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Research Review No. 93

Review of AHDB-funded research on phosphorus management in arable crops

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1. Abstract

AHDB has recently published three Research Reviews and three Project Reports on strategies for phosphorus (P) nutrition of cereals. Current strategy involves maintenance of a level of soil available P that does not restrict full economic yield of the crop. P is applied annually to ensure this level does not decrease due to offtake by crops. The level of soil P is checked at intervals by soil testing. The P recommendation system in the Nutrient Management Guide (RB209) derives from this strategy with index 2 as the level of soil available P to be maintained (the target index) and 3–5 years as the interval for soil testing. One of the Project Reports (No. 529) and one of the Research Reviews (No. 74) reviewed here assessed the application of this strategy in RB209. The general conclusion was that index 2 remained appropriate as the target for most soils to achieve 95% or 98% of potential yield. For well-structured soils, index 1 might be the appropriate target. Application of fresh fertiliser P could raise crop yield at index 1 to that achievable at index 2. However, application of P could not raise yield at index 0 to that at index 2. This Project Report and Research Review provided support for the current recommendation system.

An alternative strategy ('feed the crop') was described in Project Report No. 569 and Research Review No. 83. This was based on the premise that the current strategy for P fertilisation is inefficient, wasteful of resources and should be replaced by one that allows a lower concentration of available P in the soil and increased recovery of applied P. Various ways to improve the efficiency of fertiliser P were described: placement, foliar application, seed treatment, a coating for TSP and use of water-insoluble P sources (struvite). None of these showed reliable and convincing benefits. This is not to say that these techniques or products are not worth pursuing and most of them already are used on farms. However, they do not appear to provide a sound basis for a general 'feed the crop' strategy. 'Feed the crop' as described is not a recommendation system. Some guidance on the effectiveness of P use might be provided by grain or other tissue analysis but this is retrospective whereas soil analysis for P index is predictive.

Available data for P offtake by wheat, barley, winter oilseed rape and forage maize were collated and assessed in Research Review No. 92. It was concluded that the typical offtake of 7.8 kg P₂O₅/kg grain assumed for wheat should be reduced to 6 kg P₂O₅/kg grain. It also was concluded that a single value would be appropriate for both wheat and barley. However, there were fewer data points for barley (400) than there were for wheat (700) so a change to the typical value for barley might wait for further data.

Themes developed in these Project Reports and Research Reviews were drawn together in Project Report 570. Use of grain P concentration was proposed as a method for assessing crop P status, with 0.32% P in grain dry-matter suggested as the critical value.

Grain P analysis could be a useful way to assess P fertilisation strategy. P offtake in wheat grain of 6.5 kg P₂O₅/t was proposed, slightly greater than that indicated in Research Review No. 92.

Based on these reports, some amendments to RB209 have been proposed: reduction in typical offtake in wheat grain to 6.5 kg P₂O₅/t, periodical use of grain P analysis for assessing farm P strategy, calculation of P balances to supplement regular soil analysis and indication of circumstances where soil index 1 might be an appropriate target.

2. Review of 'Critical P'

2.1 Documents

'Critical P' comprised *Research Review No. 74 Response of cereals to soil and fertilizer phosphorus* and *Project Report No. 529 Identification of critical soil phosphate (P) levels for cereal and oilseed rape crops on a range of soil types*. The Research Review and Project Report form one body of work covering past data and new field experiments respectively. The overall objective was to describe the relationship between cereal yield and soil Olsen-P and to determine the P index at which soil should be maintained for cereals and oilseed rape. The current phosphate recommendation system, based on a target soil P index 2, therefore was taken as the basis for possible improvement and not as something possibly to be replaced.

2.2 Research Review 74

Data were available from 102 cereal crops grown between 1969 and 2008. However, these data derived from just three sites, all on heavy soils:

- Well-structured silty clay loam at Rothamsted (Exhaustion land): 16 crops of winter wheat and 7 of spring barley
- Poorly structured sandy clay loam at Saxmundham: 44 crops of winter wheat and 23 of spring barley
- Poorly structured, heavy silty clay loam at Rothamsted (Agdell): 8 spring barley crops

The small number of sites was due to the need for a range of Olsen-P values within every experiment. This restricted the source of data to the few relevant long-term field experiments in the UK.

The justification for labelling soils well or poorly structured is not stated. The importance of soil structure for P uptake is described in Appendix D but only soil organic matter is associated with structure.

Data were excluded from four crops of spring barley in Agdell which were grown on soil with little organic matter (p8) and where standard errors of yield and Olsen-P were large (Table 4), hence the 98 crops listed above against the overall total of 102 crops.

Values for critical Olsen-P were calculated for every crop where data allowed. In this review, critical Olsen-P is the value needed to achieve 98% of the fitted maximum yield. Choice of 98% is arbitrary and could be criticised but it seems reasonable. Apart from the exclusion of data from the four crops in Agdell, there appears to have been no selection of data for the statistical analyses.

