P losses in surface run-off at Kingsbridge, Devon.

At Kingsbridge, event flow ranged from 0.2 – 10.7 mm, representing from 3–55% of incoming rainfall (mean 26%). Storm events produced highly variable loads of P and SS (Table 7.3), with runoff SRP, TDP, TP and SS concentrations ranging up to 0.24, 0.70, 23.3 and 24.2 mg L^{-1}, respectively across all plots and events (Appendix 2). As at Cockle Park, particulate forms dominated TP export, and with clearly higher range and median SRP and TDP concentrations at the highest Olsen-P level (23 mg L^{-1}). Soil Olsen-P had a highly significant ($P < 0.001$) effect on dissolved P concentrations (Figure 7.5), but not on runoff TP concentrations (Figure 7.6) when averaged across all the seven events monitored. Sediment-P concentrations were very similar to those at Cockle Park except for one plot (Church 6) which showed much a much lower value (Figure 7.6b).

The concentrations of SRP and TDP at Olsen P concentrations of 10, 16 and 25 mg L^{-1} were estimated by linear regression to be 30, 65 and 118 μg L^{-1} and 72, 130 and 217 μg L^{-1}, respectively. Lowering Olsen-P from 25 to 10 mg L^{-1} reduced the flow-weighted SRP concentration by 75% (88 μg L^{-1}) and TDP concentrations by 67% (145 μg L^{-1}). DHP fell below 50% of TDP when Olsen-P increased above 16 mg L^{-1}. Flow-weighted TP concentrations averaged 4.4 mg L^{-1}, and were much higher than at Cockle Park, reflecting the vulnerability of the Kingsbridge site to erosion (Figure 7.6a).

Two storm events (events 5 and 6) were continuously monitored to provide an insight into the effect of the different levels of soil P on the different P fractions. Storm runoff from event 5 was very small (0.2 mm) compared to event 6 (6.12 mm). For both events, the highest concentration of each of the P fractions were recorded at the start of the event (i.e. after 0-2 hours), with concentrations decreasing as the event progressed. Concentrations were usually highest from the plots with the highest soil P (i.e. Church 5) and lowest from those with the lowest soil P (i.e. Big Combe or Lower 3). Dissolved P fractions tended to show different rates of decline, while PP fractions declined at a similar arte across the different soil Olsen-P concentrations. There was no relationship between the duration of the event and TP or PP concentrations

7.3.3 **Incidental P losses in surface run-off at Loddington**

The simulated rainfall generated large and similar amounts of runoff on most runoff plots (averaging 30-56 L), and there was no significant treatment effect on runoff volume (Table 7.4). Concentrations of SS were also relatively uniform across the different fertiliser treatments (averaging 3-4.5 g L^{-1}) suggesting the simulation rainfall conditions were reasonably similar for all the different fertilisers tested. The mains water at Loddington used for the simulation study unusually contained a large amount of dissolved P (1.1 mg SRP/TP L^{-1}). There was no statistically significant treatment interaction in the effects on runoff P concentrations and therefore soil P and fertiliser P treatment effects have been averaged across plots in Table 7.4 (note the data have not been corrected for the background concentrations of P in the water used for the simulation).

Although there was a large difference in soil Olsen-P between the two monitoring areas, there was no significant effect of soil P fertility level on dissolved or particulate P concentrations in the runoff (Table 7.4). Previous analysis of soil P release from Loddington soils by the DESPRAL test (Withers *et al.*, 2007; Withers *et al.*, 2009) found that TDP concentrations in runoff at 17 and 65 mg L^{-1} Olsen-P were approximately 0.06 and 0.18 mg L^{-1} respectively. The measured concentrations of TDP on the control (nil P) monitoring areas in this study at 17 and 65 mg L^{-1} Olsen-P were 0.94 and 0.42 mg L^{-1} respectively (N.B. excluding one replicate plot with high P values, the runoff TDP concentration at 17 mg L^{-1} Olsen-P was 0.05 mg L^{-1}, which is similar to the DESPRAL value). This suggests there was a soil P effect on dissolved P concentrations but that it was heavily masked by the large amounts of incidental P mobilised by the fertiliser treatments. Total P concentrations on the nil P plots were ca. 5 mg L^{-1} at both low and high Olsen-P levels and were dominated by particulate P (70% of TP) as expected under simulated rainfall.

Table 7.4 Soil P Index and fertiliser (TSP, TSP+AVAIL® or struvite) treatments effects on run-off volume, TP, SRP, TDP, DHP, PP, SS,and SSP concentrations and for the untreated control at Loddington.

Treatment	**Run-off (l)**	**TP (mg/l)**	**SRP (mg/l)**	**TDP (mg/l)**	**DHP (mg/l)**	**PP (mg/l)**	**SS (mg/l)**	**SSP (mg/kg)**
P Index 2	47.4	14.5	6.66	9.76	3.12	4.75	3863	1237
P Index 4	34.7	13.4	6.08	8.34	2.26	5.11	3128	1845
	NS (0.10)	NS (0.94)	NS (0.68)	NS (0.44)	NS (0.50)	NS (0.76)	NS (0.39)	NS (0.06)
Control	44.4	5.18	1.67	1.78	0.11	3.40	3,317	1,054
TSP	39.4	18.7	9.15	13.8	4.60	4.96	3,653	1,601
TSP/Avail®	45.4	27.6	13.3	19.3	6.02	8.27	4,294	2,322
Struvite	35.1	4.46	1.38	1.38	0.03	3.08	2,720	1,186
	NS	<0.001	<0.001	<0.001	<0.01	<0.05	NS	<0.05

The fertiliser treatments produced highly significant effects on runoff dissolved and particulate P concentrations (Table 7.4). For the AVAIL® and TSP treatments, TP, SRP, TDP and DOP concentrations were much higher than both the untreated control and struvite treatments (*P*<0.01). The largest treatment differences were in SRP and there was a tendency for TSP+AVAIL® to give greater P release than TSP, especially soon after rainfall was applied. Sampling of runoff from the soil P Index 2 area at intervals through the 30 minute monitoring period showed a pattern of decreasing concentrations over time, but with initially greater concentrations form the TSP+AVAIL® treatment than TSP alone (Figure 7.7). Particulate P concentrations and SS-P concentrations were also significantly higher from the TSP+AVAIL® treatment compared to the other fertilisers (Table 7.4), suggesting the high dissolved P release from the TSP+AVAIL® fertiliser was being partly adsorbed by the eroding particles during transit, a process previously observed by Sharpley (1985). In contrast, there was no significant (*P*>0.05) P release from struvite and runoff dissolved P concentrations were very similar to the untreated control plots both during the runoff simulation (Figure 7.7) and in total (Table 7.4).

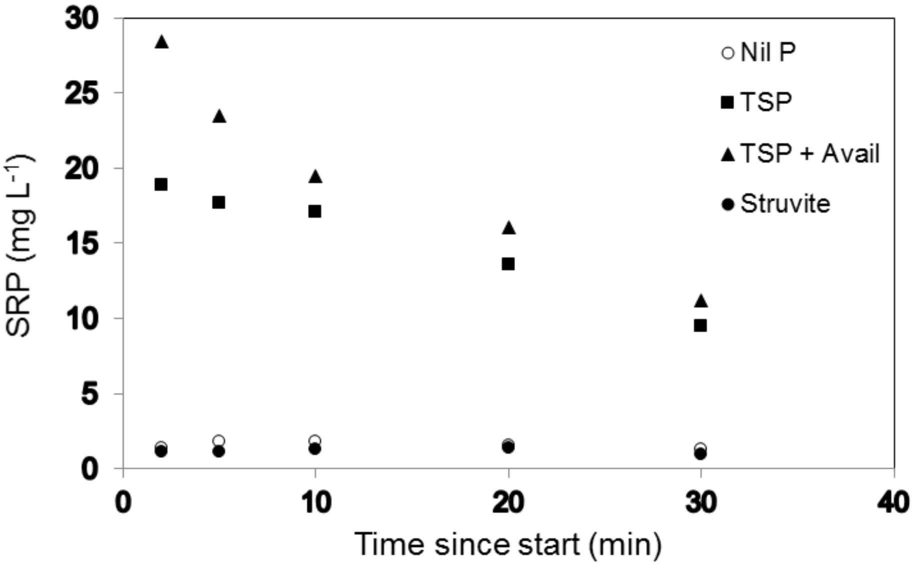

Figure 7.7. Concentrations of soluble reactive P (SRP) in run-off during a simulated rainfall event applied to areas with Olsen-P of 17 mg L^{-1}, after receiving conventional (TSP) or novel P fertilisers (TSP+AVAIL® and struvite) at Loddington.

7.3.4 The DESPRAL test on contrasting soils

Soil Olsen-P at the four sites typically varied from <10 up to 25 mg kg^{-1}, except at Peldon where a value of 51 mg kg^{-1} was measured on one plot (Figure 7.8). For all runoff parameters measured, Olsen-P had a positive effect. The rate of increase in TDP concentrations between sites was not statistically different, and a common line suggested that for each additional increase in Olsen-P of 10 mg kg^{-1}, TDP concentrations would increase by about 17 µg L^{-1} (Figure 7.8a). However, for TP and SS-P, sites differed in their response to Olsen-P, with largest rates of increase in TP concentrations at Great Carlton (Figure 7.8b), and largest increases in SS-P concentrations at the sandy Caythorpe site (Figure 7.8c). This shows that Great Carlton was the most erosion prone site.

Table 7.5 Site details of the sites used for DESPRAL analysis.

Location	**Topsoil texture**	**Soil Association**	**No. of samples**	**Olsen-P (mg kg^{-1})**
Peldon	Clay	Windsor	18	6 - 51
Caythorpe	Sandy Loam	Quorndon Blackwood	18	6 - 21
Great Carlton	Fine loam	Holderness	18	4 - 20
Loddington	Clay loam	Denchworth	4	9 - 25

