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Can grain P concentration be used as an indicator of fertilizer requirements in winter wheat?

S.M. Haefele [a,*], A.S. Gregory [b], P.R. Poulton [a], J. Hernandez-Allica [a], R.P. White [c], S.P. McGrath [a]

[a] *Sustainable Soils and Crops, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[b] *Protecting Crops and the Environment, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[c] *Net Zero and Resilient Farming, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*

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ABSTRACT

Context or problem: Available phosphorus (P) management is a continuous task in wheat-based systems of the UK, primarily to balance applying enough P to support high yields while avoiding unnecessary costs and damaging losses to the environment by applying too much.
Objective or research question: Grain P concentration with a corresponding threshold value of 0.32 % has been proposed as a new method for P management, supporting or replacing soil test-based evaluations. The objective of this study was to investigate if this approach was a reliable option.
Methods: We used data from the long-term "Exhaustion Land" experiment on the Rothamsted Farm in southeast England, to investigate the relations between winter wheat grain yield, grain P concentration, and Olsen P values in winter wheat over the last 32 years.
Results: Our results show that maximum grain P concentrations in high yielding years are much lower than in low yielding years, indicating a dilution effect through high assimilate transfer to grains. We could not confirm a lower threshold of 0.32 % grain P as an indicator of crop P deficiency at high yields, in our trial the value was closer to 0.24 % grain P. The Olsen P test at our site was a good indicator of P response, and the Olsen P threshold value of 20 mg P kg^{-1} was sufficient to support the highest yields of winter wheat.
Implications or significance: We conclude that P recommendations for cereals should continue to be based on soil Olsen P values, possibly supported by better estimations of P exports using grain analysis. Evaluation of the suitability of grain P concentration as a tool for P fertilizer management in cereal based systems would require more research. In the future, the existing Olsen P Index classes in the current UK Nutrient Management Guide ('RB209') should be reviewed to possibly increase P fertilizer use efficiency and reduce P losses to the environment whilst maintaining current production levels.

1. Introduction

Phosphorus (P) is a macro-nutrient in plants, and available soil P can be a limiting nutrient for intensive crop production. It is therefore regularly applied as mineral fertilizer and constitutes an important component of the production costs. Dependent on the P balance of a cropping system, it can be accumulated or depleted in the soil over time. Soil P depletion increases the risk of yield losses whereas accumulation is costly and may increase losses to the environment.

The P ion released from applied P fertilizer (usually $H_2PO_4^-$) is not very mobile in the soil and, if not taken up by the roots, enters more stable soil P fractions. Phosphorus taken up by the crop is partly removed with the yield or recycled into the soil with crop residues. Small amounts of soil and fertilizer P dissolve in the soil solution and may be taken up by plant roots (and other soil organisms) or drain with the percolating soil solution into the ground water (Heckrath et al., 1995). More significant losses can occur with erosive surface run-off during heavy rain events, where P is mostly transported as part of organo-mineral complexes (Panagos et al., 2022). This is the main process of P loss from arable agriculture, causing considerable pollution of natural terrestrial and aquatic environments, and these increase with increasing soil P status (RB209, 2023; Panagos et al., 2022).

* Corresponding author.
E-mail address: stephan.haefele@rothamsted.ac.uk (S.M. Haefele).

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Phosphorus taken up by the plant is quickly transported into the vegetative parts to be included in DNA/RNA molecules, proteins, phospholipids of membranes, and it has an important role in energy transfer. It is particularly important in early growth phases for cell and leaf expansion, and to maintain high photosynthetic efficiency. Surplus P in the vegetative plant parts is stored in the cell vacuoles and regulated to maintain the cytoplasmatic P status (Bieleski and Ferguson, 1983). In later growth stages, P is re-mobilized from vegetative plant organs to the grains, resulting in high grain and low straw P concentrations. In wheat, P concentrations can vary considerably, for example between 0.14 % and 0.43 % in grain and 0.01–0.11 % in straw, in this study. These numbers are typical for cereals and indicate the efficient translocation of vegetative P into the reproductive P pool, which is important, evolutionarily, given the P deficiency in most unfertilised natural soils.

Soil P availability for P management can be determined by a soil test, and different tests can be recommended based on the country and sometimes the target crop (e.g., Richner and Sinaj, 2017; Jordan-Meille et al., 2012). In the UK and Europe, the Olsen P test (Olsen et al., 1954) is one of the commonly recommended soil P tests for cereals (Jordan-Meille et al., 2012). Its relation to crop response in the region has been investigated over many years and many experiments, and threshold values for target phosphorus fertility classes have been proposed (e.g., Steinfurth et al., 2022; Nawara et al., 2017; Jordan-Meille et al., 2012). In the UK, based on the existing Nutrient Management Guide (hereafter referred to by its predecessor code 'RB209'; AHDB, 2023a), the soil, or usually the tested field, is assigned to a P Index based on the test result. Depending on this P Index, the manager can then decide to a) apply a recommended fixed rate of P fertilizer, b) only replace P removed with the last crop (calculated from yield and grain P concentration), or c) to omit any P application for that season and field (AHDB, 2023a).