On well-structured soil, critical Olsen-P was within the Index 1 band but on other soils usually was in Index 2 or lower 3. In the Exhaustion land, on a well-structured soil, maximum yield occurred at soil P index 0/1 in 20 of 23 wheat crops years. By contrast, at Saxmundham, on a poorly structured soil, maximum yield occurred at soil P index 2/3 in 38 of 67 crop years. Where the amount of nitrogen applied was insufficient to achieve maximum yield, critical Olsen-P tended to be greater than where nitrogen supply was adequate (p31). Critical Olsen-P also tended to be greater with dry soil conditions during the growth period (p29).

While soil P index 1 might be adequate in well-structured soils, it was concluded that, until more data were available, the general recommendation should be to maintain soils at P index 2. This would ensure that maximum yield could be achieved in most years and would allow for spatial variation in Olsen-P within fields.

The review also dealt with the input of applied phosphate needed to increase soil P index and the rate at which Olsen-P decreased when no phosphate was applied. For the Saxmundham and the Exhaustion land at Rothamsted it was calculated that input of 268 to 327 kg P_2O_5 /ha was needed to increase soil P index from the mid-points of index 0 to 1 and from 1 to 2. Input here was defined as the positive phosphorus balance (applied minus offtake) over a number of years. It was calculated that without phosphate application, Olsen-P would decrease in six years from mid-point index 2 to the bottom of index 1 in the Exhaustion land and to upper index 1 at Saxmundham. These changes support the current recommendation to sample soils every 3-5 years to avoid any serious decrease in Olsen-P.

2.3 Project report No. 529

Six new field experiments were conducted on soils low in Olsen-P to extend the data used for the review. Soils were deep clays, loams and shallow soils over limestone or chalk and were ploughed or cultivated without inversion to at least 15 cm. Seedbed conditions varied among sites and years but were poor in five of the 24 site years. Soil pH was greater than 7 in four of the six sites and between 6 and 7 in the other two. There was an apparently anomalous pH of 5.6 at one continuously ploughed site in 2012/13. Generally, the sites provided a useful extension to those used for the review though shallow minimum tillage was not represented.

Every experiment was continued on the same plots for four years (2009/10 to 2012/13). A range of Olsen-P was established in 18 large plots at every site in 2009 by applying nine rates of TSP. The target range of Olsen P levels, once the Olsen P levels had equilibrated, was from Index 0 or low Index 1 (10 mg/l or less) to Index 3 (26–45 mg/l). No further phosphate fertiliser was applied to any plots in the first two cropping years. For the third and

fourth years, each large plot was split into three sub plots, two of which continued to receive no phosphate fertiliser. The third sub plot received 200 kg P_2O_5 /ha fresh phosphate fertiliser prior to cultivation and sowing in autumn 2011 and again in autumn 2012 to measure the response of the crop grown to the freshly applied phosphate, and to maintain the Olsen-P level.

Mean wheat yields for 14 site years in plots where no phosphate fertiliser was applied after 2009 were 7.02 t/ha at P index 0, 8.08 at index 1, 8.72 t/ha at index 2 and 8.94 t/ha at index 3. Yield at index 1 was greater than that at index 0 in all site years. Year at index 2 was greater than that at index 1 in 13 of the 14 site years. Compared to index 2, the mean yield penalty was 1.7 t/ha at index 0 and 0.6 t/ha at index 1.

During the course of the experiments, four oilseed rape crops, three spring barley crops and one spring bean crop were grown. Mean yields of winter oilseed rape and spring beans increased with soil P index but spring barley yields did not change with Olsen-P.

The 200 kg P_2O_5 /ha applied in 2011 and 2012 increased mean wheat yield (five site years) at index 1 to that achieved at index 2. However, this fresh phosphate did not increase yield at index 0 to that at index 2. There is a statement (p55): *This suggests that there is the possibility to maintain soils at P Index 1 rather than 2, provided fresh P is applied annually to each crop although the amount needed is likely to be much larger than the normal maintenance application...* This is not quite the same as using index 1 as the target. If the additional P over and above offtake is applied, soil P index might increase (as is assumed for current RB209 recommendations with index 2 as target). Relationships between Olsen-P and crop yield indicated index 1 (quoted on p10) might be used as the target for well-structured soils with offtake replaced by fresh P application.

Asymptotic response curves relating crop yield to Olsen-P were fitted to data from the 18 large plots in 2010/11 and separately to data from the sub-plots receiving fresh phosphate fertiliser and from sub-plots not receiving fresh phosphate in 2011/12 and 2012/13. Data from 2009/10 were not included in the estimation of critical Olsen-P as soil values had not yet equilibrated following the TSP applications in 2009. Data were discarded where the standard error of yield or of critical Olsen-P were large. For eight wheat crops where data were adequate, the average critical Olsen-P was around 16 mg/kg (range 9-23) for 95% of maximum yield and 20 mg/kg (range 11-32) for 98% of maximum yield, both in P index 2. These data were included in Research Review 74.

