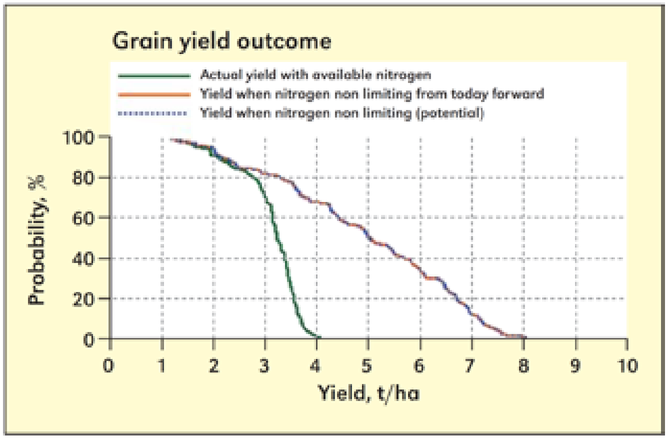

Figure 2. Probability of exceedance for a range of seasonal conditions using weather conditions to June 22, measured soil N and other agronomic inputs for a wheat paddock in the Wimmera region of Victoria.

Prophet® website showing the probability of exceedance of grain yield at a site in the Wimmera of Victoria. The outcome in the graph is based on yields from 100 years of rainfall records from the date of the report until crop maturity. This shows that if no added N is used, the median (50% probability) yield would be around 3.3 t/ha, while the conditions suggest yields would not exceed 4 t/ha. This outcome is based on the current N status of the paddock (101 kg N/ha).

The second line on the graph shows the yield in response to added N modeled over 100 years. This shows there is adequate water to take the median yield to 5 t/ha if N was not limiting, and the yield response ranges from 0 to 4 t/ha. This provides growers with the magnitude of the typical response, plus the range of responses likely given the variable climate.

Managing Risk Around the Right Rate for P

Phosphorus is usually applied at seeding in the drill row as this has long been seen as the most efficient delivery strategy. Rates are usually based on average removal, but this tends to over apply P in poor years and under apply it in better years. Topdressing of P in-crop does not supply the P near the roots because it is relatively immobile and will not leach into the root zone. Provided the important early crop demands are met with an at-sowing P source, and if products are developed that do not damage the crop canopy at appropriate use rates, P application could become tactical (Noack et al. 2010), similar to common N management strategies. Research into the right source, rate, time, and place for tactical P for wheat is currently under investigation (Noack et al. 2010).

Conclusion

In a variable climate, matching nutrient demand to supply relies on a good estimate of the yield potential. Nutrient budgets for N can be tailored around these variable yields to provide adequate N to prevent N stress early in the crop's life with little or no yield penalty. As the seasonal conditions unfold, additional N can be added (or not) to meet the rising (or falling) yield potential and nutrient demand. A similar approach to tactical application of P is an attractive option and current research is investigating appropriate products and their deployment to make this a viable strategy.

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Modern Corn Hybrids' Nutrient Uptake Patterns

By Ross R. Bender, Jason W. Haegele, Matias L. Ruffo, and Fred E. Below

Biotechnology, breeding, and agronomic advancements have propelled corn yields to new highs with little guidance as to how to fertilize these modern corn hybrids to achieve their maximum yield potential. Current fertilization practices, developed decades ago, may not match uptake capabilities of modern hybrids that contain transgenic insect protection now grown at population densities higher than ever before. A re-evaluation of nutrient uptake and partitioning can provide the foundation for fine-tuning our practices as we strive to achieve corn's maximum yield potential.

As summarized by Bruulsema et al. (2012), optimizing nutrient management includes using the right source at the right rate, right time, and right place—the 4R ap-proach. Research pertaining to primary macronutrient uptake, partitioning, and timing (Sayre, 1948; Hanway, 1962; Karlen et al., 1988), though fundamentally accurate for previous hybrids and management practices, may be unrepresentative of modern hybrids in higher yielding environments. The objective of this study was to determine how modern, transgenic insect-protected corn hybrids in high-yielding systems take up and utilize nutrients.

