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WITH PLANT FOOD

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C O N T E N T S

Note: Reprints of this issue are available under the title of *Phosphorus for Agriculture*. Contact PPI at the address shown at left.

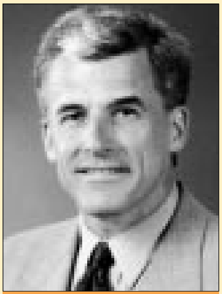
John H. Sultenfuss Elected Chairman, William J. Doyle Vice Chairman of PPI and FAR Boards of Directors

John H. Sultenfuss, Senior Vice President, Marketing and Sales, CF Industries, Inc., was elected Chairman of the PPI Board of Directors at a recent meeting. He will also serve as Chairman of the Foundation for Agronomic Research (FAR) Board of Directors. **William J. Doyle**, President and Chief Operating Officer (COO) of the Potash Corporation of Saskatchewan Inc. (PCS), was elected Vice Chairman of the PPI and FAR Boards.

John H. Sultenfuss

"The management talents of these industry leaders will be important to PPI in the coming year," said Dr. David W. Dibb, President of PPI. "We value their willingness to serve in these key responsibilities for the Institute."

During his 26-year career with CF Industries, Mr. Sultenfuss has held a number of management and executive positions for the interregional cooperative headquartered in Long Grove, Illinois. In 1972, he joined the company at its phosphate complex in Plant City, Florida. Throughout the 1970s and 1980s, his positions included General Manager of the phosphate complex in Bartow, Florida; Vice President, Nitrogen Operations; and Vice President, Supply & Distribution. He was named Vice President, Marketing and Sales, in 1988, and became Senior Vice President in 1995. A native of Tampa, Florida, Mr. Sultenfuss earned a bachelor's degree in Chemical Engineering from the University of Florida in 1969.



William J. Doyle

Mr. Sultenfuss serves as Chairman of Canadian Fertilizers Limited, a nitrogen fertilizer manufacturing entity jointly owned by CF, Coopérative Fédérée de Québec, Growmark, and Western Cooperative Fertilizers Limited.

Mr. Doyle was named to his current positions with PCS in June of 1998 and now has responsibility for all PCS production subsidiaries. Since 1989, Mr. Doyle has served on the Board of PCS. In 1987, he joined PCS Sales as its President, with worldwide responsibility for the sale and distribution of potash produced by the Potash Corporation of Saskatchewan Inc. In March of 1995, Mr. Doyle was promoted to Executive Vice President with the parent company. He was in charge of all sales for the company, including the phosphate and nitrogen acquisitions.

Mr. Doyle is a Board member of Canpotex Limited, having served as Chairman earlier. He is Chairman of the International Fertilizer Industry Association's Potash Committee and a Board member of Fersan S.A. in the Dominican Republic. A graduate of Georgetown University with a major in Government, Mr. Doyle is married and has three children.

In other action of the PPI Board, John U. Huber, President of IMC Crop Nutrients and a Senior Vice President of IMC Global Inc., was elected Chairman of the Finance Committee. New members of the PPI Board include: Henk Mathot, representing Cargill, Inc.; Edward Cavazuti, representing Farmland Hydro, Inc.; and C. Steve Hoffman, representing IMC Global Inc. BC

World Production of Phosphate Rock

Phosphate rock is the only economical source of P for production of phosphate fertilizers and phosphate chemicals. Most of the U.S. and world phosphate rock resources are widely distributed marine phosphorite deposits.

Identified reserves and reserve bases of this vital resource are shown in **Table 1**. Morocco has the greatest reserves, followed by South Africa and U.S. China's reserves may be much greater than indicated and could rank as high as fourth in the world.

Phosphorus (P) is a vital resource for sustaining world agriculture. Reserves of phosphate rock are identified in many regions of the world.

Phosphate rock is produced in some 40 countries, but 12 countries account for 92 percent of the world's production (**Table 1**). Approximately 144 to 150 million tons of phosphate rock were produced annually between 1995 and 1997. Igneous deposits in Russia, Brazil, and the Republic of South Africa accounted for about 17 million tons of production in 1997. The remaining production (about 133 million tons or 89 percent) was from sedimentary deposits.

The U.S. is the world's leading producer, with about 33 to 34 percent of total production, followed by China, Morocco and Russia. In 1996, 10 U.S. companies operated 18 phosphate rock mines in four states. Florida and North Carolina produced about 86 percent of the marketable phosphate rock with the remaining production coming from Idaho and Utah.

Total capacity of the phosphate rock industry in the U.S. is 56 million tons, with mines currently operating at about 90 percent of capacity.

Phosphate rock production in the U.S. surpasses domestic needs, and the excess is exported to international markets. Domestic

TABLE 1. World phosphate rock reserves, reserve bases, and production.

Countries	Reserves	Reserve base	Production 1995	Production 1996	Production 1997
	million tons		thousand tons		
United States (U.S.)	1,300	4,900	47,937	50,031	51,023
Brazil	360	410	3,890	3,967	4,408
China	230	230	23,142	23,142	24,244
Israel	200	200	4,477	4,188	4,298
Jordan	100	630	5,492	5,896	6,061
Kazakstan			2,424	551	551
Morocco and Western Sahara	6,500	23,100	22,260	22,922	23,142
Russia		1,100	9,698	9,367	9,367
Senegal		180	1,763	1,763	1,763
South Africa	2,800	2,800	3,075	2,975	2,975
Togo		70	2,204	2,865	2,865
Tunisia		300	8,166	7,824	7,934
Other countries	1,100	2,800	10,019	11,130	11,020
World total (rounded)	**12,600**	**36,700**	**144,362**	**146,566**	**149,872**

Reserve and reserve base cost less than $36/ton and $90/ton, respectively. Cost includes capital, operating expenses, taxes, royalties, and a 15 percent return on investment, FOB mine.

consumption was about 46.3, 48.2 and 46.8 million tons in 1995, 1996 and 1997, respectively. The Republic of Korea, Japan, and India were the top importers of U.S. phosphate rock in 1996.

Mining of phosphate rock in the U.S. and elsewhere is accomplished mainly by strip mining techniques. Shaft mining is practiced at one mine in Montana.

Apatite in several different forms is the basic P compound in commercially important deposits of phosphate rock. Phosphorus in apatite minerals is only slightly soluble and of limited availability to crops. However, reactive phosphate rock and partially acidulated phosphate rock are satisfactory sources of P for crops grown on some acid tropical soils.

Acidulation or heat treatment of phosphate rock is usually necessary to break the apatite bond to render the contained phosphate more soluble. Wet process sulfuric acid acidulation is the most commonly used technique for improving the agronomic suitability of phosphate rock. The majority of finished P-containing materials used in North American agriculture are made from wet process phosphoric acid. Phosphoric acid is made from the reaction of sulfuric acid with phosphate rock.

Wet process orthophosphoric acid is often further concentrated by evaporation of water to form superphosphoric acid. In this process, two or more orthophosphate molecules combine to form polyphosphate compounds. These polyphosphate products are well suited for the manufacture of clear liquid fertilizers.

Phosphate materials widely used in modern crop production systems are listed in **Table 2**, with both P and P_2O_5 concentrations expressed as percent. Some of these products supply other essential plant nutrients including nitrogen (N), calcium (Ca), and sulfur (S).

For many years, normal or ordinary superphosphate was the predominant phosphate fertilizer. Because of relatively low analysis and high shipping and handling costs, it has been largely replaced by higher analysis, more economical sources such as concentrated superphosphate and ammonium phosphates.

TABLE 2. Concentration of P in phosphate products.

Material	Concentration, % P	Concentration, % P_2O_5
Superphosphoric acid	30-35	68-80
Wet process phosphoric acid	23-24	52-55
Concentrated superphosphate	20	46
Diammonium phosphate	20-21	46-48
Monoammonium phosphate	21-24	48-55
Normal superphosphate	7-10	16-22
Phosphate rock	12-18	27-41

TABLE 3. Top 10 states in P_2O_5 consumption, 1996-1997

State	P_2O_5 Consumption, thousand tons
Illinois	444
Iowa	320
Minnesota	294
Texas	242
Nebraska	212
California	208
Indiana	202
Kansas	196
Missouri	187
North Dakota	183
Total in U.S.	**4,613**[1]

Source of data: Association of American Plant Food Control Officials (AAPFCO) and The Fertilizer Institute (TFI).
[1]Note: The original value published was 4,569, later corrected upward to 4,613 thousand tons.

Consumption of fertilizer phosphate in the U.S. increased steadily from the early 1960s, peaking at a high of approximately 5.2 million tons annually during the 5-year period

(continued on page 7)

Courtesy of Potash Corporation of Saskatchewan Inc.

Most phosphate rock mining in the U.S. is by strip mining methods.

Functions of Phosphorus in Plants

Phosphorus is one of 17 nutrients essential for plant growth. Its functions cannot be performed by any other nutrient, and an adequate supply of P is required for optimum growth and reproduction. Phosphorus is classified as a major nutrient, meaning that it is frequently deficient for crop production and is required by crops in relatively large amounts. The total P concentration in agricultural crops generally varies from 0.1 to 0.5 percent.

> Phosphorus (P) is vital to plant growth and is found in every living plant cell. It is involved in several key plant functions, including energy transfer, photosynthesis, transformation of sugars and starches, nutrient movement within the plant and transfer of genetic characteristics from one generation to the next.

Uptake and Transport of Phosphorus

Phosphorus enters the plant through root hairs, root tips, and the outermost layers of root cells. Uptake is also facilitated by mycorrhizal fungi that grow in association with the roots of many crops. Phosphorus is taken up mostly as the primary orthophosphate ion ($H_2PO_4^-$), but some is also absorbed as secondary orthophosphate ($HPO_4^{=}$), this latter form increasing as the soil pH increases.

Once inside the plant root, P may be stored in the root or transported to the upper portions of the plant. Through various chemical reactions, it is incorporated into organic compounds, including nucleic acids (DNA and RNA), phosphoproteins, phospholipids, sugar phosphates, enzymes, and energy-rich phosphate compounds...for example, adenosine triphosphate (ATP). It is in these organic forms as well as the inorganic phosphate ion that P is moved throughout the plant, where it is available for further reactions.

Plant Energy Reactions

Phosphorus plays a vital role in virtually every plant process that involves energy transfer. High-energy phosphate, held as a part of the chemical structures of adenosine diphosphate (ADP) and ATP, is the source of energy that drives the multitude of chemical reactions within the plant. When ADP and ATP transfer the high-energy phosphate to other molecules (termed phosphorylation), the stage is set for many essential processes to occur.

Photosynthesis

The most important chemical reaction in nature is photosynthesis. It utilizes light energy in the presence of chlorophyll to combine carbon dioxide and water into simple sugars, with the energy being captured in ATP. The ATP is then available as an energy source for the many other reactions that occur within the plant, and the sugars are used as building blocks to produce other cell structural and storage components.

$$\text{Photosynthesis} = \text{Carbon Dioxide} + \text{Water} \xrightarrow[\text{Phosphate Energy}]{\text{Chlorophyll} \quad \text{Sunlight}} \text{Oxygen} + \text{Carbohydrates}$$

Genetic Transfer

Phosphorus is a vital component of the substances that are building blocks of genes and chromosomes. So, it is an essential part of the process of carrying the genetic code from one generation to the next, providing the "blueprint" for all aspects of plant growth and development.

An adequate supply of P is essential to the development of new cells and to the transfer of the genetic code from one cell to another as new cells are formed. Large quantities of P are found in seeds and fruit where it is believed essential for seed formation and development.

Phosphorus is also a component of phytin, a major storage form of P in seeds. About 50 percent of the total P in legume seeds and 60 to 70 percent in cereal grains is stored as phytin or closely related compounds. An inadequate supply of P can reduce seed size, seed number, and viability.

Nutrient Transport

Plant cells can accumulate nutrients at much higher concentrations than are present in the soil solution that surrounds them. This allows roots to extract nutrients from the soil solution where they are present in very low concentrations.

Movement of nutrients within the plant depends largely upon transport through cell membranes, which requires energy to oppose the forces of osmosis. Here again, ATP and other high energy P compounds provide the needed energy.

Phosphorus Deficiency

Adequate P allows the processes described above to operate at optimum rates and growth and development of the plant to proceed at a normal pace.

