Table 3. Soil supply with plant available phosphorus as determined by the Olsen method.

Phosphorus sufficiency ranges	Soil test P_2O_5, mg/kg		
	Yanishevskii, 1996	Agrochemical methods of Soil Examination, 1975	Proposed ranges
Low	< 11	< 25	< 18
Medium	11-23	25-50	19-34
Increased	23-41	50-90	35-50
High	> 41	> 90	51-66
Very high	-	-	> 67

opinion is that alkaline soils are poorly supplied with available P. The parallel use of salt solutions (Karpinskii–Zamyatina, 0.03 N K_2SO_4 with pH 5.8; Schofield) shows that no actual decrease in available P occurs in alkaline soils. Thus, the disappearance of P is an illusion related to a limitation of the method as an alkaline extract loses its extraction capacity under alkaline conditions. The maximum underestimation is about 18 mg P_2O_5/kg—a value equivalent to the effect of a single application of at least 600 kg P_2O_5/ha in a heavy soil.

Rigorous application of soil test protocols lose their value given a lack of official nutrient sufficiency ranges in terms of plant available P supply. The P status of soil cannot be impartially assessed without adequate nutrient sufficiency ranges. Available literature data are contradictory (**Table 3**). Studies performed at the Institute for Soil Science and Agrochemistry Research reveal that the P sufficiency ranges estimated by the Olsen method in accordance with the P sufficiency ranges developed earlier (Yanishevskii, 1996; Agrochemical methods of soil examination, 1975) do not usually agree with the values obtained by other alkaline and salt methods.

The authors propose refined P sufficiency ranges, as determined by the Olsen method, which now coincide with estimates of soil P supply from other mild chemical methods (Machigin, pH 9.0; Chang–Jackson, Al–P fraction, pH 8.5; Karpinskii–Zamyatina, pH 5.8). A category of very high supply was also added in hopes of further contributing to the more rational use of the resources available. Optimum plant available P for stable, high crop yields lies within the range corresponding

to high P supply. An increase above the optimum level results in an abrupt decrease in crop response to P fertilizer. Liberal application of P fertilizers to highly alkaline soils is also unadvisable as high alkalinity (pH_{KCl} 8.0 or pHwater 8.5 and higher) is frequently due not only to the presence of calcium carbonates, but also to the presence of Na. The latter compound is detrimental to the growth and development of many agricultural crops, which abruptly decreases the efficiency of fertilizers applied.

Mathematical models and the corresponding software were developed by the authors for the determination of the actual supply of alkaline soils with available P depending on the pH_{KCl} or pHwater values (Khristenko, 2009). The use of these mathematical models or software, as well as the improved scale for soil P supply, will contribute to the optimization of fertilizing systems and, hence, expenditures per ha of fertilized area. For example, finding that the supply of soil P is 25 mg P_2O_5/kg (medium P supply) rather than 5 mg P_2O_5/kg (low P supply), the farmer can significantly reduce fertilizer application without fear of crop yield reductions.

Dr. Khristenko is Leading Scientist of the Department of Agrochemistry, National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky", Kharkov, Ukraine. e-mail: khristenko.an@mail.ru

Dr. Ivanova is Vice-President of the International Plant Nutrition Institute for the Eastern Europe, Central Asia, and the Middle East. e-mail: sivanova@ipni.net

References

Agrochemical Methods of Soil Examination. 1975. In A.V. Sokolov (Ed)., Moscow: Nauka, 1975, p. 106-190.

Khristenko, A.A. 2009. Utility Patent No. 41725 Ukraine, MPK (2009) G01N 33/24 // Byull. Izobr. No. 11

Olsen, R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. U.S. Dept of Agric. Cir. 939.

Yanishevskii, P.F. 1996. Agrokhimiya, No. 4:95-116.

A New Approach to Assessing Phosphorus Use Efficiency in Agriculture

By A.E. (Johnny) Johnston and J. Keith Syers

It is frequently stated that P is used inefficiently in agriculture, with percent recovery of P applied in fertilizers usually between 10 and 20%. We argue that such low efficiencies are primarily an artifact of the method used to calculate efficiency. When efficiency is measured by the "Balance Method" – P removed in crop expressed as a percentage of P applied – and when soil P levels are being maintained near the critical level, the efficiency of fertilizer P use frequently exceeds 90%.