Nutrient contents of N, P, K, S, Zn, and B were determined at six incrementally spaced growth stages: V6 (vegetative leaf stage 6), V10, V14, R2 (blister), R4 (dough), and R6 (physiological maturity) (Hanway, 1963). Field experiments were conducted at the Northern Illinois Agronomy Research Center in DeKalb, Illinois and the Department of Crop Sciences Research and Education Center in Urbana, Illinois. A total of six hybrids ranging in relative maturity from 111 to 114 days were used with genetic resistance to feeding from Western Corn Rootworm (Diabrotica virgifera virgifera), European Corn Borer (Ostrinia nubilalis), and other species in the Lepidoptera order. In all cases, hybrids were seeded to obtain a final stand of 34,000 plants/A. Representative plants were separated, analyzed, and evaluated in four tissue fractions: 1) stalk and leaf sheaths; 2) leaf blades; 3) tassel, cob, and husk leaves; and 4) corn grain, respectively referred to as stalk, leaf, reproductive, and grain tissues. Agronomic management at planting included a soil insecticide and a broadcast application of 150 lb P_2O_5/A as MicroEssentials® SZ™ along with 180 lb N/A as urea. This was followed by 60 lb N/A as Super-U (with urease and nitrification inhibitors) side-dressed at V6 and a fungicide at VT/R1 (tasseling/silking).

Nutrient Uptake and Removal

Across the two sites in 2010, these transgenic corn root-worm resistant hybrids yielded an average of 230 bu/A (range of 190 to 255 bu/A) and we will base our discussion of nutrient needs assuming this yield level.

When developing fertilizer recommendations, two major aspects of plant nutrition are important to understand and manage in high yield corn production including: 1) the amount of a given mineral nutrient that needs to be acquired during the growing season, referred to as "total nutrient uptake," or nutrients required for production, and 2) the amount of that nutrient contained in the grain, referred to as "removed with grain" (**Table 1**). Our grain nutrient concentration values, in units of lb/bu (**Table 1**) are in agreement with those recently used by the fertilizer industry to determine replacement fertilizer rates (Bruulsema et al., 2012). In the past 50 years, however, the quantity of N, P, and K required for production and the amount of nutrients removed with the grain have nearly doubled across a variety of management systems used in the 1960s (Hanway, 1962).

Individual nutrient HI values were calculated, which quantify the percentage of total plant uptake that is removed with the grain. Nutrients with high requirements for production (N, P, K) or that have a high HI (P, Zn, S, N) allude to key nutrients for high yield

Fully-filled ears of corn—an indicator of successfully matching soil nutrient supply with crop demand.

(**Table 1**). In relation to total uptake for example, nearly 80% of P is removed in corn grain compared to K and B, which are retained to a greater percentage in stover. For each nutrient, the fraction that is not removed with the grain remains in leaf, stalk, and reproductive tissues and constitutes the stover contribution that is returned to the field. Production practices that utilize all or portions of aboveground stover (i.e. cellulosic ethanol, corn grown for silage) may remove an additional 20.8 lb N, 4.0 lb P_2O_5, 23.3 lb K_2O, 1.9 lb S, 0.5 oz Zn, and 0.2 oz B per ton of dry matter.

Maximum Uptake Rates

Further improving fertility practices require matching in-season nutrient uptake with availability, a component of the right source applied at the right rate and right time. The maximum rate of nutrient uptake coincided with the greatest period of dry matter accumulation during vegetative growth (**Figure 1**) for all observed nutrients (**Figures 2** to **7**). Be-tween V10 and V14, greater than one-third of total B uptake occurred, compared to the other nutrients which ranged from 20 to 30%. During the V10 to V14 growth stages, corn required the availability of 7.8 lb N/day, 2.1 lb P_2O_5/day, 5.4 lb K_2O/day, 0.56 lb S/day, 0.21 oz Zn/day, and 0.05 oz B/day. Fertilizer sources that supply nutrients at the rate and time that match corn

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Zn = zinc; and B = boron; HI = harvest index; R1 = silking (silks visible outside the husks); R2 = blister (kernels are white and resemble a blister in shape); R4 = dough (milky inner f uid thickens to a pasty consistency); R5 = dent (nearly all kernels are denting); R6 = physiological maturity (the black abscission layer has formed); V6 = six leaves with collars visible; V10 = 10 leaves with collars visible; V14 = 14 leaves with collars visible; VT = last branch of tassel is completely visible.

Table 1. Total macronutrient and micronutrient uptake and removal in Urbana, IL and DeKalb, IL (2010).