When P is limiting, the most striking effects are a reduction in leaf expansion and leaf surface area, as well as the number of leaves. Shoot growth is more affected than root growth, which leads to a decrease in the shoot-root dry weight ratio. Nonetheless, root growth is also reduced by P deficiency, leading to less root mass to reach water and nutrients.

Generally, inadequate P slows the processes of carbohydrate utilization, while carbohydrate production through photosynthesis continues. This results in a buildup of carbohydrates and the development of a dark green leaf color. In some plants, P-deficient leaves develop a purple color, tomatoes and corn being two examples. Since P is readily mobilized in the plant, when a deficiency occurs the P is translocated from older tissues to active meristematic tissues, resulting in foliar deficiency symptoms appearing on the older (lower) portion of the plant. However, such symptoms of P deficiency are seldom observed in the field...other than loss of yield.

Other effects of P deficiency on plant growth include delayed maturity, reduced quality of forage, fruit, vegetable, and grain crops, and decreased disease resistance. BC

World Production... *(continued from page 5)*

1975 to 1979 (**Figure 1**). Consumption declined to an average of 4.3 million tons yearly during the 1985-1989 period, but has since begun increasing, averaging about 4.5 million tons since 1995.

Illinois led the U.S. in phosphate consumption in 1997, followed by Iowa, Minnesota and Texas (**Table 3**). Others in the top 10 consuming states included Nebraska, California, Indiana, Kansas, Missouri, and North Dakota. These 10 states accounted for 55 percent of U.S. phosphate consumption.

Canadian consumption of fertilizer phosphate followed similar trends to the U.S., but reached a high of 798,164 tons of P_2O_5 in 1985 (**Figure 1**). Consumption declined to 637,175 tons in 1991, but has since increased to 775,370 tons in 1997. About 75 percent of Canada's phosphate consumption occurs in the prairie provinces (Alberta, Manitoba and Saskatchewan). BC

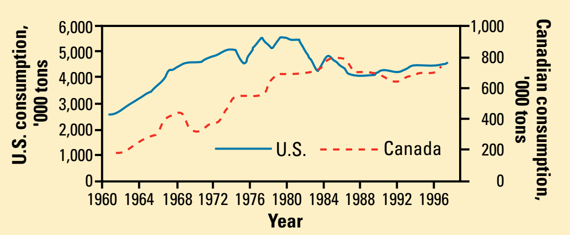


Figure 1. Consumption of P_2O_5 in North America.

Yield and Economic Responses to Phosphorus

Higher yields and greater profits are major reasons why farmers apply P to crops. All crops need P for profitable yields. However, assessing the profitability of P fertilization is difficult. The effects last well beyond the year of application. In addition, there are many economic benefits to proper P nutrition beyond yield responses, such as earlier maturity, reduced grain moisture, and improved quality.

> The most important reason for phosphorus (P) application is to increase profit.

Corn

The data in **Table 1** show the residual effects of a large, single application of P. These data clearly show that P has residual effects upon yield beyond the year of application. Therefore, costs associated with P fertilization should be amortized over time. Without amortization, the first year net return would be minus \$79.42/A, and the residual effects of P would be ignored. An amortization schedule was created by expressing the annual increase in yield as a percent of the total yield increase over the 14-year period. Expressed in this way, net returns to P are positive for each of the 14 years studied. The large response in the last year indicates that benefits would likely continue.

Research in Ohio showed corn yields increasing up to the highest rate of P_2O_5

TABLE 1. Long term effects upon corn grain yield from a large, single application of P (Iowa).

Year	Yield, bu/A 0 lb P_2O_5/A	Yield, bu/A 298 lb P_2O_5/A	Yield increase from P, bu/A	Increased yield income from P, \$/A[1]	Increased harvest costs from P, \$/A[2]	Amortization schedule (% of total 14 yr. yield increase from P)[3]	Amortized yearly fertilizer application costs, \$/A[4]	Amortized yearly fertilizer material costs, \$/A[5]	Net return to P, \$/A
1976	138.0	138.9	0.9	2.03	0.32	0.3	0.02	0.22	1.47
1977	134.1	135.3	1.2	2.70	0.42	0.4	0.03	0.30	1.95
1978	150.9	157.2	6.3	14.18	2.20	2.2	0.15	1.64	10.18
1979	160.9	176.7	15.8	35.55	5.53	5.5	0.37	4.10	25.55
1980	157.9	169.9	12.0	27.00	4.20	4.2	0.29	3.13	19.39
1981	163.2	185.0	21.8	49.05	7.63	7.6	0.52	5.66	35.24
1982	145.7	179.0	33.3	74.93	11.66	11.6	0.79	8.64	53.84
1983	120.3	147.3	27.0	60.75	9.45	9.4	0.64	7.00	43.66
1984	111.2	151.8	40.6	91.35	14.21	14.1	0.96	10.50	65.68
1985	144.6	175.0	30.4	68.40	10.64	10.6	0.72	7.90	49.14
1986	116.5	157.5	41.0	92.25	14.35	14.3	0.97	10.65	66.27
1987	129.6	152.8	23.2	52.20	8.12	8.1	0.55	6.03	37.49
1988	60.2	74.6	14.4	32.40	5.04	5.0	0.34	3.73	23.30
1989	123.4	142.7	19.3	43.43	6.75	6.7	0.46	4.99	31.22
Totals			**287.2**			**100.0**	**6.80**	**74.50**	

[1]Corn price = \$2.25/bu; [2]harvest costs = \$0.35/bu (hauling, handling, drying); [3]calculated by dividing the annual yield increase from P by the total yield increase from P over the 14-year period; [4]calculated by multiplying a 2-trip bulk application fertilizer cost (\$6.80/A) by the annual amortization percentage; [5]calculated by multiplying the P fertilizer cost (\$74.50/A) by the annual amortization percentage.

TABLE 2. Corn yield increases from P fertilization (Ohio).

P_2O_5 rate, lb/A	Corn yield, bu/A
0	150
20	166
40	175
80	183
120	191

TABLE 3. Adequate P increases wheat yields (Kansas).

P_2O_5 rate, lb/A	Wheat yield, bu/A
0	27
16	48
32	52
64	60

applied on a low-testing soil (**Table 2**).

On cold, wet soils corn often responds to row applications of P. Wisconsin research showed that even on high P soils a starter application of P boosted yields by as much as 31 bu/A.

Wheat

Most soils used for wheat production need P fertilizer for profitable yields. **Table 3** shows the difference P can make in growing wheat in Kansas.

Data from Texas indicate that P placement is critical in dry years. Phosphorus placed deeper in the soil profile is more available to wheat root systems. **Table 4** shows the yield and profitability advantages of deep banded P under dry conditions.

Wheat growers see the best grain production when both nitrogen (N) and P are applied at optimum rates. In **Table 5**, data from Manitoba show the effectiveness of balanced N and P fertilization.

Soybeans

Soybeans can be quite responsive to P fertilization, as was shown on newly cleared land in Virginia (**Table 6**). The 50 lb/A of banded P_2O_5 produced a good yield response at the zero and 200 lb/A rates of broadcast P_2O_5.

In the last 10 years of a 24-year Indiana experiment, soybeans receiving both P and potassium (K) fertilizer averaged almost 54 bu/A. When P was omitted in these 10 years, average yield dropped to 44 bu/A, or an 18.5 percent reduction without P.

Cotton

Starter fertilizer containing N and P gave consistent increases in lint yields of cotton on 18 locations over a two-year period in Mississippi. Phosphorus was found to be the nutrient producing the yield response at two locations where nutrient effects were separated, shown in **Table 7**.

Five advantages to using starter fertilizer

TABLE 4. Winter wheat responds in dry years to 40 lb P_2O_5/A placed in a deep band (Texas).

Location	Year	Fertilizer application method	Winter wheat yield, bu/A	Increased yield from P, bu/A[1]	Increased income from P, $/A	Total expenses from P, $/A[2]	Net return to P, $/A
Runnels	1988	Deep P+N	31.0	10.2	28.05	15.53	12.52
		Surface P+N	25.8	5.0	13.75	14.15	-0.40
		N only	20.8				
Wichita	1995	Deep P+N	16.4	11.6	31.90	15.74	16.16
		Surface P+N	5.1	0.3	0.83	13.45	-12.62
		N only	4.8				
Abilene	1996	Deep P+N	22.0	9.8	26.95	15.47	11.48
		Surface P+N	13.2	1.0	2.75	13.55	-10.80
		N only	12.2				

[1]Winter wheat = $2.75/bu; [2]Fertilizer + application + additional harvest costs assuming $0.25/lb P_2O_5, application costs of $3.40 and $4.00/A for surface and deep, respectively, and $0.15/bu for hauling and handling.

on cotton were observed or measured: 1) enhances the development of a better early root system; 2) helps overcome early adverse conditions; 3) initiates earlier fruiting; 4) hastens maturity; and 5) increases yields.

TABLE 5. Both N and P are needed for optimum wheat yields (Manitoba).

N rate, lb/A	P_2O_5 rate, lb/A: 0	18	45	Response to P, bu/A
	Wheat yield, bu/A			
0	14	17	20	6
54	41	42	46	5
107	47	54	64	17
Response to N	33	37	44	

Grain Sorghum

Grain sorghum gave outstanding yield responses to starter P in a three-year Kansas study on a low-P soil, as shown in **Table 8**. In the same study, there were no differences in yield responses between ortho and polyphosphate P sources.

TABLE 6. Soybean response to P on newly cleared land (Virginia).

Broadcast, P_2O_5, lb/A	Banded, P_2O_5, lb/A: 0	50	Response to banded P, bu/A
	Soybean yield, bu/A		
0	16	35	19
200	35	43	8
400	43	44	1
600	44	45	1
Response to broadcast P	28	10	

Snap Beans

Snap beans responded to P fertilization in five out of seven years of studies in Tennessee. The optimum rate was found to be about 50 lb/A P_2O_5. Higher rates sometimes depressed yields due to a possible induced zinc (Zn) deficiency. Zinc fertilization corrects such deficiencies.

TABLE 7. Effect of no starter, N starter, and N-P starter on lint cotton yield (Mississippi).

Location	No starter	N only	N-P starter
	Lint yield, lb/A		
Webb	815	796	905
Glendora	1,033	975	1,170

Potatoes

Growers know that P is an essential component of growing profitable potatoes. Yield responses to P are common even on high P soils. For example, potato yields dropped from 320 cwt/A to 239 cwt/A when 100 lb/A of P_2O_5 was omitted from the optimum fertilizer treatment in a New Jersey trial on a high P soil. Workers in Idaho found banded P not as effective as plowdown or disking in producing highest tuber yields.

TABLE 8. Starter P boosts grain sorghum yields (Kansas).

P_2O_5 rate, lb/A	Grain sorghum yield, bu/A
0	80
18	111
36	117

Alfalfa

Alfalfa removes about 12 lb of P_2O_5 for every ton of hay harvested. This high demand for P creates conditions for large and profitable yield increases to P fertilization. A long-term study in Kansas showed alfalfa response to P at various rates (**Table 9**). BC

TABLE 9. Effect of P fertilization on alfalfa yield (Kansas).

P_2O_5, lb/A annual	Alfalfa yield, tons/A: Year 1	2	3	4	5	6
0	8.1	7.7	7.4	7.1	9.1	8.2
40	9.3	9.3	8.9	8.5	10.6	9.7
80	9.3	9.7	9.5	8.8	11.4	10.4
120	9.6	10.6	10.0	9.5	12.1	11.4

Phosphorus Interactions with Other Nutrients

An interaction occurs when the level of one production factor influences the response to another factor. A positive interaction occurs when the influence of the combined practices exceeds the sum of the influences of the individual practices. Such positive interactions have served as the science-based justification for development of a "balanced" plant nutrition program. Positive interactions with P and other nutrients are well documented. In addition, P interactions have been identified with other practices such as crop varieties or date of crop planting.

Phosphorus (P) fertilization practices help to insure an adequate supply of P during peak growth demand periods of a crop. Phosphorus is affected by or affects the availability or utilization of many other nutrients. It improves the effectiveness of other production practices. The effects of P on other nutrients or practices or the effects of other nutrients or practices on P are interactions significant to profitable crop production.