According to the RB209 (AHDB, 2023a), the target index of P for arable crops and grass is P Index 2 (16–25 mg L^{-1} Olsen P). This general recommendation allows, in part, for the variation in Olsen P within a field and minimizes any risk of yield loss when crops are grown on those areas of the field where Olsen P is sub-optimal. A report by AHDB (Roques et al., 2014) supported the then current advice. As part of this study, data from the P experiments managed by Rothamsted Research were reviewed by Johnston and Poulton (2011). However, the increasing cost of phosphate fertilizer as well as the pollution risk has prompted farmers and regulators to ask whether Olsen P thresholds could be lowered without the risk of losing yield. P imbalances are said to pose the third biggest threat to planetary boundaries (Steffen et al., 2015), and the EU Green Deal has recently set targets of 50 % less nutrient losses by 2030 (European Commission, 2021).

Some farm advisors have questioned the existing (Olsen) P recommendation system as inadequate for maximum yield targets, particularly for winter wheat (Sylvester-Bradley et al., 2022), indicating that it might limit possible yield response and thereby farmer income. In addition, the usefulness of particularly the Olsen P test was questioned, because it is known to have a considerable uncertainty interval and to react differently on some soil types (Nawara et al., 2017). Therefore, grain P analysis has been proposed as a replacement or additional metric, and using grain P concentration for P fertiliser management has been accepted in the revised RB209 in the UK (AHDB, 2023a; Nutrient Management Guide, RB209). The new lower grain P threshold was set at 0.32 % based on Sylvester-Bradley et al. (2022), and according to this threshold, about 65 % of their farmer network data, covering 1683 entries between 2013 – 2021, were insufficient in P for highest yield responses. This change might have considerable impact on farmers' P management of wheat crops in the UK, potentially increasing P fertilizer rates as well as the average soil P status.

Therefore, we analysed grain P concentration and yield data using results over 30 years in a long-term experiment with different rates of P fertiliser which have created a consequent gradient of low to high soil Olsen P values. Other than the continued and distinct Olsen P levels derived from the treatments, the plots have been managed conventionally in a controlled way for many years and other inputs have not limited yields. Our objectives were 1) to investigate the relation between grain yield, grain P concentration and soil P status, 2) to discuss possible mechanisms explaining the observed results, and 3) to evaluate consequences of the results for P management in wheat crops.

2. Material and methods

2.1. Trial and site description

The long-term experiment providing data to this study is the "Exhaustion Land" experiment, situated at the Rothamsted Research farm just north of London, at about 130 MASL (central coordinates 51°48'45"N 0°22'32"W). Experiments started on the site now known as the Exhaustion Land in 1852 on four long strips, as one of the 'Classical' experiments established by Lawes and Gilbert. A fifth unmanured strip was added in 1856 and the five strips were divided in 1876 to create 10 main plots, each 105 × 6 m. The experiment has had several distinct phases, starting with annual N, P, K, Mg, and Na applications for wheat (1856 – 1875) and then including a farmyard manure (FYM) treatment for potatoes (1876–1901), an 'exhaustion' phase without organic or inorganic fertilizers for cereals mostly (1902 – 1940), and the re-introduction of basal N applied to spring barley (1940–1974) (Johnston and Poulton, 1977). In 1976, each main plot was divided to test four rates of N.

The experimental phase used for this study started in 1986 when most of the P residues from earlier phases were exhausted (hence the experiment's name), and it was decided to investigate how quickly this decline in soil fertility could be reversed. Annual cumulative dressing of 0, 44, 87, and 131 kg P ha^{-1} (P0, P1, P2 and P3, respectively) applied as triple superphosphate, were tested in four sub-plots on five of the 10 main plots (i.e. in 20 sub-plots). Applications of the three fixed P rates were conducted between 1986 and 1992 to see how quickly plant available-P could be increased such that it did not limit yield. No P was applied between 1993 and 1999 to stop further increases and since 2000, maintenance rates of P (15 kg P ha^{-1}) equivalent to offtakes have been applied, except on the P0 and, since 2016, P1 sub-plots have not received P. The purpose was to maintain the wide range of Olsen P levels that had been established on the 20 sub-plots (Poulton and Johnston, 2013). There is no true replication due to the previous strip treatments (a feature common to all Rothamsted's 19th Century-originating 'Classical' experiments); two of the original main plots had no P between 1856 – 1901, two had fertiliser P between 1856 – 1901 and one had FYM between 1876 – 1901. However, four different P treatments were established with 5 sub-plots each, even if the range of Olsen P varies between these "replicates".

Basal N and K were applied homogenously such that these nutrients did not limit yield. Spring barley (*Hordeum vulgare* L.) was grown until 1991 and, with two exceptions, winter wheat (*Triticum aestivum* L.) has been grown since 1992. Total N rates applied to the winter wheat increased over time from 192 kg N ha^{-1} (1992–2002), to 200 kg N ha^{-1} in 2003, and to 300 kg N ha^{-1} (2004–2023). Since 2003 the N has been applied as three split dressings with the first application of 50 kg N ha^{-1} being applied as ammonium sulphate so that sulphur (S) is not limiting yield. Weeds, pests and diseases were controlled according to standard farm practice. Winter wheat varieties used in the study years from 1992 were Mercia (1992–95, 1998), Hereward (1996/97, 1999/2000, 2002/03), Xi-19 (2004–14), Crusoe (2015–19), and Zyatt (2021–23).