Nutrient	Total nutrient uptake	Removed with grain	Harvest index, %	Nutrient removal coefficient, lb/bu
	----- lb/A ------			
N	256	148	58	0.64
P_2O_5	101	80	79	0.35
K_2O	180	59	33	0.26
S	23	13	57	0.06
Zn	7.1	4.4	62	0.019
B	1.2	0.3	23	0.001

† Zn and B are expressed in oz (i.e. oz/A and oz/bu).Each value is a mean of six hybrids at both locations (mean = 230 bu/A). Harvest index was calculated as the ratio between nutrient removed with grain and total nutrient uptake and is reported as a percent. Multiply grain yield by Nutrient Removal Coefficient to obtain the quantity of nutrient removal.

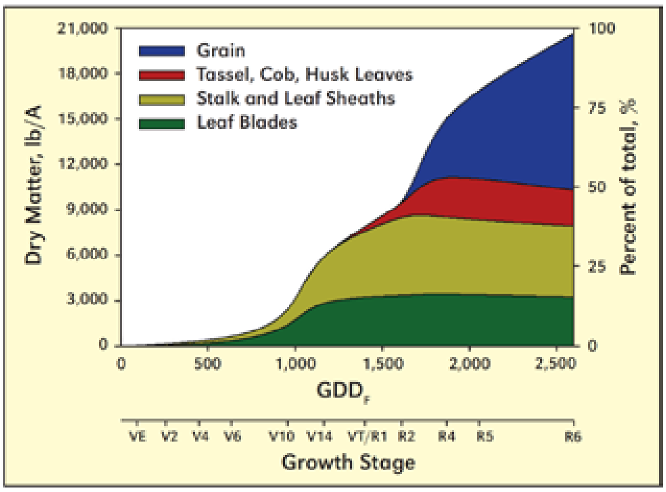

Figure 1. Total maize dry matter production and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

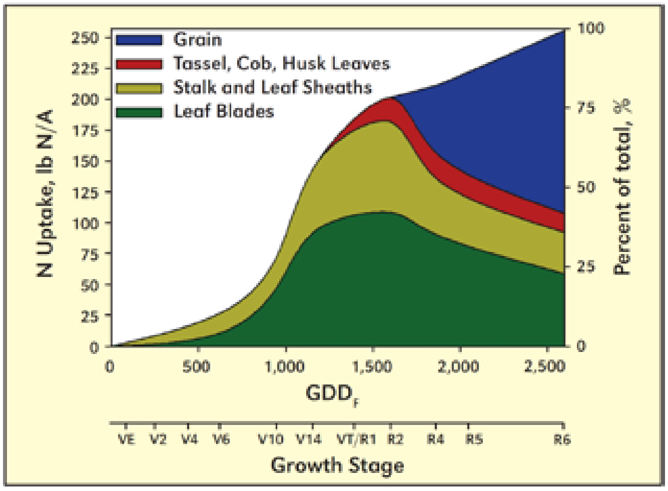

Figure 2. Total maize N uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

nutritional needs are critical for optimizing nutrient use and yield.

Timing of Nutrient Uptake

Effectively minimizing nutrient stress requires matching nutrient supply with plant needs, especially in high-yielding conditions. Sulfur and N, for example, are susceptible to simi-lar environmental challenges in the overall goal of improving nutrient availability and uptake. However, the timing of N uptake (**Figure 2**) in comparison to S (**Figure 5**) is surpris-ingly different, suggesting practices that are effective for one may not improve uptake of the other. Nitrogen uptake, unlike S, followed a more traditional sigmoidal (S-shaped) uptake pattern with two-thirds of the total plant uptake acquired by VT/R1. In contrast, S accumulation was greater during grain-filling stages with more than one-half of S uptake occurring after VT/R1 (**Figure 5**). Potassium, like N, accumulated two-thirds of total uptake by VT/R1 (**Figure 4**). Interestingly, greater than one-half of total P uptake occurred after VT/R1 as well (**Figure 3**). These figures suggest that season-long supply of P and S is critical for corn nutrition while the majority of K and N uptake occurs during vegetative growth.