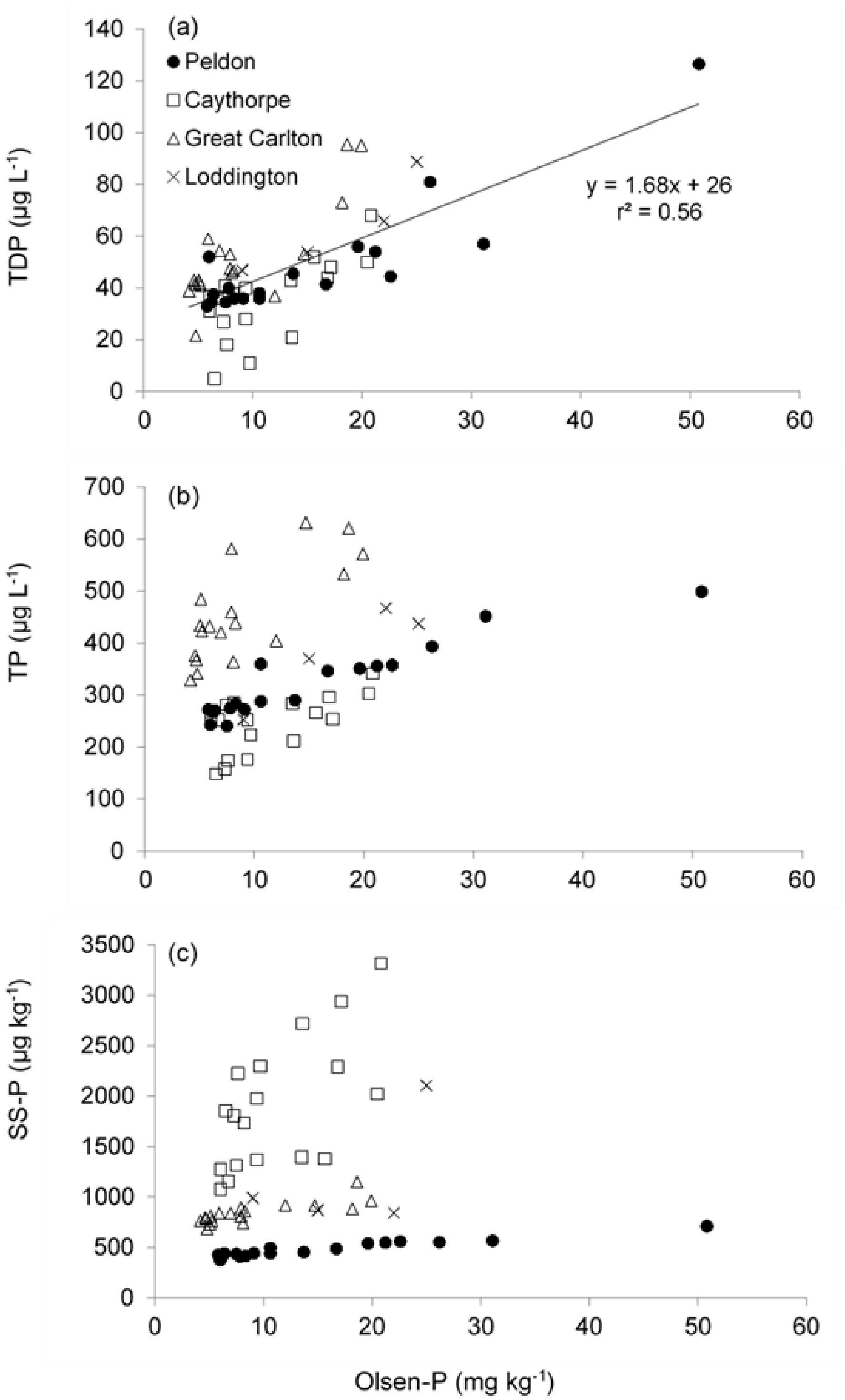

Figure 7.8. The effect of Olsen-P on the concentrations of (a) total dissolved P (TDP), (b) total P (TP) and (c) P in suspended sediment (SS-P) at four sites using the DESPTAL test.

7.4 Discussion

Soil P fertility status is only one of a number of factors influencing catchment P export and eutrophication risk, although it clearly does provide an important background runoff P signal from agricultural areas during rainfall events. Large variation in soil Olsen-P between and within fields, the ubiquity of other mobilized P sources in rural areas, and retention / remobilization processes within catchments can make it very difficult to separate out and quantify this background signal (Page *et al* 2005, Withers *et al* 2009b, Jarvie *et al* 2012). Focussed laboratory and field-scale studies can therefore provide useful insights for the development of policy strategies aimed towards sustainable agricultural intensification. At the outset, it must also be recognised that hydrology and soil stability are often equally more important drivers for P loss than soil P fertility level: for example, TP losses from low P fertility sites can exceed those on high P fertility soils simply because the amount of runoff and erosion is greater (Kleinman *et al.,* 2011; Jordan *et al.,* 2012). Notwithstanding these additional factors, we argue and hypothesize that lowering the background P signal from farmed soils can only be beneficial in the quest to achieve good water quality and ecological status in freshwaters.

Most studies investigating the effects of Olsen-P on runoff P concentrations seek to identify soil P change-points rather than assess the eutrophication impact of soil P values below the change-point (Figure 7.1). Assessing eutrophication impact becomes even more difficult when soil tests are used as surrogates for measured runoff P concentrations (Bai *et al.,* 2013). We did not find any change points in either of our field experiments, other than the tendency for runoff P concentrations to become more variable as Olsen-P concentrations increased. The range in Olsen-P concentrations established at Cockle Park and at Kingsbridge was rather limited (<25 mg L^{-1}) and inclusion of slightly higher Olsen-P values at these field sites would have given a better indication of whether Olsen-P runoff P relationships became more non-linear as Olsen-P increased. The results of the DESPRAL analysis suggested linear relationships across the four sites studied, but this is a laboratory-based procedure which does not fully mimic natural field conditions (Withers *et al.*, 2007).

To provide a more complete picture of the impact of Olsen-P on runoff P concentrations under UK conditions, the data from Cockle Park and Kingsbridge were compared with an in-depth meta-analysis of all available UK data linking soil P fertility to dissolved and particulate P concentrations in runoff from agricultural land. Full details of this meta-analysis are given in Withers *et al.* (2016); Olsen-P values at Cockle Park and Kingsbridge were first converted to mg kg^{-1} to allow comparison with these other data. This meta-analysis showed that the runoff-P data from Cockle Park and Kingsbridge were very similar to those obtained at other sites in relation to dissolved P in drain-flow (Cockle Park) and surface runoff (Kingsbridge) under natural rainfall (data for SRP are shown in Figure 7.9). When all data were combined, a single common linear (rather than non-linear) regression was statistically most appropriate to explain the variance in runoff dissolved P concentrations across sites, except for drain runoff at

Broadbalk where the relationship was non-linear, probably due to the much larger number of high Olsen-P values in the dataset.

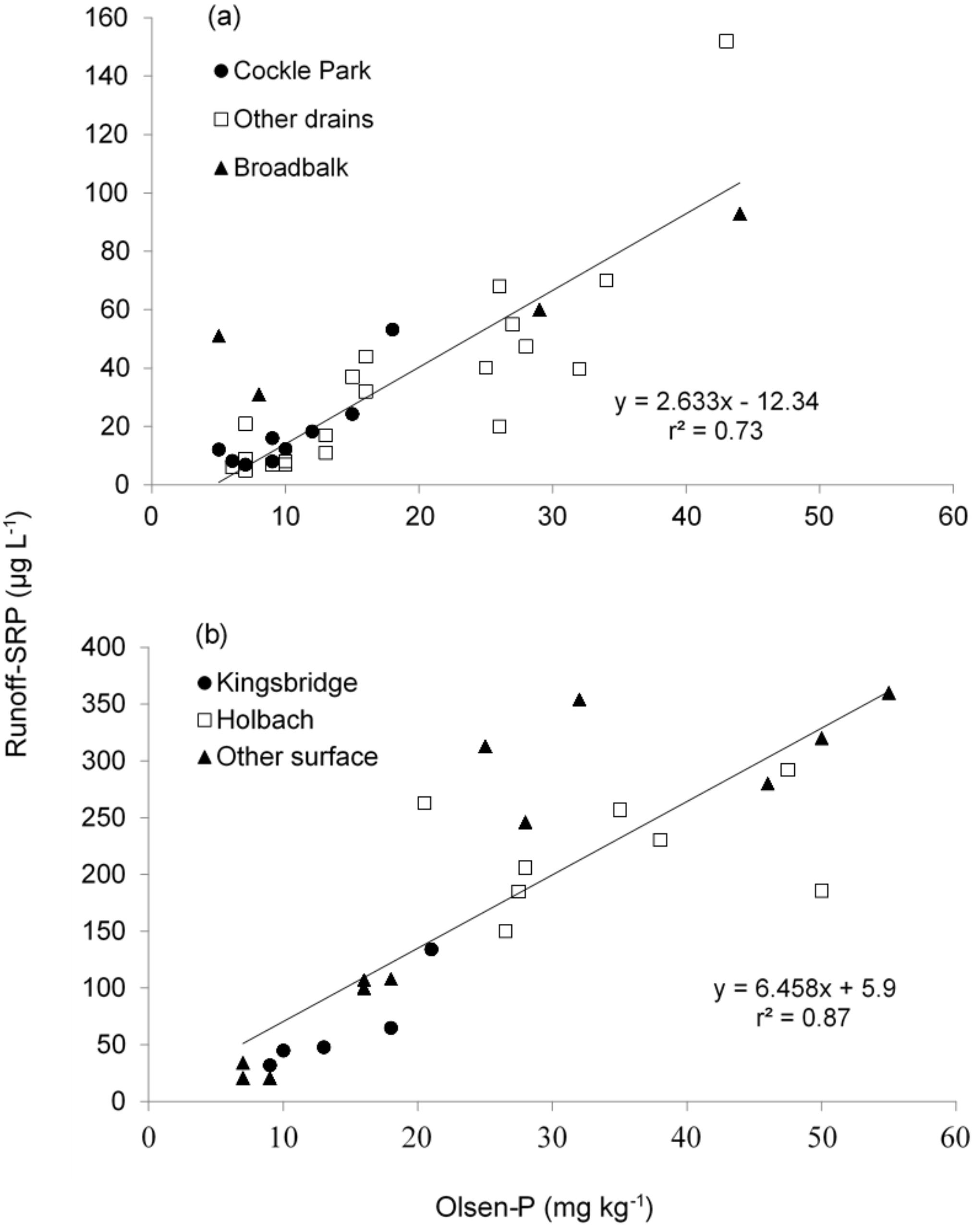

Figure 7.9. The relationship between soil Olsen-P concentration and concentrations of soluble reactive P (SRP) in (a) drain flow and (b) surface runoff collected from different sites under natural rainfall. The range in Olsen-P is restricted to < 60 mg kg^{-1} to illustrate the tendency for runoff SRP to increase above an Olsen-P of 10 mg kg^{-1}. The regression lines are common to all data. Note the difference in scale between drain flow and surface runoff P. (Reproduced from Withers et al.; 2016).

Hart & Cornish (2012) also found that linear regression was statistically most appropriate for Australian soils even though some sites showed some non-linearity due to high STP values.

The occurrence of these linear relationships clearly suggests that significant environmental gains can be obtained by reducing Olsen-P to the agronomic optimum and below, especially since over 40% of UK soils are above P Index 2 (PAAG 2015). For example, estimated decreases in SRP and TDP concentrations in drain-flow and surface runoff due to reducing Olsen-P from 50 to 25 mg kg^{-1} and by reducing Olsen-P from 25 to 10 mg kg^{-1} are large (Table 7.6).

Table 7.6 Estimated changes in soluble reactive P (SRP) and total dissolved P (TDP) in drain-flow and surface runoff from reducing topsoil Olsen-P from 50 to 25 mg kg^{-1} and from 25 to 10 mg kg^{-1}. Data are based on a meta-analysis of UK available data under natural rainfall. Percentage reductions are given in parenthesis.

Reduction in Olsen-P *(mg kg^{-1})*	**Drain flow** **SRP** *(µg L^{-1})*	**Drain flow** **TDP** *(µg L^{-1})*	**Surface runoff** **SRP** *(µg L^{-1})*	**Surface runoff** **TDP** *(µg L^{-1})*
50 to 25	-65 (55%)	-93 (49%)	-162 (49%)	-165 (43%)
25 to 10	-40 (75%)	-56 (57%)	-96 (57%)	-99 (44%)

In addition to soil available P, additions of P in inorganic fertilizers are a significant source of highly bioavailable P in land runoff, especially when surface applied and during the first few hours of rainfall (Hart *et al.*, 2004). At Loddington, the application of the water-soluble fertilisers TSP and AVAIL® significantly increased P concentration in run-off (all forms of P) compared to the lower water-soluble fertiliser struvite. Struvite application did not appear to increase the P content of run-off compared to the untreated control. Similar results were obtained by McDowell *et al.* (2010) in a paired catchment study in New Zealand, who found significantly reduced P losses when low water-soluble rock phosphate was applied as the fertiliser source compared to when highly soluble superphosphate fertiliser was used. This suggests that the eutrophication risks to water bodies from the application of slow release fertilisers such struvite are considerably less than from TSP or TSP+AVAIL® applications. It is unclear why initially higher SRP concentrations in runoff were obtained when TSP+AVAIL® was used compared to TSP alone. The presence of the surface polymer must have increased dissolution in the runoff water of this particular study.

7.5 Conclusions

Soil P fertility built up from previous applications of fertilizers and manures poses a eutrophication risk by increasing the background P loss footprint that may confound attempts to improve water quality using targeted interventions including those supported by current agri-environment schemes and voluntary initiatives. There is a clear need to minimise this background P footprint to achieve sustainable intensification, and one key policy option for eutrophication control is to put more emphasis on reducing soil P fertility. A key argument for making the transition towards more sustainable agriculture and lower soil P fertility is that it will benefit the environment in terms of lower eutrophication risk (Withers *et al.,* 2014). Since positive relationships were obtained between soil Olsen-P and dissolved P in runoff, the data at Cockle Park and at Kingsbridge, and for the DESPRAL analysis, supported by a wider meta-analysis of UK available data (Withers *et al.*, 2016; Figure 7.9), clearly supports this argument, at least in terms of achieving WFD waterbody target P concentrations in the UK.