In a recent comprehensive review of world literature on P use efficiency for a wide range of cropping systems, soil types, and climates, Syers et al. (2008) showed that the recovery (efficiency) of applied fertilizer P plus residual soil P frequently ranged from about 50 to 90% when

measured by a suitable method and over an appropriate time scale. This article shows how the concepts in the review can be developed further.

Percent recovery of an applied plant nutrient, X, is frequently calculated by the difference method:

Rothamsted Research has plots with various P treatments going back to 1856.

$$\text{Percent recovery} = \frac{\text{uptake by crop given X minus uptake by crop without X}}{\text{Amount of X}} \times 100$$

While this method is generally appropriate for N fertilizers, it has more limited value for P and K. Why? Nitrogen applied as an inorganic fertilizer containing urea, ammonium, or ni-trate and not used by the crop rarely remains as a residue of inorganic N in the soil. Nitrate left in the soil after crop harvest can be lost by leaching or denitrification and ammonium by volatilization. Thus, percent recovery of applied fertilizer N is best determined by the difference method which allows for any N taken up by a crop in the absence of applied N. However, only a very small amount, if any, of the residue from applied P and K fertilizer is lost from the soil. In most soils, any residue accumulates as a reserve of these two nutrients.

The direct method – using the isotope 32P – can be used to measure percent recovery of P applied in a fertilizer. However, percent recovery (efficiency) rarely exceeds 25%. But stop and consider. If only 25% of the P in a crop has come from the freshly applied fertilizer, the remaining 75% must have come from soil reserves of P. If soil P fertility is to be maintained, any P from the soil reserves must be replaced. So it is reasonable to consider that the total P in a crop, part from the fertilizer, part from soil reserves (which are maintained by fertilizer P addition), represents the long-term recovery of fertilizer P. Johnston and Poulton (1977) proposed this approach to mea-suring P use efficiency and it was developed further by Syers et al. (2008) who called it the "Balance Method" in which percent recovery of added P is calculated as:

$$\text{Percent recovery} = \frac{\text{P removal by crop}}{\text{P applied}} \times 100$$

This method has the advantage that the recovery of P from soil reserves is allowed for and there is no need for a control or check plot.

The second aspect of P use efficiency is related to recent developments in understanding the behavior of P in soil. In relation to the availability of soil P for uptake by plant roots, Johnston (2001) suggested that soil P could be considered to exist in four pools. This concept was further developed by Syers et al. (2008). Besides considering that the four pools of soil P were characterized by the availability of the P for uptake by plant roots, the latter authors related the four pools to the extractability of P by chemical reagents. In this way, a laboratory measure of "available" P can be related to soil P "availability" as seen by the growing crop in the field.

The overall concept can be shown diagrammatically as in **Figure 1**.

The amount of P in each of the four pools is related to differences in bonding energy for P between sites both on the surfaces and within soil constituents able to retain P and varia-tions in the proportion of such sites within the soil matrix. For P in the less readily available pool, it is further envisaged that there can be other reactions of P with soil constituents (Syers et al., 2008).

Phosphorus is taken up by plant roots as orthophosphate ions, principally $H_2PO_4^-$ and to a lesser extent HPO_4^{2-}. Earlier ideas about the fate of applied fertilizer P considered that if not used by a crop, the P became "fixed" in soil in forms that no longer supplied these ions to the soil solution and, therefore, this P was no longer available for uptake by roots. However, by the 1950s there were indications from field experiments which showed that where sufficiently large P reserves had accumulated in soil from past applications of fertilizer and organic manure, these reserves could provide sufficient P to increase crop yields.

The most important feature shown in **Figure 1** is the reversible transfer of P between the soil solution, the readily plant-available P pool, and the less-readily plant-available pool. Examples of supporting data from field experiments are given by Syers et al. (2008). Routine soil analysis for plant-available P measures the P in the soil solution and the readily plant-available pool. Because this is an operationally-defined fraction of soil P, the method of analysis used is not important. What is essential is that the data obtained accurately charac-terize a soil in terms of the response of a crop either to soil P or to an application of P fertilizer.

The reversible transfer of P between the first three pools implies an equilibrium between the P in these pools. Data for the increase in both Olsen P and total P in the top 23 cm of soil are available for a number of long-term experiments on the silty clay loam soil at Rothamsted, the sandy loam at Woburn, and a sandy clay loam soil at Saxmundham. For all three soil types there is a common linear relationship between the increase in Olsen P and the increase in total P (**Figure 2**).