Data from five sites were used to calculate the amounts of applied phosphate needed to increase soil index from mid-0 to mid-1 or from mid-1 to mid-2. These amounts varied between 154 to 470 kg P_2O_5 /ha, a similar range to that reported for earlier data in Research Review No. 74.

An economic analysis was done to quantify the effects of raising soil P index to 2 and maintaining it at that level. At one site with a limited range of Olsen-P concentrations, there were no economic benefits from raising the P Index. At the other five sites, over four years (three for one site), the net effect ranged from +£59 to +165/ha for an increase in P Index from 0 to 1, and from +£16 to +131/ha for an increase in P Index from 1 to 2. Only one site gave a consistent economic benefit from raising the P Index from 2 to 3.

2.4 Main conclusions concerning Research Review No. 74 and Project report 529

Conclusions drawn in the Research Review and Project report can be summarised:

- Data existing before the project derived from three sites, all on heavy soils but over many years. New data from the project were generated from six sites over four years. Weather conditions were unusual in some of these years. The required range in initial soil Olsen-P was generated by applying different amounts of TSP and equilibration in the soil had not completed in the first year of the experiment. These limitations of the data must be recognized.
- Critical Olsen-P where crop yield was 95% or 98% of maximum generally was in the soil P index 2 band (sometimes index 1 on well-structured soils).
- Applying fresh fertiliser phosphate at index 0 did not increase crop yield to that achieved at index 2.
- Applying fresh fertiliser phosphate at index 1 could increase crop yield to that achieved at index 2. There is the possibility therefore that some soils could be maintained at index 1 provided the need for additional applied phosphate was recognised.

The current P recommendation method is supported with general target index for cereal crops remaining 2. However, the possibility of maintaining index 1 for well-structured soils could be advised provided the need for greater annual P application is recognised.

3. Review of ‘Targeted P’

3.1 Documents

‘Targeted P’ comprised Research Review No. 83 Routes to improving the efficiency of phosphorus use in arable crop production and Project Report No. 569 Improving the sustainability of phosphorus use in arable farming – ‘Targeted P’

3.2 Research Review 83

This review ranges widely in scope from international (phosphate rock reserves and their probable longevity) to individual field experiments. It is based on the premise that the current recommendation system for fertilizer P use is inefficient.

Some criticisms of current practice are no longer relevant. For example, '*...apply bulk fertiliser dressings to the most responsive crop in the rotation*' (p9) has not been part of fertilizer recommendations for many years.

The problems associated with soil sampling and analysis are described and these generally would be acknowledged. Sampling depth can affect results particularly where the sub-soil contributes significantly to phosphorus supply and the most appropriate depth can depend on the method of cultivation (ploughing versus minimum cultivation). The Olsen test now used for soil phosphorus in England, Scotland and Wales is recognized as not perfect, for example where organic matter is a significant source of phosphorus or at extremes of soil pH and the statement '*...at best STP can only provide an approximate guideline to fertiliser requirements for individual fields, although STP may become to some extent self-correcting after regular soil analysis*' (p15) would be accepted widely.

Components of a targeted P approach are described:

- Minimizing crop P requirements
- Maximizing root recovery of inherent soil P
 - Adaptations to root architecture
 - Enhancing P mobilization
- Maximizing recovery of applied P
 - Amendment of soluble P fertilizers
 - Reducing fixation – AVAIL or Bauxsol
 - Enhanced solubility – ground rock phosphate and micronised sulphur
 - Recycled P – struvite
 - Placement of fertilizer P
 - Seed coating with P
 - Foliar P

All of these components clearly are beneficial and worth pursuing (several of the proposals have been pursued for many years). They are not alternatives to the current phosphate recommendation system. None of these options helps a farmer or adviser decide on how much phosphate to apply for a particular crop. The current recommendation system, while undoubtedly imperfect, does that.

3.3 Project Report No. PR569

This project was based on two main hypotheses which can be summarised:

- the current principle of fertilization, involving maintenance of a critical level of crop-available P in the soil, is wasteful of resources and leads to unnecessary loss of P from soil to water;
- an alternative principle of feeding the crop not the soil would improve the efficiency of P use and reduce the risk to water quality.

WP1 involved evaluation through pot experiments of several possible methods for improving P use:

- Foliar-applied P
- P seed dressing
- Placement of fertiliser P
- Struvite as a P source
- Bacterial seed dressing
- Use of Avail as a fertiliser coating

Some of the methods detailed have been evaluated previously and extensively with broad conclusions drawn. Agronomic effectiveness of struvite is well established and the more widespread use of the product now depends on production capacity. Foliar-applied P and fertiliser placement also are well researched and have been, and are, used on farms. Both techniques have been shown to be effective on occasions (placement more reliably than foliar application) but not always. The relatively small amount of additional data from this WP does not affect these conclusions.

