levels. The latest summary on soil test levels in North America by IPNI reported that an increasing percentage of U.S. and Canadian soils have dropped to levels near or below critical P, K, S, and Zn thresholds dur-ing the last 5 years (Fixen et al., 2010). Soils with decreasing fertility levels coupled with higher yielding hybrids suggest that producers have not sufficiently matched nutrient uptake and removal with accurate maintenance fertilizer applications. Integration of new and updated findings in key crops, including corn, will better allow us to achieve the fundamental goal of nutrient management: match plant nutritional needs with the right source and right rate at the right time and right place.

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The Efficient Use of Phosphorus in Agriculture

By Johnny Johnston, Paul Fixen and Paul Poulton

Data from vastly different soils located on two continents, and from both controlled experiments in England and derived state-wide aggregated data in the U.S., were merged to evaluate P use efficiency. The data suggest that there is an underlying "simple rule" for the behaviour of plant-available soil P in these soils, which can be related to a four-pools concept of inorganic soil P.

Phosphorus is an essential, irreplaceable element in all living organisms, and the global resource of readily-minable phosphate rock (PR) is limited. After process-ing, more than 80% of the PR mined annually is used in food production. Thus, extending the life span of this global resource will depend on using P more efficiently in agriculture; especially since P use will increase as the world's expanding population has to be fed. The inefficient use of P in agriculture has a direct cost to farmers.

Behavior of Soil and Fertilizer P

As a contribution to improving P use efficiency in agricul-ture, Syers et al. (2008) reviewed the current understanding of the behaviour of soil and fertilizer P and showed that the long-held view that P was irreversibly fixed in most soils was not supportable. These authors proposed that plant-available, inorganic P in soil could be considered to be in four pools related to the availability for uptake by roots and its extract-ability by reagents used in soil analysis (**Figure 1**). The first two pools are the soil solution P (pool 1, a very small amount) and the readily plant-available P (pool 2). These two pools are only a small proportion of the total P in soil, but the amount can be determined by acceptable, widely used methods for routine soil analysis.

The availability and extractability of P in the four pools is largely determined by the nature and strength of the bonding between the inorganic P and the soil constituents on which it is held. The important feature shown in **Figure 1** is the revers-ible transfer of P among the first three pools as discussed in detail with examples by Syers et al. (2008). Developed from this concept, there is a critical level of plant-available P in pools 1 and 2 below which optimum crop yield is not achieved and above which there is no need to apply P (i.e., such P is used inefficiently).

Efficiency of Fertilizer P Use

The direct determination of the amount of P taken up from an added fertilizer can only be done using 32P-labelled fertil-izer, which is expensive and has a short half-life. Consequently, the recovery of added P has been more commonly determined by the difference method:

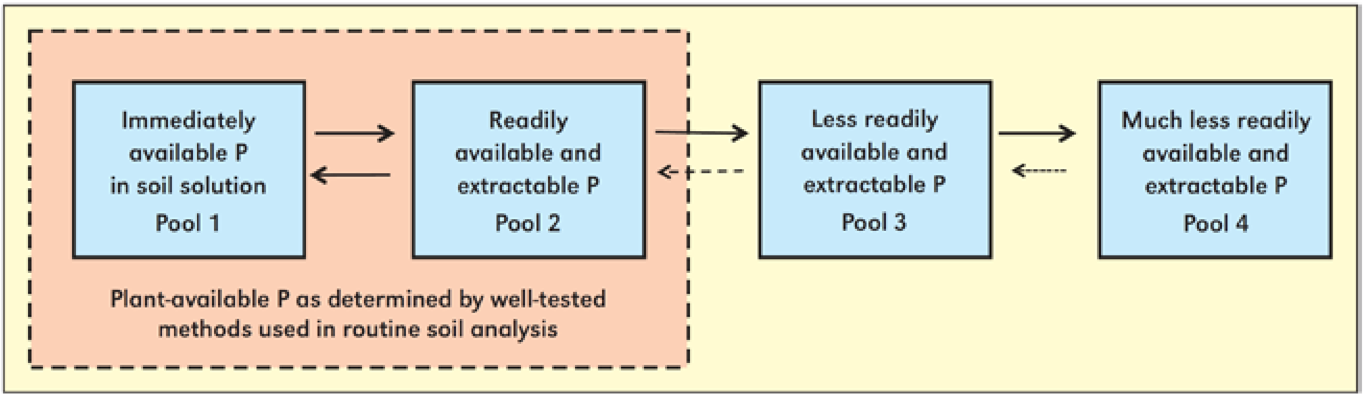

Figure 1. Conceptual diagram for the forms of inorganic P in soils categorized in terms of plant availability and extractability.

$$(Up - Uo)/Fp$$

where Up and Uo are the P taken up by a crop from soils with (Up) and without (Uo) added P and Fp is the amount of P ap-plied, expressed as a percentage.