Positive interactions of P with other essential nutrients have been documented in research studies on many crops. Certain crop production practices along with environmental conditions can serve as indicators when P interactions might occur:

- Higher crop yields place greater demand on soil nutrient reserves and applied fertilizer P. The objective is to supply nutrient needs during peak crop uptake periods.
- Liming an acid soil alters nutrient availability to growing plants. It improves P availability to most crops. Liming can reduce availability of micronutrients such as iron (Fe), zinc (Zn), manganese (Mn), or boron (B) and increase the availability of the micronutrient molybdenum (Mo).
- The shift to reduced tillage practices can alter the method of fertilizer application and often results in P accumulation in the surface zone of the soil. Lower temperature and higher moisture and organic matter content in the surface soil can reduce availability and utilization of P by certain crops.
- Solid seeded crops such as soybeans, small grains, or cotton result in more plants per unit area and smaller individual plant root systems. Soil with a high level of fertility is beneficial for optimum plant growth.
- The agronomic adaptation of genetically engineered crops provides greater tolerance to specific herbicides and/or insect protection. Site-specific nutrient requirements are being evaluated. Changes in land topography and the crop rooting zone can result from land leveling, deeper tillage, minimum tillage, and/or loss of topsoil through erosion.

Nutrient Interactions with Phosphorus

Nitrogen (N). Phosphorus and N are both involved in vital plant functions such as photosynthesis, protein formation, and symbiotic N fixation. The primary benefit from band placement of N and P fertilizers is greater P

TABLE 1. Nitrogen/P interaction affects corn yield (Illinois).

N, lb/A	P_2O_5, lb/A	Yield, bu/A	Increase, bu/A
0	0	41	—
200	0	50	9
0	160	58	17
200	160	123	82

uptake because of increased P solubility and proximity to seedling roots. Also, ammoniacal-N fertilizers can improve P availability to plants and thereby improve crop growth. Examples of positive N/P interactions are shown in **Tables 1** and **2.**

Kansas research (**Table 3**) illustrates the beneficial influence of balanced NP fertilization on no-till grain sorghum. Grain yield was increased by more than 13 bu/A, and the period from emergence to mid-bloom was shortened by seven days with proper use of N and P.

TABLE 2. Nitrogen/P interactions affect dryland wheat yields and profits (Colorado).

N, lb/A	P_2O_5, lb/A	Yield, bu/A	Prod. costs $/A	Prod. costs $/bu	Net return, $/A
0	0	32	98	3.06	-10
30	0	42	104	2.48	12
30	30	45	112	2.48	12
60	0	38	110	2.89	-6
60	60	58	125	2.16	35

Low soil test P; N 20¢/lb; P_2O_5 25¢/lb; wheat $2.75/bu.

TABLE 3. Nitrogen and P for improved no-till grain sorghum yield and maturity.

Starter, lb/A N	Starter, lb/A P_2O_5	Grain sorghum yield, bu/A	Days to bloom
0	30	88	67
90	0	87	66
90	30	101	59

Potassium (K). Phosphorus and K are both essential for photosynthesis, enzyme/energy driven reactions, seed formation and quality, stress tolerance, crop maturity, etc. Research has documented cases of P/K interactions, (**Tables 4**, **5** and **6**). They illustrate the agronomic and economic benefits of eliminating P and K as limiting factors in crop production.

Balanced fertility is essential for high corn grain yields. Phosphorus and K each boosted grain yields in a study. Together, they increased grain yield by 64 bu/A, or 38 to 41 bu/A more than when each was applied alone (**Table 7**).

TABLE 4. Positive P/K interactions can make a difference with soybeans (Virginia).

P_2O_5, lb/A	K_2O, lb/A	Yield, bu/A	Yield increase, bu/A
0	0	24	—
30	0	26	2
0	120	37	13
30	120	45	21

TABLE 5. Phosphorus and K work together for higher wheat yields (average of two varieties).

P_2O_5, lb/A	K_2O rate, lb/A: 0	40	80
	Yield, bu/A		
0	52	64	64
30	78	84	87
60	77	88	91

With Tilt fungicide; low P and K soil test; N, 75 lb/A.

Sulfur (S). Research in California illustrates the effects of a positive P/S interaction on increased forage production and the resulting improved sheep performance due to improved yields and nutritive value of the forage. Phosphorus alone did not increase lamb gain significantly, but the P/S interaction greatly increased production.

Magnesium (Mg). Phosphorus and Mg are essential for photosynthesis and seed formation. Crop uptake of both nutrients tends to decline under cold and wet soil conditions which sets the stage for nutrient interactions.

TABLE 6. Positive P/K interaction increases Coastal bermudagrass yields (Texas).

P_2O_5, lb/A	K_2O, lb/A	Yield, lb/A	Response, lb/A
0	0	5,375	—
0	300	5,294	-81
100	0	6,510	1,135
100	300	9,146	3,771

Micronutrients. Phosphorus interactions with micronutrients have been reported on a wide variety of crops. Interactions with P have been reported for B, copper (Cu), Fe, Mn, Mo, and Zn. Soils with high soil P levels (naturally or through buildup) should be monitored for a possible micronutrient interaction.

- **Boron.** Phosphorus/B interactions caused a reduced B absorption by corn seedlings grown in an acid soil high in P. However, strawberries gave no significant interaction between P and B.
- **Copper.** Phosphorus/Cu interaction was found when high levels of P accentuated an acute Cu deficiency in citrus seedlings. However, Cu and Zn solubilities can be increased by high levels of P fertilization. This interaction is believed to occur at the site of absorption...possibly with Cu precipitation at the root surface. In other studies, applied P reduced the effect of toxic levels of Cu. Excess Cu can decrease P and Fe absorption.
- **Iron.** Phosphorus/Fe interaction showed up in bush beans grown in either an excess or deficient level of soil P. In either case, Fe absorption was reduced. Both corn and rice, grown on soils containing excess Cu, exhibit severe Fe chlorosis. Heavy P fertilization is often recommended under such circumstances.
- **Manganese.** Phosphorus/Mn interactions can develop when soil Mn availability increases with higher soil P levels. On some soils this is believed partially due to increased soil acidity from high rates of P.
- **Molybdenum.** The P/Mo interaction depends upon whether the soil is alkaline or acidic in nature. For acidic soils, P increases Mo uptake while reducing Mo uptake on alkaline soils. The increase with acidic soils is believed to be the result of enhanced absorption and translocation due to the $H_2PO_4^-$ ion.
- **Zinc.** Nutrient accumulation studies in corn have found P and Zn uptake, translocation, and deposition patterns to be quite similar. Research indicates the tendency of P to depress Zn nutrition is

TABLE 7. Positive PK interaction increases corn grain yields.

	Grain yield	Response
	bu/A	
N (-PK)	113	—
NK (-P)	136	23
NP (-K)	139	26
NPK	177	64

TABLE 8. Turn negative responses on corn into positive interactions (Kansas).

P_2O_5, lb/A	Zn, lb/A	Yield, bu/A
0	0	131
80	0	119
0	20	109
80	20	175

physiological in nature and not due to inactivation in the soil. In high yield environments, negative interactions among micronutrients can develop. Results on corn in Kansas given in **Table 8** illustrate how a negative response can be turned into a positive interaction with proper fertilization.

Agronomic Significance

Crop response to applied P can be improved by making adjustments for time, rate, and method of application. It varies with soil physical and chemical properties, high yield crop management practices, and crop stress conditions such as drought or nutrient deficiencies. Nutrient interactions have been noted for cereals, vegetables, tree, specialty, and row crops.

Early diagnosis of deficiencies of P and/or other nutrients can help minimize losses in crop yield, quality, and farm profitability. In-field inspection, along with soil and plant analyses, helps to provide needed facts for immediate correction and next-season planning. BC

Effects of Phosphorus on Crop Maturity

The influence of P on crop maturity has been observed by many researchers on a variety of crops.

A five-year Ohio State University study showed that raising soil test P from low to high increased corn yield 8 bu/A and decreased grain moisture at harvest by 1.3 percentage points. Placement of P can also influence early growth, with effects often carrying through to earlier maturity. In Indiana, banding 80 lb/A P_2O_5 resulted in a 15 bu/A corn yield increase over broadcast application and 1.5 percentage points less moisture in the grain at harvest.

Recent no-till research in Kansas showed that starter containing P increased yields of responsive hybrids of corn by 17 bu/A and responsive grain sorghum hybrids by 14 bu/A (**Table 1**). Days to midsilking or midbloom were significantly reduced, and grain moisture at harvest was lowered several percentage points.

Researchers in Illinois found that earlier corn silking and lower moisture contents were associated with P fertilization and increased soil test P levels. **Table 2** shows the effects on silking, as measured by degree-days.

In Alabama research, there was a maturity advantage for in-row starter containing P compared to beside-the-row application on grain sorghum. Both advanced maturity over the zero starter treatment. Seed-placed phosphate, applied at the rate of 40 lb/A P_2O_5, hastened grain sorghum maturity an average of four days at nine locations in the Texas Blacklands. Seedlings had more vigor, and the rapid early growth made it possible to cultivate earlier, resulting in better mechanical weed control. Results are shown in **Figure 1**.

In-row starter fertilizer containing P (3 to 5 gal/A of 11-37-0 or 10-34-0) can

The influence of phosphorus (P) on crop maturity is often an added bonus to its effect on increasing yields. For example, early maturing fruits and vegetables almost always command a premium in the marketplace. In multiple cropping, a few extra days can mean a significant difference in the relative success of the system. A reduction in grain moisture at harvest can also lead to savings in drying costs per bushel.

TABLE 1. Starter fertilizer and hybrid effect on corn and sorghum maturity and grain moisture content.

Hybrid type	Number of hybrids	Grain yield response, bu/A	Reduction in: Days to midsilk/bloom	Reduction in: Grain moisture, % points
Corn				
responsive	7	17	5.7	3.8
non-responsive	5	0	0	0
Sorghum				
responsive	8	14	5.4	5.5
non-responsive	4	4	1.0	-0.1

Kansas; 3-yr average

TABLE 2. Effect of P_2O_5 on degree-days (F) between corn emergence and silking.

P_2O_5 applied, lb/A	P soil test levels, ppm[1]	Degree-days (F) between emergence and silking: Early planted	Late planted
0	25	1,482	1,446
20	40	1,398	1,419
100	132	1,398	1,356

[1]ppm = parts per million

be beneficial even on soils testing high in P. In a 6-year Louisiana study, corn yields following cotton were increased with starter P by an average of 8 bu/A, time to midsilking was decreased by four days, and grain moisture at harvest was lowered from 18.9 to 17.9 percent.

Small Grains

Research in Oklahoma has shown that P speeds maturity of wheat by as much as four to seven days. Similar results have been observed in Kansas and Texas. Drilling P with the seed at planting advanced the maturity of spring wheat in North Dakota, **Figure 2**. In New York, late-planted wheat and barley ran 6 percent higher in moisture without P fertilization at the time the P fertilized plots were ready to harvest.

In a Louisiana study, P fertilization hastened grain maturity and yield immediately after rice and one year following rice, **Table 3**.

Cotton

Phosphorus fertilization hastened cotton maturity by increasing yield of the first picking and total seedcotton yield at several locations in Arkansas. Research in Tennessee showed that P fertilization increases yield, hastens maturity, and results in a higher proportion of the total yield in the first picking. Balanced P and K fertilization provided the greatest proportion of total cotton in the first harvest, **Table 4**. In Alabama, starter fertilizer containing P increased early season plant height by 14 percent over the no starter treatment and boosted yields at the first picking by 4 to 5 percent.

Vegetables

Canadian researchers found that P fertilization advanced the maturity of green peas. Maturity of cauliflower was slightly delayed by a lack of P. In Texas, fertilizer

(continued on page 19)

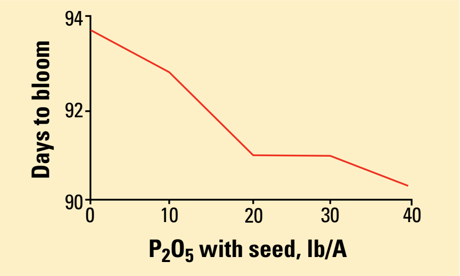


Figure 1. Effects of P applied with seed on maturity of grain sorghum.

TABLE 3. Influence of P fertilization on wheat grain maturity and grain yield.