Basal K (124.5 kg K ha^{-1}, as potassium chloride) and P treatments (as above) were applied in autumn on the stubble of the harvested crop and ploughed in; N (as above) was top-dressed in spring. Grain and straw were harvested, and grain yields reported here are adjusted to 85 % dry matter by convention. The land was ploughed annually to a depth not exceeding 23 cm. In the last decades, differential amounts of chalk were applied in 1981, 2002, 2007, 2011, 2013, 2018, and 2022 (see below).

The trial was sub-soiled in autumn 2001, and flat-lifted in autumn 2002 (sub-soiling cracks the soil vertically up the leg and breaks the soil around the leg; flat-lifting both cracks the soil and destroys subsoil compaction horizontally). Crucially, neither sub-soiling nor flat-lifting mixes sub-soil with top-soil.

The soil at the experimental sites is a silty clay loam of the Batcombe-Carstens series (Avery and Catt, 1995) or a Chromic Luvisol (IUSS, 2015). Developed from chalk deposits, the soil contains many flints and some rounded pebbles from material derived from the Reading Beds. The soil is naturally acid and free draining but at some period well before the 1850s, chalk ($CaCO_3$) was dug up from pits on the farm and applied at up to 250 t ha^{-1} (Young, 1813). This increased the topsoil (23 cm) pH_{H2O} to between 7.0 and 8.0. Since the 1950s, the soil has been maintained at a minimum of pH 7 by applying differential amounts of chalk where and when needed. The site is almost level, and has a texture of around 20 % clay, 52 % silt and 28 % sand.

2.2. Soil and plant analysis

The soil on each plot was sampled, usually in alternate years, occasionally every third year, to determine Olsen P. Each sample comprised 16–20 cores taken with a 2.5 cm semi-cylindrical gouge auger from the 0 to 23 cm horizon, after harvest and before any fertilizer was applied. Note that the Rothamsted Research laboratory weighs the sample for analysis and results are therefore reported in mg P kg^{-1}; this differs from the method used by contract laboratories which scoop samples by volume and therefore report in mg P L^{-1}. Both methods give similar results but scooping gives numerically higher values and has a bigger error because of differences in the densities of soils (personal communication, SP McGrath).

Each year from 1986 to 2024, the yields of grain and straw were measured for each sub-plot. Grain and straw subsamples (500 g and 50 g, respectively) were taken at harvest from each sub-plot, finely ground and analysed for total elements. After analysis at the Rothamsted Research laboratory, remaining samples were archived for long-term storage. Total elements in plant samples were determined using ICP-OES (Inductively coupled plasma Optical Emission Spectrometer, Optima 7300 DV, Perkin Elmer, CT, USA). Fine ground plant samples were digested using a mixture of nitric acid and perchloric acid (85:15 V/V) in open tube digestion blocks (Zhao et al., 1994). Total carbon and nitrogen content were determined by combustion (LECO, Michigan, USA), also using fine ground plant samples.

2.3. Response curves and statistical analysis

An initial analysis indicated that grain yields varied strongly between years, and that this affected the relation to grain P concentrations and Olsen P response curves. We therefore grouped years with similar maximum grain yield together, i.e., < 7 t ha^{-1}, 7–8 t ha^{-1}, 8–9 t ha^{-1}, and > 9 t ha^{-1} (Table 1). For each yield group, yields increased with increasing Olsen P until it reached a plateau, and a response curve was fitted to the grain yield/Olsen P relationship. The Olsen P used was that determined in the soil sample taken immediately after harvest in the year in which the crop was grown. Where this was not available, the arithmetic mean of the value determined in the preceding and succeeding autumn was used. The same grain yields groups were used to analyse the relationships between yield and grain P concentration, and between grain P concentration and Olsen P. The relationships between yield (y) and Olsen P (x), between yield (y) and grain P concentration (x) and between grain P concentration (y) and Olsen P (x) were described by an asymptotic regression equation (Mitscherlich type, exponential) of the form:

$$y = a + b * r^x$$

where a is the asymptote and b and r are range and parameters, respectively, estimated by maximum likelihood. This form of model was chosen because the parameters have a straightforward interpretation for this type of yield response data.

Table 1
Overview of the annual maximum grain yields achieved and the respective winter wheat varieties used. Grain yields are categorized in four yield groups. In two years, spring wheat varieties were grown because the winter wheat could not be sown due to a wet autumn and winter. The year of harvest indicates the season by convention.

	Maximum seasonal grain yield group			
Variety/season included	< 7 t ha^{-1}	7–8 t ha^{-1}	8–9 t ha^{-1}	> 9 t ha^{-1}
Mercia (1992–95, 1998)	1995	1993	1992, 1994, 1998	
Hereward (1996/97, 1999/2000, 2002/03)	2000	1997, 1999, 2002, 2003	1996	
Xi−19 (2004–14),	2007, 2013	2009	2004, 2006, 2010, 2011, 2012, 2014	2005, 2008
Crusoe (2015–19)		2017, 2018	2019	2015, 2016
Zyatt (2021–24)		2021	2022	2023
Number of years	4	9	12	5
Spring wheat (winter wheat unable to be sown)				
Axona (2001)	2001			
Tybalt (2020)	2020			

3. Results

The wheat varieties used in the trial changed during the observation period, being replaced regularly when higher yielding and more disease tolerant varieties became available. Table 1 gives an overview of which varieties were used in which year and what maximum yield level in the high N treatments were achieved. This shows that in four seasons when winter wheat was grown the maximum yields were < 7 t ha^{-1}, nine seasons had maximum grain yields in the 7–8 t ha^{-1} group, twelve in the 8–9 t ha^{-1} group, and five seasons had maximum yields above 9 t ha^{-1}. Although maximum grain yields varied from year to year, the general trend indicated higher maximum yields of newer varieties in more recent years. When a spring wheat variety was grown (when a wet autumn and winter prevented sowing of a winter variety), low maximum yields resulted, but this data was not included in the analysis. Note that this is a trial with continuous wheat, which therefore has generally lower yields than first wheat crops.