Often referred to as percent use efficiency, reported values are often 10 to 15% and rarely exceed 25%. Such small values are used to imply that applied P is used inefficiently.

If only a small amount of P in a crop has come directly from P applied as fertilizer or manure then the remainder must have come from soil P reserves, which might be naturally occurring or as accumulated P residues from past applications of fertilizer or manure. Syers et al. (2008) suggested that replacing the P taken up from the soil P reserve was equally as efficient a way of using freshly applied P as was that taken up directly from fertilizer by the crop. The concept is based on the observation that for many soils when P inputs are at a level similar to the amount of P removed in crop harvest, the sum of pools 1 and 2 in **Figure 1** remains constant. Thus, the P removal-to-input ratio, sometimes referred to as partial nutrient balance, is a useful metric of P efficiency, especially when combined with data on plant-available soil P.

Efficiency of Fertilizer P Use on Soilsat the Critical Level of Plant-available P

The efficiency of P inputs can often exceed 80%, calculated as a P removal-to-input ratio, when P is applied to maintain the critical level of soil P. In an experiment on a silty clay loam at Rothamsted, Great Britain, a "maintenance" P application (20 kg P/ha each autumn for four years) was tested on soils growing winter wheat and with plant-available P (extractable with Olsen's reagent; Olsen P) ranging from 9 to 31 mg/kg. The average annual grain yield and the total P removed in grain plus straw increased as Olsen P increased; thus the P balance declined. Where yields were near maximum, and P offtake more nearly matched the amount of P applied, then P-use ef-ficiency exceeded 90% when calculated as a removal-to-input ratio (**Table 1**). Similar experiments showing maintenance of the critical level of plant-available P by replacing that removed in the harvested crop were reported by McCollum (1991) and Halvorson and Black (1985).

Table 1. Maintaining Olsen P by replacing the amount of P removed in four winter wheat crops*, Exhaustion Land, Rothamsted, 2005-2008.

	Olsen P, mg/kg, in 2004***				
	9	14	20	23	31
Average annual grain yield, t/ha	7.6	8.3	8.1	8.5	8.5
Total P applied, kg/ha**	80	80	80	80	80
Total P removed, kg/ha	56	68	66	77	75
Phosphorus balance, kg P/ha	24	12	14	3	5
Olsen P, mg/kg, in 2008***	8	13	18	24	31
P removal-to-input ratio, %	70	85	82	96	94

** Winter wheat grown continuously.*
*** Phosphorus, 20 kg P/ha applied in autumn.*
**** Olsen P in soil sampled in autumn.*

Relating P Removal-to-Input Ratiosto Changes in Plant-available P in Soil

The ratio of P removed by crop harvest compared to P ap-plied as fertilizer, or recovered from manure, should be related to changes in plant-available P in soil. A ratio of 1 implies that output and input are in balance with probably little change in plant-available soil P. A ratio greater than 1 implies that output exceeds input and soil reserves are being depleted; when soils are at, or below, the critical value this increases the risk of not achieving optimum yield. A ratio of less than 1 (i.e., output is less than input) in most soils should allow soil P to build up. Once the critical level is reached, or slightly exceeded, input should generally be reduced to a maintenance amount.

The International Plant Nutrition Institute (IPNI) uses its Nutrient Use Geographic Information System (NuGIS) (http://www.ipni.net/nugis) to get data on nutrient balances and relate them to changes in the plant-available soil P (Fixen et al., 2010, updated by Fixen, personal communication). For example, the IPNI data for the U.S. Northern Great Plains (**Table 2**) show

Table 2. Phosphorus removal-to-input ratio and Bray-1 equiva-lent levels in three States in the U.S.

State	P removal-to-input* ratio			Median Bray-1, mg/kg		
	2002	2007	Average	2001	2005	2010
Montana	0.97	1.04	1.01	12	14	14
North Dakota	1.07	0.94	1.01	10	11	11
South Dakota	1.02	0.91	0.97	11	14	13