P concentrations were significantly less in drain-flow than in surface runoff, and the data here suggest that reducing soil Olsen-P to 10 mg kg^{-1} would reduce the background P footprint from field drains to very low SRP values (<20 µg L^{-1}). Since a large proportion of agricultural fields in the UK are under-drained, this is an important finding, and one which could lead to more effective and rapid eutrophication control from farming. Such a reduction would also help to buffer the additional P footprint associated with P losses following fresh P applications to soils and other more point-source driven P inputs to freshwaters (Withers *et al.*, 2014b). Some sites will still remain a risk even at lower soil P fertility and it will be important to identify these high-risk sites. As soil P fertility declines, field runoff will become more dominated by less available P forms (dissolved organic P) and this fraction may well become more ecologically relevant in driving standards. Soluble reactive and hydrolysable (organic) P concentrations were considerably more sensitive than total P concentrations to changes in Olsen-P status, as might be expected due to the variability in erosion risk between sites.

8. National and Global impacts (WP5)

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8.1 Introduction

8.1.1 Aims and scenarios

The original aim of this WP was "to quantify the wider economic and environmental impacts of techniques to improve sustainability of P use on arable farms". Economic impacts were expected to include effects on crop productivity and on the profitability of arable farming. Environmental impacts were expected to include effects on (i) rock-phosphate consumption, hence the sustainability of global P supplies, (ii) eutrophication, and (iii) greenhouse gas (GHG) emissions, hence on global warming. The work here thus entails extrapolating results from the project, and from the literature where necessary, to make estimates, for a range of P use scenarios of:

i. equilibrium crop yields
ii. margin over fertiliser cost from growing arable crops (cereals, oilseed rape and potatoes) in the UK,
iii. national use of fertiliser P, and
iv. equilibrium soil P concentrations.

All wider economic and environmental impacts should be directly predictable from these outcomes.

The project's Steering Group in January 2015 agreed to explore these impacts with respect to the following particular scenarios for fertiliser P use in the UK:

A. As is recommended now (in the Fertiliser Manual, RB209; Defra, 2010), using the soil as a store of P for crops, with routine soil analysis and P applications made on a rotational basis to maintain a target level of P.
B. With annual targeting (e.g. placement) of some P, to improve its recovery, but also with fertiliser P applications sufficient to replace P offtake, hence to maintain the soil P store.
C. As in Scenario B but without replacement of P offtake, so allowing the soil P store to become increasingly depleted.

D. With applications being restricted to use of re-cycled P materials only (manures, biosolids, struvite, etc.).
E. Zero P use.

However, given the results of the other WPs, particularly the poor recovery of all forms of fertiliser P and the marginal advantage of P placement shown in the response experiments in WP3 (Section 6), it now appears most important, before exploring economic and environmental impacts of P use Strategies B & C, to resolve a key question left unanswered by the project so far, which is (ignoring the strong environmental case made in Section 7) whether there are sufficient *economic* advantages (and absence of disadvantages) in the quest to enhance fertiliser P recoveries (e.g. by P targeting) to justify significant further economic investment to develop new or improved products or techniques.

8.1.2 **The economics of innovation in crop P nutrition**

In short, economic benefits to farmers or fertiliser manufacturers or plant breeders of developing more efficient fertilisers or crop varieties are subtle, rather than obvious. To explain:

- Current P use has been considered to be 100% efficient or more (Syers *et al*., 2008), since current recommendations are that P in crop produce at harvest should be matched by P inputs in manures and fertilisers (Defra, 2010). As an example, if the soil store is judged to be just adequate (soil P Index 2) a crop P offtake of 25 kg ha^{-1} will be balanced by a fertiliser P addition of 25 kg ha^{-1}. This approach clearly ignores the value of the soil P store, and of natural weathering of P, and it incurs environmental costs, but none of these factors impinges directly on farmers, manufacturers or breeders.
- The value of the realisable soil P store in UK arable soils may be quite large, and it appears from national statistics that it is already being run down (Figure 8.1; Edwards *et al*., 2015). Using the ‘apparent soil phosphate requirement’ (ASPR) suggested in the Fertiliser Manual (RB209; Defra, 2010) of 40 kg ha^{-1} P_2O_5 mg^{-1} L^{-1} soil P, and the current price of P_2O_5 (£0.65 kg^{-1}), a soil P store supporting 20 mg L^{-1} of soil P determined by Olsen analysis is worth 20 x 40 x £0.65 = £520 ha^{-1}. Using the half-life of 9 years suggested by Johnston *et al*. (2016) for Olsen’s soil P, depletion of this store from P Index 3 to Index 2 should take 5 years and from P Index 2 to Index 1 should take 6 years. However, all four ‘run-down’ sites reported here (Section 6) are clearly taking a lot longer than this (Figure 6.5).
- The potential for running down the soil P store and saving on fertiliser costs by applying less fertiliser P than P offtake is time-limited, because release from the soil P store will eventually diminish to just that P released by weathering of inherent mineral P, or mineralisation of organic P. As an example, where soil weathering releases 7 kg ha^{-1} year^{-1}

and the crop requires 25 kg ha^{-1} for growth, a fertiliser P addition of at least 25-7=18 kg ha^{-1} will be required, and even if 50% of the fertiliser P were recovered by the crop (as compared to ~10% currently; Section 6), the fertiliser requirement would be 36 kg ha^{-1} year^{-1}. The unrecovered P would then contribute to a residual soil P supply, exceeding the 7 kg ha^{-1} year^{-1} from just weathering.

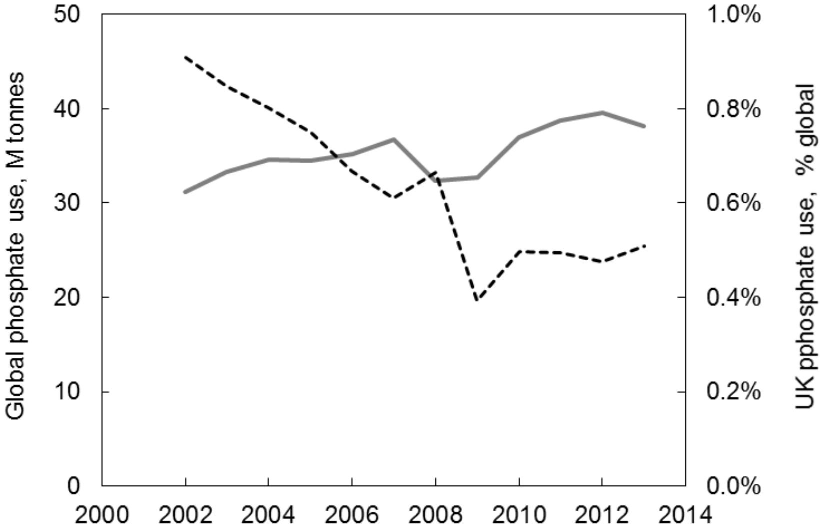

Figure 8.1. Contrasting trends in global (solid line) and national UK (broken line) phosphate (P_2O_5) fertiliser use over the past decade.

- In discussing crop P demands, we questioned whether crops must store P (especially phytates) in such large quantities (Section 6). However, it will take far longer than the timescales set to achieve good water quality (EA, 2015; UKTAG, 2012, 2016) and global food security (FAO, 2008) to breed the full range of crop species with significantly diminished crop P demands. Specific existing germplasm may be revealed with reduced requirements, and then exploited in breeding programmes, but this is unlikely to apply to all cropped species. Hence, even if systems of crop P nutrition were consciously 'designed', the designers must consider that rotations will generally include crops with significant P demands, of say 20-30 kg ha^{-1} in the UK.
- The infrastructure to mine, transport and manufacture current soluble P fertilisers has entailed considerable investments by large companies and their businesses are based on exploiting these investments; these businesses could be compromised by changing to different fertiliser forms requiring new manufacturing techniques. Thus there are vested interests in maintaining the status quo, and significant market hurdles that any new competitor must overcome.
- The success of struvite in terms of crop response, even though marginal, indicates the potential to exploit slow release mechanisms for applied P. Perhaps the most obvious

mechanism to exploit is the immobilisation and subsequent mineralisation of P in organic forms. Much P is already applied to land as organic manures and biosolids, however these are often unavailable to arable farms through their bulk and consequent transport costs. Most exports of arable crop P are in grain, and are transferred to livestock farms in the west, where the high P excreta are too bulky for economic return to distant arable lands, so they come to build often unnecessarily large soil P reserves in the west (Edwards *et al*., 2015). One possibility for innovation is to introduce large-scale processing of organic manures in regions where these are in excess (particularly to reduce bulk, by removing water and excess biomass) producing dry and transportable materials with concentrated P in organic forms (Schoumans *et al*., 2010) and with slow release properties, hence increased crop recoveries compared to soluble inorganic fertilisers. The economics of such innovations are complex and driven by regulations as well as enhanced product values, so are beyond the scope of this report, but the thorough analysis by Schoumans *et al*. (2010) in the context of the Netherlands provides most relevant information.

- The starting points for any investment in alternative P use strategies must differ between developed world regions such as Europe where significant soil stores of P have already been established by investments through the last half-century or so, and the developing world where P fertilisers remain less affordable or available, soils commonly remain depleted of P and where fresh P applications are crucial in the quest to sustain profitability and enhancement of arable crop production. Recent trends in P fertiliser use globally and nationally show large contrasts, with UK use decreasing from 1% to ½% of global use in the past ten years (Figure 8.1); thus, whilst nationally we have the option to change (or not) our fertiliser P strategy, this can have little direct impact on P use globally.

In conclusion, development of P nutrition technologies with enhanced performance may provide sufficient commercial opportunities for specialists targeting national or regional markets, but large scale change is more likely to be driven by regulation of environmental impacts of P use, or by more global demands for greater efficiency of crop P nutrition.

8.2 Approach and assumptions

Despite the uncertainties about how the economic and environmental drivers for change in crop P nutrition will play-out, we now offer an outline attempt to quantify the impacts of scenarios A to E, so the assumption here is that changes will be possible. Note that resources devoted to this WP have been limited by unplanned extra resource-requirements of other WPs e.g. to integrate the results of all field experiments (Section 6) into a new ‘crop demand – soil supply – fertiliser efficiency’ model (as developed in the review by Edwards *et al*., 2015). Thus a preliminary analysis is described here, with the intention of providing an example of more intensive investigations that might be attempted if and when further resource becomes available.

The general approach has been to assemble recent national data on cropping practices, crop performance, and soil P status, and to estimate outcomes for a 'business as usual' scenario, taken to equate with scenario A. We have then used relationships determined in other WPs of this project or in the literature to derive relationships from which we could estimate changes in the outcomes for the other scenarios.

Recent national data on crop areas and average yields were taken from statistics published on the government website (www.gov.uk/government/statistics). The arable land area was taken to be 4.64 Mha, being the sum of all crop areas, including 4% setaside (Table 8.1). The distribution of soil P status of this arable land (by Olsen's method) was taken from the most recent results of the Representative Soil Sampling Scheme, and from the most recent publications of the Professional Agricultural Analysts Group (PAAG; see Edwards *et al*., 2015, for details). These two data sets were in reasonable agreement (Figure 8.2) so a mean was taken. Crops are not equally distributed across soils with different P status; vegetables, potatoes and sugar beet tend to be grown on lighter soils which have higher P status than heavier soils. However, these crops represent less than 10% of the arable area so, for the sake of simplicity, this effect was ignored. Similarly, not all soils support the same crop yields but crop yields here were assumed to be the same across all soils except that yields on the minority of land at P Index 1 (17%) and P Index 0 (4%) were assumed to be reduced by 10% and 20% respectively (based on average yield responses in the long term P experiment at Saxmundham, Suffolk as described by Johnston & Poulton, 2011, in the Critical P Project; Knight *et al*., 2014, and in Table 6.21). Yields at P Index 2 or more were assumed to be 3% above national average yields, so that overall national average yields used here were the same as those published in the national statistics.