The mean soil Olsen P values for each of the four P treatments in the trial over time are shown in Fig. 1. The graph shows the very depleted soil P before applications of P1, P2 and P3 started in 1986, the rapid build-up of soil P in the treatments P1 to P3 thereafter, the draw-down of soil P reserves in the years 1993–1999, and the stabilization of available soil P with start of the replacement regime in 2000. The figure also shows the distinct and treatment-specific soil P availability over the duration of the experiment phase evaluated here (from 1992). But note that average treatment Olsen P values are shown which varied slightly between sub-plots ("replications") due to the previous history.

The relation between grain P concentration and grain yield since 1992 is presented in Fig. 2. Within a yield group, values shown are averages across all years for each sub-plot but separated for P treatments. Therefore, data from a variable number of years and different varieties is integrated in each yield group (corresponding to all the years in a yield group/column in Table 1; spring wheat data were excluded). The figure shows clearly separated response functions between grain P concentration and grain yield for the different yield groups, displaying decreasing grain P concentration with increasing seasonal grain yield potential. Or, expressed differently, the higher the yield potential in a season, the lower the grain P concentration for a given yield. A very similar trend was seen if all the individual data points in a yield group are plotted

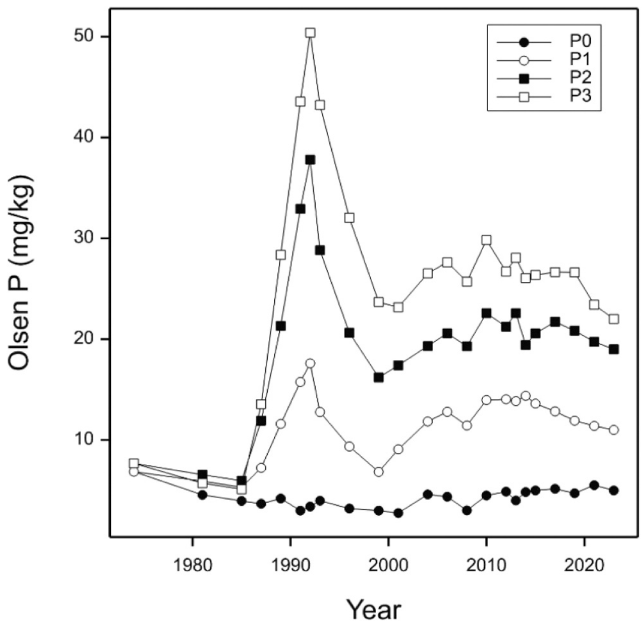

Fig. 1. Average values of five replications of available soil phosphorus (Olsen P) for the four P treatments from 1972 onwards of the Exhaustion Land experiment at Rothamsted Research, UK.

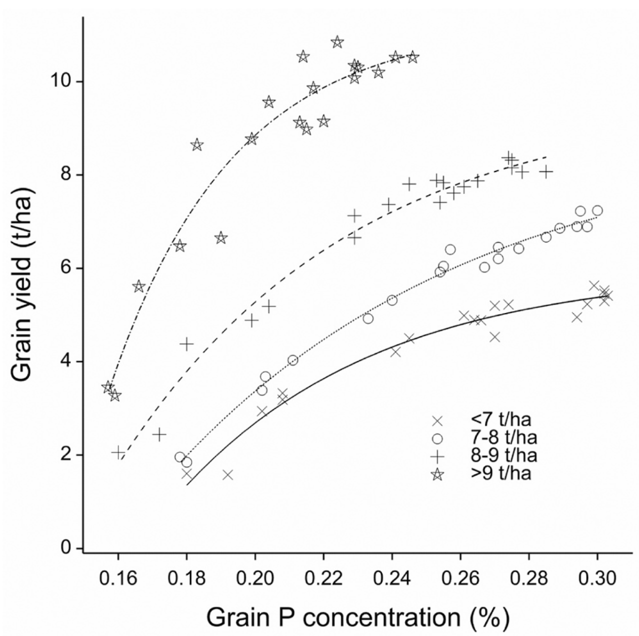

Fig. 2. The relation between grain P concentration and grain yield for the Exhaustion Land long-term experiment at Rothamsted Research, UK. Yield results from all P treatments in a season are grouped according to the highest yield reached in that season (< 7 t ha^{-1}, 7–8 t ha^{-1}, 8–9 t ha^{-1}, > 9 t ha^{-1}). Average values from each replication across all seasons in each yield group are shown, and an exponential response function was fitted to the data of each yield group.