Similarly, in an experiment in North Carolina, McCollum (1991) showed that after adding P for 9 years at rates up to 1,128 kg P/ha, only about 20% was extracted by the Mehlich-1 method.

A number of important practical questions arise from this concept of the behavior of soil and fertilizer P.

The first question is: "How much P should there be in the readily available pool to ensure optimum yield?"

When crop yield is related to readily available soil P measured by a reliable method for routine soil analysis, yield increases rapidly at first and then more slowly until it reaches a plateau – the asymptotic yield (**Figure 3**). The available soil P level at which the asymptotic yield is reached can be considered the critical level for that crop. Below the critical level, lack of available P results in a loss of yield. Applying P to soil with more than the critical level of available P would be done only to maintain soil P at a non-limiting level where no direct yield response is expected.

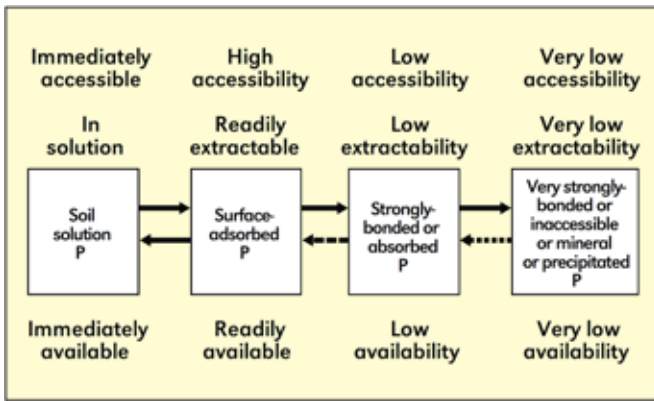Examples of yield/Olsen P response curves from

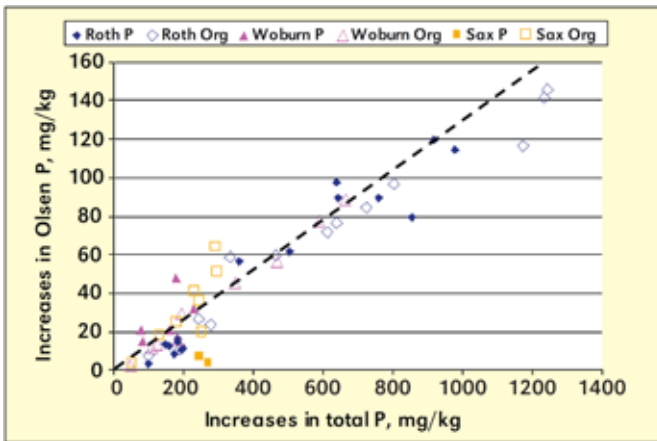**Figure 1.** Efficiency of soil and fertilizer P..

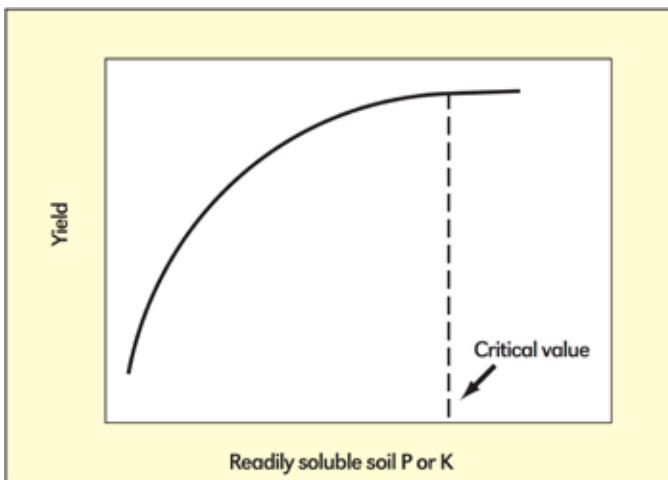**Figure 2.** Relationship between total P and Olsen P.(Dashed line represents 13% of added P remaining as Olsen P.)

Figure 3. How much P should there be in the readily available pool?

Figure 4. Example of critical values for arable crops.

Rotham-sted experiments are shown in **Figure 4**. For the three crops, sugar beet (sugar yield), spring barley, and winter wheat, although the maximum yield differed between years due to weather factors or to the amount of N applied, the critical level differed little. To achieve the larger asymptotic yield did not require more Olsen P in the 23 cm of topsoil.

The second question is: "How much P must be added to increase plant-available P to the critical level?"