Current use of fertiliser P (for Scenario A) and P contents of harvested crop produce (used to calculate P offtakes from land) were assumed to be as recommended in the Fertiliser Manual (RB209; Defra, 2010). Current use of fertiliser P was compared with statistics in the British Survey of Fertiliser Practice (BSFP, 2016) and was found to be relatively similar, with total arable fertiliser P applied being 60 Kt year^{-1} (Table 8.1), 80% of the total P estimated as being recommended (75 Kt year^{-1}). The 20% shortfall can possibly be attributed to applications of P in organic manures. The proportion of land with fertiliser P being recommended for crops other than potatoes and vegetables (i.e. at P Index 2 or less) was 49%, exactly the same as the proportion of these crops receiving fertiliser P according to the BSFP; the proportion of potato and vegetable land with fertiliser P being recommended (i.e. at P Index 3 or less) was 84%, slightly more than the 73% in BSFP data.

Table 8.1 Total areas, proportions receiving P fertilisers in a year, average annual amounts applied and total use of fertiliser P on major UK arable crops, averaged for 2014 & 2015 (from the British Survey of Fertiliser Practice, accessed here).

Crop	**Proportion of arable area, & total area**	**Area dressed with P fertiliser**	**Average rate fertiliser P applied**	**Total UK use of fertiliser P**
	%	*%*	*kg ha^{-1}*	*Kt*
Winter Wheat	39	44	27	21.4
Winter Barley	9	54	24	5.4
Spring Barley	13	67	22	9.0
Oilseed Rape	14	47	26	7.8
Sugar Beet	2	40	26	1.0
Potatoes	3	76	59	5.6
Peas & Beans	4	29	24	1.2
Maize / other	5	59	19	2.8
Vegetables	3	70	44	4.4
Set-aside	4	22	26	1.0
Total	**4640 Kha**			**59.5**

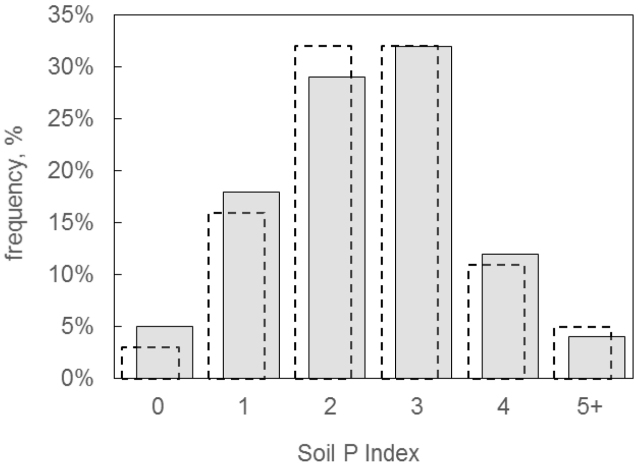

Figure 8.2. Frequency of topsoil P status of UK arable land averaged from 3,500 samples taken in the Representative Soil Sampling Scheme in 1995-1999 (broken line), and 65,000 commercial samples analysed in 2011-12 by members of PAAG (shaded, after Edwards et al., 2012),

In order to sum crop productivity for all arable crops on a standard basis, harvested biomass was estimated assuming moisture contents were 15% for cereals grains and pulses, 9% for oilseeds, 80% for potatoes, 77% for sugar beet and 65% for forage maize. An average biomass production of 8 t ha^{-1} was assumed for all field vegetables, and harvested material was assumed to have 80% moisture. Average prices of crop produce were also taken from recent Defra statistics and a price of P_2O_5 in inorganic fertiliser was assumed to be £0.65 kg^{-1} (equivalent to £1.50 kg^{-1} P). To translate land P balances into changes in soil P status an apparent soil phosphate requirement (ASPR) of 40 kg ha^{-1} mg^{-1} L^{-1} was assumed, as suggested in the Fertiliser Manual (RB209; Defra, 2010). These data were then used in a simple spreadsheet to calculate for the UK as a whole:

i. Yields of individual crops, overall crop productivity in terms of harvested biomass, and the economic value of all UK crop production
ii. Margin over P fertiliser cost from growing arable crops in the UK,
iii. National use of fertiliser P, and
iv. Offtakes of P in harvested crop materials, hence annual land P balances and thus annual changes in topsoil P (by Olsen's method). This enabled estimation of average arable UK topsoil P concentrations after a period (set arbitrarily) of 10 years.

For scenarios B & C, placement of P fertiliser was assumed to increase yields by 5% of maximum yield if soils were at less than P Index 2. In these cases P recovery was increased proportionately.

For Scenario D (applications being restricted to use of re-cycled P materials only) it was assumed that only half of the normal fertiliser P consumption could be replaced by recycled sources but that all of this would be in organic forms, hence its equilibrium efficiency over 10 years) would be 20% rather than 10% for conventional broadcast fertilisers.

8.3 Results

The main outcomes of each scenario are presented in Table 8.2 and are explained in the following five sub-sections. .

Table 8.2 Estimated outcomes of the current strategy for the UK (A) as they affect global P reserves, eutrophication risk, food security, and farm profitability, and effects of four alternative strategies for P fertiliser use (B-E). Crop recovery from 'Targeted' P was presumed small (~10%) in Scenario B and large (~50%) in Scenario C.

Fertiliser use scenario	**Amount of P used**	**Soil P balance**	**Total crop biomass**	**Total crop value**	**Margin over fertiliser (A) & +/- effects**[1]
	Kt year^{-1}	*Kt year^{-1}*	*Mt year^{-1}*	*£M year^{-1}*	*£M year^{-1}*
A Maintenance (M)	75.2	-24.4	26.9	£5,239	£5,127
B M + 'targeted'	75.2	-25.3	27.2	£5,296	+ £57
C 'Targeted' only	25.7	-76.3	27.7	£5,359	+ £232[2]
D Recycled only	(22.7)[3]	-73.9	26.1	£5,011	- £117[4]
E None	0.0	-94.4	25.3	£4,959	- £168

[1]..Values for scenarios B-E are differences from Scenario A.
[2] Excluding a large one-off benefit from utilising soil-stored P.
[3]..All from recycled sources.
[4]..No cost was attached to recycled P.

8.3.1 Scenario A: Business as Usual i.e. with Maintenance of the Soil P Store

Total national (UK) arable crop productivity is estimated to be about 27Mt of harvested biomass, worth approximately £5.4 billion at farm gate prices. Wheat constitutes about 45% of the biomass but only 34% of the value, whereas potatoes and vegetables together constitute only 8% of the biomass but 34% of the value.

Although national statistics indicate 60Kt of fertiliser P are currently used annually to grow all these crops, the assumption in this Scenario is based on current recommendations which are to apply 75Kt P annually. By assuming the recommended amounts, on the basis that they are similar in total, it becomes possible to assess fertiliser P amounts applied to each crop at each soil P Index. Thus it can be estimated that 12%, 38%, 46% and 4% of all fertiliser P was used at P Indexes 0 to 3 respectively, and none was used at greater P indices. The similarity between P recommendations and P use in terms of areas dressed each year tends to support the conclusion that most farms are using annual rather than rotational applications. [This conclusion depends on the detail of how the questions in the BSFP survey are asked and answered.] Thus it appears that most crops are receiving 'fresh' fertiliser P already and, if the effects of fresh P applications are to be enhanced and exploited, it is only the form and method of these applications that needs to change, and not their frequency as well.

The net ongoing effect of this scenario on national arable soil P reserves is to reduce the soil P stock by approximately 25 Kt year^{-1}, because the total amount of P removed from land in harvested arable produce (100 Kt) exceeds the fertiliser P applied (75 Kt). This arises because 48% of the area has a soil P status exceeding the target Index of 2, whereas only 21% of the area has a P status of less than Index 2. Whether sufficient recycled P is applied to arable land to make up the 25 Mt shortfall is uncertain.

Of course, if this strategy is maintained, land at P Index 0 or 1 will increase its soil P status and land with P Index greater than 2 will decrease its soil P status. Assuming the ASPR is 40 kg ha^{-1} mg^{-1} L^{-1} it appears that all low P soils should attain P Index 2 after about a decade, whereas it would take about five decades for all high P soils to run down to P Index 2. However, these estimates are very crude, since it is clear that ASPRs vary (Heming, 2007; Rollett *et al*., 2016) and that some P fixing soils will take far longer to change their status.

8.3.2 **Scenario B: Soil P Maintenance, but with improved P fertiliser efficiency**

Although this scenario is labelled as involving fertiliser placement (Table 8.2), it acts for any scenario which involves increased P fertiliser efficiency. The only changes from Scenario A in the model for this scenario were to increase crop yields, particularly where low soil P status is still low. However, the small proportion of soils that are currently at less than P Index 2 means that the overall effect of this scenario is to increase overall production and crop value by only 1%, worth £57M.

The assumptions of a 5% benefit in crop yield at P Index 1 as well as at P Index 0 are loosely based on results reported in Section 6 and on results of Knight *et al*. (2014). The intention is that these effects would represent the average yields with P fertilisers providing approximately 12% P recovery by the initial crop; thus the yield effect is not sufficient to overcome the 10% or 20% yield shortfalls that would occur in the long term at P Index 1 or 0 respectively with just annual applications of fertilisers with 4% initial recovery (as Scenario A).

It appears from Section 6 and from the literature (Edwards *et al*., 2015) that it is the pattern of P recovery through the life of the initial crop that affects yield generation, and not just the absolute proportion of applied P that is recovered. It is possible to imagine P fertilising technologies, perhaps based on an enhanced formulation of a struvite-like product, that would act with similar dynamics to those provided by inorganic nitrogen fertilisers (Figure 8.3), where approximately 60% of the N applied is recovered by the initial crop and 10% by the second crop after application (Bhogal *et al*., 2000). The P fixation properties of most soils are significantly more problematic to overcome than their N immobilising properties (King *et al*., 2001) but clearly, if such P fertilising techniques could be devised with equally large and reliable recoveries by the initial crop plus prolonged patterns of crop uptake throughout its growth, it would be likely that fresh fertiliser P applications could completely overcome any shortfall in yield formation where soils have a low P status. This would open the way to run-down the soil P store, maybe working with a target soil P Index of 1 or indeed, just treating any soil P reserves as a bonus, rather than as essential to support optimal crop performance as now.

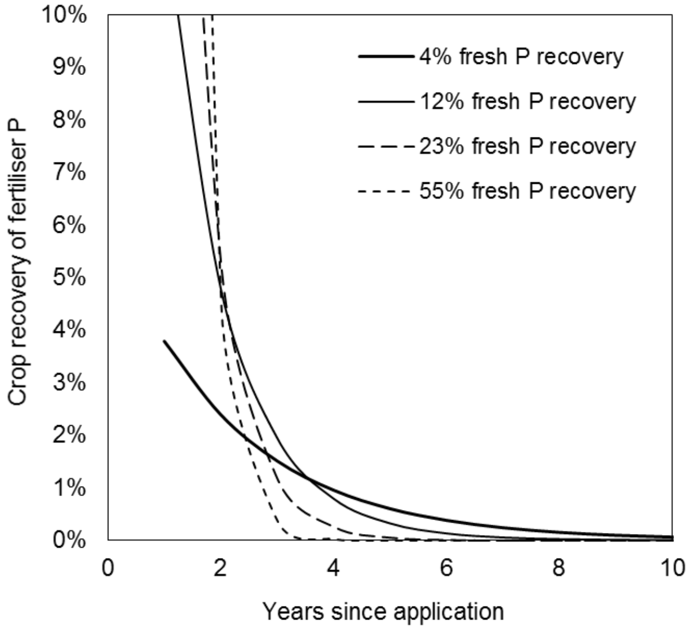

Figure 8.3. Proposed durations of effectiveness of P fertilisers differing in the recovery of P that they might provide for the first crop after application.