Struvite is just one of several 'water-insoluble' P fertilisers. At present, ashed poultry manure is much more widely used in UK agriculture. The assumption that release of P from TSP occurs in a short period after application while that from struvite occurs later in the season (p31) is not quite warranted. Water solubility in fertilisers is measured by a laboratory test involving a 30 min extraction that was developed to distinguish superphosphate products from those adulterated with unprocessed rock. This test will show TSP to have 90-95% water solubility but the very low solubility of phosphate in water means P will be released from TSP over an extended period, certainly over the season of application. Some of the P released from any fertiliser will be adsorbed by the soil during the season, the amount depending on the soil's sorption capacity (taken into account in the latest P recommendations in Scotland (SRUC 2015)).

In WP2 a soil/plant model was developed to describe P uptake by plants and to compare uptake under different fertiliser strategies. The model included processes of P behaviour in soil, P movement into roots and translocation to stems and leaves and biomass growth. A rather limited set of data was used for validation and it is acknowledged in the report that further data are needed for calibration. It was concluded that placement of fertiliser P close to the seed could increase P uptake by 4% 'over doing nothing' and that a uniform distribution of available P down the soil profile, rather than a stratified distribution, would be advantageous for P uptake.

Later, (p114) there is a statement referring to models *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* that implies the lack of success of models in affecting farm practices is due to an inability to absorb their outputs. It seems more likely that the lack of success is due to the models not properly representing reality. However, this does serve to emphasise that, to be successful, a new concept not only must be scientifically plausible but it must be effective in practice and capable of being implemented by farmers.

Different ways for using fertiliser P to meet crop demand were assessed in WP3 through three sets of field experiments:

- '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 (placement v broadcasting) on crop responses at ten 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).

Of the ten response experiments, two were at soil P index 0, four were at index 1, three were at index 2 and one was at index 4 (Table 6.3).

The treatments applied in the P targeting experiments were not successful in improving crop growth. The experiments were conducted at one site (Ropsley) so might not be representative for all arable soils. However, results are consistent with the existing body of

knowledge that shows effects of placement and of water-insoluble P sources can be variable and related to site conditions.

The discussion section of this WP introduces the concept of a critical P concentration in plant tissues as an indicator of plant P status. The concentration is then used to determine crop demand for P. This is based on literature reviewed and not on experiments conducted in this WP.

Supply of P from the soil is then subtracted from crop demand to leave a gap in P supply that must be filled through application of fertiliser P. P uptake by crops to which no P was applied was used as the measure of soil P supply. However, it is not clear that this P supply (inadequate for full crop yield) would be maintained when fresh P is applied. Application of fresh P could inhibit movement of non-labile soil P into the labile fraction.

The amount of fertiliser P that must be applied to match the gap in supply depends on recovery of fertiliser P by the crop (expressed as a percentage). Recovery is calculated in this WP using data from the year of P application and does not take account of the extended period during which uptake of applied P can occur (as acknowledged on p126). Calculation of P recovery in this way is inconsistent with the currently used concept of maintaining a critical concentration for soil available P ('feed the soil') so the low recoveries calculated are not sufficient, on their own, to call this concept into question

WP4 examined the environmental impact of P application. The statement *Fresh applications of fertiliser invariably lead to elevated run-off P losses in addition to those derived from the soil* (p133) might be questioned.

Surface runoff and/or drain-flow during storm events, or under simulated rainfall, were monitored at three experimental sites (Cockle Park, Kingsbridge and Loddington) 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 TSP.

These sites were known to generate significant run-off. The Cockle Park site was so wet that crops could not be established in 2010, 2011 and 2012. The potential for movement of dissolved and particulate P was determined by the DESPRAL test at three other sites used in the Critical P project.

Linear regression was used to relate concentrations of soluble reactive P (SRP) and of total dissolved P to soil Olsen-P at Cockle Park and Kingsbridge (Fig 7.5). However, from their appearance, the plotted data could be consistent with a 'change point' in Olsen-P at which loss of P increases sharply from a stable value at lower Olsen-P. Similarly, the linear relationship described between suspended sediment P (SS-P) and soil Olsen-P (Fig 7.6, not 7.5 as indicated in the text) could be non-linear or even non-existent given more data. The benefit more data would bring here is acknowledged on p150. The small amount and variability of data means the calculations of P concentrations in run-off at different Olsen-P values (p145) should be treated with caution, especially if extrapolated to other soils. The combined data used in Fig 7.9 are more convincing.

At Loddington, no significant differences in any form of run-off P were found between soils at P index 2 and index 4 (Table 7.4). There were differences between fertiliser treatments with Avail-treated TSP giving the greatest run-off P concentrations, struvite the smallest and TSP intermediate. Rainfall was applied 'shortly after' fertiliser application and more information on the method of fertiliser application and timing of rainfall would be helpful for interpreting these differences between fertilisers.