(data not shown), as expected however, there was more variability in the observed values and slight overlap between yield groups.

As a next step, the same grain P concentration data were plotted against the available Olsen P data in the respective sub-plots (Fig. 3). As for Fig. 2, mean values of sub-plots with a variable number of years and different varieties were integrated in each yield group (Fig. 3). The data indicated again an exponential response function for the relation

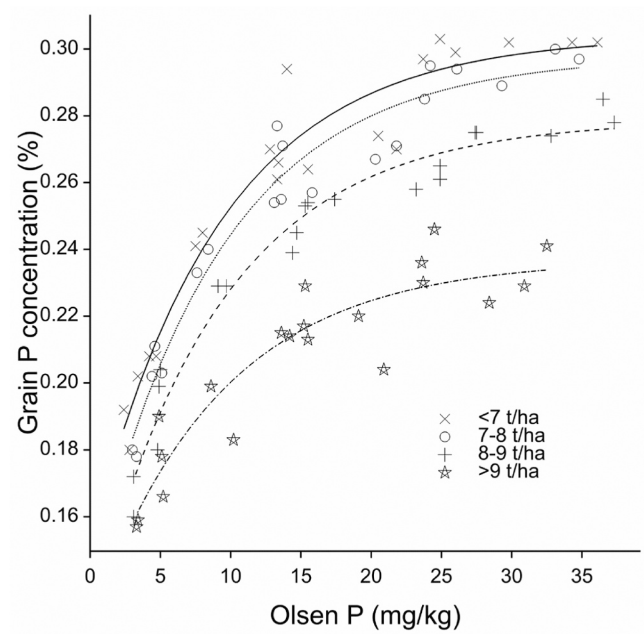

Fig. 3. The relation between the soil P availability (Olsen P) and grain P concentration for the Exhaustion Land long-term experiment at Rothamsted Research, UK. Yield results from all P treatments in a season are grouped according to the highest yield reached in that season (< 7 t ha^{-1}, 7–8 t ha^{-1}, 8–9 t ha^{-1}, > 9 t ha^{-1}). Averages from each replication across all seasons in this yield group are shown, and an exponential response function was fitted to the data of each yield group.

between grain P concentration and available Olsen P in all yield groups. According to the parameters for the fitted curves (Table A1), asymptotes of maximum grain P concentrations were reached at 0.304 % for the yield group < 7 t ha^{-1}, 0.298 % for the yield group 7–8 t ha^{-1}, 0.279 % for the yield group 8–9 t ha^{-1}, and 0.237 % for the yield group > 9 t ha^{-1}. Thus, the higher the yield achieved, the lower the maximum grain P concentration was. This observation does not indicate that P supply at high Olsen P availability was a limiting factor for grain P concentration. Rather, it seems that when sufficient soil P was available, the P concentration in grains was determined by the yield levels achieved. Exponential functions describe the observed data very well and percentage-variance- accounted-for values in all cases were above 90 %.

The yield response to plant-available soil P as indicated with the Olsen method is shown in Fig. 4, again separated for the four different yield groups (again mean values for subplots across years and varieties). The data in each grain yield group were clearly separated and plateaus of maximum grain yield were reached in all four groups at between 15 and 20 mg Olsen P kg^{-1} soil. Exponential functions again described the observed data very well and percentage-variance-accounted-for values in all cases were above 90 %.

The last graph (Fig. 5) shows the average grain P concentration across all five subplots with the same P treatment over time, starting from 1992 onwards. The general trend was that grain P concentrations have decreased over time, and that the grain P concentrations related to the four P treatments. In the last fifteen years of the trial, highest grain P concentrations (mostly in P3) were usually between 0.20 % and 0.25 % with only a few exceptions. In addition, concentrations went up and down from year to year, mostly in unison in the four P treatments applied from 1986 to 1992 and corresponding to low and high yielding seasons. The initial decrease of grain P concentrations from 1992 to 2021 accompanied both the decreasing Olsen P values (Fig. 1) and newer varieties with a higher yield potential (Table 1).

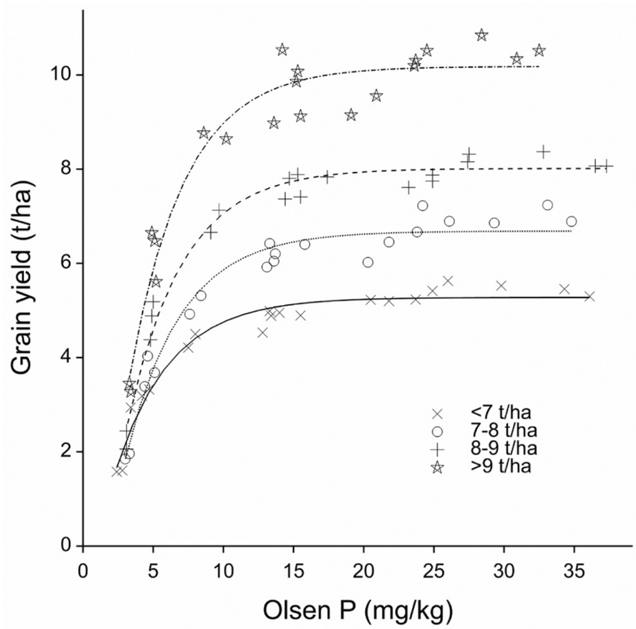

Fig. 4. The relation between the soil P availability (Olsen P) and grain yield for the Exhaustion Land long-term experiment at Rothamsted Research, UK. Yield results from all P treatments in a season are grouped according to the highest yield reached in that season (< 7 t ha^{-1}, 7–8 t ha^{-1}, 8–9 t ha^{-1}, > 9 t ha^{-1}). Averages from each replication across all seasons in this yield group are shown, and an exponential response function was fitted to the data of each yield group.