** Input = Fertilizer P applied plus recoverable manure P.*
Data derived using IPNI NuGIS data, 1/12/2012, see text.

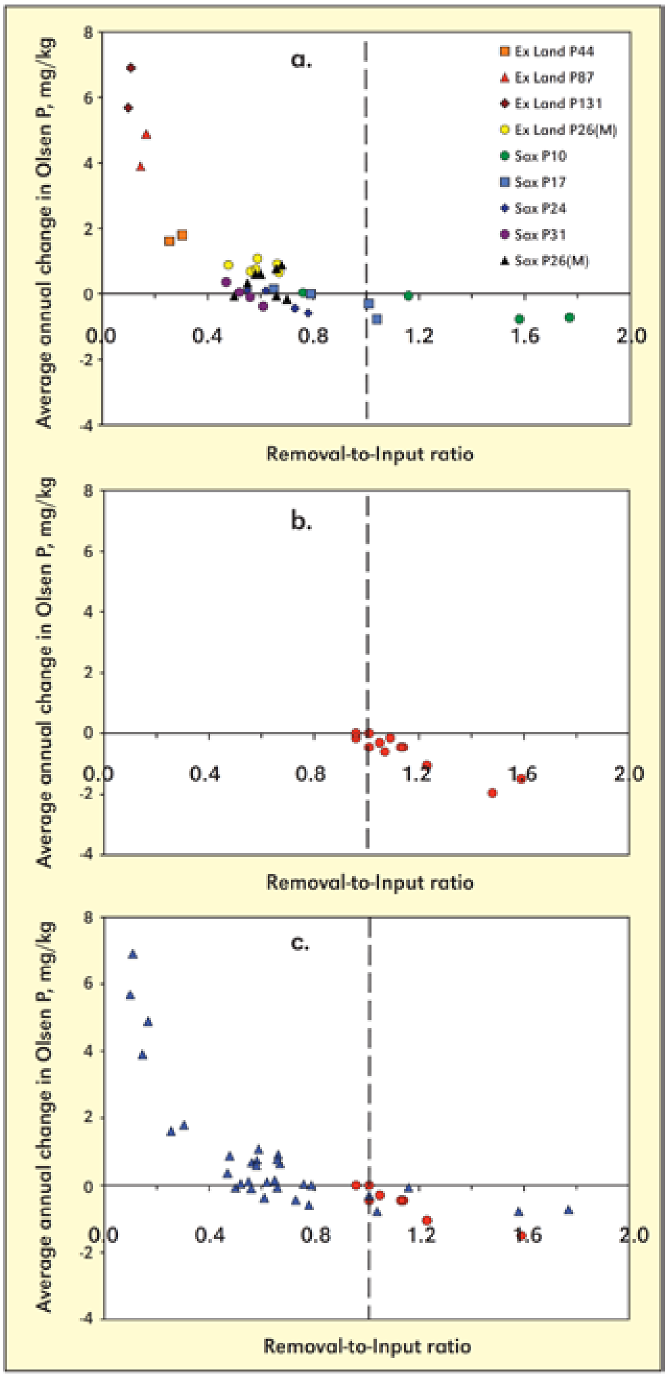

Figure 2. Relationship between the removal-to-input ratio (P removed by the crop divided by fertilizer P inputs) and the change in plant-available P for (a) two long-term experiments in the U.K. [P44 etc. denotes average annual application of fertilizer P; (M) denotes a maintenance dressing]; (b) 12 states in the U.S. (P Fixen, Pers. Comm.); (c) all U.S.●, and U.K.▲, data.

that where the P removal-to-input ratio for each state approxi-mates to 1 there is little change in the median Bray-1 levels for the 340,000 soil samples submitted to soil testing laboratories from these states for the three sampling years available. The conclusion from the data in **Table 1** (Rothamsted) and **Table 2** (U.S.) is that where the P removal-to-input ratio is about 1, and there is little or no change in the level of plant-available soil P then the efficiency of P use is very high as discussed initially by Syers et al. (2008).

Removal-to-input ratios, which are mainly less than 1, and changes in Olsen P in two long-term field experiments at Rothamsted are shown in Figure 2a. There is a strong curvilinear relationship that can be fitted with a polynomial function with an r2 of 0.84.

Figure 2b shows the relationship between P removal-to-input ratios and change in plant-available P for 12 U.S. Corn-Belt States derived using NuGIS. In this case an estimate of "recoverable manure P" is included in the total P input; for this figure, Bray-1 data were converted to Olsen P values by multiplying by 0.75. Although there are uncertainties about the accuracy of individual observations because of the assump-tions that have to be made, each point in Figure 2b is the average of many individual values, which suggests that it is an acceptable approximation of what is occurring for each state. The data can be fitted with a straight-line function with an r2 of 0.85. Most of the ratios are greater than 1 (i.e., there was a negative P balance and soil P reserves are being depleted).

Visual inspection of Figures 2a and 2b suggests that there is a degree of commonality, and it is of considerable interest that when both sets of data were put on the same basis they could be combined to produce Figure 2c. We have chosen not to show a line through the data points because they can be considered in two ways. First, a log function can be fitted to all the data with an r2 of 0.84, or second, a lower straight line can be fitted to the soils with small annual inputs of P with an r^2 of 0.63 and another straight line to the six soils to which large amounts of P were added with an r2 of 0.84. Irrespective of the approach used, this combined graph is for data from vastly different soils and two continents, and from both controlled experiments in England and derived "State-wide" aggregated data in the U.S. That the combined data can be described us-ing a single simple function makes a powerful and convincing statement. It suggests that for the agricultural soils from which these data were obtained, there is an underlying "simple rule" for the behaviour of plant-available soil P, which can be related to the four-pools concept of inorganic soil P proposed by Syers et al. (2008) and discussed in detail by Johnston et al. (2014).

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