It was concluded that linear relationships between soil Olsen-P and dissolved run-off P indicated *significant environmental gains can be obtained by reducing Olsen-P to the agronomic optimum and below*. This might be so but it is not certain. The movement from soil to water of all forms of P, including particulate, need to be quantified to provide estimates of typical annual total P movement to water and the seasonal variation in this movement under field conditions. Addition of P to surface water in November for example is likely to have a smaller environmental impact than the same loss would have in June. These estimates also would allow effects on eutrophication of reducing soil Olsen-P and those of minimising soil erosion to be compared and prioritised.

WP5 was to quantify the wider economic and environmental impacts of techniques to improve sustainability of P use on arable farms. Three scenarios were described:

- 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

Scenario A is not as recommended in the Nutrient Management Guide (RB209) or in the previous two editions of RB209. These editions of RB209 do not recommend rotational application of P.

Scenario B is most similar to recommendations in RB209. However, for scenario B, it is assumed that placement or other methods will increase crop yields by 5% which seems optimistic and is not consistent with findings in WP3.

In scenario C, it is assumed that new efficient fertilisers or application methods would allow crops to be grown without loss of yield at soil P index 1 and that this would reduce annual P fertiliser use. However, the conclusion depends entirely on the assumption being realistic and achievable.

Scenario D involves another set of assumptions that lead to certain conclusions. Different assumptions would change the conclusions. Nevertheless, it is in this scenario that the potential role of organic P sources is first considered. For arable cropping, these sources include sewage sludge, poultry manures (in both fresh and ashed forms), pig manures, anaerobic digestate and compost. Improving the utilisation of P from these sources might offer greater potential than the methods for improving fertiliser use described in scenarios B and C.

3.4 General comments on Research Review No. 83 and Project report PR569

Research Review No.83 and Project No. 569 are based on the premise that the current system for P fertilisation ('feed the soil'), as described in RB209, is inefficient and wasteful of resources. This system should be replaced by one that allows a lower concentration of labile P in the soil and relies on increased recovery of applied P ('feed the crop'). Such a change also would reduce P movement from soil to surface water. However, it is acknowledged that the current recommendation system used in RB209 should be maintained until a better one is developed (p11). In the meantime, efforts to improve utilisation of applied P should continue.

Various ways to improve the efficiency of fertiliser P were described: placement, foliar application, seed treatment, Avail as a coating for TSP and use of water-insoluble P sources (struvite was the only one assessed). None of these showed reliable and convincing benefits. This is not to say that these techniques or products are not worth pursuing (most

of them already are used on farms) but they do not appear to provide a sound basis for a 'feed the crop' system.

Current P fertilisation, as described in RB209, is not just a philosophy for P use – it is a recommendation system that provides guidance on how much P should be applied in different situations. 'Feed the crop' as described is not a recommendation system. Some guidance on the effectiveness of P use might be provided by grain or other tissue analysis but this is retrospective whereas soil analysis is predictive. The issues associated with soil analysis (need for consistency in sampling, choice of sampling depth etc) and its value as a guide rather than as a precise measure of available P are well known and appreciated.

4. Review of 'Cost-effective P'

4.1 Documents

There were four documents relating to Project No. 570: Project Report No. 570 Cost-effective phosphorus management on UK arable farms, Report on Work-Package 1: Apparent soil phosphate requirements, Report on Work Package 2: Critical levels of soil P and Report on Work Package 3 and summary of WP1 to WP3.

For this project, three of the field experiments used in Project 529 ('Critical P') were continued for three further years (2013-2016) for WP2 and WP3. Twelve tramline trials were conducted for WP3.

4.2 Work package 1: Apparent soil phosphate requirements

The statement in the introduction (p5) that in the past thirty years, P inputs to arable land have halved mainly as a result of lower application rates (BSFP, 2015) is not strictly correct. The average rate of fertiliser P application on fields where P fertilisers were applied has remained fairly stable. However, the proportion of arable land to which fertiliser P was applied has decreased, for example from around 75% to 50% in wheat. Fertilizer consumption statistics do show a steady decrease in the amount of fertilizer P applied overall to arable crops and to grassland over the past twenty years. However, organic manures are applied to 25% of tillage crops in Great Britain (BSFP 2017) and it has been calculated that, overall, these contribute around 20 kg P₂O₅/ha to winter sown arable crops and 28 kg P₂O₅/ha to spring sown crops (FACTS 2018).

The numerical conclusions from Ropsley data (p15/16) should be treated with caution. Using the linear equation derived from all data, only 10% of the variation in the change in Olsen P could be explained by P balance. The linear relationship derived for livestock manure applications (p17) was somewhat better but changes in P balance still explained

only 16% of the variation in change in Olsen-P. Again, the numerical conclusions drawn (p17) should be treated with caution.