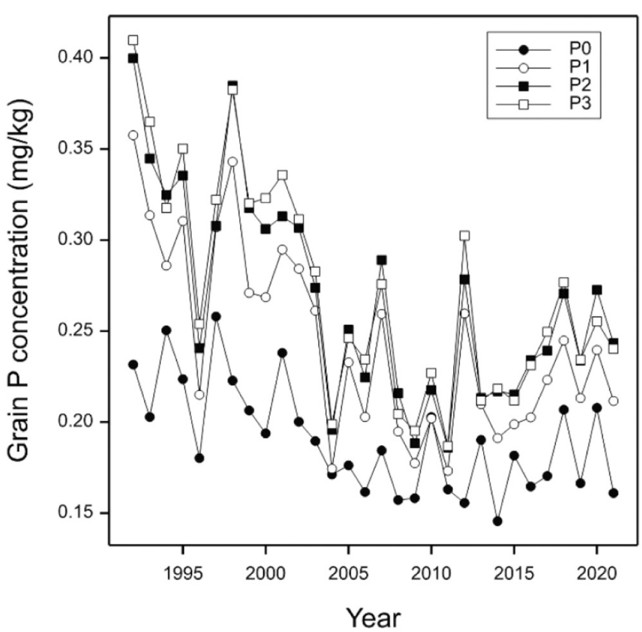

Fig. 5. Treatment dependent grain P concentrations throughout the duration of the Exhaustion Land long-term experiment focussed on in this study. Shown are average values for five sub-plots for each P treatment.

4. Discussion

4.1. Yield versus grain P relationships

Using grain P concentration as an indicator of the crop P status depends on a stable relationship between grain yield and grain P concentration. Only if this relationship exists across seasons, farms and crop varieties could the grain P concentration be used as an indicator of P sufficiency or lack of P supply. The argument given by Sylvester-Bradley et al. (2022) that this relationship should exist was that “large yields are borne by large crops (i.e., canopies) which, to function satisfactorily, must contain larger quantities (kg ha^{-1}) of essential nutrients than crops with small yields. If that was true, it seems reasonable to assume that consistent grain nutrient concentrations should be diagnostic of crop nutrient deficiency or sufficiency, irrespective of crop yield”.

Our results presented in Fig. 2 show that this assumption only held for seasons with a similar yield potential. For each of the yield groups shown in Fig. 2, there was a clear exponential response function between grain P concentration and grain yield. And within a yield group, this assumption also held across different seasons (with a similar yield potential) and different varieties but only for the one experimental site used. However, it cannot be confirmed across seasons with different yield potentials, which clearly showed a strong dilution effect of large yields on grain P concentrations. Or expressed differently, lower-yielding seasons in soils with good P supply tended to accumulate high grain P concentrations.

To explain these observations, it is necessary to consider the physiological P processes in the plant. P is particularly important in early growth phases for cell and leaf expansion, and to maintain high photosynthetic efficiency (Marschner, 1986). Therefore, a better P status of the plant generally contributes to higher yields. This was also supported by controlled trials, where an increase of P supply from suboptimal to an optimal level, increased all measured functional P fractions in the plant. However, above the optimal level, only the inorganic P (Pi) in the vacuole increased, representing a cellular P storage option (Kakie, 1969). This represents a safety mechanism for the plant/crop, where potential limiting nutrients are stored beyond the current physiological requirements (luxury uptake). Thus, it is observed that in plants with an adequate P supply, 85–95 % of the total Pi is stored in vacuoles. This P is activated and transported out of the vacuoles when the concentration of Pi in the cytoplasm declines due to deficiency or translocation to the grain (Bieleski and Ferguson, 1983). These mechanisms explain that within a season there is a clear relation between grain yield and grain P concentration. But across seasons with different yield potential, grain P concentration is a function of soil P availability and accumulation in the vegetative parts, and the subsequent dilution in the sink, i.e., the whole of the grain yield. Naturally, higher grain yields would then mean more dilution and lower grain P concentrations.

Unfortunately, long-term data only exist from a limited number of long-term experiments including the Exhaustion Land experiment at Rothamsted. However, it seems reasonable to assume that these mechanisms apply also across more diverse sites. Therefore, we conclude that grain P concentrations only have limited value to monitor the crop P status in cereals.