Unlike N, P, K, and S, which have a sigmoidal or relatively constant rate of uptake, micronutrients exhibited more intricate uptake patterns. Uptake of Zn and B, for example, began with a sigmoidal (S-shaped) uptake pattern in the early vegetative stages and plateaued at VT/R1 (**Figures 6** and **7**). Thereafter, Zn exhibited a constant uptake rate similar to that of P and S, while B uptake included a second major sigmoidal uptake phase concluding around R5 (dent). Zinc and B favored shorter periods of more intense uptake in comparison to macronutrients. During only one-third of the growing season, late vegetative and reproductive growth accounted for as much as 71% of Zn uptake (**Figure 6**). A similar trend was noted for B; as much as 65% of B uptake occurred over only one-fifth of the growing season (**Figure 7**). Matching corn micronutrient needs in high-yielding

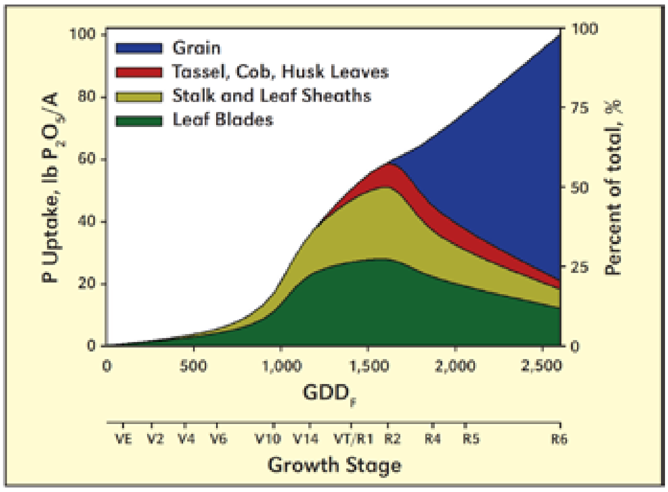

Figure 3. Total maize P uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

conditions clearly requires supplying nutrient sources and rates that can meet crop needs during key growth stages.

Plant Nutrient Mobility

Unlike plant dry matter, specific nutrients possess mobility characteristics allowing them to be utilized in one tissue, then later transported (remobilized) and used in another (Sayre, 1948; Hanway, 1962; Karlen et al., 1988). For many nutrients, including N, P, S, and Zn, a large percentage of total uptake is stored in corn grain at maturity (**Table 1**). Nutrients with high HI values accumulated them from a combination of as-similation during grain fill (after VT/R1) and remobilization from other plant parts. Phosphorus, for example, accumulated more than one-half of total uptake after VT/R1 and remobilized a significant portion that was originally stored in leaf and stalk tissues (**Figure 3**). Nitrogen and S achieved similar HI values although through two different mechanisms. Post-flowering S uptake was

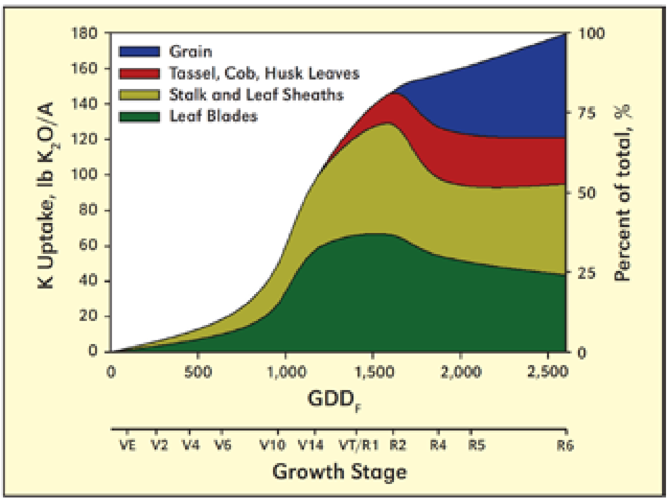

Figure 4. Total maize K uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

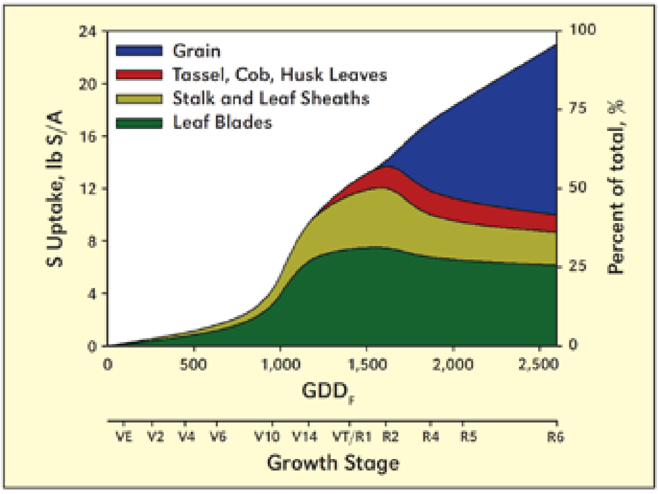

Figure 5. Total maize S uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

the major source of grain S (Figure 5) compared to N, which was largely obtained from remobilization (**Figure 2**). Plant Zn exhibited a unique mobility characteristic in which stalk tissue served as a major, but temporal Zn source. By R6, nearly 60% of stalk Zn was remobilized, presumably to corn grain. Similar to that of Karlen et al. (1988), leaf B content appeared to drop around VT/R1, indicative of its role in reproductive growth (**Figure 7**).