In the description of results from the SOYL samplings (p37) it should be noted that fertiliser P application data were taken not from farm records but from the recommendations made by SOYL (p13). It was assumed that farmers followed these recommendations exactly. Crop yields were on a field rather than a sampling point basis and were the target yields set by the farmers. Experience suggests that target yields tend to be optimistic and, if this was the case here, calculated P balances would be too small. Crop P concentration data also were not measured but were taken from typical offtake values in RB209. The P balances calculated therefore derived largely from the SOYL algorithm and RB209 and might or might not reflect actual application and crop offtake. The degree to which actual P inputs and offtakes differed from SOYL recommendations and target yields might be part of the explanation for the farm effect described (p44) and for the low values for ASPR found in the SOYL data.

Much is made of the Apparent Soil P Requirement of 40 kg P_2O_5 /mg/l Olsen-P in RB209 but this value is shown as an example and is not expected to be representative for all soils. It has been appreciated for at least fifty years that soils vary in the amount of applied P needed to change Olsen-P by a given amount.

The suggestion that farms should calculate their own ASPRs (p52) is a good one. This would help current P recommendations in the RB209 tables to be seen as part of a method for decision making that includes regular soil testing and calculation of field P balances. The need for consistent soil sampling on farms (p55) would be accepted by advisers and farmers and guidance is already available. Use of crop P analysis to complement soil testing seems a good idea.

4.3 Work package 2: Critical levels of soil P

Averaged over 20 site years, wheat yields at soil P indices 0 and 1 were 1.46 t/ha and 0.54 t/ha lower than at index 2 respectively (pp36-38). Application of fresh P did not raise yield at index 0 to that at index 2. However, fresh P could increase yield at index 1 to that at index 2. It was concluded that, in certain situations, it could be appropriate to maintain soil at index 1 provided fresh P is applied annually. The amount applied might need to be greater than offtake (p78).

It is unfortunate that the laboratory used for Olsen P measurements had to change from Rothamsted Research in 2009-2013 to NRM in 2013-2016. The calibration of the two

methods showed NRM to give results that were around 25% lower than those given by Rothamsted Research (p16). It is not clear if this difference is due to the use of w/w measurement by Rothamsted Research (mg P/kg soil) and w/v by NRM (mg P/ml soil). For the present WP, all Rothamsted Research Olsen-P data were converted to NRM equivalent values. This resulted in an appreciable change in estimated soil P availability in the 2-4 years after P application and in critical P concentrations (p74, p77).

The lack of an end point, and consequent sensitivity to test conditions, in the Olsen method is pointed out (p15). Resin extraction involves a 12 hour extraction so has an end point but the method has not been used commercially in the UK since 2001. Unless the method is re-introduced, it is no longer an alternative as suggested (p3).

4.4 Work Package 3 and summary of WP1 to WP3

The tramline trials described here were an innovation and subject to difficulties associated with involvement of farm equipment and operations. While the technique might be developed, these particular trials do not appear to have added appreciably to overall conclusions.

There are a few points in the discussions:

The paper by Johnston et al from which a half-life for Olsen-P of 9 years was quoted (p24, p49) does not appear in the reference list. This half-life was estimated in a paper by Johnston and Poulton (2014) that is in the reference list but it refers to data from just one site near Saxmundham and was not indicated as typical for different soil types. The concept of a half-life for soil available P attributed to Johnston et al (2016) and based on a first order reaction was developed by several research centres in the 1960s. It was appreciated at the time that the half-life varied widely among soils. It was also appreciated that the half-life of recently applied P was shorter than that of pre-existing soil available P (e.g. Richards 2001). The average 'optimum' grain P% or the value at which no response to fresh P occurred was 0.30-0.31 (Table 3 p23). Later (p54) a grain concentration of 0.32% P was estimated as the level indicating a yield response of 0.3 t/ha so sufficient to cover the cost of 60 kg P₂O₅/ha. Table 3 includes values from individual site/years from 0.24% up to 0.41%. Use of a single threshold concentration to indicate P sufficiency might be an over-simplification.

The proposal for a 'Phosphorus management guide' separate to RB209 (p56) and based on a different philosophy would cause confusion. It would be better to incorporate any changes to P guidance in RB209.

The proposed new table of P₂O₅ and K₂O offtakes for RB209 (Table 18, p57) shows 6.5 kg P₂O₅/t as proposed typical offtake in wheat grain. The table includes significant changes to

K₂O offtake values and to offtakes for peas and beans but the basis for these changes is not stated.

On p11 there is a statement RB209 recommendations are that fresh P additions cannot fully make up for residual soil P i.e. crop yields on soils at P Index <2 are inevitably reduced, irrespective of fresh fertiliser P applications but this is not what is stated in RB209 (Section 1 of RB209, p28).

Some suggested revisions to RB209 were described in the overall conclusions (p55):

Develop P management to have a crop focus:

This calls for better monitoring techniques that reliably identify impending crop P deficiencies and better application systems (fertilisers, manures, formulations & application methods and timings) giving more immediate recoveries of applied P by crops. However, this project and the related 'targeted P' project have not come up with anything practically useful here apart from grain P analysis as a retrospective indicator of the P status of a crop. Placement (combine drilling) and foliar P application were found to have variable, usually small, effects on P recovery (as would be expected from field experience over the past twenty years or so).