P_2O_5, lb/A	Wheat immediately following rice: Days to maturity	Wheat immediately following rice: Relative yield, %	Wheat one year after rice: Days to maturity	Wheat one year after rice: Relative yield, %
0	151	68	150	79
25	150	86	149	86
50	149	97	148	93
100	148	100	147	100

Research indicates that earlier corn silking and lower moisture content are associated with P fertilization and increased soil P levels.

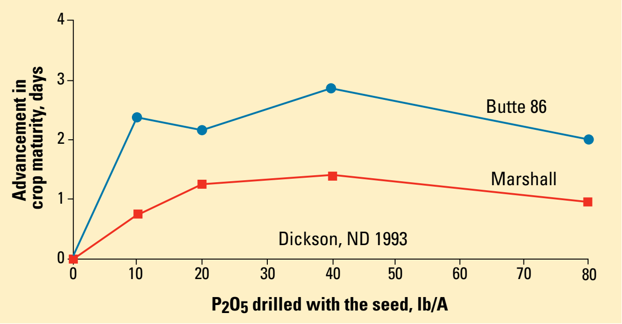


Figure 2. Effect of drilled P and variety on spring wheat development in North Dakota.

Important Factors Affecting Crop Response to Phosphorus

Phosphorus responses are expected in crops growing on soils testing medium or lower in soil test P. Plant roots of annual crops typically explore less than one percent of the soil volume. This helps explain why many factors other than soil test level should be considered in P application decisions. Some are manageable, others are not. They include soil characteristics, crop grown, climate, tillage systems, interactions with other nutrients, crop management, and fertilizer management.

> Although soil test level is a major consideration, numerous other factors also affect crop response to phosphorus (P).

Soil Physical Factors

- **Soil texture.** Responses to fertilizer P at a certain P soil test level tend to be greater on sandy soils than on those containing more silt and clay. Diffusion, which occurs mainly through soil water films, is an important process in P movement toward roots and is slower in coarse-textured soils. Higher P soil tests or higher rates of fertilizer P are needed on such soils. Some soil components react readily with fertilizer P to lower its availability (P fixation). Fixation increases as soil clay content increases. This means that larger amounts of P must be applied to those soils in order to increase soil test values and P availability to plants. Highly weathered soils are likely to have this characteristic.
- **Soil aeration and compaction.** Phosphorus uptake by plant roots requires energy from carbohydrates. Generating that energy requires oxygen for normal root metabolism. If soils are compacted, pore space is diminished, oxygen is limited, and P absorption suffers. Compaction also limits P use by decreasing the thickness of water films on soil particles through which P moves to root surfaces. Increasing concentrations of soil P by adequate fertilization can help offset this effect.
- **Soil temperature.** Low soil temperatures depress P availability and plant uptake. Lower temperatures reduce the rate of mineralization of soil organic P because of lowered microbial activity. Low soil temperatures also reduce root growth rates and the rate of diffusion of P, causing a decrease in the amount of P accessed by roots. The metabolic release of energy, which drives P absorption mechanisms, is also slowed by low soil temperatures.

  Cold soils are often associated with large P responses, even at high test levels. Lower soil temperatures are associated with reduced tillage systems because of surface shading by residues. Studies have shown that reduced tillage corn and other crops frequently respond to starter P at high soil test levels, even when responses in other tillage systems are unlikely.
- **Soil moisture.** Moisture stress also reduces P availability and uptake. Greater crop response to P at a given level of soil P may be expected under moisture stress conditions. Low soil moisture has been found to decrease P availability to wheat more than added P fertilizer increased availability. The percentage of P in the crop from fertilizer has been reported highest when moisture availability was lowest. Field studies indicate larger corn and soybean incremental responses to P on a medium P testing soil under low rainfall conditions.

Soil Chemical Factors

- **Soil mineralogy.** Forms of mineral P in the soil are a result of the soil's parent material, weathering, and, to a lesser degree, P fertilization. Types of clay, amounts of iron (Fe) and aluminum (Al) oxides, and amounts and forms of calcium (Ca) affect a soil's ability to fix fertilizer P.
- **Soil organic matter.** Generally, higher soil organic matter levels are related to greater P availability. Studies have emphasized the importance of organic P in plant nutrition. Apparently a fairly constant portion of organic P is converted into inorganic forms which are taken up by plants. Gradual release of organic P provides a steady supply of P under conditions which would otherwise result in P fixation.
- **Soil pH.** Soil pH has an important role in P availability and affects the efficiency of applied P. Phosphorus fixation by Fe and Al oxides is greatest in acid soils, but declines as soils are limed. Availability in most soils is at a maximum in the pH range 6 to 7. As soil pH increases above 7, Ca and magnesium (Mg) react with P, and the availability again declines. Trying to lower the pH of calcareous soils to improve P availability is not practical. Placement of P near the seed or seedlings is much more feasible.
- **Interactions with other nutrients.** Crop responses to P are affected by the availability of other nutrients. Interactions of P with micronutrients, particularly zinc (Zn), usually involve lowered micronutrient availability and uptake when P availability is high. Deficiencies of other nutrients can limit crop response to P.

  Phosphorus fertilizer absorption and use efficiency by crops is improved by the presence of ammonium-nitrogen (NH_4-N) in the soil with the P. Ammonium-N absorption by roots lowers the pH in the vicinity of the root surface improving P uptake. High concentration of NH_4-N can also change the soil chemistry of P and delay normal fixation reactions.

Soil Biological Factors

Soil biological processes, in addition to mineralization of organic P, can influence availability and responses to applied P.

- **Effects of crop residues.** Incorporation of crop residues increases microbiological action and can result in immobilization of available P into microbial cells. The same process affects the availability of N, sulfur (S), and other nutrients. Immobilized P is gradually released for plant use as residues decompose. Soil aeration, temperature, soil moisture, pH, and supplies of other nutrients such as N have a direct effect on biological action, immobilization, and release of P.
- **Effects of plant roots.** Roots affect the biology of the soil by providing energy sources for microbes and influencing soil properties such as tilth, structure, and nutrient availability.
- **Effects of mycorrhizae.** Mycorrhizae (meaning "fungus-root") are a close association of plant roots and a fungus where both partners benefit. Plants grow better when colonized by the beneficial fungi, which act as extended root surfaces. Improved nutrient absorption, especially P, results from the plant-fungus association. Increasing the soil P concentration to the levels needed for high yielding crops may essentially eliminate mycorrhizae as a factor in overall plant growth. However, even with high P testing soils, mycorrhizae may be important in early season plant growth. Mycorrhizal infection may be severely reduced by fallow periods in crop production, which increases the importance of starter P fertilization for crops grown in a fallow rotation. Prolonged wetness and flooding can decrease the mycorrhizal inoculum levels to the point that increased P fertilization may be needed.

Crop Factors

Crop species, varieties, and hybrids vary in their abilities to absorb and respond to fertilizer P. Several factors are associated with those differences.

- **Root development and distribution.** Most available P is present in the surface soil and helps concentrate roots in that zone. However, if surface moisture is limiting, soil P becomes less useable and P use-efficiency declines. High levels of applied P can increase P movement into the subsoil and help overcome this problem, by allowing better root development in the subsoil and increasing the ability to extract water.

  Outstanding corn yields are often associated with deep distribution of nutrients, including P.

  Root length and density affect response to P since length is the major determinant of absorbing surface area.
- **Crop varieties and hybrids.** Crop varieties and hybrids differ in their requirements for P. Corn hybrid responses to P have differed by over 100 percent in dry matter production and by over 200 percent in terms of P uptake in some studies. Sizeable yield increases have been documented, even at high soil test P levels, with N- and P-containing starter fertilizers (**Figure 1**). In the future, specific recommendations for P fertilization of individual hybrids and varieties may be a part of intensive crop management.
- **Crop yield levels.** Some corn and soybean studies have indicated that the amount of P taken up by plants per bushel or per ton of grain yield does not vary substantially. Yield effects on P requirements are often estimated as essentially a straight line function. Increased yields with increased P fertilization can result in a higher grain P content and a greater P removal than what may be predicted with simple linear relationships from lower-yielding studies. Alfalfa, for example, tends to remove more P per ton of production as yields increase due to P fertilization.

Fertilizer Factors

Chemical and physical characteristics of P fertilizers may influence crop response and management decisions on P sources.

- **Water solubility.** Water solubility of P fertilizers is considered important in some countries, but there is little agreement on what percent of the total P should be water soluble. Available P is that soluble in ammonium citrate and includes the water-soluble fraction. Research in North America has shown that water solubility is important, but it is difficult to find data that indicate superiority of one P fertilizer source over another based on water solubility, provided water solubility is 60 percent or higher.
- **Chemical forms of phosphorus.** Studies of P fertilizer materials indicate that ammonium phosphates, superphosphates, and nitric phosphates are largely equal as P sources for plants. These classes of compounds have a high percentage of P availability. Although research has shown some advantages to the presence of NH_4-N with P in terms of plant P absorption, modern crop production practices frequently involve high concentrations of N in the soil which diminish differences among these classes of compounds.

Comparisons of monoammonium phosphate (MAP), diammonium phosphate (DAP), ammonium polyphosphate (APP), and urea-

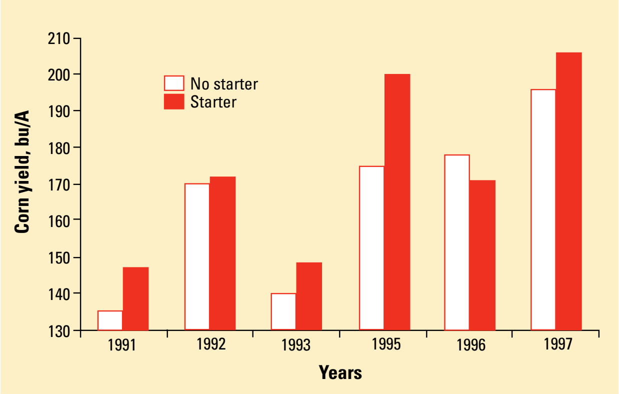


Figure 1. Corn response to in-furrow starter P fertilizer on a high P soil. (Mascagni and Boquet. Louisiana, 1998)

ammonium phosphate (UAP) show few consistent differences. At high rates, DAP can cause germination damage when placed in direct seed contact on alkaline soils, due to the release of some free ammonia. Limited rates of application control the problem. Formulations of UAP have an even greater probability of germination damage in direct seed contact due to ammonia release from urea hydrolysis. Application rates of UAP in seed contact should be lower than DAP. While APP provides some superior physical characteristics in liquid fertilizers, agronomic capabilities of MAP, DAP, APP, and UAP are essentially equal.

- **Physical form of phosphorus fertilizers.** Solid and fluid forms of P involve the same compounds mentioned earlier. Agronomic capabilities of solid and fluid P sources are essentially equal. Handling differences, adaptability to methods of application, and abilities to co-apply micronutrients as well as pesticides are valid management considerations when evaluating P fertilizers.
- **Phosphorus placement.** Placement can have tremendous effects on crop responses to applied P. For more information on placement, see the article beginning on page 34.

Crop Maturity... *(continued from page 15)*

TABLE 4. Balanced P and K increase proportion of cotton in first picking (Tennessee).

P_2O_5, lb/A	K_2O, lb/A: 0	30	60
	% cotton in first picking		
0	65	71	74
40	77	77	77
80	78	78	78
120	78	81	79

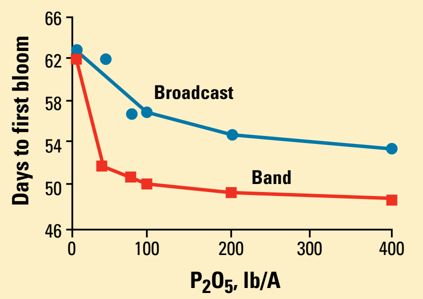


Figure 3. Influence of P rate and placement on time to first bloom of tomato plants.

P hastened first bloom in tomatoes by as much as 10 days or more. Broadcast treatments were less effective in promoting early bloom, **Figure 3**.

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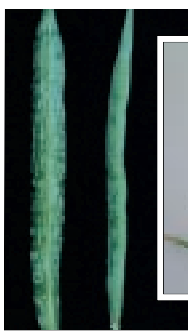
Donald L. Armstrong, Editor

Phosphorus Deficiency Symptoms in Some Crops

The classic deficiency symptoms for phosphorus (P) or other nutrients in crops can be described, but they may not always be so obvious in the field. Sometimes, other conditions can complicate the appearance and cause difficulty in diagnosis. For example, herbicide effects, insect damage, weather, or soil conditions are common field problems and can be related to nutrient deficiency or toxicity. Interactions involving more than one nutrient may also affect appearance of symptoms.