8.3.3 **Scenario C: Improved P fertiliser recovery, without soil P maintenance**

This scenario represents the ambition of this Project, to run down the soil store and depend almost entirely on fresh P applications having high recovery, as illustrated in Figure 8.3. The difficulty in quantifying the outcomes of this scenario are that current UK arable soils have unnecessarily large soil P reserves, so to fully quantify the impacts, it would be necessary to model (i) a transition period before soils reach a new equilibrium between the new form and quantity of P inputs and the soil P store (resulting from the much smaller residual effects of the new crop nutrition strategy) and then (ii) the equilibrium state, when soil P reserves have reached a new and smaller stable state. Withers *et al*. (2001) calculated that since the 1930's the surplus of P which has accumulated in UK soils is ca. 12 million tonnes (equivalent to ca. 1000 kg P or ~2,300 kg P_2O_5 per hectare), so it is anticipated that any run-down phase will take many years and so, for the time being, only the initial phase has been modelled. Assumptions are that, due to the greater efficiency of new fertilisers or fertilising techniques, there are no yield shortfalls on low P soils, and that quantities of P applied are equivalent to current crop P demands at P Index 1 (taken to be 44 kg ha^{-1} for potatoes and vegetables, and averaging 21 kg ha^{-1} for other crops) unadjusted for incomplete recovery of fertiliser P. It is presumed that, even if crops recovered only (!) 50% of the new forms of applied P, soil P reserves would provide the shortfall.

Results suggest that this scenario (Table 8.2) entails a dramatic reduction of 50 KT year^{-1} in use of fertiliser P, which would be good for the longevity of P supplies, and entails an equivalent large increase in the P depletion of soil P reserves, which would (gradually) be good for P run-off to water bodies. Crop productivity in terms of biomass or value would increase a little, whilst the margin over fertiliser cost would increase by perhaps £240M year^{-1}. So this scenario looks very attractive in most respects. However, the key considerations are:

- The new efficient crop nutrition system needs to give recoveries of applied P that are as close to complete as possible, in order that fertiliser requirements do not markedly increase, as soil P reserves and soil-derived P supplies to crops diminish.
- Without soil P reserves, risks of crop P deficiencies could increase, unless the new crop P nutrition technology was shown to be highly reliable for all crops grown throughout the chosen rotation. This applies particularly to the most valuable crops such as vegetables and potatoes, where the economic impacts of deficiencies are most telling.
- Risks of deficiencies would need to be minimised by much more reliable crop P monitoring techniques than are currently provided by STP.

8.3.4 **Scenario D: Recycled materials only**

As discussed in Section 8.1.2, the achievement of P nutrition systems giving high crop recoveries could well involve organic processes and be associated with organic fertiliser products. These will most likely originate from recycled sources (as happens to be the case with struvite) of which by far the greatest supply is in excreta from housed livestock. In the UK the P in these manures significantly exceeds the amount of P used in fertilisers (Edwards *et al*., 2015; their Figure 1) so potentially there are adequate feedstocks for the development of high-recovery organic P fertilisers for arable crops. Schoumans *et al*. (2015) advocate a scenario similar to this, and their review (Schoumans *et al*., 2010) details a range of possible P-rich products and ways that they could be derived from organic manures, biosolids and food wastes, but the key question here (because it affects environmental impacts) concerns the levels of P recovery that these products might support when they are applied to arable crops. Whilst it is likely that they would provide slower release of available P than TSP, considerable further work would be required to develop this recycled P into forms which would also support large recoveries by arable crops.

Thus, for the purposes of this scenario, which imagines complete cessation of the use of manufactured fertilisers (through some unspecified mechanism), we assume that (i) arable farms must work with existing sources of recycled P, mainly bulky organic manures and other wastes, (ii) a market will be created for moving manures in the UK, possibly after processing, from livestock areas in the west to arable areas in the east, and the P in these materials will consequently be expensive for arable farms (say three times the price of manufactured fertiliser P), (iii) arable farms will thus only use the recycled P imports on low P soils (Index 0 & 1) or on high value crops (vegetables and potatoes) up to P Index 2, and (iv) the crop recovery of P in these products will remain poor, such that crops cannot yield to their full potential where soil P status is low (Index 0 or 1).

The predicted outcomes of this scenario are of course that fertiliser manufacturers and suppliers would lose their entire P fertiliser market, only about 23 Kt P year^{-1} would be applied to arable land, all from recycled materials (Table 8.2), but there would be no further depletion of global P stocks. UK soil P stocks would be depleted by 74 Kt year^{-1}, three times the rate under the current regime, and P status of the majority of soils would decrease to P Index 1 over a period of 10-20 years. Crop production would be slightly reduced (by up to 5% after 10 years) compared to Scenario A, but the joint effects of greater P costs and smaller crop productivity would reduce UK arable farm profitability considerably, by more than £100M year^{-1}. In addition some significant market transformations and infrastructure investments would be required, associated with ceasing P fertiliser supply, and providing large-scale processing and distribution of animal manures. Other repercussions would probably include a shift in the location of many grain-dependent mono-gastric livestock units from west to east, and greater valuation of other organic materials in the east.

8.3.5 **Scenario E: With no applied P**

The scenario of not making any P additions to arable land was devised to explore extreme repercussions of crop P nutrition. The main impact amongst the predicted outcomes in Table 8.2 is on crop productivity (-6%), balanced to some extent by savings of fertiliser costs. Although this immediate productivity change may appear minor, it results in much the largest reduction in arable farm profitability of any of the four new scenarios investigated here: -£168M, equivalent to £36 ha^{-1}.

Note that the estimates in Table 8.2 are only the average impacts over the first ten years of changing to each scenario. The real impact of this scenario (E) would be felt after ten or twenty years from its initiation. After this time, all crop production would be dependent on depletion of the soil P store, and this would take place (until crop deficiencies became significant) at a rate of almost 100 Kt P year^{-1}. Crude estimates are that the proportion (20%) of soils currently having a soil P status of less than P Index 2 would increase to 50% after 10 years, and 90% after 20 years. With no means of addressing the shortfall in crop P requirements crop production would have decreased from 95% of current production in the first few years to 80% after ten years and 60% after 20 years.

Although this scenario must be considered entirely theoretical as no prospect of its introduction is envisaged, it provides a useful benchmark against which current and new strategies for future P use may be gauged.

8.4 Discussion and suggestions for further research

In considering the outcomes of the five scenarios examined here, it is clear that the initial effects all tend to be rather small, even if applied farm-wide or country-wide. This is because current and previous P management strategies have resulted in a huge soil P store which will buffer any immediate changes. Thus it is only after the passage of more time than has been considered in most of these scenarios that larger effects will become apparent. However, the enormous benefit of this large P store is that it can provide the time necessary for innovation. Whether at a farm level or at a national level, there is every prospect of being able to test prospective improved P management strategies on a commercial scale without risking major economic or environmental repercussions. With sufficient monitoring (which must mean more than just use of STP) it should become evident whether a P use strategy is proving viable before any serious repercussions of non-viability are felt.

8.4.1 **Security of P supplies**

The UK uses only 0.5% of current global P supplies (Figure 8.1), and less than is currently recommended. Amounts of P used globally are increasing, whilst use on UK arable crops in recent years has stabilised at approximately 65 Kt year^{-1}. Thus UK use is small in global terms and the value of P to UK agriculture is such that the industry could probably bear significant increases in price of imported P. Whilst there has been much debate about the extent of global P reserves, and when they will run out, probably the greater risk to supplies for UK agriculture relates to the stability and tenor of political relations with the few countries from which UK supplies are imported: Russia, the Middle East, and North Africa (de Ridder *et al*., 2012).

8.4.2 P emissions to water bodies

Soil P balances of all scenarios here were negative, even the current scenario (A) which was based on recommendations in the Fertiliser manual (RB209; Defra, 2010). It is possible that increasing use of livestock manures and other organic wastes on arable land (23% of arable area received organic manures in 2015; BSFP, 2016) partly makes up the shortfall. Certainly, following the major decrease in fertiliser P use on arable land over the last 20-30 years there is little evidence yet that available soil P is decreasing (PAAG, 2015). However, should negative balances persist, it is highly likely that these will impact on P emissions to water bodies, as well as being affected directly by the amounts and ways in which P fertilisers are applied. This is because, as well as the management of soil P fertility, the management of fresh fertiliser applications affects incidental P loss.

Whilst the current negative balance is only ~25 Kt year^{-1}, the prediction is that this could increase three-fold with just use of targeted P (Scenario C). Thus the potential benefits of a transition to a targeted P approach that relies on a lower soil P fertility status and the use of potentially more efficient P fertilisers was assessed at the catchment and national scale through the application of the 'PSYCHIC' model. PSYCHIC (**P**hosphorus and **S**ediment **Y**ield **Ch**aracterization **I**n **C**atchments) is a process-based model that estimates the loss of sediment and P from land at field and catchment scale (Davison *et al*., 2008). At the catchment-scale, the model works as a characterisation and screening tool to identify areas within a catchment at elevated risk of enhanced P loss and is useful to assess the potential impact of mitigation options. The model uses national scale datasets to infer all necessary input data (for full details see Davison *et al*., 2008). For each spatial unit within the catchment (1 km grid squares) the model estimates the amount of P reaching rivers from different sources and processes (Figure 8.4). The model is widely used in river basin management planning assessments for meeting the requirements of the WFD (e.g. Zhang *et al.*, 2014).

The PSYCHIC model was applied to estimate a baseline scenario for P losses to water across England. Two basic scenarios were then investigated with respect to the effect of targeted P options on changes in the baseline P export: the targeted P option scenarios were a reduction in soil fertility status from P Index 2 to P Index 1 and a gradual replacement (25, 50 and 100%) of highly soluble TSP fertiliser by a more insoluble fertiliser such as struvite. The impacts of these two management strategies on P export were calculated as the reduction on total P loss across England. The baseline P export for England suggested a TP loss to water of 4.35 Kt, of which 1.72 Kt (40% of total) were lost from organic manures and livestock excreta, 0.325 Kt (7% of total) were lost from fertilisers, 0.204 Kt (5% of total) were lost as dissolved P from soil and 2.1 Kt (48% of total) was lost as particulate P from soils.

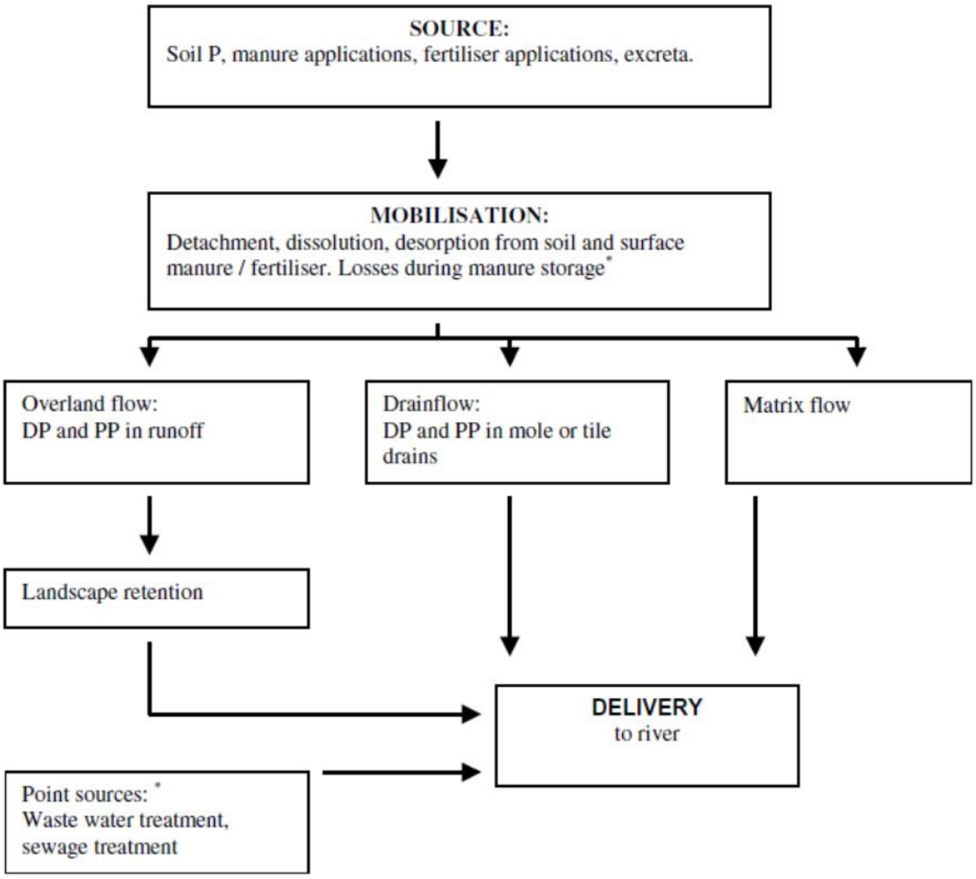

Figure 8.4. Conceptual diagram of the mobilisation and delivery of different agricultural P sources that provides the modelling framework for PSYCHIC (from Davison et al., 2008).

