PHOSPHORUS PLACEMENT FOR CORN, SOYBEANS, AND WHEAT[1]

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Root-Soil Interface

Transport Pathways

Three mechanisms are commonly cited for how nutrients reach plant roots: 1) root interception, 2) mass flow, and 3) diffusion.

Root interception occurs when a plant root, as it grows, comes into direct contact with a nutrient. Quantities of nutrients reaching plant roots in this manner are estimated to be proportional to the volume of soil occupied by roots (Barber et al., 1963). For instance, if roots occupy one percent of the soil volume, then the quantity of nutrients supplied by root interception is estimated from the quantity of nutrients contained in an equivalent one percent of soil volume. Consequently, as the amount of nutrients in the soil increases, a greater quantity will be encountered as the plant root grows in to a given soil volume.

Mass flow is the transport of nutrients that accompanies the movement of water to plant roots (Barber et al., 1963). When higher concentrations of nutrients exist in the soil solution and/or when more water moves to plant roots during increased transpiration, mass flow increases. When nutrient movement to the root exceeds the rate of nutrient uptake, nutrients can accumulate at the root surface and become higher in concentration than the surrounding soil (Barber et al., 1963).

Diffusion is the movement of nutrients from more concentrated to less concentrated zones in the soil. As the plant root takes up nutrients, soil supplies in the immediate vicinity are depleted. Unless these nutrients are replenished or accumulate at the root surface by mass flow, soil concentrations near the root will become lower than the surrounding soil.

Soil nutrients vary in their diffusion rates. **Table 1** shows comparative diffusion rates for P and K measured on the same soils under identical environmental conditions. Soil levels of each nutrient were not equivalent, however. Rates of K diffusion were several times that of P for both soils studied.

Barber (1995) attempted to summarize, for maize, the quantities of nutrients reaching plant roots through the three mechanisms just discussed. **Figure 1** shows that the relative contributions of each pathway differ among nutrients, with P and K relying more heavily on diffusion than N, which moves to the maize roots primarily through mass flow.

Nutrient Influx

An important concept for understanding the effectiveness of fertilizer placement is nutrient

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influx (Barber, 1995). Nutrient influx is a term used to describe the rate of nutrient absorption by plant roots. Rates of nutrient uptake by plant roots can change with plant age. **Figure 2** shows that root nutrient uptake rate of P is several times greater when a maize plant is younger than when it is older. When uptake rates decline over time, as has been observed for corn, soybean, and wheat (Mengel and Barber, 1974; Barber, 1978; Anghinoni et al., 1981), then a greater amount of root surface area will be needed later in the season, along with a corresponding increase in accessible fertilized soil volume, just to maintain nutrient uptake. However as the above-ground portions of the plant develop, nutrient uptake requirements increase further, requiring more extensive root development.

Mechanisms for Procuring P in Low P Soils

Particularly in dicot (broadleaf) species, plants respond to P deficiency by reducing rhizosphere pH. The plant lowers the pH of the soil adjacent to roots, either by shifts in cation/anion uptake ratio, or by excretion of organic acids (Marschner, 1995, p. 544). Some plants can increase their uptake of P by desorption of P from clay surfaces through the action of the polygalacturonic acid component of excreted mucilage (Marschner, 1995, p. 551). Organic acids, such as citrate, and phenolics are also important in bringing sparingly soluble inorganic phosphates into solution (Marschner, 1995, p. 554), and keeping them there through chelation of iron and aluminum. Phosphatase enzymes, either excreted from plant root cells or by the microorganisms supported by root exudates in the rhizosphere, can be important in making organic forms of soil phosphorus available to species including wheat, red clover and rapeseed (Marschner, 1995, p. 559).