4.2. Grain P concentration versus Olsen P as a management tool

Regarding a threshold for grain P concentrations limiting yields, our data provided some clues, but nothing conclusive. Highest average yields of about 11 t ha^{-1} were achieved with grain P concentrations of 0.22–0.25 % grain P (Fig. 2) and the highest yield of 11.8 t ha^{-1} had a grain P concentration of 0.25 % (data not shown). The Olsen P versus grain P relationship (Fig. 3) for the high yielding group also indicated a plateau at about 0.24 % grain P. But the trial yields were limited by the continuous wheat cropping treatment and data from more sites including first wheat crops within a rotation would be required to make a better estimate of the minimum grain P threshold for yield response. The usefulness of the P response figure used by Sylvester-Bradley et al. (2022) to determine this threshold (see their Figure 8) is unclear; as our data shows, continued yield response was observed at high grain P concentrations particularly in low yielding seasons (Fig. 2, yield group 7–8 t ha^{-1}) when P was obviously not the yield limiting factor. And as Fig. 5 indicates, old data should probably be used carefully because newer varieties have a higher yield potential and possibly lower grain P concentrations, indicating increased P use efficiency (defined as grain yield per unit Olsen P in the soil). Related to this is that the average grain P concentrations used in the RB209 guidelines (AHDB, 2023b) for estimations of P removals are 0.28 % in winter wheat and 0.35 % in other cereals. These values are higher than observed here for high yielding crops and adjusting them could further reduce applications and resulting costs and P losses.

The relationship between yield and Olsen P in our data (Fig. 4) confirm previous reports on threshold values of crop response in Europe (e.g., Steinfurth et al., 2022; Nawara et al., 2017; Jordan-Meille et al., 2012). In most cases reported for winter wheat, but also covering a wide variety of crops (Steinfurth et al., 2022), a threshold range of 15–20 mg P kg^{-1} covered a 95 % confidence interval of crop response (based on Mitscherlich-type functions and corresponding Olsen-P_{crit} values). Adjustments of this general range were proposed for specific crops (e.g. potato which usually respond to higher concentrations of available P) or texture classes (e.g., sandy soils) by a range of studies (e.g., Steinfurth et al., 2022; other refs). However, several authors note that there is a considerable scatter around the 95 % confidence interval of crop response, possibly justifying higher critical ranges to avoid possible crop response losses in favourable seasons (Steinfurth et al., 2022). But response observations above the 95 % confidence interval are rare by definition and might not justify the fertilizer expenses needed to maintain respective high soil P levels, and yield response might be observed at high P supply levels even though P is not the limiting factor (Fig. 2, yield group 7–8 and 8–9 t ha^{-1}). Accordingly, Steinfurth et al. (2022) concluded that "the uncertainty of yield often is still present at very high Olsen-P values, further reducing the advantages of increased fertilizer application". Therefore, we conclude that the Olsen P test is a reliable tool for P management for many crops and a wide variety of soils.

Advantageous characteristics of the Olsen P test are that there is a lot of research and farm data available, it works on most soils across Europe (and on specific soil types there is additional advice available), it has been established for a range of crops, results are not affected by seasonal weather, and sample results can be attributed to low or high areas within fields. In contrast, there is not much research available on grain P concentrations; the effect of soils on grain P thresholds is not really known; deficiency thresholds will be different for different crops; grain P concentrations are certainly affected by seasons and possibly varieties; and it is perhaps more difficult to get grain samples for a defined area of the field (needed for fertilizer recommendations in precision farming).

4.3. Consequences for P fertilizer management

As outlined above, we do not think that the minimum grain P threshold of 0.32 % for P response in winter wheat is backed by a wide range of data and studies, and certainly not by the data presented here for a long and well-controlled experiment. Also, the study of Sylvester-Bradley et al. (2022) does not provide much detail on the experiments, the treatments, the data transformation, and the consideration of uncertainty around the 0.32 % threshold value. But if it were used as an indicator for P management, as partly recommended in the new RB209 (AHDB, 2023a), it may cause P overfertilization with the resulting consequences of higher than necessary costs and increasing P contamination of the environment over time. Another indication for this interpretation comes from the data presented by Sylvester-Bradley et al. (2022) and related data from NRM, one of the largest provider of soil analysis for UK farmers (NRM, 2023). According to Sylvester-Bradley et al. (2022), the new grain P threshold of 0.32 % indicated that about 65 % of their farmer network data, covering 1683 entries between 2013 – 2021, were deficient in P. In contrast, the annual report of NRM (NRM, 2023) showed that about 66 % of the tested arable fields were sufficient, i.e. having soil P Index of 2 or above (> 15 mg L^{-1} available Olsen P; representing more than 64,000 field tests; personal communication with NRM) and that the average Olsen P value for these fields was about 23 mg L^{-1} Olsen P.

Thus, according to NRM data and the P recommendation based on Olsen P (AHDB, 2023b) two-thirds of UK farmers would apply standard P rates, whereas according to the new grain P threshold (AHDB, 2023b), two-thirds of UK farmers would need to increase their P rate (although the new RB209 does not give advice on how much more would need to be applied). The validity of the existing RB209 recommendations based on the Olsen P tests has also been confirmed by the study of Lark et al. (2019), including yields up to 15 t ha^{-1}.

Furthermore, the latter study, our data and larger studies of European P response data (e.g., Steinfurth et al., 2022; Nawara et al., 2017; Jordan-Meille et al., 2012) indicate that an Olsen P range of 16–20 mg P kg^{-1} together with the recommended P rates for the index 2 (RB209; AHDB, 2023a) is sufficient to support the largest grain yields of winter wheat (with the exception of shallow and alkaline soils). However, this narrowing of the current index 2 class (from 16 to 25 mg P kg^{-1} to 16–20 mg P kg^{-1}) would need extensive discussions with stakeholders and might be something to target for the future, accompanying the efforts to increase fertilizer P use efficiency in Europe.