8.4.2.1 Soil P fertility

A build-up of soil P fertility due to previous inputs of fertilisers and manures increases the amounts of dissolved and particulate P in surface and sub-surface (e.g. drain-flow) runoff. This is an important P source because it occurs every time runoff is generated and is therefore endemic and largely chronic. Dissolved P loss from soils has previously been considered to be a problem only at very high Olsen P levels (e.g. >60 mg kg^{-1} or L^{-1}, Higgs *et al.*, 2000), while particulate P is governed more by the susceptibility of soils to erosion than to soil fertility status (Quinton *et al.*, 2003). Soil-derived P in runoff may also not all reach the waterbody due to variable retention during transfer, but a high proportion does reach the waterbody, and in concentrations which greatly exceed current eutrophication control targets (e.g. Haygarth *et al.*, 1999). Soil fertility status has most impact on dissolved P concentrations in runoff, and we found highly significant linear relationships between Olsen-P and SRP in both surface runoff and drain-flow (Section 7). On average in the meta-analysis of UK data (Withers *et al*., 2016), SRP concentrations in runoff were reduced by 67% (63 µg L^{-1}) by lowering soil Olsen-

P concentrations from 25 mg kg^{-1} (top of Index 2) to 10 mg kg^{-1} (bottom of Index 1), so improved the probability of reaching eutrophication control targets. Effects of soil P fertility on particulate P concentrations were much less pronounced; at the two specific sites at Cockle Park and Kingsbridge (Section 7) there was no effect of Olsen-P status and in any case the eutrophication impact of particulate P is unclear and probably small due to its generally low bioavailability, especially in rivers where residence times are low.

In the PSYCHIC model soil P fertility only affects dissolved P loss and not particulate P; this is supported by the experiments at Cockle Park and Kingsbridge. However the algorithm used in PSYCHIC for effects on dissolved P is non-linear and assumes only a small difference in runoff P when lowering soil P from Index 2 to Index 1. For example, in PSYCHIC, reducing soil Olsen-P from 25 to 10 mg L^{-1} reduces soil P release from 116 to 86 µg L^{-1} (a reduction of 26%), and such a reduction had only a negligible effect on total P loss (1%) because dissolved P loss from soil represents only 5% of the TP loss across England. Such reductions are considerably less than those reported in the recent meta-analysis (Withers *et al*., 2016) discussed earlier (Section 7.4). However, even assuming an average reduction of 67% in the dissolved P load (0.14 Kt), this would reduce total P loads from agriculture in England by only 3%. This relatively low figure reflects the low proportion of dissolved P loss originating from the soil relative to particulate P losses and the incidental losses estimated from fresh fertiliser and manure applications. Larger reductions in P loss can be anticipated where dissolved P loss from soil represents a much larger proportion of the TP loss and where soil fertility status affects particulate P concentrations.

8.4.2.2 Struvite substitution

Fresh application of fertilisers and manures to the land surface can lead to episodic and acute P loss in largely dissolved form when rain follows soon after applications (Withers *et al*., 2003). The average incidental loss of TP from freshly applied fertiliser in England is estimated to be 0.32 Kt or 7% of the estimated total TP load delivered to water (Withers *et al*., 2003). In the Loddington experiment, 25% of the TSP fertiliser was lost within 30 minutes under very intense rainfall, whilst dissolved P losses following struvite were negligible under the same conditions due to its very low solubility. When struvite was substituted for TSP in the PSYCHIC model across England at 20%, 50% and 100%, total TP loss from England was predicted to reduce by 0.07 (1.5%), 0.17 (3.9%) and 0.35 (8.1%) Kt, respectively. The spatial distributions of the reductions in incidental fertiliser loss across England if struvite was substituted for TSP at 20% and 50% are shown in Figure 8.5.

The combined environmental benefit of the targeted options tested in this project are therefore relatively small (<10%) in terms of savings in total P loss nationally, assuming current

PSYCHIC modelling capability. This reflects the dominance of manure losses and particulate P losses in runoff, which are not as sensitive as dissolved P losses to changes in soil P fertility from P Index 2 to P Index 1. However, eutrophication control standards have been set as concentrations of SRP and there is a primary difficulty in converting TP losses from land into channel SRP concentrations for meeting these eutrophication control standards, because of the low bioavailability of particulate P.

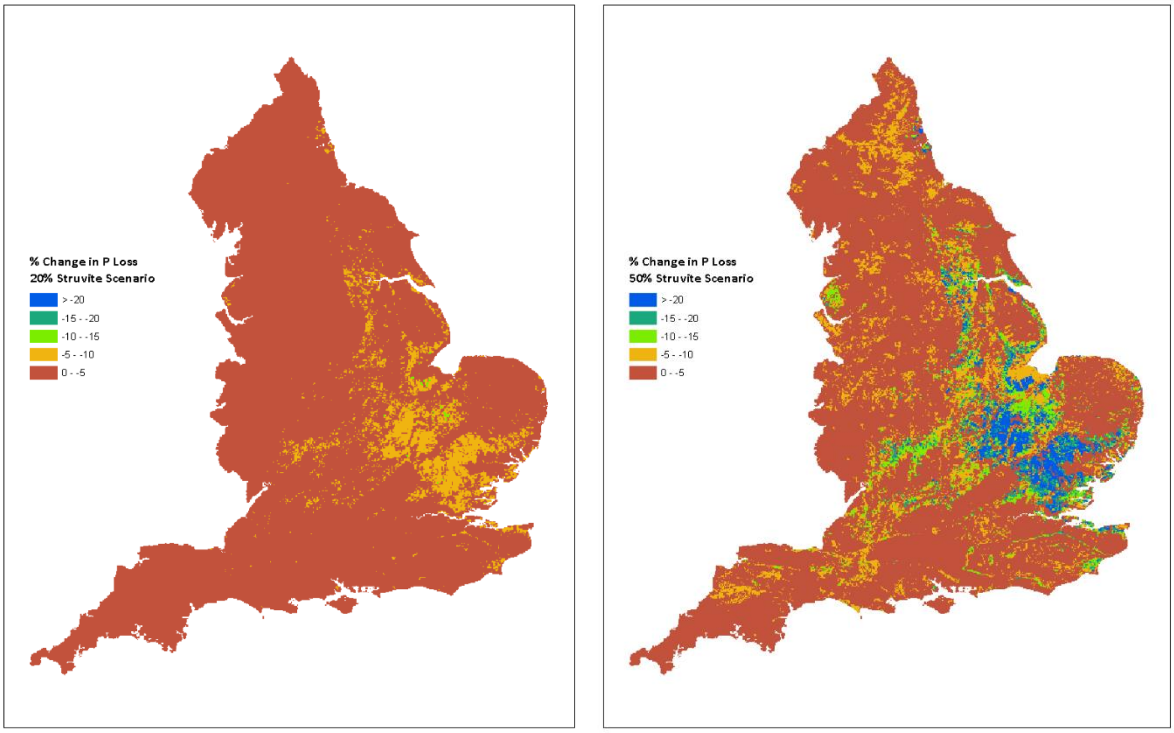

Figure 8.5. The distribution of changes in TP loss in runoff from agricultural land in England when slow release struvite fertiliser is substituted for highly soluble TSP fertiliser.

8.4.3 **Security of food and bioenergy supplies**

In the short-term UK crop productivity in terms of biomass appears remarkably resilient in the face of changes in P management of arable land (Table 8.2). The main concerns however, are in the longer term; should public pressures for less P emissions to water take effect, either via Government regulations or through constraints on P use imposed via retailers, it must be assumed that these would apply for decades, and the outcome of the extreme scenario of nil P use (E) clearly illustrates the worst fears of eventual impacts on food production and economic viability of arable farming. It thus appears vital for the farming and crop nutrition industries, and their technical agencies, to assess the risks, and to act to devise and test solutions within the short-term, so that the much more dramatic long-term impacts are never felt.

8.4.4 **Commercial viability of farming and associated industries**

Clearly there are commercial costs attached to changes in P management on arable farms. Even though initially, as they apply to farming, these are not large (Table 8.2) the small benefits of improved responses to fresh fertiliser P have already been sufficient to encourage investment in appropriate seed drills for fertiliser placement and in wider use of organic materials. Probably the main risks of poor P nutrition apply to growers of potatoes or vegetables where the high costs of growing these crops and their high returns make them much more vulnerable to P deficiencies. Of course, whilst we do not have efficient P fertilisers, soil P fertility remains important, hence all growers must ensure adequate soil P fertility, and growers of high value crops must be particularly attentive to maintaining soil P fertility for the whole rotation. Overall, the reduced use of fertiliser P over recent decades has probably sensitised arable farms to the risks of crop deficiencies, so they are open to innovations, should any look promising.

Of course the threats for the fertiliser industry of changing P management are much more serious than for farming, so it is interesting that at present there is little evidence of the major TSP suppliers investing in research to improve crop recovery of P from their products. Rather, the businesses that have been developing improved fertiliser products have been smaller than the main players (such as those engaged in this project), and therefore have less resources to address the very significant technical challenges of improving fertiliser P recovery, as revealed by this project. Improvements in fertiliser performance have been small so far, so it seems likely that, if water quality failures are to be moderated on a reasonably short timescale, much more intensive investments into fertiliser and manure technologies are now required.

WP3 (Section 6.4.1) has highlighted that most crop species store large amounts of P and it questioned whether, in an arable environment (as opposed to the natural environment from which crop species evolved), these stores are really necessary. It is disappointing that, despite some international research effort, plant breeders have shown little appreciation of an apparent market opportunity to provide P-insensitive varieties. Possibly it is for the testing agencies (such as AHDB) to take a lead here, by undertaking P analysis of harvested produce from all variety testing experiments. This would initially be useful in detecting whether any of the trial sites was providing insufficient P for potential yields to be expressed, but it might also reveal genetic differences in crop P storage, and any low storage lines could be marketed as being potentially suited to production on land of low P fertility.

8.4.5 **Conclusions**

Environmental benefits of reduced P use and reduced P fertility appeared significant and useful from WP4 (Section 7) but the other previous WPs were disappointing in the sense that they did not reveal any large improvements in fertiliser P performance or much scope to reduce soil P fertility. For as long as P fertilisers are used very inefficiently by the crop to which they are applied, it will remain wise to maintain a sufficient soil P store that prevents crop P deficiencies. P recoveries from any of the different forms and methods of fertiliser P application tested, although different, were nevertheless small, and whilst their use appeared profitable, fresh P applications of whatever sort appeared unable to overcome crop P deficiencies identified by small crop P concentrations.

However this WP has reaffirmed that there are strong drivers and opportunities, both in time and in technologies, for a shift in P management strategies. The small effects and slight differences shown here indicate that this project should be regarded merely as a pilot, outlining the scope and setting some directions for much more intensive efforts to develop more efficient ways of fertilising arable crops with P. The following final section of this report suggests the main arenas in which further work might best take place.

9. Conclusions

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9.1 Introduction

Section 2 has already provided an overall summary of the project and its findings; this section provides an overview of how the aims of the project now look, after project completion, it provides some more detail on the key issues raised by the project, and particularly on the recommendations for intensive research effort that the project has shown to be required, with suggestions of where responsibilities and opportunities for that effort might lie.