Develop bespoke soil P management for each field and its crop rotation:

This is largely a re-stating of guidance in RB209 with the exception of a proposed target soil P index of 1 where only autumn-sown crops are grown, soil structure and crop establishment tend to be good, and some fresh P fertiliser can be applied each year. There is a call for standardisation in soil sampling conditions and for AHDB to work with PAAG on QA in sampling and analysis. Detailed guidance on soil and plant tissue sampling is available in RB209 and from PAAG (at www.nutrientmanagement.org) and PAAG has participated since 2009 in the WEPAL proficiency testing scheme ('ring test') operated by Wageningen University. A change in grain analytical procedure by NRM apparently increased reported P concentrations between 2014 and 2015 (p14) so there is a need for standardisation of grain as well as soil analysis.

Maximising crop recovery from P applications:

Annual application of P rather than rotational application is proposed as it is in RB209. Rotational application has not been recommended for many years and the practice is rarely encountered now. Other possibilities listed (placement, foliar application) are acknowledged as unlikely to offer consistent improvement. Use of organic manures where possible would

be universally accepted. Nothing is proposed that would have a significant and reliable effect on P recovery.

5. Research Review No. 92 Offtake values for phosphate and potash in crop materials

The objective of this review was to compare available field experimental data on P_2O_5 and K_2O offtake by grass and arable crops with the typical offtake values (kg nutrient/t fresh crop) used in the *Nutrient Management Guide (RB209)*.

The typical offtake values now in RB209 were agreed following an extensive review of published data for the 7th edition RB209 that appeared in 2000. However, the cereal grain values of 7.8 kg P_2O_5 /t and 5.6 kg K_2O /t are older, appearing in SAC Technical Note No. 13 in 1992. The 7.8 kg P_2O_5 /t offtake appeared in *Crop Nutrition and Fertiliser Use* by John Archer (1985). HGCA Research Review No. 16 in 1990 refers to ADAS values of 7.8 kg P_2O_5 /t and 5.6 kg K_2O /t in wheat grain. It seems the typical offtake values for cereal grain have remained unchanged for at least thirty years and are due for refreshing.

Most of the data available for the current review were for grass and winter wheat with smaller sets for barley, winter oilseed rape and forage maize. More detail on methodology would be helpful. It could be made clear in this methodology section that the cereal data were for grain only and that offtake in straw was not included. Details of the field experiments from which data were taken are rather sparse. Botanical composition will affect P and K concentrations in herbage (white clover tending to have a greater K concentration than perennial ryegrass for example) so the types of sward used for grassland data should be stated. 'RB209 grassland' presumably refers to experiments conducted for the latest review of RB209 but this could be stated.

Data from the experiments were compared with analytical results for grass samples from commercial laboratories. No information on sward type, stage of growth at sampling or sometimes even sample type (fresh grass or silage) was available for the commercial grassland data.

There appears to be an error in Fig 5b where the RB209 values for 15% DM grass and 20% DM grass are transposed.

Two broad and contradictory tendencies are clear from the review:

- data from grass and cereal field experiments showed significantly smaller P and K offtakes than the typical values in RB209;

- analytical data from commercial laboratories showed greater P and K concentrations in grass than those equivalent to the typical offtake values in RB209.

Reasons for these differences between the data sets and the offtake values in RB209 cannot be identified reliably from the information available. Various reasons could be proposed but they would remain speculative.

Main conclusions stated in the review were:

- with the exception of P_2O_5 offtake in cereals, data used for the review did not support conclusively a change to the offtake values in RB209;
- a single P_2O_5 offtake value for wheat and barley remained appropriate;
- the offtake value for cereals in RB209 should be changed from 7.8 kg P_2O_5 /t fresh grain to 6.0 kg P_2O_5 /t fresh grain.

These conclusions generally appear appropriate for the data available. However, a larger data set of at least 500 points might be better to support a change in typical P offtake in barley.

6. Overall assessment of all Research Reviews and Project Reports

While they contain a great deal of detailed data and discussion (and much repetition), the project reports and reviews describe two broad approaches to P fertilisation:

- Maintenance of a target concentration of available soil P (index 2 in R209 with some exceptions) ('current system').
- Meeting crop need for P by applications specific to that crop ('feed the crop').

The 'feed the crop' approach has some attraction but there are issues:

- If soil available P is not to be depleted over the medium to long term, the amount of P removed by crops must be replaced by P application. Increasing P recovery in crops, while desirable, would not change this need for longer term P balance. There is a question of what minimum level of soil available P could be maintained without affecting crop yields but this question applies both to 'feed the crop' and 'current system'. The difference between 'current system' and 'feed the crop' is not as great as at first appears.
- Most of the proposed components of 'feed the crop' failed to match their initial promise. Fertilizer P placement, foliar P application, use of Avail and seed dressings brought no consistent and reliable improvements in P utilization. These techniques can have a role in specific situations but their use might not be appropriate for most cereal and oilseed crops. The only component that survived field testing was use of grain P concentration as an indicator of crop P sufficiency.