Following are photos and descriptions of P deficiency for several major crops.

Alfalfa: Symptoms of P deficiency in alfalfa may include dark green or purplish leaves, with tip death in some cases. Upward tilting of leaflets and stunted growth may occur. Reduced nodulation and increased winterkill may be other consequences. Alfalfa plants deficient in P may appear water stressed. The photo at left above shows alfalfa in a plot fertilized with P. The photo at right above shows severe P deficiency in alfalfa



Canola: Phosphorus deficiency restricts root and top growth in canola. Mildly deficient plants are small, but appear normal. With more severe deficiency, the root system is poorly developed and stems are thin and erect with few branches and small, narrow leaves. Leaves and stems may develop a purplish discoloration, or leaves may become a dark bluish-green. In the photos shown here, P-sufficient plants and pods are on the left, P-deficient on the right.

Corn: Inadequate P may result in dark green plants with reddish-purple tips and leaf margins. It is more likely to appear on young plants, especially on soils that are cold, wet, or too dry. The purple color does not necessarily signal P deficiency, because that is the normal appearance in some hybrids. Some hybrids may be deficient without obvious symptoms.

Cotton: Deficient plants may be stunted, with leaves darker green than normal. Flowering may be delayed and boll retention poor. Premature senescence of leaves may occur on P-deficient plants later in the season. Deficiency does not usually occur in early growth of cotton.

Grapes: Deficiency of P has not been a widespread problem in vineyards. Where symptoms have been observed, they are variable depending on variety. In white varieties the primary and secondary veins remain green while the interveinal tissue becomes chlorotic. Symptoms first appear on the leaf margin. In red grapes interveinal tissue yellows and turns red, producing islands of red tissue surrounded by yellow-green veins. Few grapes clusters form per vine, are small with poor set, and shot berries.

Potatoes: Stunted growth and dark green color may be signs of P deficiency. Leaf roll and upward cupping of leaf blades sometimes occur as severity of deficiency increases. Symptoms are more likely when soil temperatures are relatively low. Phosphorus deficiency is more frequent on acid and calcareous soils or on kaolinitic soils.

Source: LSU Agricultural Center Louisiana Cooperative Extension Service

Rice: Phosphorus deficiency does not always show a distinct purple color in rice and other grass plants. Symptoms may be observed in seedling rice as severe stunting, small diameter stems, and lack of tillering. The dark green color of deficient leaves can vary to light green or yellow, lighter leaf colors being associated with cool temperatures.

Sorghum: Plants deficient in P appear stunted and may be spindly, with low vigor. Dark green leaves may also show dark red color. Leaf tips and interveinal tissue show redness that progresses toward the base, veinal tissue, and midrib. The entire leaf may become red. With more severe deficiency, leaves turn pale brown and die, and roots may turn dark and discolored.

Sugarcane: Because P is mobile in the plant, deficiency usually occurs first in older tissues. Distinct symptoms are not always obvious. The main effect of deficiency is retarded growth. Older leaves may turn yellow and eventually die back from tips and along margins.

Soybeans: Phosphorus is required for normal fixation of nitrogen (N) in soybeans. Relatively large amounts of P are needed, especially at pod set. Uptake of P may be reduced in cool, wet soils; deficiency symptoms are not always clear. Leaves may turn dark green or bluish green, and the leaf blade may curl up and appear pointed. Phosphorus deficiency can delay blooming and maturity.

Turfgrasses: Phosphorus is critical to the establishment of most turfgrasses. Various turfgrass species respond differently to seedbed P application and have differing requirements. Common bermudagrass seedlings are shown here in P-deficient conditions.

Wheat: Wheat and other small grains deficient in P tend to be stressed and more susceptible to root diseases. Deficient plants may maintain a healthy-looking green color, but grow slowly and mature late. Leaf tips may die back when deficiency is severe, and some varieties may show shades of purple or red.

Phosphorus and Water Use Efficiency

Phosphorus helps crops use water more efficiently in a complete and balanced soil fertility program. Water use efficiency (WUE) can be expressed as units of yield per inch of water used. Phosphorus increases WUE and drought tolerance of crops in several ways.

- Earlier and fuller canopy development reduces soil water evaporation and the erosive energy of raindrops.
- Heavier crop residues decrease soil crusting and increase soil organic matter and tilth, resulting in increased water infiltration and reduced runoff and soil erosion.
- Root activity and proliferation are increased, thereby expanding the soil volume from which roots extract water and nutrients.
- Vigorous and healthy plants have greater resistance to diseases and nematodes and can better compete with weeds.
- Earlier maturity avoids heat and moisture stress during the pollination period for corn and other crops.

Phosphorus (P), in a balanced soil fertility program, increases water use efficiency and helps crops achieve optimal performance under limited moisture conditions.

Phosphorus and WUE

When P fertilization increases root density and rooting depth, the amount of water available to the plant is increased. Furthermore, when P increases yield, WUE also increases. In an Arizona study, alfalfa receiving high P fertilization levels produced higher yields for a given amount of moisture (**Table 1**).

The interaction of P with other nutrients is often important in determining WUE. On a Texas soil that tested medium in P, WUE increased little beyond nitrogen (N) rates of 120 lb/A where no P was applied. However, WUE increased markedly with P fertilization within each N rate (**Figure 1**). The highest N and P rates resulted in a WUE of over 200 percent higher than the control.

Temperature and Phosphorus Affect WUE

Starter P can help overcome slow growth due to cold soil temperatures. Cool soil temperatures inhibit root growth. Phosphorus placed in a concentrated band near the seed can encourage vigorous early growth that results in a larger root system, increased

TABLE 1. Phosphorus increases alfalfa yield and WUE.

P_2O_5, lb/A	Yield, tons/A	WUE, lb/inch of water
100	8.3	188
200	9.4	213
400	11.2	253
600	11.8	267

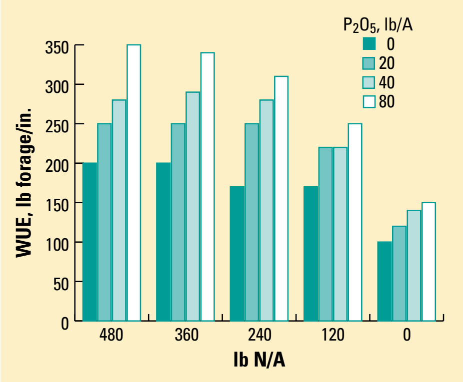


Figure 1. Effect of N and P fertilization on ryegrass water use efficiency.

TABLE 2. Effect of P rate and placement on forage wheat yield.

P rate, lb P_2O_5/A	P placement	March 9	April 2	April 22	Total
		Harvest dates			
		Yield, lb/A			
0	—	500	980	1,814	3,294
30	Surface	430	1,016	1,970	3,416
60	Surface	361	1,208	2,190	3,759
90	Surface	458	1,286	2,278	4,022
30	Deep	616	1,473	2,338	4,427
60	Deep	844	1,807	2,824	5,475
90	Deep	967	1,895	3,380	6,242

WUE, and higher yields. A Texas study showed that yield increases from P placed with forage sorghum seed were higher in cooler soil temperatures (**Figure 2**). These yield increases were observed even though soil test P was very high.

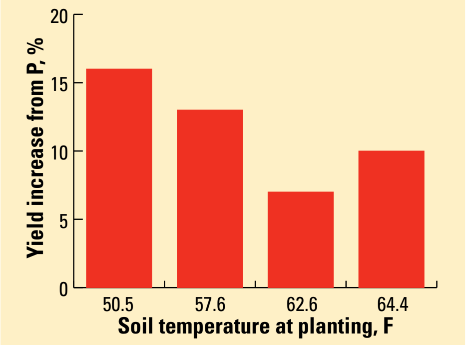


Figure 2. Percent yield increase of forage sorghum due to in-furrow P fertilization.

Phosphorus Placement and WUE

Placement of P can affect WUE. Studies conducted in arid west Texas have shown that deep placement of P increases wheat forage yield over surface incorporated application (**Table 2** and **photo**). Where moisture is low in the upper few inches of soil and P is placed near the surface, neither P nor water is used efficiently. When P is banded 8 to 10 inches deep, where soil water is more abundant, WUE is increased. Optimizing positional availability of P is important in maximizing WUE, especially during dry periods.

Deep-placed fertilizer benefits wheat forage production. On the right, N, P, potassium (K), and sulfur (S) were deep-banded, while the center received N only.

Phosphorus Improves Crop Yields in Saline Conditions

Crop yields may suffer in saline soil conditions. South Dakota research showed that P fertilization can help overcome the adverse effects of salinity (**Figure 3**). The yields of both oats and barley increased remarkably under saline soil conditions as P rate increased. Furthermore, application of P with the seed proved to be much more effective in alleviating the adverse affects of salinity then broadcasting P. Symptoms of salt injury in the field were completely alleviated with applications of at least 40 lb broadcast or 20 lb in-furrow banded P_2O_5/A.

Summary

- Phosphorus increases water use efficiency by increasing crop yields and root density and depth.
- Good P nutrition helps maximize crop

(continued on page 27)

Phosphorus Nutrition Improves Plant Disease Resistance

Phosphorus improves resistance and tolerance to diseases that can reduce crop yield and quality. The protection that P provides is often related to the role it plays in plant development. For example, P is important in early root development and plays a key role in promoting proper seed development. In addition, it provides the stored energy necessary for driving major plant functions.

Phosphorus (P) is an important element in a complete and balanced fertility program that can improve crop health and reduce the incidence and severity of many crop diseases.

Root System

One of the best defenses against root diseases is a vigorous and well developed plant root system. The role that P plays in promoting rapid root development in young plants is well established. Under adverse or stressful conditions early root development is especially important. The negative impact of root diseases in several crops may be reduced by the application of P fertilizer.

Application of 100 lb P_2O_5/A to a soil low in P in Canada reduced yield losses from common root rot from 15 percent to 9 percent with four varieties of barley. Applied P reduced disease infection of barley in other studies from 42 percent without P fertilization to 21 percent with P.

In Oregon, researchers recommend banded application of P where there is a high probability of take-all root rot infection. The scientists noted that response to banded P is likely when take-all is present in soils that would otherwise be non-responsive. In addition, the Oregon research demonstrated the importance of the interaction between banded P and chloride (Cl) fertilization and its effect on wheat yield in a soil with high risk of take-all infection (**Table 1**).

Stem and Leaf Diseases

The likelihood of stem and leaf disease problems increases with crop stress and nutrient shortages and imbalances. The results of a Virginia experiment, illustrated in **Figure 1**, show the effect of P and potassium (K) fertilization on reduced pod and stem blight infection of soybeans.

In a Kansas study, wheat yields were increased and leaf rust pressure was decreased by applying adequate P and K fertilizer. Yields were increased by as much as 30 bu/A, and leaf rust was reduced by an average of 27 percent by the improved nutrition provided by both P and K fertilization.

Foliar applications of P, K, and P+K to cucumbers in a greenhouse study provided up to 94 percent systemic protection from powdery mildew. The scientists conducting this study concluded that "The efficiency of induction of systemic protection and curative properties of phosphate and potassium fertilizers

TABLE 1. Influence of P and Cl fertilization and planting date on wheat yield.

	Planting date			
	October 4		October 27	
	Cl rate, lb/A			
P_2O_5 rate, lb/A	35	435	35	435
	Yield, bu/A			
0	41	50	61	74
60	40	73	65	82

High soil test P and high risk of take-all infection.

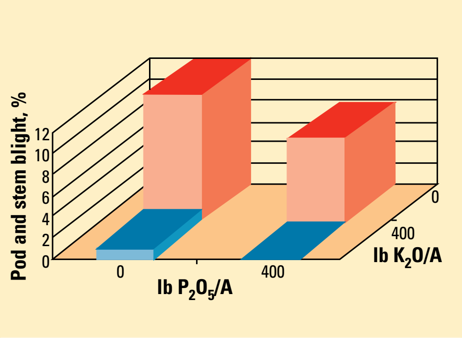


Figure 1. Effect of P and K fertilization on pod and stem blight infection of soybeans.