9.1.1 **Environmental imperatives**

The current UK arable P management philosophy comes with a big price-tag. The UK's Office for National Statistics has estimated that water resources contribute £39.5 billion to the UK economy (ONS, 2015) and eutrophication greatly degrades these services. P from agriculture is the main cause (63% of cases) of waterbodies failing to achieve good ecological status, and new lower standards for P in freshwaters have been introduced to combat eutrophication (EA, 2015; UKTAG, 2012, 2012). From the research here and elsewhere, the connection between P management on arable land and P in freshwaters is undeniable, and the potential to address the challenging target P concentrations (ca. <30 µg L^{-1} soluble reactive phosphorus, SRP, under the Water Framework Directive) by reducing soil P fertility (from say 25 to 10 mg kg^{-1} Olsen-P) is attractive. This is likely to lead in the near future to introduction of regulatory controls relating to inorganic or organic fertiliser management, livestock management, and soil management. In 2015 the government consulted on new basic rules for farmers to tackle diffuse water pollution from agriculture in England, with a focus on phosphorus. Responsible bodies such as National Farmers Unions, the Agricultural & Horticultural Development Board, Agricultural Industries Confederation, Environment Agency, and government through the Department of Environment, Food and Rural Affairs are all well aware of this challenge but generally, as in policy-making to address pollution by other nutrients, particularly nitrogen, the possibilities of technological transformation of the current P management strategy may not be considered of sufficient feasibility for close attention. Thus policies tend towards encouraging the farming industry to adhere more closely to current guidelines, rather than to innovate.

9.1.2 Evolution of P management philosophies

Philosophies can change. The current philosophy of P management – 'feed the soil to feed the crop' – was introduced in the 1960s in England and Wales following the development of the Olsen method of soil analysis to estimate potential soil P availability for a crop. At that time soil analysis data were grouped into Indices to indicate likely response of a crop to applied P fertiliser. This approach replaced one that had predominated through the early 20th century which assumed that any P 'fixed' by the soil was irretrievable by crops, hence cropping was considered to rely entirely on use of large fresh P applications. Thus national P management philosophy has changed in living memory, and could change again, to accommodate the need to improve water quality and the efficiency with which the UK uses its fertiliser P imports, and for the financial benefit of farmers and for sustainability of global P resources.

Clearly the current approach should remain in use for the majority of farmers, and it should be what is recommended in the new edition of the Fertiliser Manual (RB209). However, there would be merit in admitting that, whilst current recommendations are 'safe' in terms of avoiding crop deficiencies, they are grossly inefficient and will be unsustainable in the long term. Thus, whilst advocating the existing approach, the value of striving for more efficient technologies should be recognised. At the same time, work on new approaches should not be used to undermine confidence in the existing approach. Rather, the industry needs to promote that it has a plan for progress in the way it manages P, which is supported by research into P fertilisation which is both:

1. refining an existing and accepted national P management strategy that relies on building up and maintaining soil P fertility indices (the Critical P approach), whilst
2. developing the essential components of a new, more resource conscious and possibly better, P management strategy (the Targeted P approach) which would need a suitable period of validation before general adoption, hence is 'for the future'.

The initial step in moving from the existing approach to the new approach must be an appreciation of the fundamental difference between the two underlying methods of analysing P efficiency, which have been termed respectively the 'balance method' and the 'difference method'. The difference in the 'difference method' is in inclusion of one additional element in the way that fertiliser P use is rationalised (and the way P input efficiencies are judged). Thus in the new approach, instead of considering just P offtake and soil P availability (with respect to a critical soil P level) as now, it will be necessary to consider 'crop P *demand*' instead of 'crop P offtake', and then to separate 'soil P availability' into two elements: the residual supply of soil P, and the recovery of fresh fertiliser P. Thus in the new approach:

$$\text{Fertiliser P required} = \frac{\text{crop P demand (CPD)} - \text{soil P supply (SPS)}}{\text{Fertiliser P recovery (\%)}}$$

This equation mimics the way that crop nitrogen nutrition is analysed (Sylvester-Bradley, 2009), hence it recognises effects on crops of inherent soil P supplies as distinct from effects of fresh fertiliser P. The value of the approach was demonstrated through its application to all of the field experiments reported here (Section 6) and it enabled a clear demonstration of the gross inefficiencies of soil-applied P fertilisers, as currently used.

9.2 An industry plan for improved P efficiency

We propose that, as a first step, the introduction of a new philosophy for P management on arable land in the UK should be debated through a bespoke conference between key stakeholders who are particularly concerned to improve the efficiency of P use.

Out of the many issues addressed in this project, its research has identified two key technical developments that are needed before a new more efficient philosophy of ‘feed the crop, not the soil’ can be advocated; these are (i) nutrition systems giving improved recoveries of applied P, and (ii) monitoring techniques that reliably predict crop P deficiencies.

9.2.1 **Efficient crop P nutrition:**

Whilst the work here showed some improvements in P fertiliser performance due to placement and due to use of struvite, they were not large and, although they were not robustly tested for this, these techniques did not appear able to cure crop P deficiencies. The likely mechanism of struvite’s advantage is through providing P release throughout the growing season, and this finding should encourage the increasing interest currently being shown by arable farms in more widespread use of organic materials. Similarly it appears that most farms may be using P fertilisers annually rather than rotationally, so are already exploiting the small benefits of ‘fresh P’ shown here. Given that AVAIL®-treated TSP was directly targeted at improving fresh P recovery it was disappointing that results were not generally positive. However there are many more P containing products available to farmers than it was possible to test here, so there is some hope that others will be shown to have merit through farm testing.

Farms are unlikely to venture into testing P seed dressings or foliar P so these remain targets for commercial and public R&D. Possibly wider industry meta-data could also validate the suspicion that wheat and oilseed rape were less responsive to fresh P than barley of potatoes.

9.2.2 **Better soil P analysis:**

This project used STP as a tool and in doing so it encountered the several significant issues associated with use of STP without directly addressing STP methodology; however, key issues with STP use were summarised by Edwards *et al*. (2015). Reliance on STP as the basis for P management in arable crop production of most countries continues to raise global concerns about its accuracy, reliability and precision, and there have been various initiatives to find alternatives, particularly to Olsen’s method. In general it must be concluded that soil tests for P status are not sufficiently accurate or precise to predict whether a crop will become P deficient, or whether crops will respond to fresh P applications. At the run-down sites, substantial seasonal variations in soil P analysis exceeded any fertiliser effects and highlighted the significant uncertainties underlying the use of STP for routine monitoring of the soil P store (Figure 6.5). Most users of soil P analysis must encounter similar issues and come to realise the significant inherent uncertainties in STP. However, these should not be taken to justify disuse of STP. Work here showed that soil P analysis provided a worthwhile if crude guide to soil’s P-supplying status. Thus, for the time being in the UK, soil P analysis is probably best regarded as one risk indicator within a farm’s broader P management approach; an approach which could also usefully include:

- Assiduous standardisation of all sampling conditions (including previous crop, sampling month, sampler, sample positions, sampling depth, lab. choice, etc.).
- Taking and considering results from many samples together, and repeating analyses showing large contrasts or surprises. i.e. sampling should be organised in ‘campaigns’, whole farms or even several adjacent farms being sampled, analysed and interpreted together (in any case this will be convenient where a sampling agency is employed).
- Routine recording of yields and P contents (see below) of harvested materials for each managed land unit.
- P_2O_5 accounting; maintaining a continuous log of P_2O_5 additions in fertilisers, manures or other amendments from which crop offtakes in all removed produce, such as grain and straw, are subtracted to give an estimated P_2O_5 balance for each managed land unit, whether field or soil zone.
- Using spatial variation in soil P changes to determine location-specific Apparent Soil Phosphate Requirements (ASPRs; Alison *et al*., 2016), and using these (rather than national standards) to estimate how best to balance P offtakes.
- Annual P analysis of leaf tissues and harvested crop produce. These will have the dual purpose of monitoring for crop deficiencies (see next section) and monitoring crop P removals.

9.2.3 **Crop P analysis:**

A review of relevant literature reported in Section 6.4.1 revealed good UK evidence to support adoption of routine crop P analysis to augment soil P analysis. Measurement errors for crop P are less than for soil P, and a 'critical' P content in whole shoot biomass has been specified for most UK crop species (as approximately 0.25%). Although P analysis of harvested produce is likely to prove easier logistically on most arable farms, as well as being more telling and useful than analysis of growing crops (because harvested biomass contains most of the P taken up by arable crops), standards for interpretation of harvested biomass P contents need to be properly resolved for UK crops. At present the best estimate of 'critical' P content in grain or tuber dry matter is 0.32% (or 0.4% in oilseeds), as indicated by overseas literature.

Comparing actual P contents of materials harvested in the field trials reported here with these 'critical' values, it appears that they provided reasonable summaries of the shortfalls in crop P supply provided by the soils, and the responses in yield achieved with fertilisers (Figure 9.1).

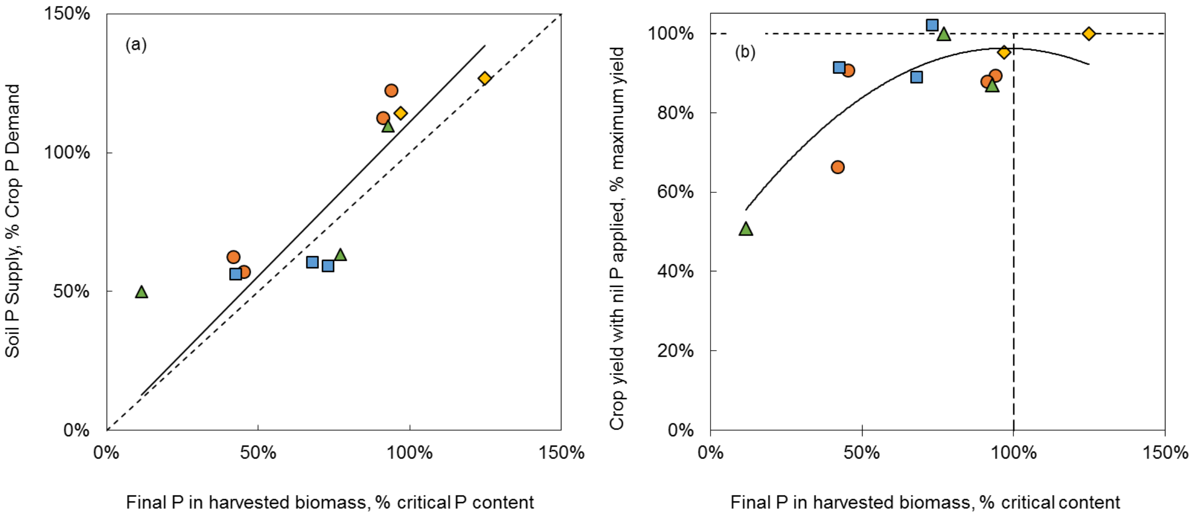

Figure 9.1. Relationships from all the Response and Targeting experiments reported here, showing the potential value of crop P analysis to detect (a) crop P deficiencies (linear: R^2=0.65; the dotted line indicates equality) and (b) yield responses to fertiliser P (quadratic: R^2=0.66; dotted and dashed lines indicate 100%).

However, these results remain to be validated so, initially, just as with STP, it is suggested that crop P analysis should be considered as a strategic tool to support soil P analysis rather than to support tactical use of fertiliser P.

9.2.4 **Beta testing a new philosophy:**

Some of the difficulties encountered in setting up and interpreting the field experiments here can be turned to advantage in the future. In particular there is scope to test more efficient P use strategies at farm scale, without farms incurring large economic risks. The difficulties in showing responses to fertiliser P, even after searching out sites at P Index 1, show that omission of fertiliser P for just one season usually has a small or negligible risk, and the time it is taking for all four 'run-down' experiments to show any decrease in STP (Figure 6.5) suggests that UK farms have 'time and space' to test their own ways of achieving efficient P use. The widespread omission of P fertiliser use when prices increased dramatically in 2008 shows that the industry generally appreciates the small risk associated with P experimentation.

