A new perspective on the efficiency of phosphorus fertilizer use

Keith Syers[A] Edward Johnston[B] and Denis Curtin[C]

[A]Faculty of Agriculture, Natural Resources and Environment, Naresuan University, Phitsanulok, Thailand, Email keiths@nu.ac.th
[B]Rothamsted Research, Harpenden, Herts, UK Email johnny.johnston@bbsrc.ac.uk
[C]Plant and Food Research, Christchurch, New Zealand, Email Denis.Curtin@plantandfood.co.nz

Abstract
It is commonly believed that the efficiency of phosphorus (P) fertilizer use is low--of the order of 10-25%. When efficiency is assessed using the 'balance' method, which takes into account the recovery of P added in previous applications and when an adequate time period is considered, the efficiency of P use is high—up to and sometimes in excess of 80%. It is possible to establish a 'critical' level of P for a given soil and farming system and at this level the efficiency of use is at or close to 100%. The objective should be to reach and maintain this critical level to optimize P-use efficiency.

Key Words
Residual phosphorus, critical soil level, strategy

Introduction
The efficient use of phosphorus (P) fertilizer is important for three main reasons (Syers *et al.* 2008): (i) Phosphate rock from which P fertilizer is produced is a finite, non-renewable resource; (ii) P deficiency in soils and crops is still widespread and must be corrected; and (iii) The transfer of soil and fertilizer P to surface waters should be minimized to prevent adverse effects on water quality.

It is commonly believed that the efficiency of P fertilizer use by plants is low, of the order of 10-25% (Lindsay, 1979) due to the strong retention ('fixation') of phosphate ions by reactive soil components (Sample *et al.* 1980). The small recoveries of added P by plants when calculated using the 'difference' method (percent recovery equals P in the crop with added P *minus* P in the crop without added P divided by the amount of added P times 100), was also taken as evidence that the efficiency of P use was low.

Work by Barrow (1983) questioned the validity of P fixation and proposed that the retention of P by adsorption (surface) reactions and subsequently by absorption following diffusive penetration into soil components (Evans and Syers, 1971) was largely reversible over time. This was consistent with evidence from field experiments which indicated that the residues of P added in fertilizers and manures over a number of years could be recovered by crops in subsequent years.

This paper presents the findings of an extensive review, analysis, and synthesis of information on the efficiency of soil and fertilizer P obtained with different crops grown in a range of soils in different agro-ecological zones.

Methodology
Phosphorus use efficiency by a crop must include the recovery of P from a current application and/or the recovery of soil P reserves from past applications. For the latter, long-term experiments, at least 10 years are required. To allow for the recovery of residual P, the balance method for calculating percent recovery (Syers *et al.* 2008) must be used, namely: P uptake by the crop divided by the P applied times 100.

Results
The percent recovery of P from both single and cumulative applications by crops grown on different soils in different climates in Brazil, New Zealand, Western Canada, England, Peru, India, China and the USA indicated that the smallest recovery calculated by the balance method was 43%, many values exceeded 60%, some values exceeded 80% and an occasional value was larger than 100% (for full details see Syers *et al.* (2008)). Percent recovery larger than 100% indicates that P offtake in the harvested crop exceeds the amount of P applied and that soil P reserves are being depleted. To achieve a percent recovery frequently exceeding 60% and indeed up to and exceeding 80%, would not be possible if P was irreversibly fixed in soils, as was previously thought.

Current thinking suggests that much of the inorganic P is retained by soil components with a continuum of bonding energies related largely to the nature of the physical association of P with soil components. This implies that the strength of bonding controls both the availability of P for uptake by plant roots and its extractability by chemical reagents. Thus soil P can be described (using operational definitions) as being readily and less-readily available to plants and as being readily and less-readily extractable by chemical reagents. This is expressed diagrammatically in Figure 1. The key point is the reversible transfer of P between the first three pools and it is in this respect that current understanding of the behavior of soil and fertilizer P differs from earlier thinking; there is much field-based evidence for the reversible transfer of P (Johnston *200*1; Syers *et al.* 2008).

Routine soil analysis for plant-available P measures the P in the soil solution and the amount of P in the readily-available pool. Because this is an operationally-defined fraction of soil P, the method of analysis is unimportant. What is essential is that the data obtained accurately characterize a soil in terms of crop response of existing soil P or added P.

The reversible transfer of P between the first three pools in Figure 1 implies equilibrium between the P in these pools. For example, there is a strong, common linear relation between the increase in total and Olsen P in contrasting soils in long-term experiments at Rothamsted, Woburn, and Saxmundham in England; 13% of the increase in total P is extracted by Olsen reagent. Similarly, in an experiment in North Carolina only about 20% of the 1128 kg P/ha added over 9 years was extracted by the Mehlich-1 reagent. Data from these long-term experiments also show that when no P was applied, the decline in Olsen P, in kg/ha, was less than the total P removed by the crops over a number of years, showing that the readily plant-available pool of P was in part replenished by P from the less-readily plant-available pool of P.