The answer to this question is site-specific. For this reason much further work is required. Soil type, soil bulk density, depth of P incorporation and sampling will influence the result. Two examples show what can
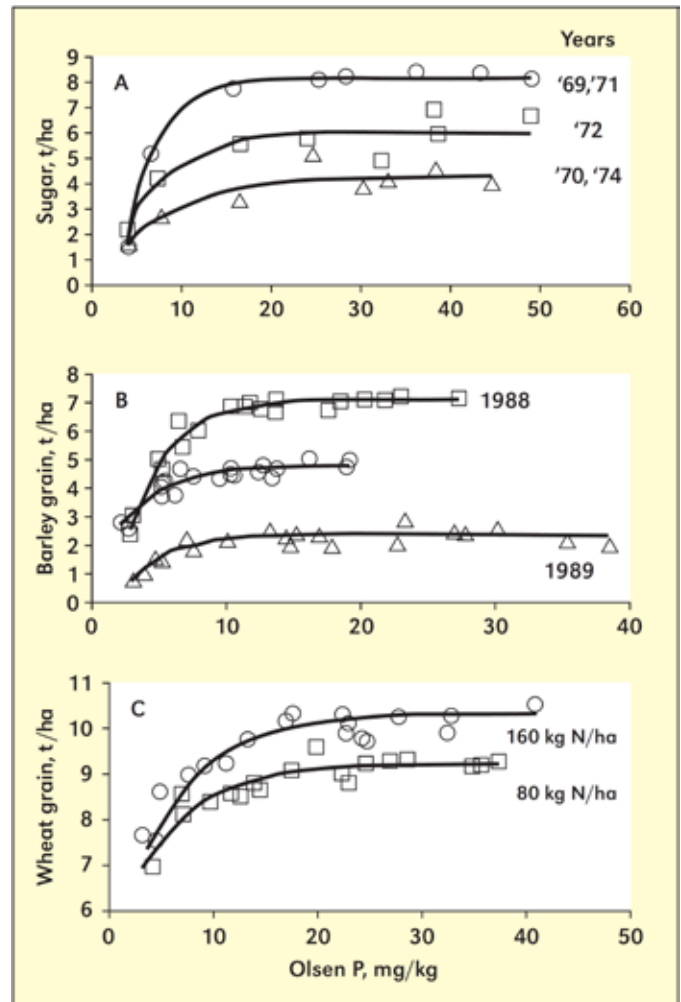
be done. An experiment started in 1856 on the silty clay loam at Rothamsted Research has been modified to measure the amount of P required to increase Olsen P (Poulton and Johnston, personal communication). Five P treatments between 1856 and 1901 had given a narrow range of Olsen P levels. The range of Olsen P was increased between 1986 and 1991 by applying 264 to 786 kg P/ha. Av-eraged over appropriate treatments, the total P applied, the P balance, and the initial and final Olsen P levels are given in **Table 1**. On soils initially with 7 mg/kg Olsen P, a positive P balance of 182 kg P/ha increased Olsen P to 18 mg/kg. Spring barley was grown each year (1986 to 1991). From the P response curve, the mean 98% asymptotic grain yield was 52.1 t/ha and the associated Olsen P was 14 mg/kg. Thus, 182 kg P/ha incorporated into the top 23 cm of soil was sufficient to increase Olsen P in 6 years to above the critical level. In the experiment discussed by McCollum (1991), the soil was a fine sandy loam and Mehlich-1 P was measured in the top 15 cm of soil during the initial 9-year period when P was added. At the start of the experiment, the soil was already at about the critical level for maize (18 to 22 g/m^3) and above that for soybean. However, over the 9-year period, 0 to 1,120 kg P/ha was applied; the increase in Mehlich-1 P was linear and 10 kg P/ha increased Mehlich-1 P by 1 g/m^3.

The third question is: "How much P is needed to maintain the critical level of Olsen P?"

The Rothamsted experiment was continued, but no

Effectiveness of Phosphorus Fertilization

Table 1. Total P added and P balance 1986-1991; Olsen P, mg/kg, in 1986 and 1991.			
P added, kg/ha	**P balance[1], kg/ha**	**Olsen P, mg/kg**	
		1986 г.	**1991 г.**
786	700	7	48
522	437	8	38
264	182	7	18
[1]P applied in excess of removal by crops.			

Table 2. Relationship between Olsen P, maximum yield of winter wheat grain, total P removed in grain plus straw, P applied annually, and percent recovery of applied P, estimated by the balance method.				
Olsen P, mg/kg, in 2004	9	14	23	31
Winter wheat grain, t/ha	7.1	7.8	7.9	7.9
P removed in grain plus straw, kg/ha	14	27	19	19
P applied annually, kg/ha	20	20	20	20
Percent recovery of applied P estimated by the balance method	70	85	95	95

P was added between 1993 and 1999. By 1999, Olsen P ranged from 2 to 31 mg/kg so that the yield response to Olsen P could be measured. From 2002 to 2006 when winter wheat was grown, 20 kg P/ha was applied each year to replace the maximum offtake in grain plus straw on plots that had received P from 1986 to 1991. These additions maintained the 1999 Olsen P levels.

The data from this experiment show that maximum grain yield was with a soil at the critical level of plant available P (Olsen P) and when this level was maintained by replacing the P removed in the harvested crop, then P use efficiency of the annual application exceeded 90% (**Table 2**).

Table 2 shows that the maximum yield was 7.9 t/ha at 23 mg/kg Olsen P and yield was not further increased at 31 mg/kg. On soil with less than 14 mg/kg Olsen P, yield was decreased, which would result in a financial loss to the farmer. Maintaining the Olsen P at the critical level by replacing the P removed in the harvested crop resulted in more than 95% efficiency of the annual application. Similarly, in the experiment described by McCollum (1991), replacing the P removed in the harvested crop maintained the critical level of Mehlich-1 P.

Summary

A recent review of the behavior of soil and fertilizer P envisages soil P as existing in four pools according to the availability of the P for uptake by roots and extractability of the P by reagents used for routine soil analysis, and that these two measures are closely correlated.

This concept has practical implications for the efficient use of P fertilizer. Namely, for most soils the amount of P in the readily plant-available pool of soil P should be raised to a critical level such that yield is not limited by lack of P and the benefits of all other inputs, especially N, required to achieve optimum yield are used as effectively as possible. For most soils that can be maintained at about the critical level of P, replacing the P removed each year in the harvested crop will typically result in P efficiency exceeding 90% when measured by the balance method. A project to develop an experimental protocol is being formulated, and sponsors sought, to extend the critical P concept to a wider range of cropping systems, soil types, and climates.

Mr. Johnston (e-mail: johnny.johnston@bbsrc.ac.uk) is Lawes Trust Senior Fellow, Rothamsted Research, Harpenden, Herts., AL5 2JQ, United Kingdom. Dr. Syers (e-mail: keiths@nu.ac.th) is with Office of the President, Naresuan University, Phitsanulok, Thailand.

References

Johnston, A.E. and P.R. Poulton. 1977. Rothamsted Experimental Station Report for 1976, Part 2: 53-85.

Johnston, A.E. 2001. Principles of crop nutrition for sustainable food production. Proceedings 459. York, UK, International Fertilizer Society. 39 pp.

McCollum, R.E. 1991. Agron. J. 83, 77-85.

Syers, J.K., A.E. Johnston, and D. Curtin. 2008. Efficiency of soil and fertilizer phosphorus use. FAO Fertilizer and Plant Nutrition Bulletin 18. Rome, Italy.

Role of Crop Nutrition in Narrowing the Yield Gap for Spring Wheat in Siberia

By G. Gamzikov and V. Nosov

Mineral fertilizers and other agro-inputs are important for achieving high and stable yields of spring wheat, the principle field crop in Siberia. This article reviews the at-tainable yield of spring wheat by the major soil-climatic zones through the region. The authors characterize the present status of fertilizer consumption in Siberia and, based on minimum nutrient requirements of crops, give a short-term estimate of fertilizer consumption in the region.

Siberia is located in the Asian part of Russia, occupying an area of about 10 million square kilometers (M km2). Arable farming and animal husbandry are concentrated in the southern part of Siberia, with more than 56 M ha of agricultural lands. Siberia has about 23.5 M ha of arable land, representing about one-fifth of the total arable land area in Russia. Spring cereals such as wheat, barley, oats, and millet, as well as buckwheat, pulses, sunflower, potato, and vegetables are traditional crops in Siberia. Winter cereals include rye and triticale. Spring rapeseed, soybean, and sugar beet are promising crops giving high yields in this region. Cereals are grown on 70% of cropped area. Spring wheat dominates the cereal acreage (75 to 80%). However, the average grain yield of spring wheat in Siberia over the 5-year period of 2004 to 2008 was only about 1.3 t/ha.