One initiative in this direction has been undertaken through the current AHDB Research Project 2160004 'Cost-Effective Phosphorus', where Frontier are working with a group of farmers to test the efficacy of modern seed drills equipped for fertiliser placement. Because

- it is possible to apply these treatments at tramline scale,
- many of their fields have variable P levels,
- treatments can be replicated across farms, and
- many more yield measurements can be made by yield-mapping combine harvesters than in small plot experiments,

there is a reasonable expectation of being able to test quite precisely for interactions between fertiliser P placement and soil P status. However, this is only one aspect of possible future 'beta-testing' of aspects of the philosophy of P targeting. Others that might be tackled in a similar way by other farm groups include jointly:

- Testing yield responses to new fertiliser products, including seed dressings, foliar sprays and processed organic manures,
- Interpreting past on-farm P balance data in each locality,
- Comparing crop P analyses as a barometer of crop P deficiency / sufficiency,and
- Testing for subsoil P (when samples are taken for soil mineral N testing).

As in the example of AHDB Research Project 2160004, such initiatives are often best facilitated by agronomy companies or fertiliser suppliers, and supported by new software developed to analyse the large datasets (Kindred *et al*., 2016).

9.3 Requirements for Further Research

This report makes a strong case for more intensive research into techniques for improving crop recovery of fresh P applications, and it shows scope for innovations across a broad range of technologies including machinery for placement, chemistry to inhibit soil sorption, seed dressings to ensure seedling establishment in variable P soils, foliar P leaf-targeting and absorption, manipulation of soil micro-flora to ensure crop P availability, and plant breeding (with under-pinning genetical studies) to improve crop P uptake and reduce crop P demands.

More academic questions are also raised, particularly concerning the dynamics and logistics of farming systems as they affect transitions of P between fertiliser, soil, crop, livestock and manure, hence how best to optimise P management strategies in the interests of both sustainability and productivity.

Recommendations for specific lines of research (in proposed order of priority) are as follows:

a. A P-Targeting Strategy: Whilst none of the ‘P targeting’ approaches tested here produced effects that would enable UK arable producers to change any time soon from partly or fully relying on an accumulated soil P store, some pointers here and in the literature indicated feasible future systems that should prove more environmentally and economically sustainable. The design of such systems remains a challenge, and should initially be debated between experts, possibly through a conference involving diverse players with knowledge of:

  - Choice of varieties with reduced crop P storage e.g. by breeding for reduced phytate formation (Burnett *et al*., 1997; Rose *et al*. 2012; 2013a; 2013b), and testing of grain P in variety trials (e.g. for the AHDB Recommended List)
  - Seed dressings to replace seed P storage (e.g. Nadeem *et al*., 2012)
  - Development of fertiliser P forms with available P inhibited biologically, chemically or physically from soil fixation and with improved immediate recovery, possibly involving combination with other products causing local acidification (e.g. ammoniacal nitrogen),
  - Foliar P was taken up through stomata, and rapid rates of P distribution from leaves indicated scope to increase foliar P application rates. The combination of foliar P applications with P-dressed seed looked promising.
  - Machinery to provide banded or placed application of organic or inorganic P fertilisers
  - Slow-release fertilisers, perhaps in organic form and derived from organic materials, with potential to inhibit soil fixation and / or to release P late in the growing season, when plant demand is at its peak.
  - Enhanced arbuscular mycorrhizal associations
  - Germplasm with enhanced rhizosphere acidifying capacity, through enhanced excretion of organic acids

b. Development of P targeting technologies: In most world regions, soil storage of P in quantities sufficient to sustain uninhibited crop growth is infeasible because P fertilisers are unavailable or too expensive. Thus there is a large commercial opportunity for industry to find better ways of satisfying crop P requirements on a global scale. Such work is already taking place but needs to be augmented through more intensive work in controlled conditions on the targeting techniques thought to be most promising. Then greater resources will be needed (compared to those available here) to transfer any promising techniques into the field, so that there is sufficient monitoring and analysis to identify causes of variation in any product's field performance. Finally, wider farm-scale farm testing is needed, using modern field-scale machinery across normal field scale soil variability, much as was discussed in Section 8.4.5.

Given the subtlety of some P nutrition effects, as exemplified by some of the products tested here, there is a case for some independent testing of any new products arising from commercial R&D programmes as above.

c. <u>A test-bed for P efficient products</u>: It is fundamental to the agenda being set by the report that the four 'run-down' sites become funded and monitored for the long term. These are essential to support development of more efficient systems of crop P nutrition. Tests at these sites may be of the P use efficiency of new germplasm by plant breeders, or new P efficient products or practices by fertiliser or machinery manufacturers. In preparation for such tests the behaviours of the crops and soils at these sites need to be monitored more closely so that the effects of any new 'P-efficient' technologies (be they physical, chemical or biological), can be validated and evaluated as quickly and robustly as possible.

d. <u>Soil P dynamics:</u> The four run-down sites are also crucial for understanding soil P buffering dynamics of legacy soil P and assessing the economic impact of omitting P fertiliser on farms. Whilst a few long-term sites have been maintained in the UK and their data have been modelled thoroughly, it is almost certainly quite inaccurate to extrapolate from these few sites to the rest of the UK; there are too many gross effects on soil P behaviour including soil sorption capacity, pH, cultivations, rotations, and yield levels for just a few sites to be representative.

e. <u>Understanding crop responsiveness to P</u>: At present there is inadequate understanding of physiological mechanisms for crop responses (particularly in yield, but also in P concentration) to differences in P supply. Some potential hypotheses should be framed, tested and resolved, so that predictions of P responses become more feasible. For example, it seems likely that critical soil P levels originate early in the life of a crop, when roots systems are inadequate to satisfy shoot demands for P. Recent empirical work (Knight *et al*., 2014) has shown, along with extreme variability in critical soil P levels, increased critical levels when seedbed conditions were poor. It will be important to show whether targeting can provide satisfactory (or better) growth in such instances, and especially where low P soils have poor rooting conditions.

f. Soil testing: The many issues concerning current use of STP have already been highlighted as needing investigation (Edwards *et al*., 2015; Rollett *et al*., 2016). These include issues such as interpretation for different soil types, as recently introduced in Scotland (Sinclair *et al*., 2016), and for different crop species (as indicated in this project, differentiating between soils that have been running down P levels from those that have been building them up), presence or not of significant subsoil P, best sampling practices when cultivation depths have recently changed, and how to interpret changes across a farm or farms between one sampling campaign and the last.

g. Crop P analysis: The development and implementation of an effective 'targeted P' strategy would diminish the reliance of crop P nutrition on soil P analysis, and increase reliance on crop P analysis. Proposals here (Section 6.4.1) for use of routine crop P analysis (as well as STP) to monitor P use on arable land need to be supported by more evidence. Critical P contents of harvested biomass need to be determined from any data or samples remaining from the Critical P Project (Knight *et al*., 2014). Additionally there is a need for a wide ranging survey of crop P concentrations in the UK, both of leaves from growing crops, and of harvested produce, so the prevalence and patterns of crop P variations and deficiencies can be revealed. An initial approach would be to collate existing data from agricultural chemistry labs. However, a more structured survey should also test for the likely influences of soil type, organic matter, pH and P analysis, rotations and crop species, and organic and inorganic P applications.

h. Reducing Crop P demands: Whilst recognising that the ultimate panacea of crops with reduced or minor P storage capacities is a distant objective, the potential to improve UK P usage by choosing crops and varieties known to have low P storage capacities would be realisable in the relatively short term if more information was made available on genetic differences. Such information could come from P analysis of grain from AHDB RL trials.

i. Modelling The dynamics of crop P nutrition are evidently complex, with farming, fertiliser, soil, root, and shoot processes all interacting (Lynch *et al*., 1997; Greenwood *et al.*, 2001). Our attempt to model some of these interactions focussed on the short term (daily to season long) timescale, and addressed soil, root and leaf aspects. Considerable further work is now needed to extend or augment this model so that it can help to resolve the multi-season, multi-soil-type, multi-fertiliser, multi-species interactions that our empirical evidence indicates are governing optimal P nutrition in UK arable conditions. This work should augment work on soil P dynamics and crop P responsiveness proposed above.

For such models to be helpful in exploring strategies for more efficient P use they must be reconciled with empirical evidence of field crops with contrasting rooting patterns, different arbuscular mycorrhizal associations, metabolic strategies of different crop species for acquiring soil P, P sorption properties of different soil types, plant P storage strategies (e.g. inorganic P storage in vacuoles, and deposition of phytate in vegetative and generative tissues) of different species, and effects of contrasting rainfall and solar radiation on crop growth, yield potential and soil conditions.

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12. Appendix.

Appendix 1. Range (minimum and maximum) in run off flow rate, runoff volume, MRP, TDP, DOP, TP, PP and SS concentrations for all events for each plot at Cockle Park.

Plot	**Mean Soil P (mg/l)**	**Flow (l s^{-1})**		**Volume (l)**		**MRP (mg L^{-1})**		**TDP (mg L^{-1})**		**DOP (mg L^{-1})**		**TP (mg L^{-1})**		**PP (mg L^{-1})**		**SS (mg L^{-1})**	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
1	14	0.003	0.320	3,313	23,874	<0.01	0.045	<0.01	0.118	0.000	0.080	0.019	0.371	0.000	0.344	22.3	799
2	17	0.003	0.411	7,070	29,547	<0.01	0.066	<0.01	0.139	0.000	0.109	0.040	1.848	0.011	1.836	24.4	1443
3	10	0.021	0.182	2,270	18,603	<0.01	0.035	<0.01	0.101	0.000	0.096	0.005	0.346	0.000	0.283	30.7	614
4	5	0.013	0.224	9,304	27,639	<0.01	0.019	<0.01	0.095	0.000	0.076	0.154	0.402	0.123	0.367	172	369
5	8	0.019	0.584	6,379	38,507	<0.01	0.019	<0.01	0.154	0.000	0.149	<0.01	0.273	0.000	0.239	26.4	354
6	11	0.010	0.187	1,962	17,441	<0.01	0.051	<0.01	0.186	0.000	0.149	0.165	1.322	0.096	1.303	131	3437
7	21	0.008	0.325	8,820	32,031	0.010	0.087	0.017	0.184	0.000	0.155	0.074	0.323	0.000	0.252	26.3	159
8	7	0.012	0.275	7,126	19,852	<0.01	0.024	<0.01	0.059	0.000	0.054	<0.01	0.284	0.000	0.279	38.7	594
9	11	0.010	0.152	1,097	14,953	<0.01	0.023	<0.01	0.093	0.000	0.078	0.136	1.138	0.097	1.109	93.0	953

Appendix 2. Range (minimum and maximum) in run off flow rate, runoff volume, MRP, TDP, DOP, TP, PP and SS concentrations for all events for each plot at Kingsbridge.

Plot	**Soil P**	**Flow (L s^{-1})**		**Volume (l)**		**MRP (mg L^{-1})**		**TDP (mg L^{-1})**		**DOP (mg L^{-1})**		**TP (mg L^{-1})**		**PP (mg L^{-1})**		**SS (mg L^{-1})**	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Church 4	15	0.0001	0.007	6	553	<0.01	0.12	<0.01	0.23	0.00	0.11	0.37	20.9	0.25	20.8	73.6	16,592
Big Combe	10	0.0002	0.012	10	946	<0.01	0.11	<0.01	0.28	0.00	0.17	0.09	12.5	0.06	12.3	10.6	14,601
Lower 3	11	0.0002	0.008	10	749	0.02	0.07	<0.01	0.18	0.00	0.11	0.25	23.3	0.20	23.1	39.6	24,183
Church 6	21	0.0002	0.003	10	269	0.02	0.15	0.03	0.26	0.01	0.16	0.31	14.2	0.24	18.7	71.7	15,448
Church 5	23	0.0002	0.005	10	400	0.04	0.24	0.04	0.70	0.00	0.11	0.51	19.0	0.20	13.9	67.5	11,882