Mycorrhizae serve as important sources of nutrients for host plants in two ways (Smith and Read, 2008). First, mycorrhizal hyphae add to the soil volume from which nutrients are extracted for plant use. Mycorrhizae take up nutrients from the soil in the same form as plant roots: $H_2PO_4^-$, NO_3^-, NH_4^+, Zn^{2+} and Cu^{2+}. Fungi also transfer these same nutrient forms to the plant, except for N, which is transferred only as NH_4^+. Second, mycorrhizae can access chemical forms of nutrients in the soil that are either not easily accessed by plants or simply not accessed at all, effectively expanding the available soil nutrient reserves (Cardoso et al. 2006). Symbiosis may not necessarily result in greater total nutrient uptake by host plants but instead may result in a greater proportion of the total coming from mycorrhizae.

Flooded soil conditions adversely affect mycorrhizal symbiosis. There appear to be several possible causes. First, spores may not germinate under anaerobic conditions. Le Tacon et al. (1983) showed that after 11 days of no oxygen, spores of *Glomus mosseae*, a mycorrhizal fungus, failed to germinate. However, once aerobic conditions returned, germination proceeded, although at somewhat reduced levels. The development of germ tubes, which are the immature hyphae emerging from spores, were also irreversibly damaged under anaerobic conditions and were 5 to 13 times shorter than those developed under atmospheric oxygen levels. Flooding has also been shown to reduce fungal colonization of host plant roots as well as the number of arbuscules, which are branched hyphal structures within host plant root cells where nutrient exchange is thought to take place (Ellis, 1998).

Fallow periods have a deleterious effect on plant-fungus symbiosis similar to flooding. The lack of a host crop during fallow does not allow the mycorrhizae to complete their life cycles nor spread hyphae as extensively throughout the soil. The consequence is reduced numbers of both fungal spore numbers as well as numbers of root fragments with existing colonies (Thompson, 1994). Reduced inocula are most likely the cause of lower mycorrhizal colonization of roots of the following crop (Vivekanandan and Fixen, 1991). Like the effect of flooding, the deleterious effect of fallow is short lived, usually extending through only one cropping season.

Root Architecture

Differences among Corn, Soybean and Wheat

Root architecture is the 3-dimensional, spatial configuration of a root system and refers to the geometrical arrangement of plant roots in the soil (Lynch, 1995). Root architecture among plants can be very different. Corn and wheat both have fibrous root systems while soybean has a tap root system. The initial development of the root system of winter wheat is characterized by the first and second pair of seminal roots growing initially at an approximately 45 degree angle from the seed, then downward (**Figure 3**). A similar architecture has been observed for corn in early growth stages (**Figure 4**). Soybean, however, has a tap root system that is characterized primarily by elongation of the tap root early in the season (**Figure 5**). These different architectures impact the effectiveness of various nutrient placement options.

Root Proliferation in Response to Localized Enrichment in Available Nitrogen (N) and P

An important concept to nutrient placement is that roots proliferate where soil N and P supplies are higher. Research on P revealed that a greater proportion of roots in the zone of high nutrient concentration came from the formation of more and longer first and second order laterals (Drew, 1975). Consequently, nutrient placement affects more than just the location of nutrient supplies; it also affects how much of the root system will be in those supplies.

Principles of Placement

Optimum Proportion of Soil Volume to Enrich

Greenhouse studies have shown that there is a certain volume of soil within the root zone that must be fertilized for maximum plant growth. **Figure 6** shows that as P application rate increased on a P deficient soil, shoot growth was maximized at higher P application rates distributed throughout more of the soil volume (Anghinoni and Barber, 1980). When low rates were applied, fertilizing a smaller soil volume maximized dry matter yield, but yields were lower than where higher rates had been mixed with more soil. The need for greater volumes of fertilized soil is consistent with the observation that individual roots can take up nutrients only so quickly. As the plant requires ever-increasing quantities of nutrients as it grows, an extensive root system well supplied with nutrients is needed.

Interactions with Other Nutrients

An important interaction occurs between N and P for corn. In pot studies, Ohlrogge and coworkers banded P 1.5-2 in. to the side of the seed (Miller and Ohlrogge, 1958). Nitrogen in an ammonium form was either not applied, banded with the P, or banded 1.5-2 in. to the side of the seed opposite the P band. It was found that N and P applied in the same band resulted in the greatest plant utilization of band-applied P as well as the highest early season dry matter yield. Nitrogen applied on the side opposite the P band produced nearly as high a dry matter yield but reduced P recovery from the band by about 25-30%. Banding P alone without N resulted in the lowest dry matter yield and P recovery from the band.