For the moment, we recommend staying with the existing Olsen P based recommendation, possibly combined with a better estimation of P removal with grain and straw (based on grain analysis as proposed by Sylvester-Bradley et al., 2022) to adjust the annual replacement rate for an improved P management for cereals. As our results show, P management based on annual replacement rates and regular corrections informed by Olsen P testing every second or third year can maintain stable soil P availability (Fig. 1), stable grain P concentration levels (Fig. 5) and support highest yields (Fig. 2). This could be combined with an initiative to halt P applications on fields in the Index 3 (> 25 mg P kg^{-1}) targeting lower costs and reduced losses there until the Olsen P drops into Index 2. Introduction of a grain P threshold and related management advice should be reversed until more and better data becomes available.

5. Conclusions

Re-visiting existing fertilizer recommendations regularly is good practice, to either confirm current practice or to adjust guidelines in the light of new research or changed objectives of best practice. In the case of P management for cereals in the UK, a new P management system based on grain P concentration was proposed and included in the latest version of RB209, to either improve or even replace the existing system based on soil testing, using the Olsen P method. We used existing data and samples from a long-term experiment at Rothamsted to address this issue. The data set was ideal for this objective, as it provided grain yield and P concentration data for winter wheat, and soil Olsen P data, since 1992, albeit limited to one experimental site on one single soil type under continuous wheat. The results of the analysis showed exponential response functions of grain P concentration to increasing P supply and grain yield, but the grain P concentrations decreased with increasing yields, indicating luxury P uptake at lower yields and good soil P supply. In contrast, the Olsen P soil test clearly identified response plateaus at Olsen P values of 15–20 mg P kg^{-1} soil, as repeatedly reported for various crops and soils in Europe. We could not confirm the proposed minimum threshold in grain P of 0.32 % because the grain P concentrations seem to be variable depending on season, yield potential and possibly variety. Our data indicate improved P use efficiency in modern varieties. We propose to continue basing P recommendations for cereals on Olsen P values, possibly supported by better estimation of P exports based on grain analysis. In the near future, the existing Olsen P Index classes in the UK Nutrient Management Guide RB209 should be reviewed to possibly increase P fertilizer use efficiency and reduce P losses to the environment whilst maintaining current production levels.

CRediT authorship contribution statement

SP McGrath: Writing – review & editing, Investigation. **Stephan M.**

Haefele: Writing – original draft, Investigation, Conceptualization. **Javier Hernandez-Allica:** Investigation. **RP White:** Writing – review & editing, Formal analysis. **AS Gregory:** Writing – review & editing. **PR Poulton:** Writing – review & editing, Investigation, Data curation.

Ethical compliance

We complied with all relevant ethical regulations regarding human research participants. All authors followed ethical guidelines stated in Elsevier's Publishing Ethics Policy.

Contributions

SMH, SPM and PRP designed and conducted the research and compiled the data; SMH, SPM, RPW, JHA and PRP analysed the data; SMH wrote the first draft of the paper; SMH, SPM and PRP had primary responsibility for final content; all authors, including ASG, contributed to the editing and final version of the paper and approved it.

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Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use any AI technologies in the writing process of this manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex

Table A.1
Parameter values for the fitted response curves in Figs. 2–4.

Fig. 2		
Parameter	Estimate	s.e.
R fymax < 7 t/ha	0.000000039	0.000000202
B fymax < 7 t/ha	−99.4	86.9
A fymax < 7 t/ha	5.971	0.501
R fymax 7–8 t/ha	0.0000153	0.0000532
B fymax 7–8 t/ha	−51	24.6
A fymax 7–8 t/ha	8.92	1.17
R fymax 8–9 t/ha	0.00000043	0.00000137
B fymax 8–9 t/ha	−81.9	37.2
A fymax 8–9 t/ha	9.633	0.728
R fymax > 9 t/ha	8.07E−13	3.41E−12
B fymax > 9 t/ha	−627	396
A fymax > 9 t/ha	11.244	0.43
Fig. 3		
Parameter	Estimate	s.e.
R	0.89664	0.00898
agr%P ['< 7 t/ha']	−0.15292	0.00816
agr%P ['7–8 t/ha']	−0.15922	0.00897
agr%P ['8–9 t/ha']	−0.15084	0.00897
agr%P ['> 9 t/ha']	−0.10929	0.00916
A fymax < 7 t/ha	0.30398	0.00424
A fymax 7–8 t/ha	0.29795	0.00431
A fymax 8–9 t/ha	0.27878	0.00391
A fymax > 9 t/ha	0.23696	0.00379
Fig. 4		
Parameter	Estimate	s.e.
R	0.7754	0.0134
ayld ['< 7 t/ha']	−6.65	0.565
ayld ['7–8 t/ha']	−10.419	0.818
ayld ['8–9 t/ha']	−12.134	0.901
ayld ['> 9 t/ha']	−15.34	1.120
A fymax < 7 t/ha	5.275	0.105
A fymax 7–8 t/ha	6.683	0.109
A fymax 8–9 t/ha	8.015	0.106
A fymax > 9 t/ha	10.183	0.113

s.e.: standard error

Data availability

Data will be made available on request.

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