The concepts of the behavior of soil and fertilizer P developed here have a number of important practical implications:

1. It is possible to define a 'critical' level of available soil P for a soil and crop at which the yield asymptote is reached. Below the critical level, yield decreases. Increasing available P above the critical level is an unnecessary expense and may contribute to P-induced eutrophication in surface waters;
2. How much P should be added to increase plant-available P to the critical level? Site-specificity of the data requires that much further work is needed. But as an example, when spring barley was grown on a silty clay loam soil at Rothamsted (initially containing 7 mg/kg Olsen P), 264 kg P/ha was added over a six-year period and the P balance (i.e., P remaining in the soil) was 182 kg/ha and this increased Olsen P to 18 mg/kg, i.e., above the critical level of 14 mg Olsen P/kg.

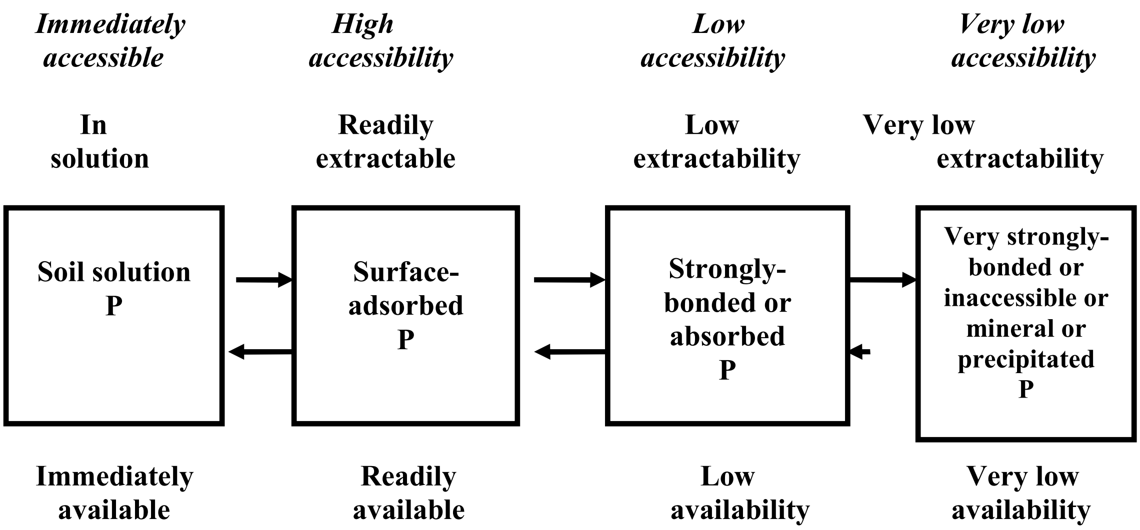

Figure 1. Conceptual diagram for inorganic P forms in soil categorized in terms of accessibility, extractability, and plant availability.

3. How much P is needed to maintain the critical level? Soils at Rothamsted with Olsen P ranging from 9 to 31 mg/kg grew winter wheat between 2002 and 2006 (Table 1). Each autumn 20 kg P/ha was applied to replace the maximum P removed in the harvested grain plus straw and to assess whether this would maintain the Olsen P level. The average maximum annual grain yield was 7.9 t/ha at 23 mg/kg Olsen P; yield was not further increased at 31 mg/kg, but was less than optimum on a soil with 14 mg/kg Olsen P. The maximum offtake of P in grain plus straw was 19 kg/ha and the application of 20 kg/ha maintained the Olsen P at 23 mg/kg. Maintaining the Olsen P at the critical level by replacing the P removed in the harvested crop resulted in 95% efficiency of the applied P when calculated by the balance method.

Table 1. Relationship between Olsen P and winter wheat yields and recovery of added phosphorus, average for 2001-2006, Exhaustion Land experiment, Rothamsted.

Olsen P, mg/kg, in 2004	9	14	23	31
Winter wheat grain, t/ha	7.1	7.8	7.9	7.9
Phosphorus uptake, grain + straw, kg/ha	14	17	19	19
Phosphorus applied annually, kg/ha	20	20	20	20
Percent recovery of applied phosphorus by the balance method	70	85	95	95

Conclusion

The efficient use of P in agriculture is essential to increase and maintain crop yields on many soils, as well as to safeguard the quality of surface waters and conserve resources of phosphate rock. The present study shows that, contrary to common belief, the efficiency of P use is high, up to and in excess of 80% when evaluated by a method which takes into account residual P from previous applications and considered over an adequate period of time. It is possible to identify a critical level of soil P in a particular soil and farming system. Once established, it is only necessary to reach and maintain that critical level to optimize crop yield and the use of other inputs. At the critical level, the efficiency of P use is at or near 100%. What is now required is the development, implementation, and evaluation of strategies for reaching and maintaining the critical level of soil P on a range of soils and in different farming systems so that the high efficiency of P fertilizer use reported here can be achieved more widely.

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