- As described, 'feed the crop' is a philosophy for P use and it is not a recommendation system. It does not provide guidance to the farmer on how much P to apply to the next crop. Grain P analysis is a diagnostic test and is not predictive in the way that soil analysis is. The 'current system', while no doubt imperfect, is a recommendation system.

At its present stage of development, the 'feed the crop' approach does not offer a practical alternative to the 'current system'. However, some improvements to the 'current system' seem desirable and achievable. Two practical points should be borne in mind when considering possible improvements:

- Fertilizer P represents a relatively small cost to the farmer. A maintenance application of 75 kg P_2O_5 /ha for a 10 t/ha wheat crop costs around £55/ha or 20% of fertilizer cost and 10% of total variable costs. So, unless required to do so by regulation, a farmer is unlikely to spend a great deal of time and effort to refine P use by a few kg P_2O_5 /ha.
- Fertilizer P usually is applied with K as a compound fertilizer. Separate application of P and K is possible but it incurs an additional application cost. The range of available fertilizer P/K ratios will not meet the individual P and K requirements of every crop and field. In principle, custom blends could be produced for individual crops but economics constrain the range of ratios available in practice. Some compromises in application rates are unavoidable.

The 'current system' depends on soil analysis to provide a P index that is used to derive recommended rates of P from tables. The Olsen test for available soil P is standard for England/Wales/Northern Ireland. Other test methods are being, or have been, used in the UK and around the world and all have their pros and cons. All depend on representative soil sampling as described in the guidance available from RB209 and PAAG. In practice, sampling does not provide a perfectly representative result on every occasion. The 'current system' therefore relies on regular soil sampling so that the effect of errors tends to be corrected over time.

The target P index for arable crops usually is 2. For calcareous soils where P availability is restricted by reactions with calcium, index 1 might be appropriate. Research reviewed here supports index 2 as a general target but indicates that index 1 could be used for well-structured soils with continuous winter cropping. Application of P at index 1 might need to be greater than offtake to ensure crop yield is no lower than it would be at index 2. There was no suggestion that crop yields could be maintained, even with additional P application, at soil P index 0.

P balance (crop offtake minus P applied in manures and fertilizers) is easily calculated for arable crops and should be seen as an essential part of the 'current system'. The trend in balance provides a useful cross-check on soil analysis results.

In Research Review 92 a change to typical offtake in wheat grain from the 7.8 kg P₂O₅/t in RB209 to 6 kg P₂O₅/t is recommended. This is equivalent to a change from 0.40% P in grain DM to 0.31% P in grain DM. Project 529 ('Critical P') reviewed here contributed one third of the data used to calculate P offtake in wheat grain in Research Review 92. There is some overlap in data therefore but the weight of evidence presented supports a reduction in typical P offtake in wheat grain. In the WP3 report for Project No. 570, a typical offtake of 6.5 kg P₂O₅/t wheat grain is proposed and this might be preferred as it provides a small safety margin.

In summary, changes to RB209 that should be considered in the short term are:

In Section 4 Arable crops:

- Description of P (and K) recommendations as parts of a system the essential components of which comprise regular soil analysis and use of recommendation tables with calculation of annual P (and K) balances and examination of trends in balances as highly desirable adjuncts (p21).
- Change in typical P offtake in wheat grain from 7.8 to 6.5 kg P₂O₅/t (Table 4.11, p20). This is based on 700 data points for wheat which seems adequate to support the change. Any change in typical offtake for other cereals or oilseed rape should await availability of adequate sets of at least 500 data point for each species.
- Use of grain P analysis periodically to assess P strategy on the farm with 0.32% P in grain dry-matter as a typical indicator of sufficiency (p23).

In Section 1 Principles of nutrient management and fertiliser use and Section 4 Arable crops:

- Clearer description of situations where soil P index 1 might be appropriate as the target (p28):
- Calcareous soil (as currently indicated in RB209).
- Cropping with autumn-sown cereals on soils that are well-structured throughout the rotation and where P is applied annually. Guidance is needed on what would be regarded as adequately well-structured ideally as the appropriate VESS score.

Longer term, the variation among soils in P behaviour described in the Research Reviews might be taken into account, at least partly, by introduction of soil P sorption capacity alongside Olsen-P, as it now is alongside the modified Morgan's test in Scotland (SRUC 2015). Use of grain P analysis also might be developed to provide more than a single threshold value as an indicator of sufficiency.

7. References

Archer, J (1985) *Crop Nutrition and fertiliser use*. Farming Press, Ipswich.

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SRUC (2015) *Technical Note TN668 Managing soil phosphorus*. fas.scot/downloads/managing-soil-phosphorus