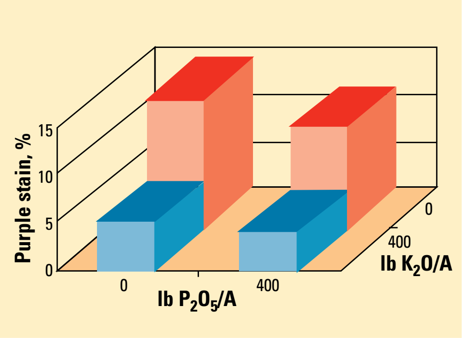


Figure 2. Effect of P and K fertilization on purple stain of soybean seed.

can be considered for disease control in the field".

Scientists concluded in a survey of Illinois field research that applied P reduced cob rot of corn on low P soils when the causal organism was Fusarium. Other studies have revealed that P can reduce the incidence of boil smut of corn.

Phosphorus and K helped reduce purple stain, Cercospora, in soybean seed in a Virginia study (**Figure 2**). Purple stain can lead to dockage and reduced profit. Other studies relate sound P nutrition to less shriveled seed and improved soybean seed germination.

Plants under nutrient stress are more susceptible to disease attack. Therefore, balancing P with other nutrient inputs is essential in reducing the risk of disease occurrence. For example, high levels of nitrogen (N) relative to P and other nutrients can lead to severe outbreaks of *Pythium*, *Rhizoctonia*, *Drechslera*, *Bipolaris*, *Typhula,* and other diseases in turfgrass.

Plant resistance to diseases can be reduced by any of several factors that result in stress. Some of these factors are drought, compaction, excess moisture, temperature extremes, physical plant injury, and nutrient imbalances. Phosphorus is a critical component of a balanced fertility program that results in crops that are better able to withstand stress and are consequently less susceptible to disease infection. BC

Water Use Efficiency... *(continued from page 15)*

yields and water use efficiency in periods of moisture stress and in saline conditions.

- Placement may be a factor in maximizing the moisture-related benefits of P. BC

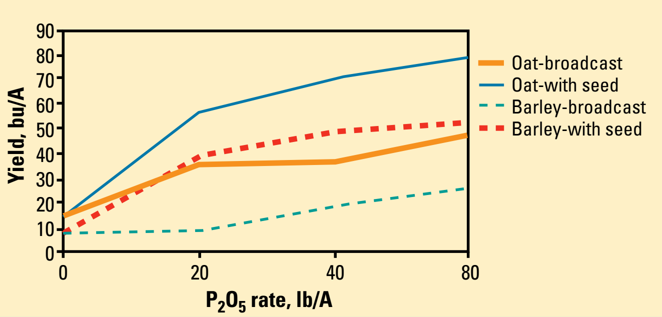


Figure 3. Effect of P fertilization rate and placement on yield of oats and barley under saline soil conditions.

Phosphorus Improves Crop Quality

Higher crop quality from P fertilization is a bonus on top of higher yields. Phosphorus improves crop quality in many ways: less grain drying expense, higher sugar content, less disease loss, improved winter survivability, less dockage, a greater proportion of marketable yield, better feed value, and improved drought resistance.

Improved crop quality is a benefit of phosphorus (P) which may be overlooked. Quality factors include maturity, winterhardiness, sugar content, feed value, or reduced disease loss for various crops.

Lower grain moisture of corn at harvest is an added advantage of P fertilization often overlooked.

It is easy to see corn maturing faster. However, another important benefit of P fertilization is a lower drying expense. An example from Ohio, shown in **Table 1**, demonstrates this well.

Phosphorus increased corn yield by a profitable 34 bu/A, while reducing grain moisture by nearly 3 percent. This translated into a savings of $10/A, assuming a drying charge of 2¢ for each percent of moisture removed per bushel.

Iowa State research has shown that when corn is grown on high P soils, grain produced is significantly higher in P content. Producing high yielding corn on high P soils could help reduce the soil P content while at the same time providing a higher P grain for livestock feed. This also means that uptake and removal estimates used for nutrient management planning should be based on grain analysis rather than standard tables.

A higher sugar content was the result of P fertilization of sugarcane in a Louisiana experiment.

Improved survival of winter barley was a quality benefit of P found by New York researchers. The initial level of soil P played a major role in determining barley yield. Direct applications of fertilizer P could not compensate completely for a low P soil, as shown in **Table 2**.

In Manitoba, P increased winter survival of zero-tilled wheat. Without P, 60 percent of the plants survived compared to 74 percent survival with 45 lb/A of applied P_2O_5. In Alberta, 40 lb/A of P_2O_5 improved the cold hardiness of winter wheat crowns. Temperature causing 50 percent mortality was 11.3 degrees F without P_2O_5, compared to 7.2 degrees F with P_2O_5.

Virginia workers found that in addition to raising soybean yields, germination and the percent of sound seed were improved by 120 lb/A of P_2O_5 (**Table 3**). A 400 lb/A rate in a separate study reduced purple seed stain of soybeans by 6 percent.

Orange quality and total marketable yield were improved by P in Arizona research. Several important characteristics of orange production were affected.

- Percent juice by weight was increased by 7 percent.
- Solid-acid ratio was reduced by 7 percent,

TABLE 1. Phosphorus increases corn yields, reduces grain moisture, and cuts drying costs (Ohio).

P_2O_5 rate, lb/A	Corn yield (15.5% moisture), bu/A	Grain moisture, %	Drying cost saved,[1] $/A
0	145	27.0	—
20	158	26.0	3
40	169	25.5	5
80	174	24.6	8
120	179	24.2	10
Response to P	34	2.8	

[1]Assuming 2¢ for each percent of moisture removed per bushel.

indicating a sweeter fruit.

- Marketable fruit yield was increased by 16 percent.
- Peel thickness was reduced by 8 percent.
- Fruit culled by weight was reduced by 12 percent.

TABLE 2. For best survival of winter barley both a higher soil test P level and applied P are needed (New York).

Applied P_2O_5, lb/A	Initial soil P level: Low	Medium	Medium-high	Response to soil P, %
	% plant survial			
0	17	43	79	62
20	33	59	81	48
40	35	59	84	49
80	45	63	92	47
Response to applied P	28	20	13	

TABLE 3. Phosphorus increases soybean yield and improves seed quality.

	P_2O_5, lb/A: 0	120	Yield/ quality response to P
Soybean yield, bu/A	32	41	9 bu/A
Sound seed, %	70	80	10%
Germination, %	85	95	10%

TABLE 4. Effect of residual P applications and applied P on raising the P content of wheat grain.

P applied with seed, lb/A P_2O_5	Residual P, lb/A P_2O_5: 0	820	Response to residual P
	Percent P in grain		
0	0.31	0.40	0.09
102	0.35	0.41	0.06
Response to applied P, %	0.04	0.01	

The P content of wheat is an important quality factor because it affects the grain's worth as an animal feed. Wheat grown in Saskatchewan, for example, often tests below the minimum P requirement for animal feeding. Researchers looking for ways to elevate wheat grain P content to acceptable levels found that residual soil P was more effective than P applied with the seed at planting (**Table 4**). The benefit from the residual P persisted for eight years.

Improved drought resistance is another quality benefit of P fertilization. In Ohio research, a good year was followed by a year of greater heat and moisture stress. The P in the stress year boosted soybean yields by 6 bu/A, compared to no yield increase in the good year.

Market quality of potatoes is strongly affected by P nutrition. Inadequate P results in small tubers that do not meet size and grade standards. Adequate P produces a large percentage of U.S. No. 1 potatoes.

Apple quality also appears to be linked with P compounds. In fruit with superficial scald, when comparing the scald-affected side to the unaffected side, all P compounds are higher in the good side.

Processor interest in protein and oil components is increasing, and understanding the P nutrition impacts on these components will become more important. Research into the impact of soil nutrient levels on the food and feed quality constituents of soybeans and grains is just beginning. Initial work shows that variability of quality components is controlled up to 60 to 65 percent by environmental conditions, including soil nutrient levels. The other 35 to 40 percent is controlled by genetics.

Genetic engineering is providing a wide range of new crop varieties, some specifically developed to produce pharmaceuticals and special nutrient components for human or animal diets. These "nutraceutical" crops are just beginning to be studied in production systems, but it is anticipated that soil fertility levels, including P, will be important in determining yield and composition of such crops. BC

Effects of Phosphorus on Nitrogen Fixation

Phosphorus is an essential ingredient for *Rhizobium* bacteria to convert atmospheric N (N_2) into an ammonium (NH_4) form useable by plants. *Rhizobium* are able to synthesize the enzyme nitrogenase which catalyzes the conversion of N_2 to two molecules of ammonia (NH_3). The pink color, typical of healthy and effective nodules, is due to the presence of a protein called leghemoglobin. This special protein contains both iron (Fe) and molybedenum (Mo) and is responsible for binding oxygen. This creates a low oxygen environment within the nodule which allows *Rhizobium* bacteria to live and to fix N_2. Phosphorus becomes involved as an energy source when 16 molecules of adenosine triphosphate (ATP) are converted to adenosine diphosphate (ADP) as each molecule of N_2 is reduced to NH_3. The ATP is generated during the process of photosynthesis, when light energy is transformed and stored in the form of ATP for later use by the plant.

Phosphorus (P) enhances the symbiotic nitrogen (N) fixation process in legume crops. Generally, legumes require more P than grasses for root development and energy driven processes.

Phosphorus influences nodule development through its basic functions in plants as an energy source. Inadequate P restricts root growth, the process of photosynthesis, translocation of sugars, and other such functions which directly or indirectly influence N fixation by legume plants. The fundamental practice of liming acid soils to the pH range of 6.5 to 7.0 is significant to the relationship between P and the symbiotic N fixation process. It improves the availability of soil P for plant absorption and creates a soil environment more favorable for beneficial bacteria such as the different strains of *Rhizobium*.

Research documents the influence of P on nodule development and the N fixation process by legumes. For example, when P was applied to alfalfa, nodules developed earlier. On high P soils, nodules were first noted on alfalfa roots 11 days after seeding. Nodules developed about three days later on low P soils. As shown in **Table 1**, nodule number, volume, and dry weight can be increased by treating P deficient soils with fertilizer P. The nodules became pink earlier, developed more quickly, and became active sooner in response to P fertilization.

Phosphorus Increases Yield and Nitrogen Content in Legumes

Other studies reveal that P applied to low P soils can increase the percent N in legumes and result in greater dry matter yields (**Table 2**). This is believed to be one of the reasons why legumes, dependent on symbiotic N, have a higher P requirement than grasses which depend on fertilizer N.

Facts Related to Phosphorus and Nitrogen Fixation

- Nodules develop when a root hair (growing out from active roots) is infected by Rhizobium bacteria. Plant tissue develops around the infected area, forming the nodule and site of bacterial growth and the fixation of elemental N from the soil

TABLE 1. Effect of P on nodule development of alfalfa 26 days after seeding.

P_2O_5 rate, lb/A	Measurements of nodule development: Dry weight	Weight/nodule	N content
	mg	mg	mg
0	0.13	13	0.01
125	1.06	28	0.07
255	3.31	60	0.15

TABLE 2. Effect of P fertilization on the yield and N content of legumes.

Crop	Yield, lb/A		Tissue N, %	
	No P	P	No P	P
Sub. clover	2,400	3,400	2.5	2.8
Alfalfa	4,980	10,710	3.8	4.3

atmosphere. Any restriction to root development, a shortage of essential nutrients such as P or Mo, an excessively acid soil, or a decline in photosynthesis can restrict nodulation and N fixation.

- The N fixation process requires a readily available source of energy for bacterial growth and the transformation of N_2 into NH_3. Photosynthesis generates the high energy sugars. Phosphorus provides the mechanism for energy storage in the form of ATP and the transfer of that energy source to fuel vital plant functions such as N fixation.
- The translocation of photosynthate from leaves to roots and the movement of N-containing compounds from nodules to other plant parts are vital to an efficient symbiotic system. Phosphorus is an integral part of the compounds needed to drive the system.
- The concentration of P in the tissue of healthy, active nodules is often two to three times higher than in the roots on which they are formed. Legumes need a readily available supply of P from the soil. It serves during critical growth periods such as seedling root development and over a more prolonged period for optimum photosynthesis.

Summary

Phosphorus plays a key role in the symbiotic N fixation process by:

- Increasing top and root growth (restricted root development reduces the ability of that plant to fix N)
- Decreasing the time needed for developing nodules to become active and of benefit to the host legume
- Increasing the number and size of nodules and the amount of N assimilated per unit weight of nodules
- Increasing the percent and total amount of N in the harvested portion of the host legume
- Improving the density of *Rhizobia* bacteria in the soil surrounding the root BC

Phosphorus encourages root growth and N fixation in legumes. These soybean root nodules contain N-fixing bacteria.

Phosphorus in Animal Nutrition

In the animal body, about 80 percent of P is found in the skeleton. Its major role is as a constituent of bones and teeth. The remainder is widely distributed throughout the body in combination with proteins and fats and as inorganic salts.

> Phosphorus (P) is an essential nutrient for all animals. Deficiency of P is the most widespread of all the mineral deficiencies affecting livestock. Phosphorus must be balanced in the animal diet with adequate calcium (Ca) and vitamin D for growth, reproduction, gestation, and lactation.

Phosphorus constitutes about 22 percent of the mineral ash in an animal's body, a little less than one percent of total body weight. It is essential in transfer and utilization of energy. Phosphorus is present in every living cell in the nucleic acid fraction.

Calcium and P are closely associated with each other in animal metabolism. Adequate Ca and P nutrition depends on three factors: a sufficient supply of each nutrient, a suitable ratio between them, and the presence of vitamin D. These factors are interrelated. The desirable Ca:P ratio is often between 2:1 and 1:1.

Vitamin D_3 is essential for Ca utilization. Inadequacies in the vitamin will imbalance the available Ca:P.

A liberal supply of Ca and P is essential for lactation. Calcium and P make up about 50 percent of the ash of milk.

Earliest symptoms of P deficiency are decreased appetite, lowered blood P, reduced rate of gain, and "pica", in which the animals have a craving for unusual foods such as wood or other materials. If severe deficiency occurs, there will be skeletal problems.

Milk production decreases with P deficiency, and efficiency of feed utilization is depressed. Long-term P deficiency results in bone changes, lameness, and stiff joints.

Cattle: Young and growing animals require relatively more P than do mature ones. Gestating and lactating animals need more P than other classes of mature animals. Specific P requirements for maintenance, growth, lactation, and pregnancy depend on many factors. Recommendations in National Research Council (NRC) publications are based on complex models that consider body size, breed, milk production levels, and environmental conditions.

For dairy cattle, the Ca:P ratio should be at least 2.4:1 for cows when lactating, but should be less than 1.6:1 for dry cows to minimize Ca intake during that period. For beef cows and feedlot cattle, the ratio is not so critical, although normally it would not be allowed to exceed 4:1.

Supplemental dietary P is needed under most practical feeding situations. Deficiency of P is the most widespread and economically important of all the mineral deficiencies affecting grazing livestock.

On grazed pasture, where soils are low in P, fertilizing with P can reduce risk of grass tetany. Research in Missouri showed that adding about 60 lb/A of P_2O_5 increased the magnesium (Mg) content of tall fescue leaves.

Phosphorus enhances reproductive performance at several stages in the reproductive cycle. In Arizona tests, P increased rebreeding efficiency for beef cows. Irregular estrus periods have been associated with moderate P deficiency, infertility with marginal P levels, and anestrus with low P levels in Australia. In Texas tests, 64 percent of the control cows produced a calf on range alone compared to 85 percent of the cows on range plus P supplement.

Phosphorus has been shown to increase fertility, calving rates, calf growth rates, and, when applied to pastures, carrying capacity.

Swine: A suggested ratio of total Ca to total P is between 1:1 and 1.25:1. When based on available P, the ratio between total Ca and digestible P should be 2.8:1 to 3.3:1. Adequate vitamin D is needed for Ca and metabolism, but a very high level of vitamin D may mobilize excessive amounts of Ca and P from bones.

The biological availability of P in cereal grains is variable, ranging from less than 15 percent in corn to as much as 46 percent in wheat (see **Table 1**). The greater availability of wheat P is due to a naturally occurring phytase enzyme. Estimates of availability of P differ somewhat between European and North American sources. In particular, the European feed industry is tending to use monocalcium phosphate in preference to dicalcium phosphate. Low-phytate varieties of corn and barley are being developed. These will likely have normal P content with much higher bioavailability to both swine and poultry (non-ruminants).

Microbial phytase can be added to cereal grain-oilseed meal diets to make grain P more digestible. The P in a typical corn-soybean meal diet is only about 20 percent digestible, but adding phytase can increase the digestibility to as much as 46 percent.

The use of phytase can reduce dietary P requirements and lower P excretion by as much as 30 percent. Recent studies in Europe suggest that adding phytase can also improve feed conversion slightly, by 1 to 2 percent. One difficulty with phytase is its sensitivity to heat during feed processing.

Poultry: Hens use most of their P in bodily functions other than egg production. But adequate P is important to achieve a high rate of egg production.

Phosphorus deficiency causes lower body weight, reduced feed efficiency, skeletal problems, and reduced eggshell quality. Low diet P can depress egg hatchability, but P content of the egg is not altered.

Caged layer hens require high P, more than hens on litter. "Cage layer fatigue syndrome" is caused by low P levels in diet. There is a high death rate.

Much work on recommended P levels has found NRC recommendations to be sound and adequate.

Horses: The Ca and P requirements of horses have received considerable attention. Both nutrients are essential for strong bone development, proper mineralization of osteoid tissue, and adequate energy utilization.

The Ca:P ratio should be monitored when P intake is greater than Ca and when low Ca utilization from feedstuffs occurs. Calcium: P ratios of 6:1 do not appear detrimental to mature horses if P intake is adequate. Foals and yearlings have been fed Ca:P ratios of 3:1 with no problems.

Goats: Phosphorus is required for tissue and bone development. A deficiency will result in slow growth, "pica" appetite, and unthrifty appearance. Low levels of P in the blood often accompany it.

Dogs and Cats: Low P diets seldom occur in properly fed pets. However, animals require adequate Ca and P in their diets to ensure strong bones and teeth and good muscle development. A P deficiency in puppies causes rickets and poor growth. In cats, a high meat diet can cause an imbalance of Ca to P, because meat is high in P. BC

Appreciation is expressed to Dr. Larry Chase of Cornell University and to Dr. Jock Buchanan-Smith, Dr. Steve Leeson and Dr. C.F.M. de Lange of the University of Guelph for their assistance in reviewing this chapter.

TABLE 1. Amounts and estimated availability of P in selected feed materials for swine.

	Corn	Barley	Wheat	Soybean meal	Dehulled canola meal	Meat and bone meal	Dicalcium phosphate	Monocalcium phosphate
				%				
P content (NRC-U.S.)	0.28	0.36	0.37	0.65	1.01	4.98	18	25
P availability (NRC-U.S.)	13	27	45	28	19	81	87	90
P availability (CVB-Europe)	16	37	46	38	30	80	65	80

Phosphorus Fertilizer Placement

Phosphorus added to soil quickly becomes fixed in less available forms as the P reacts with other soil components. Fertilizer placement helps overcome fixation. However, P moves very little in most soils so application close to where root development occurs is often desirable.

Specific recommendations for phosphorus (P) placement are difficult. There is no one best method of application. Soil and growing conditions influence placement choices. Application method can offset the effects of P fixation by soils and increase P efficiency.

Phosphorus Placement Options

Phosphorus placement can be broken into two general application methods: broadcast or band.

Broadcast. Application of fertilizer to the soil surface, with or without subsequent incorporation. Broadcast is the simplest application method and is best suited for high-speed operations and heavy application rates. When plowed or disked in, broadcasting produces the most uniform P distribution within the root zone and provides more root contact with P. However, it also maximizes contact between the soil and fertilizer so the opportunity for fixation is higher.

Band. Applications that concentrate the fertilizer in narrow zones or bands that are kept intact to provide a concentrated source of nutrients. Banding is advantageous where soil test levels are low, where early season stress from cool or wet conditions is likely to limit root growth and nutrient uptake, and for soils that have a high tendency to fix P in unavailable forms.

Phosphorus may be banded prior to, during, or after planting. Banding options include:

Deep band. Applications 2 to 6 inches below the soil surface. Knifing a narrow concentrated band of fertilizer below the soil surface as a preplant or side-banding fertilizer to the side and/or below the seedrow are forms of deep banding. Also included is dual banding, or double shooting, which is placement of two fertilizers, usually nitrogen (N) and P, together in the band.

Surface band or surface strip. Application of solid or fluid fertilizer in narrow strips on the soil surface prior to planting (may be incorporated) or over the row after planting.

Point injection. Use of a spoked wheel to inject fluid fertilizer into the rooting zone 4 to 6 inches deep at 8-inch intervals.

Starter or seed placement. Applying small amounts of fertilizer in direct contact or close to the seed (i.e. 1 to 2 inches below and to the side) at planting. Starter P is especially helpful in promoting early plant growth and enhancing seedling vigor. This early stimulation of crop growth is often termed "pop-up effect". However, starter fertilizer must be used cautiously because many crops are sensitive to seed placed fertilizer and can only tolerate low rates near the seed.

TABLE 1. Dual banding N and P increases winter wheat yields and P efficiency (Kansas).

Method N	Method P	Wheat yield, bu/A	Plant P, %
0	0	46	0.22
Band	0	51	0.21
Broadcast	0	44	0.23
Band	Band	64	0.27
Band	Broadcast	53	0.22
Broadcast	Band	56	0.23
Broadcast	Broadcast	53	0.23

Crop Response to Placement

Small grains and canola. Band applied P is generally superior to broadcast P in small grains, especially on low P soils or on soil with high fixing capacity. A "pop-up" effect from starter P is commonly observed in the Northern Great Plains, regardless of the soil P level because of cool soil conditions early in the spring.

Dual banding N and P in the fall or spring prior to seeding has increased P efficiency and yields (**Table 1**). When placed together in a band, the ammonium-N keeps fertilizer P available longer by delaying the effects of normal soil reactions that fix P.

Recent developments in reduced tillage seeding equipment and openers have permitted high rates N and P to be placed together in close proximity to the seed during planting. This equipment increases the separation between seed and fertilizer and allows all the nutrient requirements to be safely applied in a one-pass seeding and fertilizer operation. Good seed/fertilizer separation and precision placement of P are crucial for small seeded crops such as canola because oilseeds are highly susceptible to seedling damage from any fertilizer placed in direct contact with the seed.

Sunflower. Germinating sunflower seed is very sensitive to soluble salt in the soil and fertilizer applied in the row at seeding. Phosphorus requirements are similar to wheat, but P placement below and to the side of the seed is apparently beneficial.

Corn and grain sorghum. Broadcasting P before primary tillage operations is the most common application method for conventional corn. Building P fertility to high level throughout the root zone optimizes yields. However, broadcast application in conservation tillage systems leads to high concentrations of P near the soil surface. This works well where soils are warm, soil test levels are high, and adequate moisture throughout the growing season ensures root proliferation near the surface. But if soil test levels are low and growing conditions do not encourage rooting activity near the soil surface, band application is recommended.


Courtesy of Flexi-Coil.

Optimum P fertilizer placement offers greater efficiency and higher yield potential.

The effectiveness of application method in conventional and reduced tillage systems is demonstrated in the data in **Table 2**. The difference between application methods disappears when soil fertility is high.

Starter P is very effective in increasing corn and sorghum yields, but especially so in conservation tillage systems which often have cooler and wetter soils early in the spring. It can also have significant effects on grain moisture. Advanced maturity and higher yields combine to produce lower grain moisture at harvest and reduced drying costs.

Alfalfa and perennial grasses. Banding starter P directly below the seed at planting will ensure good root development and seedling establishment. Banding has also shown advantages on acidic, high-fixing soils. On low-fixing soils, broadcasting and incorporating large P applications before planting can supply P needs for several years.

TABLE 2. Phosphorus placement and soil fertility influence corn yield in conventional and reduced tillage systems (Minnesota).

	Low fertility		High fertility	
	Fall chisel	Ridge-till	Fall chisel	Ridge-till
Placement	Two-year average, bu/A			
Control	84	87	156	150
Broadcast	110	102	151	151
Surface band	108	112	152	152
Deep band	118	123	153	153

Broadcast application works well on established forages. Although P movement is restricted, perennial crops have greater root density and higher nutrient removal near the soil surface compared to annual crops. Banding P into established forage has shown little advantage over broadcasting, largely due to stand damage during the banding operation. However, recent studies have shown banding can be effective if the opener causes minimal disruption of roots and the stand.

Vegetables and potatoes. High concentrations of P in the vicinity of vegetable plant roots help avoid early season stress. Banded P has been found to be important for early season, direct-seeded tomatoes on cold, high pH soils. Starter P placed one to three inches below onion seed produced best seedling vigor, uniformity, and plant development. Researchers concluded that placement had a larger effect on onions than did rate. When N, P, and potassium (K) are banded together, potato yields may be better than broadcast application due to the complimentary effect of ammonium-N on P uptake.

Soybeans and field beans. Soybeans generally prefer broadcast placement. They respond best to an overall high P fertility in the root zone which is usually best accomplished by incorporating broadcast P. However, under drier conditions and low P soils, some Canadian researchers have found banding P below the seed will produce better yields than broadcasting. Field beans (dry beans) are sensitive to direct seed placement of fertilizers. Recommended placement is either below and to the side of the seed or broadcast.

Cotton. Broadcast and incorporation or shallow banding (2 to 4 inches) are the recommended placement methods for cotton. On medium and high P soils, there appears to be little difference between methods. However, subsoil can be very low in available P and K. Research in Mississippi has shown that when these nutrients are deficient in the subsoil, banding 6 to 15 inches deep produces better yields than broadcasting. Cotton also responds well to starter fertilizer regardless of the main method of application.

TABLE 3. Starter P increases corn yields at very high soil test levels (Wisconsin).

Soil test P, ppm[1]	Starter P_2O_5, lb/A: 0	20	40
	Corn yield, bu/A		
35	103	137	134
56	122	142	148

[1]ppm = parts per million

Summary

Band-applied P normally outperforms broadcast P at low soil test levels and modest P rates. But the differences between methods usually decrease with increasing application rates or increasing soil test levels. However, even at high soil test levels, response to starter P often occurs. For example, **Table 3** shows how starter P at rates as low as 20 lb P_2O_5/A dramatically increased corn yields even though soil test levels were very high. Similar responses have been reported for wheat, barley, potatoes, and other crops.

Cold soil conditions are usually a factor when high P soils respond to starter P, but the possibility of response on high P soils is good when any condition imposes stress early in the growing season or other production factors are optimized.

There is no one best P application method. Field conditions, soil test level, soil P buffering capacity, crop, time of application, equipment, and other management factors all influence application choice. However, some general considerations follow:

- Placement of P for small grains may be more critical than for row crops and forages. Limited root systems, shorter growing seasons, and cooler temperatures enhance the response to banded P over broadcast.
- Placement of ammonium-N with P improves P uptake and slows fixation.
- On high P soils, maintenance P applications may be effective regardless of placement method.
- Reduced tillage crops, row crops, and spring-seeded small grains may require P placement close to the seed, regardless of P soil test.
- Limited root systems in some specialty

(continued on page 39)

Phosphorus and the Environment

Phosphorus is an extremely immobile nutrient in the soil. It is adsorbed very strongly to soil particle surfaces and quickly forms stable compounds by reacting with common soil constituents such as iron (Fe), aluminum (Al) and calcium (Ca). For this very reason, P is commonly a limiting nutrient for plant growth, and P inputs are needed for crop production.

Phosphorus (P) is essential for all life. Without adequate levels, profitable agriculture would be impossible and food production inadequate. The loss of P to surface water is an environmental risk that can be controlled with attention to erosion and runoff factors influencing P transport and appropriate management of P sources.

Its tendency to remain undissolved is also the reason why P is often the limiting nutrient in surface waters for the growth of aquatic plants and algae. When P losses increase, enrichment or eutrophication to the point of undesirable blooms of algae can occur in some situations.

Eutrophic conditions can occur in surface waters when P concentrations exceed 0.01 to 0.03 parts per million (ppm). However, most crop plants need to have P concentrations roughly 10-fold greater in the soil solution in the rooting zone throughout the growing season. Although it would appear there is a direct conflict between levels of P desired for agronomic and environmental concerns, the conflict is not nearly so fundamental. In aquatic systems, just as in soil, P tends to form stable compounds, precipitate, and settle out.

One well-known example is Lake Erie. Programs implemented in the last 25 years to reduce P loadings to the lake from industrial, municipal, and agricultural sources have resulted in reduced lakewater P concentrations. In the lake's central basin, P concentrations have declined from as high as 0.025 ppm in the early 1970s to less than 0.010 ppm in the 1990s. In fact, P loadings have declined to the point where fisheries agencies have called for a halt to further reductions. There is concern that additional reductions in P inputs would cause serious harm to the lake's most important fish species, such as yellow perch, rainbow smelt, and walleye.

The main pathway of P loss to surface water is in runoff water. Runoff can carry suspended particles of soil, which carry the bulk of P lost from agricultural fields. In addition, runoff carries some dissolved P. Drainage water, particularly from tile drains, can also carry small amounts of both forms of P. The relative amounts lost in each pathway depend on the crop, soil management, and the level and source of nutrient loading. The pathways other than erosion generally become important only for soils with excessive loadings from organic sources of P.

Tillage management to reduce erosion and runoff also reduces P losses. When one of

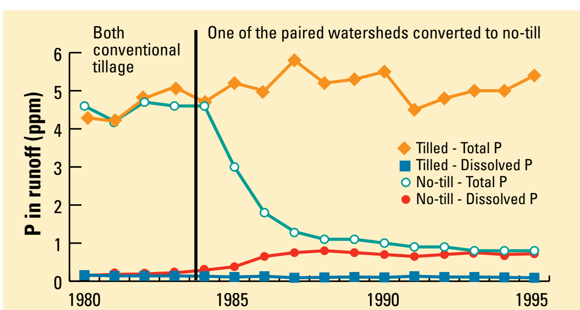


Figure 1. No-till management, starting in 1984, reduced the concentration of total P in runoff in an Oklahoma watershed.

a pair of watersheds in a wheat growing area of Oklahoma was converted to no-till management, it reduced the concentration of total P much more than it increased dissolved P concentrations (**Figure 1**). In addition, runoff volume and erosion were reduced by 95 percent with no-till, so no-till management dramatically reduced the total loss of P.

An estimated 50 percent of total soil loss due to erosion in recent years in the U.S. occurred on 10 percent of the nation's cropland. This suggests big gains could be made by controlling erosion on these very erodible acres.

TABLE 1. Percentage of soils testing medium or less for P.

State	Percent medium or less for P 1975	1986	1997
Manure-surplus states			
North Carolina	37	37	26
Delaware	37	39	26
Maryland	54	43	33
Crop-surplus states			
Illinois	48	44	36
Ohio	45	38	49
South Dakota	59	76	71
North American average	**60**	**53**	**46**

Soil Test Phosphorus Status

Where localized surpluses of animal manure are applied to cropland, soil test P levels tend to build up. On the other hand, nutrient exports from states producing surpluses of crops can lead to declining soil test levels if not balanced by adequate fertilization. The percentage of soils testing medium or less for P is declining where manure is in surplus, but usually holding steady or increasing where the major crops are grown, as shown for selected states in **Table 1**. Regions with a small percentage of soils medium or less in P are not necessarily a greater risk to the environment, as the critical level used here is for agronomic rather than environmental purposes, and important soil hydrological factors are not considered.

While some soils have been built to high P levels, a very substantial number of soils still test in the medium or less range. Across North America in 1997, 46 percent of soils tested medium or less in P. With good crop production management, many of these soils would benefit from buildup applications of P, in addition to the annual maintenance rates, to help assure a profitable yield level and the most efficient use of nitrogen (N) and other inputs.

Nutrient Balance

The total amount of P applied in the U.S. as commercial fertilizer was 4.6 million tons in 1997. In comparison, estimates of the amount of P_2O_5 in recoverable manures range from 1.4 to 3.1 million tons. In the Corn Belt, the corn-soybean rotation is in deficit, removing more P in the crop than is applied in

TABLE 2. A modified Phosphorus Index, with suggested weighting factors. The transport factors are multiplied by the sum of the source factors to rate the site for potential risk of P loss. For example, a site with every characteristic at 'medium' would have a rating of (0.8 x 0.8 x 0.8 x 0.6) x (1.0 x 2 + 0.75 x 2 + 0.5 x 2 + 1.0 x 2 + 1.0 x 2) = 3.5.

Site characteristic	Weighting factor	Loss rating Zero	Low	Medium	High	Very high
Transport						
Soil erosion	1.0	0.6	0.7	0.8	0.9	1.0
Irrigation erosion	1.0	0.6	0.7	0.8	0.9	1.0
Soil runoff class	1.0	0.6	0.7	0.8	0.9	1.0
Distance from watercourse	1.0	0.2	0.4	0.6	0.8	1.0
Source						
Soil test P	1.0	0	1	2	4	8
Fertilizer rate	0.75	0	1	2	4	8
Fertilizer P placement	0.5	0	1	2	4	8
Organic P rate	1.0	0	1	2	4	8
Organic P placement	1.0	0	1	2	4	8

TABLE 3. Generalized interpretation of the Phosphorus Index.

Phosphorus Index	Generalized interpretation
less than 5	**LOW** potential for P loss. If current farming practices are maintained, there is a low probability of adverse impacts on surface waters.
5-8	**MEDIUM** potential for P loss. The chance for adverse impacts on surface waters exists, and some remediation should be taken to minimize the probability of P loss.
9-22	**HIGH** potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and a P management plan are needed to minimize the probability of P loss.
more than 22	**VERY HIGH** potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and a P management plan must be implemented to minimize the P loss.

manure and fertilizers. However, in areas of the country with concentrated animal production, local P surpluses can be large.

The Phosphorus Index

Soil test levels are not adequate indicators of risk of P loss. An index must consider both source (soil test P and applied P) and transport factors. Erosion and runoff are the primary transport pathways. These depend on soil and landscape properties such as slope, soil cover, distance to watercourse, and infiltration properties. Placement of applied P is important, as these transport pathways are most active at the soil surface.

The Phosphorus Index is being developed as a screening tool to rank sites for potential loss of P. The site characteristics used in the index are shown in **Table 2**. Weighting of the factors and the method of calculating the index vary in different versions. **Table 3** shows how the index can be interpreted.

Several watershed studies have shown that 90 percent of the P lost to surface water arises from 10 percent or less of the land area. Such areas occur where both the source and transport factors are high. Use of the Phosphorus Index will allow greater flexibility in placement of manure and fertilizer to build soil fertility in areas where the benefit to crop production will be the greatest and the risk of harm to the environment will be at a minimum. Management efforts for high yield cropping systems, focused on areas unlikely to harm the environment, will produce more food on less land, relieving pressure to use marginal, erodible land for crops. BC

*Phosphorus Fertilizer Placement...**(continued from page 36)*

and vegetable crops make P placement an important management practice.

- Where P fixation is an overriding factor, banding all the P is probably advisable. High P concentrations in bands help delay fixation reactions.
- High yielding row crops, especially corn, may require relatively high P levels throughout the rooting zone for maximum yields. On low to medium P soils, banding at least some of the P may provide a yield advantage.
- Where P use has been minimal in the past and resources are limited, banding moderate amounts of P on more acres will likely optimize returns. BC

Phosphorus for All

What's so great about phosphorus? Phosphorus is present in every living cell. Without it, there would be no life...human, animal or plant.

Did you know that phosphorus is the second most abundant mineral element in the human body – that it makes up more than 20 percent of the body's minerals? What we eat is our source of this life-giving element.

Research shows that most of the soils of the Earth cannot naturally supply the phosphorus necessary to produce the world's food needs.

For centuries, farmers have added phosphorus to the soil through manures and organic residues. Even with this, it is impossible to feed the world's burgeoning population without the phosphate fertilizer industry.

The North American industry mines phosphate rock in areas where natural deposits occur and converts it into forms useable by plants.

With this industry...healthy plants, good yields, less erosion, environmental protection

With this industry...strong bones, healthy bodies, vital energy

All impossible without phosphorus. We can live without computers or cars, but not without phosphorus.

The phosphate industry has long recognized its responsibility – to the people of the world. Through PPI/PPIC, industry supports research and educational programs to determine phosphorus needs for an improved environment and greater farm profits.

How often do we fail to recognize our blessings.

J. Fielding Reed

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