Later studies demonstrated the importance of N form on P nutrition of soybean and corn (Riley and Barber, 1971; Soon and Miller, 1977). The results of these investigations showed that when N was applied in the ammonium form, the pH in the soil zone adjacent to the root, termed the rhizosphere, was reduced, sometimes more than 1 pH unit, depending on the soil. This lower pH resulted in greater orthophosphate concentrations and greater P uptake. Nitrogen applied in the nitrate form had the opposite effect, increasing the rhizosphere pH and decreasing P uptake.

When higher rates of P are applied, there can be a reduction in soil solution Zn (Norvell et al., 1987). This reduction is not due to the formation of insoluble P-Zn compounds (Boawn et al., 1957). Instead, it is thought that P increases the adsorption of Zn to soil surfaces. Additionally, P additions can reduce the activity of mycorrhiza, causing them to contribute less to the acquisition of Zn by the plant (Kothari et al., 1991).

Practical Aspects of Placement Methods

A large number of studies, summarized in Randall and Hoeft (1988), support the generalization that band application of phosphorus produces larger corn and wheat yield responses than broadcast when soil test levels and rates of application are low, but that these differences disappear once soil test P reaches optimum levels. Their review also pointed out that in low P soils, band applications alone may not be sufficient for optimum yields. Given that broadcast application is less costly and can enhance timeliness of planting, many producers with soils at optimum levels of P choose to broadcast. However, tillage methods have changed, often resulting in less vertical mixing of the soil profile. The consequences in terms of soil P stratification and its impact on the quality of surface runoff water need to be considered.

Broadcast Application

Broadcast application offers flexibility in timing and often the lowest application cost. Equipment used includes spinner-spreaders and pneumatic tubes for granular fertilizers, and sprayers for fluid forms. Sprayer nozzle types vary but are often designed to keep droplets large or keep the fluid in streams, to minimize volatile losses and spray drift, and encourage gravity-driven flow into the soil. While broadcasting must usually involve a dedicated pass over the field, it can be done very rapidly, and it can be combined with herbicide applications, especially for fluid forms. Because many acres per hour can be covered, application can wait until soil conditions are appropriate (sufficiently dry) to avoid soil compaction. In some instances, broadcasting can be done over frozen soils, providing excellent protection against soil compaction but considerably increased risk of elevated nutrient concentration in runoff. Field trials in Iowa on the timing of P fertilizer application found no difference between fall and spring broadcasting on no-till corn and soybean in 20 trials conducted over 3 years (Mallarino et al., 2009).

Band

Band application has traditionally been done with the planter, providing precise location relative to the seed. Today's large planters, however, are limited in the amount of granular fertilizer they can carry, since the total weight may exceed the hydraulic lift capacity of the tractor. Fluid fertilizers can be band-applied with large planters, but are usually at low rates, and require either tractor-mounted or pull-behind tanks. Air carts allow application of granular P forms along with the planter, but are not used in all areas.

Advanced GPS guidance systems now allow band placement in advance of planting. These provide a new opportunity to place nutrients directly below the seed—which can greatly benefit tap-rooted crops like beans—without disturbing the seedbed. Fall-banding done in conjunction with zone tillage has been found in some instances to produce good yields of corn and to minimize stratification, but often produces less response than fertilizer P applied in the spring. In Iowa, yield responses from band applications rarely differ from those obtained with broadcast application.

In southern British Columbia, band-applied manure sludge high in P produced as large a corn yield response as the same amount of fertilizer P (Bittman et al., 2012). The manure sludge was injected to 5” to 6” depth 1 to 10 days before planting. Better results were achieved with band placement 2” beside the row than at 4” or 6”.

Sander and Eghball (1999) reported that winter wheat fertilized with 10-34-0 with the seed produced responses as large as those with a ‘dual-band’ (N plus P) knife at optimum seeding dates, in Nebraska soils of very low to low P fertility. When seeding was delayed, however, placement with the seed was superior owing to better ability to stimulate tillering and head formation. The hoe-type drill and the knife applicator both used 12-inch row spacing. In contrast, for dry conditions, Harapiak and Beaton (1986) and Karamanos et al. (2008) noted larger responses with deep-banded fertilizer P than when it was seed-placed, for wheat and barley. Most researchers agree, however, that for cereals in the semi-arid Great Plains, either seed-placed or deep-banded P produces better responses than surface broadcasting.

With Seed

Band placement in the seed trench at very low rates can be sufficient for P nutrition of corn in soils testing above optimum in P, but cannot safely provide rates adequate to maintain soil fertility. Seed-placed P is particularly effective for early growth of corn seedlings, but its benefits in terms of final yields seem to be seen more in northern than in southern and mid-latitude Corn Belt growing environments (Bates, 1971; Lauzon and Miller, 1997; Eghball and Sander, 1989). Randall and Vetsch (2008) concluded from a corn-soybean strip tillage study in Minnesota that “if soil test P is less than high, a combination of deep-band and seed-placed pop-up fertilizer should produce the highest yields and give the greatest P efficiency.” In Iowa, on the basis of 16 trials conducted with no-till or chisel-plow tillage, Kaiser et al (2005) concluded “In-furrow starter P-K fertilization for corn is not an effective practice when applied in addition to 2-year broadcast P-K fertilization rates for corn-soybean rotations.” For soybeans, placement with seed risks harm to seedlings and does not effectively increase yield (Rehm, 2001; Lauzon and Miller, 1997).

In a 3-year trial on corn in southern British Columbia, Bittman et al (2006) reported that in-furrow application of P fertilizer at rates of 2 to 14 lb/A of P_2O_5 increased yields in high P soils, but not as effectively as a rate of 60 lb/A of P_2O_5 applied in a band 2” beside and below the seed.

Stratification of P in Soils

Tillage effects

Comparing strict long-term no-till to annual moldboard plowing, soil test P levels in the top 2” of soil can be three times higher than in the 4” to 8” depth (**Figure 7**). Annual chisel plowing resulted in about half as much stratification as no-till, at least in the top 4”. In this Purdue University study, P was applied broadcast in the fall prior to tillage. Corn yields were 5 to 15% lower in no-till compared to tilled plots. The lower yields and lower P removal may explain the higher overall soil test P levels in no-till, or it may be due to the higher organic matter in the surface layer protecting the P from fixation by the soil.

In a rotation involving corn, soybeans and oats, Duiker and Beegle (2006) reported that that soil test P stratification occurred under both no-till and chisel-disk management, but not with a moldboard plow, even though most of the P fertilizer was applied in a starter band 2 inches beside and below the seed. After 25 years, the ratio of soil test P in the top 2 inches compared to that in the 4 to 6 inch depth was over 4 in the no-till, almost 2 in the chisel-disk, and 1.1 in the moldboard treatment. Diaz-Zorita and Grove (2002) also noted that on high P soil, even with no fertilizer P addition, P stratification ratios (0 to 1” depth compared to 7 to 8” depth) increased over time from 1.2 with 1-2 years no-till to 2.5 with 29 years no-till.

Placement Effects

Two factors cause stratification with no-till or conservation tillage: the accumulation of P in crop residues, and the placement of applied P without soil mixing. Stratification develops within a few years after switching from moldboard plowing, more rapidly when P is applied than when it is not, and more rapidly with broadcast than with band application (**Figure 8**).

Sampling in Soils with Bands

Band-applied P is indeed quite immobile in the soil, and thus a sample taken from a band location will differ sharply from one taken only a few inches away. Nevertheless, there are guidelines for effectively sampling soils with a history of band application.

If the band locations are known, and the P band is narrow—as occurs in a V-trench associated with single or double coulters as openers—a ratio of 1:20 in-band cores to between-band cores should be used for bands spaced 30 inches apart. If the location of the bands is unknown, a paired sampling approach can be effective: one sample consisting of cores taken at random, and the second consisting of cores each taken at a distance of half the band spacing from each of the first cores, perpendicular to the direction of the bands. Since the greatest deviation from the ‘true’ soil test P level occurs when the band location is over-sampled, the sample with the lower soil test P level is most likely to be representative (Kitchen et al., 1990).

If the banded zone is wider, as in strip tillage, the ratio should be the same as the strip width to the non-strip width. In strip-till corn-soybean rotation with P applied in the strips 6 inches deep in the fall, a 1:3 ratio of in-row to between row samples seemed adequate to estimate soil fertility (Fernandez and Schaefer, 2012).

Impact of Placement on Environmental Protection

Generally, band placement prevents a great deal of potential loss of dissolved P in runoff. In no-till systems, injection by coulter or knife can lead to preferential surface runoff if the bands run up and down slopes rather than on contour (Seo et al., 2005). Point-injection of P fertilizer did not increase the concentration of P in runoff water from a rainfall simulator, but as much as 3% of surface-applied broadcast P fertilizer was lost in runoff (Baker and Laflen, 1982). Similarly, an artificial rain applied for 90 minutes resulted in runoff loss of 2.5 to 7.3% of the P fertilizer broadcast-applied one day earlier in an Indiana study (Smith et al., 2007). While the amounts lost were small in terms of economic loss of the purchased fertilizer, they were sufficient to elevate the concentration of P in the runoff water by two orders of magnitude or more.

On an undrained permanent pasture, Sharpley and Syers (1983) reported that a fine granular (<100 mesh) form of P fertilizer produced greater losses of dissolved and total P in 26 natural runoff events than a liquid form. Total P loss as % of applied was 2.3% for fluid and 5.8% from solid. Differences between placement of fertilizer P often disappear for runoff events that occur two or more months after application (Ruark et al., 2006). Kimmel et al (2001) reported significantly greater loss of P from broadcast as compared to knifed-in fluid P fertilizer, in natural runoff events in a Kansas grain sorghum-soybean rotation.

Generally, the concentration of dissolved P in runoff is proportional to soil test P levels in the top 2” of soil. No-till is an important tool for controlling loss of sediment, but it does not reduce—and in fact it may sometimes increase—dissolved P in runoff. Stratification will be less, however, if P is band applied into the soil rather than broadcast on top. Applying P below the soil surface is important to minimize stratification and dissolved P loss in both no-till and chisel-plowed soils.

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Table 1. Comparative times needed for P and K to travel one cm in 2 different soils (Silberbush and Barber, 1983).

	Time to travel one cm[†]		K diffusion rate, expressed as a multiple of the P diffusion rate
Soil	P	K	
	------------ (yr) ----------		(times as fast as P)
Raub silt loam	3.45	0.42	8.1
Chalmers silt loam	1.89	0.41	4.6

[†] Time was calculated from the following equation, using the apparent diffusion coefficients for P and K (D_e): $t = d^2/(4D_e)$, where t is time (s) and d is the distance travelled (cm).

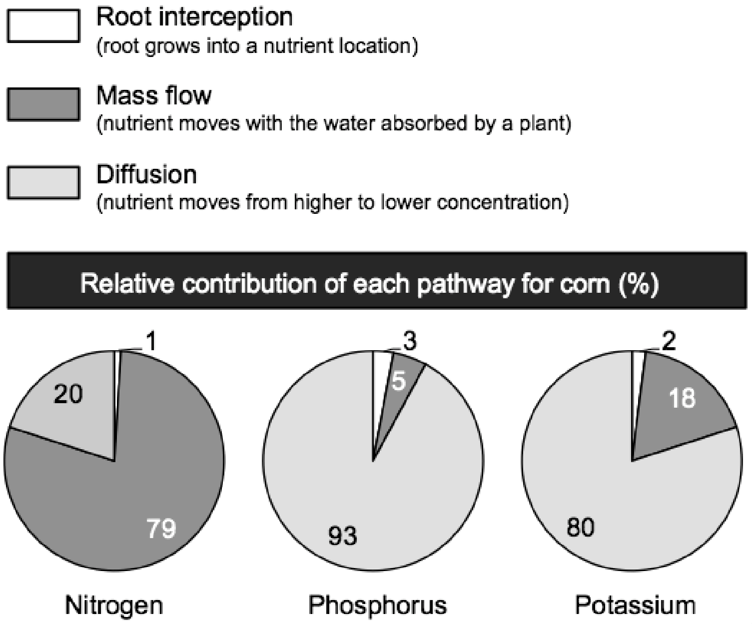

Figure 1. Relative contributions of the three nutrient transport pathways to corn uptake (Barber, 1995).

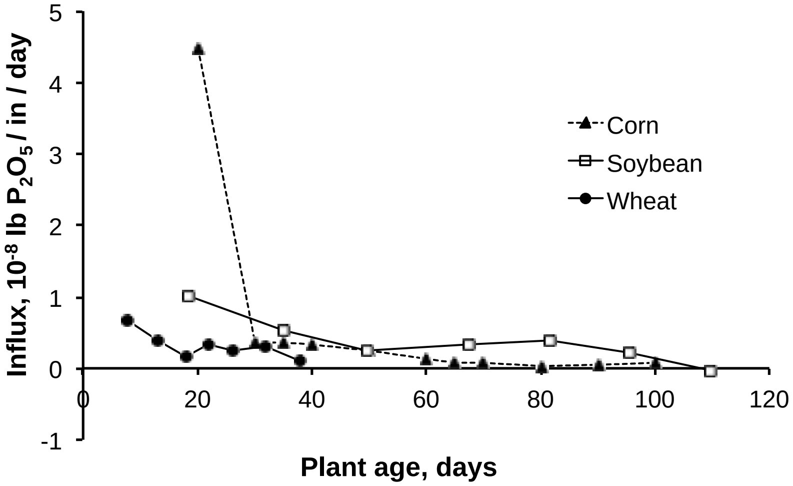

Figure 2. Influx at different plant ages for corn, soybean, and wheat (Mengel and Barber, 1974; Barber, 1978; Anghinoni et al., 1981).

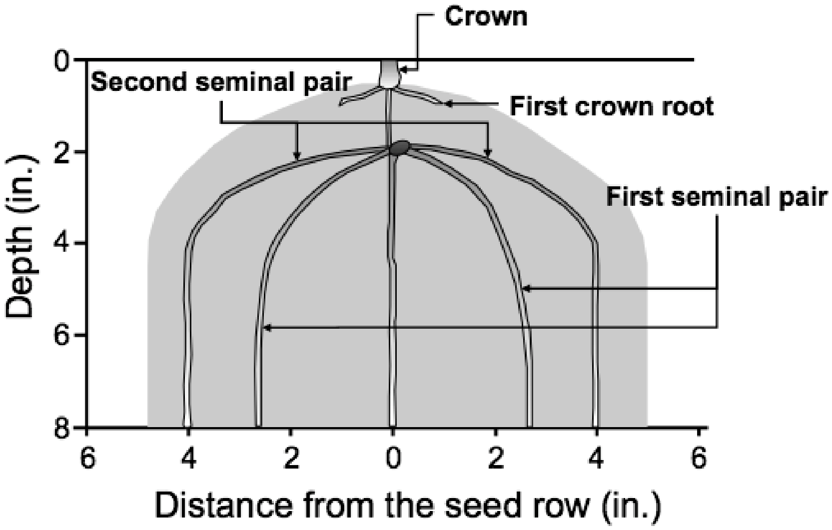

Figure 3. Growth patterns for the primary root (extending downward from the seed), first seminal pair, and second seminal pair. Diagram is for winter wheat at the 4 leaf stage with 1 tiller. The shaded area represents the volume filled by laterals of various orders (Veseth et al., 1986).

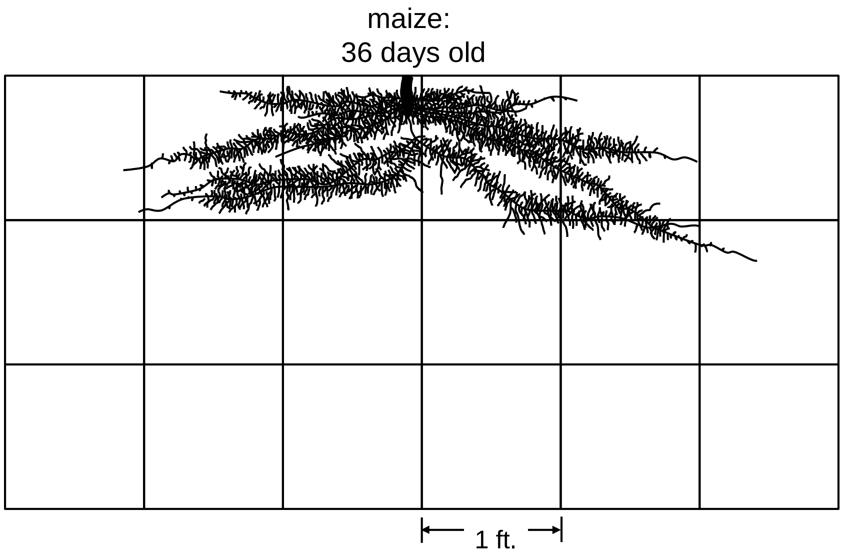

Figure 4. Growth patterns for corn at 36 days old (Weaver, 1926).

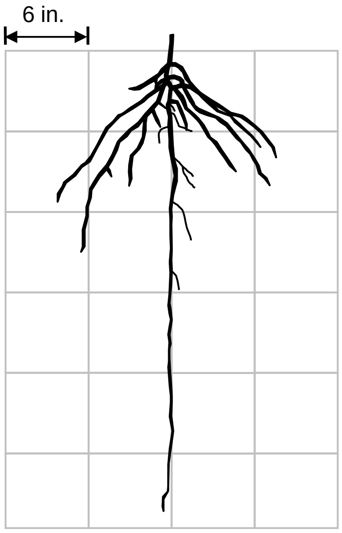

Figure 5. Soybean root distribution 1 mo. after planting (Mitchell and Russel, 1971).

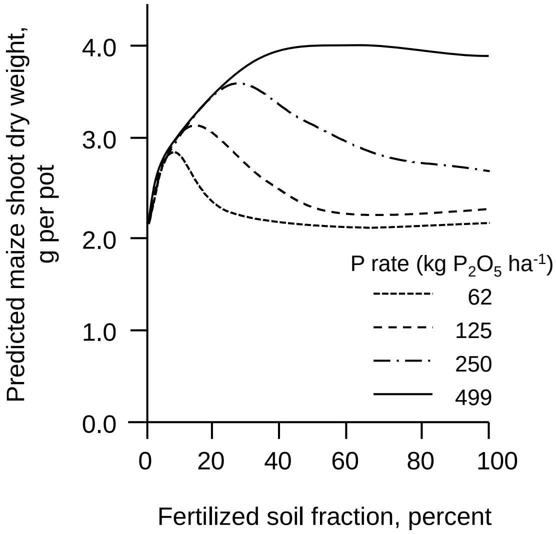

Figure 6. The influence of fertilizer application rate and fertilized soil volume on dry matter biomass yield of 18 day-old maize. Soil was assumed to weight 2x10^6 lb acre^{-1} (Anghinoni and Barber, 1980).

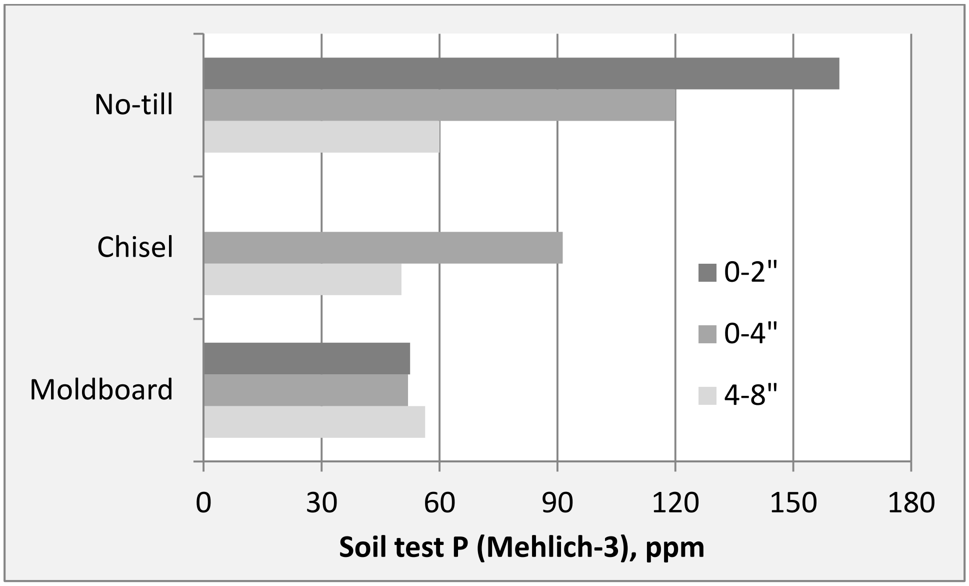

Figure 7. Soil test P distribution with depth in a long-term tillage experiment on a poorly drained Chalmers silty clay loam soil near West Lafayette, Indiana. Moldboard and chisel plots were plowed annually to a depth of 8”. Data from Gál (2005) and Vyn (2000).

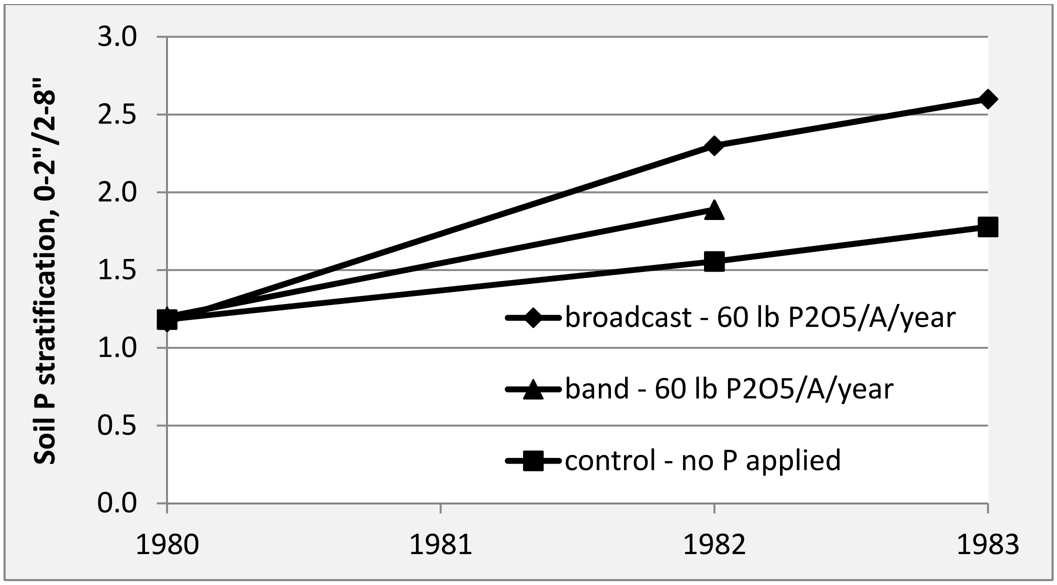

Figure 8. Soil P stratification—the ratio of soil test P in the top 2” compared to that in the 2-8” depth—increased over time more with broadcast than with band application. Silt loam soil near Wooster, Ohio; continuous corn, no-till from spring 1980. Data from Eckert and Johnson (1985).

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