Optimization of Nutrient Management

Although nutrient management is a complex process, improving our understanding of uptake timing and rates, partitioning, and remobilization of nutrients by corn plants provides opportunities to optimize fertilizer rates, sources, and application timings. Unlike the other nutrients, P, S, and Zn accumulation were greater during grain-fill than vegetative growth; therefore, season-long supply is critical for balanced crop nutrition. Micronutrients demonstrated more narrow periods of nutrient uptake than macronutrients, especially Zn and

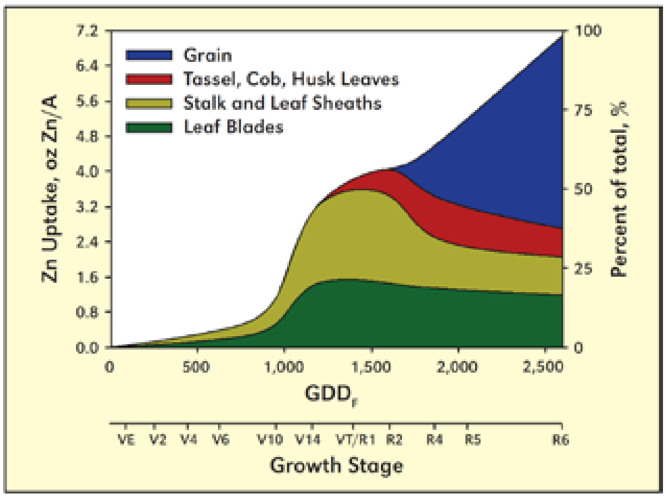

Figure 6. Total maize Zn uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

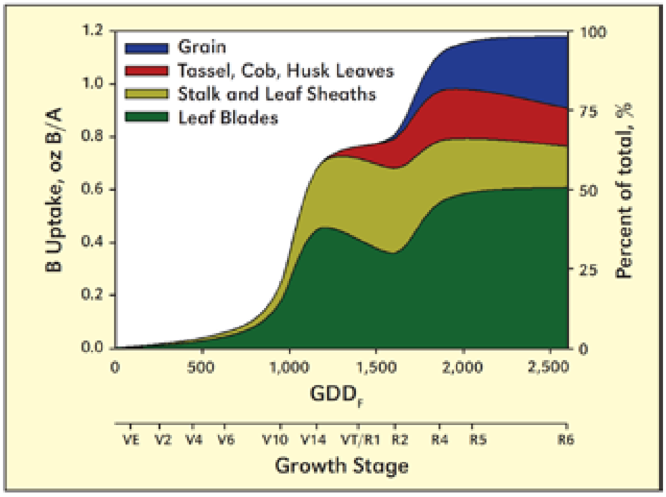

Figure 7. Total maize B uptake and partitioning across four plant stover fractions: leaf, stalk, reproductive, and grain tissues. Each value is a mean of six hybrids across two site-years at Urbana, IL (2010) and DeKalb, IL (2010). GGDF = growing degree days (Fahrenheit)

B. As a percentage of total uptake, P was removed more than any other nutrient. In a corn-soybean rotation, it is commonplace in Illinois to fertilize for both crops in the corn production year. While farmers fertilize, on average, 93 lbs P2O5 for corn production (Fertilizer and Chemical Usage, 2011), the 80% of soybean fields receiving no applied P would have only 13 lbs P2O5 remaining (Fertilizer, Chemical Usage, and Biotechnology Varieties, 2010). These data suggest a loom-ing soil fertility crisis if adequate adjustments are not made in usage rates as productivity increases. This plant nutrition knowledge is critical in understanding our current nutrient management challenges.

Summary

As a result of improved agronomic, breeding, and bio-technological advancements during the last 50 years, yields have reached levels never before achieved. However, greater yields have been accompanied by a significant drop in soil macronutrient and micronutrient 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: