3 Phosphorus

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3.1 BACKGROUND INFORMATION

3.1.1 Historical Information

Incidental phosphorus fertilization in the form of manures, plant and animal biomass, and other natural materials, such as bones, probably has been practiced since agriculture began. Although specific nutritional benefits were unknown, Arthur Young in the *Annuals of Agriculture* in the mid-nineteenth century describes experiments evaluating a wide range of products including poultry dung, gunpowder, charcoal, ashes, and various salts. The results showed positive crop responses to certain materials. Benefiting from recent developments in chemistry by Antoine Lavoisier (1743–1794) and others, Theodore de Saussure (1767–1845) was perhaps the first to advance the concept that plants absorb specific mineral elements from the soil.

The science of plant nutrition advanced considerably in the nineteenth century owing to contributions by Carl Sprengel (1787–1859), A.F. Wiegmann (1771–1853), Jean-Baptiste Boussingault (1802–1887), and Justus von Liebig (1803–1873). Based on the ubiquitous presence of phosphorus in soil and plant materials, and crop responses to phosphorus-containing products, it became apparent that phosphorus was essential for plant growth.

Liebig observed that dissolving bones in sulfuric acid enhanced phosphorus availability to plants. Familiar with Liebig's work, John Lawes in collaboration with others, evaluated several apatite-containing products as phosphorus nutritional sources for plants. Lawes performed these experiments in what ultimately became the world's most famous agricultural experiment station—his estate in Rothamsted. The limited supply of bones prompted developments in the utilization of rock phosphates where Lawes obtained the first patent concerning the utilization of acid-treated rock phosphate in 1842, The first commercial production of rock phosphate began in Suffolk, England, in 1847. Mining phosphate in the United States began in 1867. Thus began the phosphorus fertilizer industry.

Crop responses to phosphorus fertilization were widespread. For many years phosphorus fertilization practices were based on grower experience often augmented with empirical data from experiment station field tests. Although researchers and growers realized that customized phosphorus fertilizer recommendations would be invaluable, early work often focused on total element content of soils and produced disappointing results. The productivity of soil essentially showed no correlation to total content of nutrients in them.

It was during the twentieth century that the recognition that the plant itself was an excellent indicator of nutrient deficiency coupled with considerable advances in analytical methodology gave way to significant advances in the use of tissue testing. Hall (1) proposed plant analysis as a means of determining the normal nutrient contents of plants. Macy (2) proposed the basic theory that there was a critical concentration of nutrient in a plant above which there was luxury consumption and below which there was poverty adjustment, which was proportional to the deficiency until a minimum percentage was reached.

Also during the twentieth century, a greater understanding of soil chemistry of phosphorus and the observation that dilute acids seem to correlate to plant-available phosphorus in the soil gave way to the development of successful soil-testing methodologies. The early contributions of Dyer (3), Truog (4), Morgon (5), and Bray and Kutrz (6) are noteworthy. Plant tissue testing and soil testing for phosphorus are discussed in greater detail in the subsequent sections. For more detailed history on plant nutrition and soil–plant relationships, readers are referred to Kitchen (7) and Russell (8).

3.1.2 Phosphorus Functions in Plants

Phosphorus is utilized in the fully oxidized and hydrated form as orthophosphate. Plants typically absorb either $H_2PO_4^-$ or HPO_4^{2-}, depending on the pH of the growing medium. However, under certain conditions plants might absorb soluble organic phosphates, including nucleic acids. A portion of absorbed inorganic phosphorus is quickly combined into organic molecules upon entry into the roots or after it is transported into the shoot.

Phosphate is a trivalent resonating tetraoxyanion that serves as a linkage or binding site and is generally resistant to polarization and nucleophilic attack except in metal-enzyme complexes (9). Orthophosphate can be condensed to form oxygen-linked polyphosphates. These unique properties of phosphate produce water-stable anhydrides and esters that are important in energy storage and transfer in plant biochemical processes. Most notable are adenosine diphosphate and triphosphate (ADP and ATP). Energy is released when a terminal phosphate is split from ADP or ATP. The transfer of phosphate molecules to ATP from energy-transforming processes and from ATP to energy-requiring processes in the plants is known as phosphorylation. A portion of the energy derived from photosynthesis is conserved by phosphorylation of ADP to yield ATP in a process called photophosphorylation. Energy released during respiration is similarly harnessed in a process called oxidative phosphorylation.

Beyond their role in energy-transferring processes, phosphate bonds serve as important linkage groups. Phosphate is a structural component of phospholipids, nucleic acids, nucleotides, coenzymes, and phosphoproteins. Phospholipids are important in membrane structure. Nucleic acids of genes and chromosomes carry genetic material from cell to cell. As a monoester, phosphorus provides an essential ligand in enzymatic catalysis. Phytic acid, the hexaphosphate ester of *myo*-inositol phosphate, is the most common phosphorus reserve in seeds. Inorganic and organic phosphates in plants also serve as buffers in the maintenance of cellular pH.

Total phosphorus in plant tissue ranges from about 0.1 to 1%. Bieleski (10) suggests that a typical plant might contain approximately 0.004% P as deoxyribonucleic acid (DNA), 0.04% P as ribonucleic acid (RNA), 0.03% as lipid P, 0.02 % as ester P, and 0.13% as inorganic P.

3.1.3 Nature and Transformations of Soil Phosphorus

Soils contain organic and inorganic phosphorus compounds. Because organic compounds are largely derived from plant residues, microbial cells, and metabolic products, components of soil organic matter are often similar to these source materials. Approximately 1% of the organic phosphorus is in the phospholipid fraction; 5 to 10% is in nucleic acids or degradation products, and up to 60% is in an inositol polyphosphate fraction (11). A significant portion of the soil organic fraction is unidentified.

Phospholipids and nucleic acids that enter the soil are degraded rapidly by soil microorganisms (12,13). The more stable, and therefore more abundant, constituents of the organic phosphorus fraction are the inositol phosphates. Inositol polyphosphates are usually associated with high-molecular-weight molecules extracted from the soil, suggesting that they are an important component of humus (14,15).

Soils normally contain a wide range of microorganisms capable of releasing inorganic orthophosphate from organic phosphates of plant and microbial origin (16,17). Conditions that favor the activities of these organisms, such as warm temperatures and near-neutral pH values also favor mineralization of organic phosphorus in soils (16,18). The enzymes involved in the cleavage of phosphate from organic substrates are collectively called phosphatases. Microorganisms produce a variety of phosphatases that mineralize organic phosphate (19).

Phosphorus released to the soil solution from the mineralization of organic matter might be taken up by the microbial population, taken up by growing plants, transferred to the soil inorganic pool, or less likely lost by leaching and runoff (Figure 3.1). Phosphorus, like nitrogen, undergoes mineralization and immobilization. The net phosphorus release depends on the phosphorus concentration of the residues undergoing decay and the phosphorus requirements of the active microbial population (16).

In addition to phosphorus mineralization and immobilization, it appears that organic matter has indirect, but sometimes inconsistent, effects on soil phosphorus reactions. Lopez-Hernandez and Burnham (20) reported a positive correlation between humification and phosphate-sorption capacity. Wild (21) concluded that the phosphorus-sorption capacity of organic matter is negligible. It is observed more commonly that organic matter hinders phosphorus sorption, thereby enhancing availability. Humic acids and other organic acids often reduce phosphorus fixation through the formation of complexes (chelates) with Fe, Al, Ca, and other cations that react with phosphorus (22–24). Studies have shown that organic phosphorus is much more mobile in soils than inorganic sources (25). The

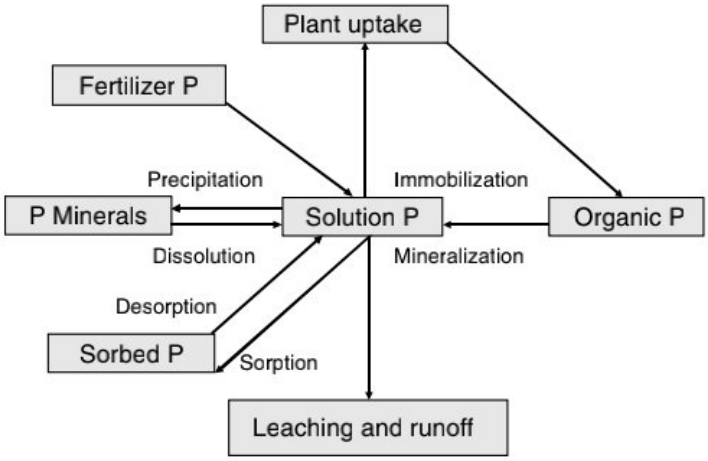

FIGURE 3.1 Phosphorus cycle in agricultural soils.

interaction between the organic and inorganic phosphorus fractions is understood poorly. It is generally presumed that phosphorus availability to plants is controlled by the inorganic phosphorus fraction, although the contribution of organic phosphorus to plant nutrition should not be dismissed.

Inorganic phosphorus entering the soil solution, by mineralization or fertilizer additions, is rapidly converted into less available forms. Sorption and precipitation reactions are involved. The sorption of inorganic phosphorus from solution is closely related to the presence of amorphous iron and aluminum oxides and hydrous oxides (26–30) and the amounts of calcium carbonate ($CaCO_3$) (24,31,32).

Hydrous oxides and oxides of aluminum and iron often occur as coatings on clay mineral surfaces (27,28,33), and these coatings may account for a large portion of the phosphorus sorption associated with the clay fraction of soils. Even in calcareous soils, hydrous oxides have been demonstrated as being important in phosphorus sorption, as was demonstrated by Shukla (34) for calcareous lake sediments, Holford and Mattingly (24) for calcareous mineral soils, and Porter and Sanchez (35) for calcareous Histosols.

In calcareous soils, phosphorus (or phosphate) sorption to $CaCO_3$ may be of equal or greater importance than sorption to aluminum and iron oxides (35). In a laboratory investigation with pure calcite, Cole (31) concluded that the reaction of phosphorus with $CaCO_3$ consisted of initial sorption reactions followed by precipitation with increasing concentrations of phosphorus. Phosphorus sorption may occur in part as a multilayer phenomenon on specific sites of the calcite surface (24,32). As sorption proceeds, lateral interactions occur between sorbed phosphorus, eventually resulting in clusters. These clusters in turn serve as centers for the heterogeneous nucleation of calcium phosphate crystallites on the calcite surface.

Phosphorus sorption is probably limited to relatively low initial phosphorus solution concentrations and precipitation is likely a more important mechanism of phosphorus removal from the soil solutions at higher concentrations (31). Lindsay (36) identified, by x-ray crystallography, what he considered to be an incomplete list of 32 forms of phosphate compounds as reaction products from phosphorus fertilizers. The nature of the reaction products formed when phosphorus fertilizer is added to soil depends primarily on the coexisting cation, the pH of the saturated solution, the quantity of phosphorus fertilizer added, and the chemical characteristics of the soil (37). In acidic soils, aluminum and iron will generally precipitate phosphorus. In calcareous soils, an acidic fertilizer solution would dissolve calcium, and it is anticipated that most of the added phosphorus fertilizer would precipitate initially as dicalcium phosphate dihydrate (DCPD) and dicalcium phosphate (DCP) (38,39). These products are only moderately stable and undergo a slow conversion into compounds such as octacalcium phosphate, tricalcium phosphate, or one of the apatites.

As discussed above, soil transformations of phosphorus are complex and often ambiguous. Phosphorus availability has often been characterized in general terms (a) as solution phosphorus, often known as the intensity factor, (b) as readily available or labile phosphorus, often known as the quantity factor, and (c) as nonlabile phosphorus. The labile fraction might include easily mineralizable organic phosphorus, low-energy sorbed phosphorus, and soluble mineral phosphorus. The nonlabile fraction might include resistant organic phosphorus, high-energy sorbed phosphorus, and relatively insoluble phosphate minerals. As plants take up phosphorus from the solution, it is replenished from the labile fraction, which in turn is more slowly replenished by the nonlabile fraction. The soil buffer capacity, known as the capacity factor, governs the distribution of phosphorus among these pools. As will be shown in a subsequent section, although some soil tests aim to characterize only the intensity factor, most aim to characterize quantity and capacity factors as indices of phosphorus availability.

3.2 DIAGNOSING PHOSPHORUS DEFICIENCY

3.2.1 Visual Symptoms of Deficiency and Excess

Phosphorus deficiency suppresses or delays growth and maturity. Although phosphorus- deficient plants are generally stunted in appearance, they seldom exhibit the conspicuous foliar symptoms

characteristic of some of the other nutrient deficiencies. Furthermore, appreciable overlap often occurs with the symptoms of other nutrient deficiencies. Plant stems or leaves are sometimes dark green, often developing red and purple colors. However, when weather is cool purpling of leaves can also be associated with nitrogen deficiency, as is often observed in *Brassica* species, or with phosphorus deficiency. Plants stunted by phosphorus deficiency often have small, dark-green leaves and short and slender stems. Sustained phosphorus deficiency will probably produce smaller-sized fruit and limited harvestable vegetable mass. Because phosphorus is mobile in plants, it is translocated readily from old to young leaves as deficiency occurs, and chlorosis and necrosis on older leaves is sometimes observed. Readers are referred to tables of phosphorus deficiency symptoms specific to individual crops and compiled by other authors (40–43).

Most soils readily buffer phosphorus additions, and phosphorus is seldom present in the soil solution at levels that cause direct toxicity. Perhaps the most common symptoms of phosphorus excess are phosphate-induced micronutrient deficiencies, particularly Zn or Cu deficiencies (43,44).

3.2.2 Tissue Testing for Phosphorus

As noted previously, visual indications of phosphorus deficiency are seldom conclusive; consequently, accurate diagnosis typically requires a tissue test. Most diagnostic standards are generated using the theory of Macy (2), as noted previously concerning critical levels, sufficiency ranges, and poverty adjustment. In practice, critical levels or sufficiency ranges are usually determined by plotting final relative yield against phosphorus concentration in plant tissues and interpreting the resulting curvilinear function at some specified level of maximum yield. For many agronomic crops, values of 90 to 95% maximum yield are frequently used. However, for vegetable crops, which have a higher market value and an economic optimum closer to maximum yield, values of 98% have been used (Figure 3.2). Sometimes researchers use discontinuous functions such as the "linear response and plateau" or "quadratic response and plateau" and define adequacy by the plateau line (Figure 3.3). Yet, other researchers have suggested that the correlation to final yield is less than ideal and have proposed the use of incremental growth-rate analysis in developing critical concentrations (45).

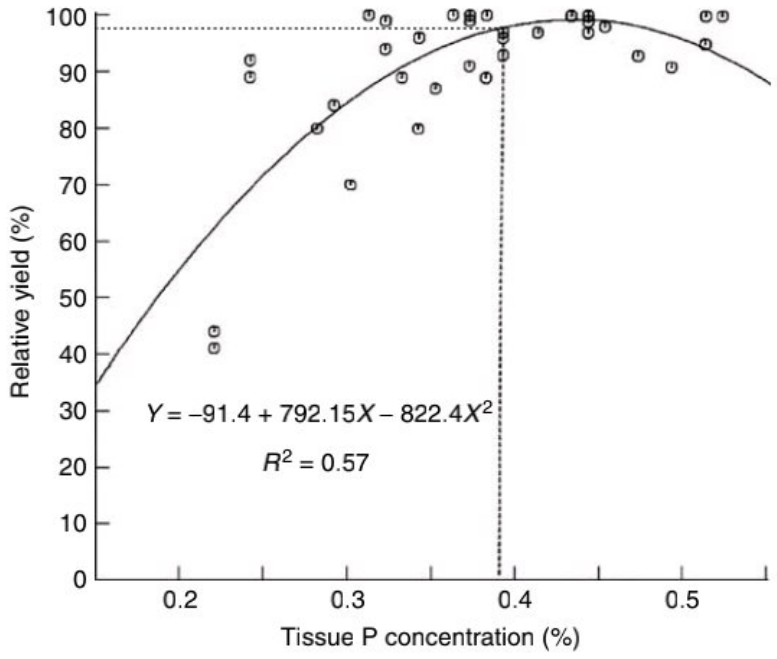

FIGURE 3.2 Calculated critical phosphorus concentration in the midribs of endive at the eight-leaf stage using curvilinear model. (Adapted from C.A. Sanchez and H.W. Burdine, *Soil Crop Sci. Soc. Fla. Proc.* 48:37–40, 1989.)

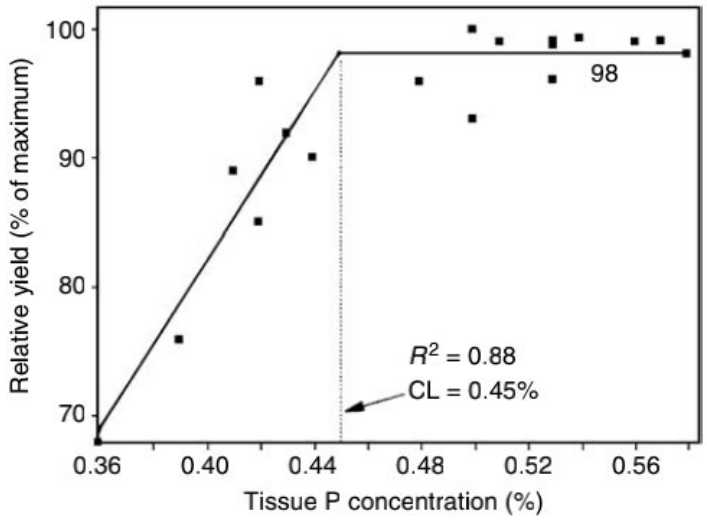

FIGURE 3.3 Calculated critical phosphorus concentration (CL) of radish leaves using linear-response and plateau model. Plateau is at 98%. (Adapted from C.A. Sanchez et al., *HortScience* 26:30–32, 1991.)

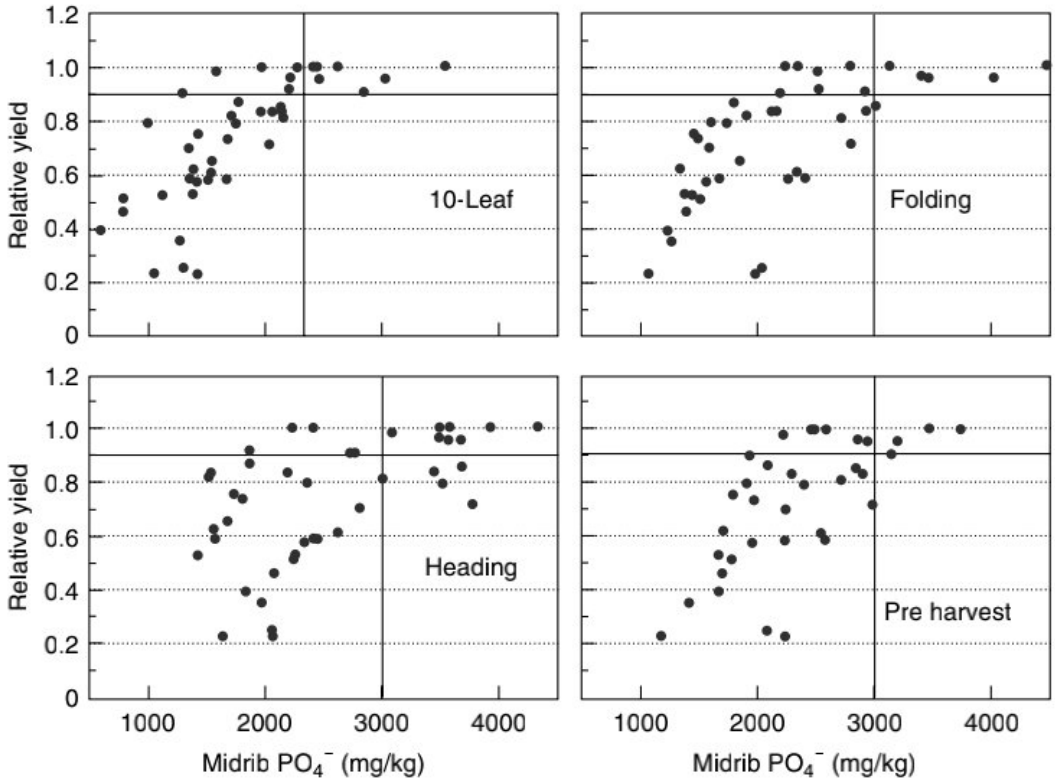

FIGURE 3.4 Calculated critical acetic acid extractable phosphate-P concentrations at four growth stages for lettuce. (Gardner and Sanchez, unpublished data.)

Levels of deficiency, sufficiency, and excess have been determined in solution culture and in greenhouse and field experiments. Total phosphorus content of a selected plant part at a certain growth stage is used for most crops. However, many standards developed for vegetable crops are based on a 2% acetic acid extraction (Figure 3.4). Diagnostic standards for various plant species are summarized in Table 3.1. This compilation includes data from other compilations and from research studies. When data from other compilations were used, priority was given to research that cited original source of data (46–48) so that potential users can scrutinize how the values were determined. However, when

TABLE 3.1
Diagnostic Ranges for Phosphorus Concentrations in Crop and Ornamental Plants

A. Field Crops

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Barley	GS 2	WP	<0.30				130
(*Hordeum*	GS 6	WP	<0.30	0.30–0.40	>4.0		130
vulgare L.)	GS 9	WP	<0.15	0.15–0.20	>0.20		130
	GS 10.1	WP	<0.15	0.15–0.20	0.20–0.50	>0.5	131
Cassava (*Manihot esculentum* Crantz)	Veg.	YML	<0.20	0.40	0.30–0.50		132
Chickpea (*Cicer*	45 DAP	WP	0.09–0.25		0.29–0.33		133
arietinum L.)	77 DAP	WP	0.15–0.20		>0.26		133
Dent corn (*Zea*	<30 cm tall	WP			0.30–0.50		134
mays var.	40–60 cm tall	WP		0.22–0.26			135
indentata	Tassel	Ear L		0.25			136
L.H. Bailey)	Silking	Ear L		0.28–0.32			137
	Silking	Ear L	<0.20		>0.29		138
	Silking	Ear L	0.22–0.32		0.27–0.62		139
	Silking	6th L from base		<0.32			140
	Silking	6th L from base	<0.21	<0.30	<0.33		141
	Silking	Ear L	0.16–0.24		0.25–0.40	0.41–0.50	142
	Silking	Ear L			0.25–0.40		143
	Silking	Ear L			0.22–0.23		135
	Silking	Ear L			0.26–0.35		144
	Silking	Ear L		0.27			145
Cotton	<1st Fl	YML			0.30–0.50		134
(*Gossypium*	July–August	L			0.30–0.64		146
hirsutum L.)	Early fruit	YML		0.31			147
	Late fruit	YML		0.33			147
	Late Mat	YML		0.24			147
	1st Fl	PYML PO_4-P		0.15		0.20	148
	Peak Fl	PYML PO_4-P		0.12		0.15	148
	1st bolls open	PYML PO_4-P		0.10		0.12	148
	Mat	PYML PO_4-P		0.08		0.10	148
Cowpea (*Vigna*	56 DAP	WP			0.28		149
unguiculata	30 cm	WP	0.28		0.27–0.35		150
Walp.)	Early Fl	WP	0.19–0.24		0.23–0.30		150
Faba or field bean (*Vicia faba* L.)	Fl	L 3rd node from A			0.32–0.41		151
Field pea	36 DAS	WP	<0.06		>0.92		152
(*Pisum*	51 DAS	WP	<0.53		>0.71		152
sativum L.)	66 DAS	WP	<0.46		>0.64		152
	81 DAS	WP	<0.40		>0.55		152
	96 DAS	WP	<0.43		>0.60		152

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
	8–9 nodes	L 3rd node from A			0.36–0.51		151
	Pre-Fl	WP			0.16		153
Dry beans	10% Fl	YML			0.40		154
(*Phaseolus vulgaris* L.)	50–55 DAE	WP	0.22		0.33		155
Oats (*Avena*	GS 10.1	WP	<0.15	0.15–0.19	0.20–0.50	>0.50	131
sativa L.)	Pre-head	Upper L			0.20–0.40		134
Peanuts (*Arachis*	Early pegging	Upper L+S			0.20–0.35		156
hypogaea L.)	Pre Fl or Fl	YML			0.25–0.50		134
Pigeon pea	91 DAP	L	0.08		0.24		157
(*Cajanus cajan*	30 DAP	L			0.35–0.38		158
Huth.)	60 DAP	L			0.30–0.33		158
	90–100 DAP	L			0.19–0.28		158
	120–130 DAP	L			0.15–0.20		158
	160–165 DAP	L			0.15–0.18		158
Rice (*Oryza*	25 DAS	WP	<0.70	0.70–0.80	0.80–0.86		159
sativa L.)	50DAS	WP	<0.18	0.18–0.26	0.26–0.40		159
	75 DAS	WP	<0.26	0.26–0.36	0.36–0.48		159
	35 DAS	WP		0.25			160
	Mid till	Y blade			0.14–0.27		131
	Pan init	Y blade			0.18–0.29		131
PO_4-P	Mid till	Y blade		0.1	0.1–0.18		161
PO_4-P	Max till	Y blade		0.08	0.1–0.18		161
PO_4-P	Pan init	Y blade		0.08	0.1–0.18		161
PO_4-P	Flagleaf	Y blade		0.1	0.08–0.18		161
Sorghum	23–29 DAP	WP	<0.25	0.25–0.30	0.30–0.60	>0.60	162
(*Sorghum*	37–56 DAP	YML	<0.13	0.13–0.25	0.20–0.60		162
bicolor	66–70 DAP	3L below	<0.18	0.18–0.22	0.20–0.35	>0.35	162
Moench.)	(Bloom)	head					
	82–97 DAP	3 L below	<0.13	0.13–0.15	0.15–0.25	>0.25	162
	(Dough)	head					
	NS	YML			0.25–0.40		163
Soybean (*Glycine*	Pre-pod	YML			0.26–0.50		156
max Merr.)	Early pod	YML		0.35			136
	Early pod	YML			0.30–0.50		134
	Pod	Upper L		0.37			164
	August	L			0.25–0.60		165
Sugar beet	25 DAP	Cotyledon	0.02–0.15		0.16–1.30		166
(*Beta vulgaris* L.)		PO_4-P					
	25 DAS	Oldest P	0.05–0.15		0.16–0.50		166
		PO_4-P					
	25 DAS	Oldest L	0.05–0.32		0.35–1.40		166
		PO_4-P					
	NS	PYML	0.15–0.075		0.075–0.40		167
		PO_4-P					
	NS	YML	0.025–0.070		0.10–.80		167
		PO_4-P					

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Sugarcane (*Saccharum officinarum* L.)	5 month ratoon	3rd LB below A		0.21			168
	4th mo.	3rd & 4th LB below A			0.24–0.30		
					0.24–0.30		169
	3 mo.	Leaves	0.15–0.18		0.18–0.24	0.24–0.30	170
	Early rapid growth	Sheath 3–6	<0.05	0.08	0.05–0.20		171
Tobacco (*Nicotiana tabacum* L.)	Fl	YML			0.27–0.50		134
	Mat	L	0.12–0.17		0.22–0.40		172
Wheat (*Triticum aestivum* L.)	GS 3–5	WP			0.4–0.70		173
	GS 6–10	WP			0.2–0.40		173
	GS 10	Flag L			0.30–0.50		173
	GS 10	WP		030			136
	GS 10.1	WP	0.15–0.20		0.21–0.50	>0.50	131
	Pre-head	Upper LB			0.20–0.40		134
B. Forages and Pastures							
Alfalfa (*Medicago sativa* L.)	Early Fl	WP		<0.20			174
	Early Fl	WP		<0.30			174
	Early Fl	WP	<0.18		0.25–0.50		174
	Early Fl	WP	<0.20	0.21–0.22	0.23–0.30	>0.30	174
	Early Fl	WP		<0.25			174
	Early Fl	WP		<0.25			174
	Early Fl	WP		<0.25			174
	Early Fl	Top 15 cm	<0.20	0.20–0.25	0.26–0.70	>0.70	174
	Early Fl	Upper stem		0.35			174
	Early Fl	Midstem PO_4-P	<0.05	0.05–0.08	0.08–0.20	>0.20	174
Bermuda grass, Coastal (*Cynodon dactylon* Pers.)	4–5 weeks between clippings	WP	<0.16	0.18–0.24	0.24–0.30	>0.40	174
Bermuda grass, Common and Midland (*Cynodon dactylon* Pers.)	4–5 weeks between clippings	WP	<0.22	0.24–0.28	0.28–0.34	>0.40	174
Birdsfoot trefoil (*Lotus corniculatus* L.)	Growth	WP		<0.24			174
Clover, Bur (*Medicago hispida* Gaertn.)	Growth	WP			2.5		174
Clover, Ladino or White (*Trifolium repens* L.)	Growth	WP		<0.23			174
	Growth	WP		<0.30			174
	Growth	WP		0.10–0.20	0.30		174
	Growth	WP		<0.25	0.25–0.30		174

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
	Growth	WP		0.15–0.25	0.30–0.35		174
	Growth	WP PO_4-P		0.06	0.06–0.12		174
Clover, Red (*Trifolium pratense* L.)	Growth	WP		<0.25	0.25–0.80		174
	Growth	WP			0.20–0.40		174
	Growth	WP		<0.27			174
Clover, Rose (*Trifolium hirtum* All.)	Growth	WP	0.10–0.14	0.14–0.18	0.19–0.24		174
	Growth	WP			0.20–0.25		174
	Growth	WP	0.07	<0.19			174
Clover, Subterranean (*Trifolium subterraneum* L.)	Growth	WP		0.30–0.31			174
	Growth	WP			0.20–0.28		174
	Growth	WP			0.26–0.32		174
	Growth	WP		<0.25			174
	Growth	WP		<0.14			174
	Growth	WP		0.08–0.13			174
	Growth	L	0.07		0.20–0.26		175
Dallisgrass (*Paspalum dilatatum* Poir.)	3–5 weeks	WP	<0.24	<0.26	0.28–0.30		174
Johnsongrass (*Sorghum halepense* Pers.)	4–5 weeks after clipping	WP	<0.14	0.16–0.20	0.20–0.25		174
Kentucky bluegrass (*Poa pratensis* L.)	4–6 weeks between clippings	WP	<0.18	0.24–0.30	0.28–0.36	>0.40	174
Millet (*Pennisetum glaucum* R. Br.)	4–5 wks after clipping	WP	<0.16	0.16–0.20	0.22–0.30	>0.40	174
Orchardgrass (*Dactylis glomerata* L.)	3–4 weeks between clippings	WP	<0.18	0.22–0.24	0.23–0.28	>0.35	174
Pangolagrass (*Digitaria decumbens* Stent.)	4–5 weeks between clippings	WP	<0.10	0.12–0.16	0.16–0.24	>0.28	174
Ryegrasses, perennial (*Lolium perenne* L.)	4–5 weeks between clippings	WP	<0.28	0.28–0.34	0.36–0.44	>0.50	174
Sudangrass (*Sorghum sudanese* Stapf.) and Sorghum sudan hybrids	4 to 5 weeks after clipping	WP	<0.14	0.14–0.18	0.20–0.30	>0.35	174
Stylo, Capica (*Stylosanthes capitata* Vog.)	56 DAP	WP		0.11–0.18			176

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Stylo, Macrocephala (*Stylosanthes macrocephala* M.B. Ferr. & Sousa Costa)	56 DAP	WP		0.10			176
Tall fescue (*Festuca arundinacea* Schreb.)	5–6 weeks	WP	<0.24	0.26–0.32	0.24–0.40	>0.45	174
C. Fruits and Nuts							
Almond	July–August	L			0.09–0.19		177
(*Prunus*	July–August	L		0.08	0.12	>0.30	178
amygdalus Batsch.)							
Apple	July–August	L	<0.11	0.11–0.13	0.13–0.20		179
(*Malus domestica*	July–August	L			0.11–0.30		177
Borkh.)	Harvest	L			0.21		43
	July–August	L		0.15–0.19	0.20–0.30		43
	June–Sept.	L/tips of shoots			0.19–0.32		43
	20 DAfl	L			0.28		43
	200 DAfl	L			0.10		43
	July–August	L		0.08	0.12	>0.30	178
	July–August	L			0.23		180
	110 DAfl	L/mid shoot			0.20		181
Apricot	August	L			0.09		177
(*Prunus armeniaca* L.)	110 Dafl	L/mid shoot			0.1		181
Avocado	Mature	L		0.065	0.065–0.20		43
(*Persea*	December–January	YML			0.10–0.15		43
americana Mill.)	August–October	YML/nonfruiting terminals	0.05		0.08–0.25	0.3	182
Banana	NS	L	<0.20		0.45		183
(*Musa* spp.)	5th L Stage	L			0.20		177
	8th L Stage	L			0.18		177
	15th L stage	L			0.15		177
Blueberry, High Bush	Mid-season	L/mature shoots	0.02–0.03	<0.07	0.10–0.32		184
(*Vaccinium*	July–August	L			0.10–0.12		177
corymbosum L.)	July–August	YML/fruiting shoot	<0.10		0.12–0.40	>0.41	185
Cacao (*Theobroma* spp.)	NS	L	<0.13	0.13–0.20	>0.20		186

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Cherry	July–August	L			0.13–0.67		177
(*Prunus* spp.)	July–August	L			0.25		180
	110 Dafl	L/midshoot			0.30		181
	July–August	L			0.13–0.30		187
Citrus,	February	L			0.05–0.11		177
Grapefruit	July	L			0.12		177
(*Citrus xparadisi*	October	L			0.07–0.11		177
Macfady)							
Citrus, Lemon (*Citrus limon* Burm. f.)	July	L			0.13–0.22		177
Citrus, Orange	4–7 mo.	L	<0.09	0.09–0.11	0.12–0.16	>0.30	188
(*Citrus sinensis*	spring flush						
Osbeck.)			0.09–0.11		0.12–0.16	0.17–0.25	189
Currants	NS	L		<0.17	0.25–0.30		190
(*Ribes nigrum* L.)							
Coffee (*Coffea arabica* L.)		L	<0.10		0.11–0.20	>0.20	191
Fig (*Ficus*	April	Basal L			0.42		43
carica L.)	May	Basal L			0.15		43
	July	Basal L			0.10		43
	September	Basal L			0.08		43
Grapevine	May–July	P/YML	<0.10		0.10–0.40		177
(*Vitis labrusca* L.)							
Grapevine	Fl	YML			0.20–0.40		192
(*Vitis vinifera* L.)							
Mango	NS				0.08–0.20		193
(*Mangifera indica* L.)							
Coconut palm	NS	YML		<0.10			43
(*Cocos nucifera* L.)							
Date palm	NS	YML			0.1–0.14		43
(*Phoenix dactyifera* L.)							
Oil palm	NS	YML			0.21–0.23		43
(*Elaeis*	NS	YML			0.23		43
guineensis Jacq.)							
Olive (*Olea europea* L.)	July–August	L			0.10–0.30		177
Papaya (*Carica papaya* L.)	NS	P/YML			0.22–0.40		49
Peach (*Prunus*	Midsummer	L			0.19–0.25		177
persica Batsch.)	July–August	L			0.26		180
	July–August	L		0.080	0.12	>0.30	178
	110 DAfl	L/mid shoot			0.3		181

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Pear (*Pyrus communis* L.)	Midsummer	L			0.11–0.25		194
	Midsummer	L			0.14–0.16		179
	Sept.	L	0.07		0.11–0.16		177
	110 DAfl	L/mid-shoot			0.20		181
Pecan (*Carya illinoinensis* K. Koch)	September	L			0.11–0.16		177
Pineapple (*Ananas comosus* Merr.)	3–12 mo.	L	0.08		0.20–0.25		177
Pistachio (*Pistacia vera* L.)	September	L			0.14–0.17		195
Plum (*Prunus* spp.)	NS	L		<0.14			196
	August	L			0.14–0.25		177
	110 DAfl	L/mid-shoot			0.20		181
Raspberry, Red (*Rubus idaeus* L.)	NS	YML nonbearing canes		<0.30			190
	Before Fl	YML			0.30–0.50		49
Strawberry (*Fragaria* spp.)	Pre-Fl	YML	0.10–0.30	0.10	0.30–0.50		197
	NS	YML			0.18–0.24		178
Walnut (*Juglans regia* L.)	July	L	0.05–0.12		0.12–0.30		177
	July–August	L		0.08	0.12	<0.30	178
D. Ornamentals							
Chinese evergreen (*Aglaonema commutatum* Schott.)	NS	YML			0.20–0.40		49
Allamanda (*Allamanda* spp.)	NS	YML			0.25–1.0		49
Amancay or Inca lily (*Alstroemeria aurantiaca*)	NS	YML			0.30–0.75		49
Anthurium spp.	NS	B+MR+P/ YML			0.20–0.75		49
Asparagus fern (*Asparagus densiflorus* Jessop)	NS	YMCL			0.20–0.30		49
Asparagus Myers (*Asparagus densiflorus* Jessop)	NS	YMCL			0.30–0.70		49

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Azalea (*Rhododendron indicum* Sweet)	Fl	YML on Fl shoot	<0.20		0.29–0.50		198
Baby's breath (*Gypsophila paniculata* L.)	NS	YML			0.30–0.70		49
Begonia spp.	NS	YML			0.30–0.75		49
Bird of paradise (*Caesalpinia gilliesii* Benth.)	NS	B+MR+P/ YML			0.20–0.40		49
Bougainvillea spp.	NS	YML			0.25–0.75		49
Boxwood, Japanese (*Buxus japonica* Mull. Arg.)	NS	YML			0.30–0.50		49
Bromeliad Aechmea (*Aechmea* spp.)	Before FL				0.30–0.70		49
Caladium (*Caladium* spp.)	NS	B+MR			0.30–0.70		49
Calathea (*Calathea* spp.)	NS	YML			0.20–0.50		49
	5 mo	5th pr L from A of Lat	<0.1–0.15				199
Carnation (*Dianthus caryophyllus* L.)	17 mo	5th pr L from A of Lat			0.25–0.30		199
	1.5–2 mo	Unpinched plants	<0.05		0.20–0.30		198
Chrysanthemum (*Chrysanthemum xmorifolium* Ramat.)	Veg.&Fl	Upper L on Fl stem	<0.21		0.26–1.15		200
Christmas cactus (*Opuntia leptocaulis* DC)	NS	YML			0.60–1.0		49
Dieffenbachia (*Dieffenbachia exotica*)	Near Maturity	YML			0.20–0.35		201
Dracaena (*Dracaena* spp.)	NS	YML			0.20–0.50		49
Eugenia (*Eugenia* spp.)	NS	YML			0.40–0.80		49
Fern, Birdsnest (*Asplenium nidus* L.)	NS	YML			0.30–0.50		49

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Fern, Boston (*Nephrolepis exaltata* Schott.)	5–10 mo after planting	YMF			0.50–0.70		202
Fern, Leather-leaf (*Rumohra adaintiformis* G. Forst.)	NS	YMF			0.25–0.50		49
Fern, Maiden-hair (*Adiantum* spp.)	NS	YMF			0.30–0.60		49
Fern, Table (*Pteris* spp.)	NS	YMF			0.21–0.30		49
Fern, Pine (*Podocarpus* spp.)	NS	YML			0.25–1.0		49
Ficus spp.	NS	YML			0.10–0.50		49
Gardenia (*Gardenia jasminoides* Ellis)	NS	YML			0.16–0.40		49
Geranium (*Pelargonium zonale* L. Her.)	Fl	YML	<0.28		0.40–0.67		198
Gladiolus (*Gladiolus tristis* L.)	NS	YML			0.25–1.0		49
Gloxinia (*Gloxinia* spp.)	NS	YML			0.25–0.70		49
Hibiscus (H*ibiscus syriacus* L.)	NS	YML			0.25–1.0		49
Holly (*Ilex aquifolium* L.)	NS	YML			0.10–0.20		49
Hydrangea, Garden (*Hydrangea macrophylla* Ser.)	NS	YML			0.25–0.70		49
Ixora, Jungle Flame (*Ixora coccinea* L.)	NS				0.15–1.0		49
Jasmine (*Jasminum* spp.)	NS	YML			0.18–0.50		49
Juniper (*Juniperus* spp.)	Mature shoots	Tips/Stem			0.20–0.75		49
Kalanchoe (*Kalanchoe* spp.)	NS	4 L from tip			0.25–1.0		49

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Japanese privet (*Ligustrum japonicum* Thunb.)	NS	YML			0.20–0.50		49
Lilac (*Syringa xpersica* L.)	NS	YML			0.25–0.40		49
Lipstick plant (*Bixa orellana* L.)	NS	YML			0.20–0.40		49
Liriope (*Liriope muscari* L.H. Bailey)	NS	YML			0.25–0.35		49
Mandevilla (*Mandevilla* spp.)	NS	YML			0.20–0.50		49
Nepthytis (*Syngonium podophyllum* Schott.)	NS	YML			0.20–0.50		49
Natal plum (*Carissa macrocarpa* A. DC)	NS				0.18–0.6		49
Norfolk Island pine (*Araucaria hetrophylla* Franco)	NS	YML			0.20–0.30		49
Orchid, Cattleya (*Cattleya* spp.)	NS	5 cm tips / YML		0.07	0.11–0.17		49
Orchid, Cymbidium (*Cymbidium* spp.)	NS	5 cm tips / YML		0.07	0.11–0.17		49
Orchid, Phalaenopsis (*Phalaenopsis* spp.)	NS	5 cm tips LYML		0.10	0.30–0.17		49
Philodendron, Monstera (*Monstera deliciosa* Liebm.)	NS	B+MR+P/ YML			0.20–0.40		49
Philodendron, Split leaf (*Philodendron selloum* C. Koch)	NS	B+MR+P/ YML			0.25–0.40		49
Pittosporum, Japanese (*Pittosporum tobira* Ait.)	NS	YML			0.25–1.0		49

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
Poinsettia (*Euphorbia pulcherrima* Willd.)	Before Fl 70 DAE	YML WP	<0.20		0.30–0.70 0.30–0.37		198 203
Pothos (*Epipremnum aureum* Bunt.)	NS	YML			0.20–0.50		49
Rose, Floribunda (*Rosa floribunda* Groep.)	Harvest	2nd & 3rd 5-leaflet L from Fl shoots	0.14		0.28–0.36		204
Rose, Hybrid Tea (*Rosa* spp.)	Harvest	2nd & 3rd 5-leaflet L from Fl shoot			0.28–0.36		204
Salvia (*Salvia* spp.)	NS	YML			0.30–0.70		49
Sanservieria (*Sansevieria* spp.)	NS	YML			0.15–0.40		49
Snapdragon (*Antirrhinum majus* L.)	NS	YML			0.30–0.50		49
Spathiphyllum (*Spathiphyllum wallisi* Regel)	< 4 mo > 4 mo	B+MR+P/YML B+MR+P/YML			0.25–1.0 0.20–0.80		49 49
Spider plant (*Chlorophytum comosum* Jacques)	NS	YML			0.15–0.40		49
PStatice (*Limonium perezii* F.T. Hubb)	NS	YMCL			0.30–0.70		
Umbrella plant (*Schefflera* spp.)	NS	Central L			0.20–0.35		205
Viburnum (*Viburnum* spp.)	NS	YML			0.15–0.40		49
Violet, African (*Saintpaulia ionantha* H. Wendl.)	NS	YML			0.30–0.70		49
Yucca (*Yucca* spp.)	NS	YML			0.15–0.80		49
Zebra plant (*Aphelandra squarrosa* Nees)	NS	YML			0.20–0.40		49

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
E. Vegetable Crops							
Asparagus (*Asparagus officinalis* L.) YP	Mid-growth	Fern needles from top 30 cm		0.17	0.20–0.23		43
	Mid-growth	New fern from 10 cm tip PO_4-P	0.08		0.16		206
Garden bean (*Phaseolus vulgaris* L.)	Harvest	L			0.24		207
	Harvest	Pods			0.30		207
	Harvest	Seeds			0.36		207
	Mid-growth	P/4th L from tip PO_4-P	0.10		0.30		206
	Early Fl	P/4th L from tip PO_4-P	0.08		0.20		206
	Mature	L			0.30		43
Beets (*Beta vulgaris* L.)	Harvest	L		0.15	0.28	0.56	43
	Harvest	R		0.10	0.27	0.62	43
	NS	YML			0.25–0.50		49
Broccoli (*Brassica oleracea* var. *italica* Plenck	Harvest	Head			0.79–1.07		43
	Mid-growth	MR/YML PO_4-P	0.25		0.50		206
	Budding	MR/YML PO_4-P	0.20		0.40		206)
Brussels sprouts (*Brassica oleracea* var. *gemmifera* Zenk.)	Mid-growth	MR/YML PO_4-P	0.20		0.35		206
	Late-growth	MR/YML PO_4-P	0.10		0.30		206
Cabbage (*Brassica oleracea* var. *capitata* L.)	Harvest	Head		0.13	0.38	0.77	43
	Heading	MR/WL PO_4-P	0.25		0.35		206
Carrot (*Dacus carota* var. *sativus* Hoffm.)	Harvest	L			0.26		43
	Harvest	R		0.14	0.33	0.65	43
	Mid-growth	PYML PO_4-P	0.20		0.40		206
Cauliflower (*Brassica oleracea* var. *botrytis* L.)	Harvest	L (immature 4 cm)			0.62–0.70		43
	Harvest	Heads		0.51	0.76	0.88	43
	Buttoning	MR/YML PO_4-P	0.25		0.35		206
Celery (*Apium graveolens* var. *dulce* Pers.)	Mid-season	YML			0.30–0.50		208
	Mid-season	Outer P		<0.55			209
	Mid-season	Outer P		<0.46			210
	Harvest	Stalks		0.43	0.64	0.90	43
	Mid-season	P PO_4-P			0.28–0.34		43
	Mid-season	PYML PO_4-P	0.20		0.40		206
	Near maturity	PYML PO_4-P	0.20		0.40		206

TABLE 3.1 (*Continued*)

Growth Species	Plant Stage	Part	Deficient	Low	Sufficient	High	Reference
Cucumber (*Cucumis*	Budding	L/5th L from tip		0.28–0.34	0.34–1.25	>1.25	49
sativus L.)	Fruiting	L/5th L from tip		0.22–0.24	0.25–1.0	>1.0	49
	Early fruiting	P/6th L from tip PO_4-P	0.15		0.25		206
Eggplant (*Solanum melongena* L)	Mature leaves	PYML		0.25–0.29	0.30–0.12	>1.2	49
Endive	8-L	YML			0.45–0.80		211
(*Cichorium*	Maturity	YML			0.40–0.60		211
endiva L.)	8-L	YML			0.54		212
Escarole	8-L	YML			0.45–0.60		211
(*Cichorium*	Maturity	YML			0.35–0.45		211
endiva L.)	6-L	YML			0.50		212
Lettuce	28 DAP	L			0.55–0.76		213
(*Lactuca*	8-L stage	MR/YML		<0.43			214
sativa L.)	Mid-growth	MR/YML		<0.40			215
	Mid-growth	MR/YML			0.35–0.60		216
	Heading	MR/YML PO_4-P	0.20		0.40		206
	Harvest	MR/YML PO_4-P	0.15		0.25		206
Melons	Harvest	B			0.25–0.40		208
(*Cucumis*	Early growth	P/6th L from GT PO_4-P	0.20		0.40		206
melo L.)	Early fruit	P/6th L from GT PO_4-P	0.15		0.25		206
	1st Mature fruit	P/6th L from GT PO_4-P	0.10		0.20		206
Onion	2-leaf				0.44		216
(*Allium cepa L.*)	4-leaf				0.31		216
	6-leaf				0.34		216
Peas	Mid-growth	YML			0.25–0.35		208
(*Pisum*	Early flowering	L			0.33		207
sativum L.)	Flowering	Entire Tops			0.30–0.35		208
		Entire Tops		0.19	0.29		43
	Early flowering	Pods			0.20		207
	Harvest	Seeds			0.35		207
	Early flowering	Pods		0.23	0.57	0.78	43
Pepper	Mid-growth	YML			0.30–0.70		208
(*Capsicum*	Early-growth	PYML PO_4-P	0.20		0.30		206
annuum L.)	Early fruit set	PYML PO_4-P	0.15		0.25		206
Potato	Mid-growth	PYML			0.20–0.40		208
(*Solanum*	Tuber initiation				0.38–0.45		217
tuberosum L.)	Tubers mature				0.14–0.17		217

Continued

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
	Early season	P/4th L from growing tip PO_4-P	0.12		0.20		206
	Mid-season	P/4th L from growing tip PO_4-P	0.08		0.16		206
	Late-season	P/4th L from growing tip PO_4-P	0.05		0.10		206
Radish	Maturity	L		<0.40			215
(*Raphanus*	Maturity	L		<0.45			219
sativus L.)							
Spinach	48 DAP	L		0.10	0.25–0.35		43
(*Spinacia*	40–50 DAP	YML			0.48–0.58		208
oleracea L.)	Mature	YML			0.30–0.50		208
	Mature	WP		0.27	0.72	1.17	43
	Mid-growth	PYML PO_4-P	0.20		0.40		206
Sweet corn	Silking	Ear-leaf		<0.25			136
(*Zea mays* var.	Silking	Ear-leaf			0.20–0.30		208
rugosa Bonaf.)	8-L stage	Ear-leaf		<0.31			220
	8-L stage	Ear-leaf		<0.38			221
	Tasseling	MR of 1st L above ear PO_4-P	0.05		0.10		206
Sweet potato	4th L	L		0.20	0.23		43
(*Ipomoea*	Mid-growth	ML			0.20–0.30		208
batatas Lam.)	Harvest	Tubers		0.06	0.12	0.22	43
	Mid-growth	P/6th L from GT PO_4-P	0.10		0.20		206
Tomato	Early fruiting	L	0.24–0.35		0.42–0.72		43
(*Lycoperscion*	Harvest	YML		<0.13	0.40		222
esculentum Mill.)	Early bloom	P/4th L from GT PO_4-P	0.20		0.30		206
	Fruit 2.5 cm	P/4th L from GT PO_4-P	0.20		0.30		206
	Fruit color	P/4th L from GT PO_4-P	0.20		0.30		207
Watermelon	Flowering	L/5th L from tip			0.30–0.80		49
(*Citrullus lanatus*							
Matsum. & Nakai)	Fruiting	L/5th L from tip			0.25–0.70		49

TABLE 3.1 (*Continued*)

Species	Growth Stage	Plant Part	Deficient	Low	Sufficient	High	Reference
	P/6th L from tip	P/6th L from GT PO_4-P	0.15		0.25		206

Note: Phosphorus is reported in units of percent total phosphorus on a dry mass basis except where designated otherwise under plant part. Units of PO_4-P are phosphorus in sap of petioles or leaf midribs.
Abbreviations used for plant parts:

A = apex	LB = leaf blade
B = blades	MR = midrib
DAP = days after planting	NS = not specified (pertaining to growth stage)
DAE = days after emergence	P = petiole
DAfl = days after flowering	PYML = petiole from young mature leaf
F = fern	R = roots
Fl = flowers or flowering	WP = whole aboveground plant
GT = growing tip	YML = young mature leaves synonymous with recently mature leaf and most recently developed leaf
L = leaves	

no other values were available, some values were drawn from sources that did not cite original research (49). Generally, crops require a preplant application of phosphorus fertilizer in the case of annual crops or before the fruiting cycle begins in the case of perennial crops. Diagnosis of a phosphorus deficiency by tissue analysis for annual crops is often postmortem for the existing crop.

3.2.3 Soil Testing for Phosphorus

As noted in a previous section, crop response to phosphorus is correlated poorly to the total amount of phosphorus in a soil. Therefore, a successful soil test should represent some index of phosphorus availability. The development of a soil test requires selection of an extractant, development of studies that correlate the amount of nutrient extracted with phosphorus accumulation by crops, and calibration studies that determine a relationship between soil test results and amount of fertilizer required for optimal production.

Over the past century, a number of soil-testing procedures have been proposed, and several excellent reviews on soil testing for phosphorus have been published (50–53).

This chapter focuses on historical developments, mode of action, and generalized interpretations of the major phosphorus soil tests utilized in the United States.

The major soil tests that have been used or proposed in the United States are summarized in Table 3.2. Most early soil tests were developed empirically and were based on simple correlations between extractant and some measure of crop response to fertilization with phosphorus. However, based on the phosphorus-fractionation method developed by Chang and Jackson (54), inferences have been made concerning the mode of action, or the forms of phosphorus extracted by various solutions. The inferred modes of action for various chemical extractant components are presented in Table 3.3. Generally, water or dilute salt solutions characterize phosphorus in the soil solution or the intensity factor, whereas acids, complexing solutions, or alkaline buffer solutions generally characterize the quantity factor. Tests based on water extraction often correlate well with phosphorus accumulation in shallow-rooted, fast- growing vegetable crops. However, soil tests capable of better characterizing the labile fraction and capacity factor generally produce more reliable results for field and orchard crops.

An early soil test for phosphorus aimed at characterizing available phosphorus was the 1% citric acid test developed by Dyer (3). This test was adapted in England but was not used widely in the

TABLE 3.2
Some Historical and Commonly Used Soil Test and Extracting Solutions for Determining Available Soil Phosphorus

Name of Test	Extractant	Reference
AB-DPTA	1M NH_4HCO_3 + 0.005 M DPTA, pH 5	59
Bray I	0.025 N HCl + 0.03 N NH_4F	6
Bray II	0.1 N HCL + 0.03 N NH_4F	6
Citric acid	1% Citric acid	3
EDTA	0.02 M Na_2-EDTA	61
Mehlich 1	0.05 M HCl + 0.0125 M H_2SO_4	224
Mehlich 3	0.015 M NH_4F + 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.013 M HNO_3	56
Morgan[a]	0.54 N HOAc + 0.7 N NaOAc, pH4	5
Olsen	0.5 M $NaHCO_3$, pH 8.5	58
Truog	0.001 M H_2SO_4 + $(NH4)_2SO_4$, pH 3	4
Water[b]	Water	225

[a]A modification of the Morgan by Wolf to include 0.18 g/L DPTA gives better correlations for micronutrients.
[b]From: C.A. Sanchez. Soil Testing and Fertilizer Recommendations for Crop Production on Organic Soils in Florida. University of Florida Agricultural Experiment Station Bulletin 876, Gainesville, 1990.

TABLE 3.3
Forms of Phosphorus Extracted by Constituent Components of Commonly Used Soil Test Extractants[a]

Chemical	Form of Phosphorus Extracted
Acid (H^+)	Solubilizes all chemical P in the following order Ca-P>Al-P>Fe-P
Bases (OH^-)	Solubilizes Fe-P and Al-P in respective order. Also results in release of some organic P
Fluoride ion	Forms complexes with Al thus releasing Al-P. Also precipitates Ca as CaF_2 and thus will extract more Ca-P as $CaHPO_4$. No effect on basic Ca-P and Fe-P
Bicarbonate ions	Precipitate Ca as $CaCO_3$ thus increasing solubility of Ca-P. Also remove Al-bound P
Acetate ions	Form weak complexes with polyvalent metal ions. Possibly prevents readsorption of P removed by other ions
Sulfate ions	Appear to reduce readsorption of P replaced by H ions

[a]Adapted from G.W. Thomas and D.E. Peaslee, in *Soil Testing and Plant Analysis*. Madison, WI: Soil Sci. Soc. Am. Inc., 1973 and E.J. Kamprath and M.E. Watson, in *The Role of Phosphorus In Agriculture*. American Society of Agronomy Inc. 677 South Segoe Road, Madison WI 53711, 1980.

United States. A dilute acid test proposed by Truog (4) and a test based on a universal soil extracting solution proposed by Morgan (5) were among the earliest soil tests used in the United States.

The test based on the Bray-I extractant was perhaps the first to be implemented widely in soil-testing laboratories in the United States, and it is still extensively used in the midwestern United States. This mild-acid solution has been shown reliably to predict crop response to phosphorus fertilization on neutral to acidic soils. However, the test is much less effective in basic soils, where the acid is neutralized quickly by the soil bases present and fluoride ions are precipitated by calcium (55).

In the southeastern United States, the Mehlich 1 (M-I) soil-test extractant is used commonly for simultaneous extraction of P, K, Ca, Mg, Cu, Mn, Fe, and Zn. The M-I soil test does not correlate with crop response on calcareous soils probably for the same reasons the Bray-I test does not. Consequently, the Mehlich 2 (M-II) test was introduced as an extractant that would allow simultaneous determinations of the same nutrients over a wide range of soil properties. However, the corrosive properties of the M-II in instruments discouraged wide acceptance of this extractant and prompted modifications that ultimately became the Mehlich 3 (M-III) extraction. The M-III has been shown to be reliable across a wide range of soil–crop production circumstances (56,57).

The sodium bicarbonate ($NaHCO_3$) (58) soil test for phosphorus generally correlates well with crop response on calcareous soils in the western United States. The NH_4HCO_3-DPTA (diethylenetriaminepentaacetic acid) soil test also has been used for the simultaneous determination of P, K, Zn, Fe, Cu, and Mn (59,60) and performs similar to the $NaHCO_3$ test with respect to phosphorus. Another test that shows good correlations on calcareous soils is the EDTA (ethylenediaminetetraacetic acid) soil test (61).

Isotopic dilution techniques (53) and phosphorus sorption isotherms (62) have been used not only to characterize the labile phosphorus fraction but also the phosphorus-buffering capacity of soils. However, these approaches are too tedious and costly to be used as routine soil tests.

Ultimately, soil-test phosphorus levels must be converted into phosphorus fertilizer recommendations for crops. A useful starting point is the determination of critical soil-test levels, that is the soil-test phosphorus level above which there is no response to phosphorus fertilizer. An example of a critical phosphorus soil-test level based on water extraction for celery is shown in Figure 3.5. Using the double calibration approach described by Thomas and Peaslee (50) information on how much fertilizer is required to achieve the critical concentration would result in a fertilizer recommendation. This approach is used for Histosols by the Soil Testing Laboratory at the University of Florida. An example of resulting fertilizer recommendations for several commodities is shown in Figure 3.6.

The laboratory mentioned above makes recommendations for Histosols over a limited geographical location. However, most soil-testing laboratories make recommendations over large geographical area and across more diverse soil types. Under most situations, quantitative information on how phosphorus fertilizer additions change with soil-test phosphorus levels across a range of soil types rarely exist. Owing to this uncertainty, most soil-testing laboratories make phosphorus fertilizer recommendations based on probability of response using class interval grouping such as low, medium, and high.

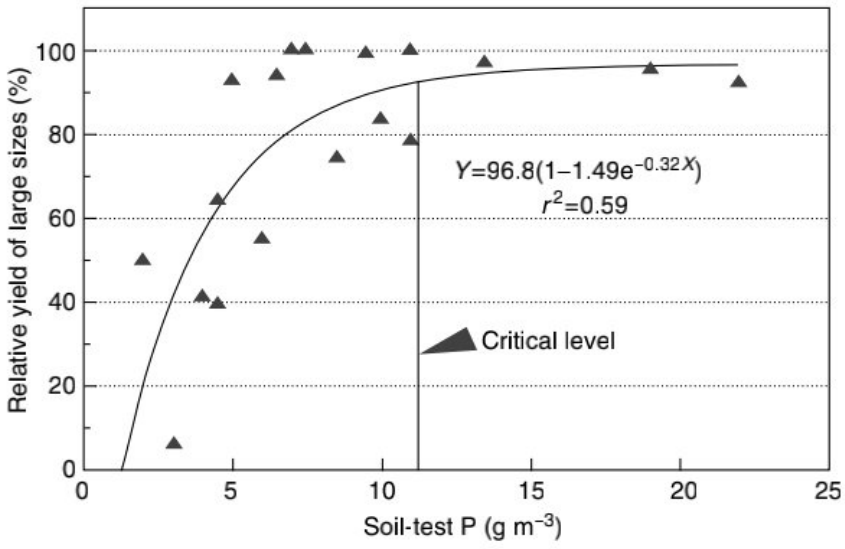

FIGURE 3.5 Critical soil-test phosphorus levels for large, harvest-size celery on Florida Histosols. (Adapted from C.A. Sanchez et al., *Soil Crop Sci. Soc. Fla. Proc.* 29:69–72, 1989.)

Crops produced on a soil scoring very low or low have a very high probability of responding to moderate to high rates of fertilization. Crops produced on soils classified as medium frequently respond to moderate rates of fertilization, and typically, crops produced on soils testing high for phosphorus would not respond to fertilization (Table 3.4). General soil-test phosphorus interpretations for mineral soils in California and Florida are shown in Tables 3.5 and 3.6 for comparative purposes. In California, only the probability of response to $NaHCO_3$-phosphorus is indicated, and it is presumed that specific fertilizer recommendations are left to service laboratories, crop consultants, or the grower. In Florida, specific fertilizer recommendations for phosphorus are made for each level of M-I-extractable phosphorus. Furthermore, research aimed at validating and calibrating soil-test fertilizer recommendations for phosphorus in Florida is ongoing (63–65). It must be stressed that all fertilizer recommendations must be calibrated locally, and readers are advised to consult the cooperative extension service for recommendation guidelines specific to their region.

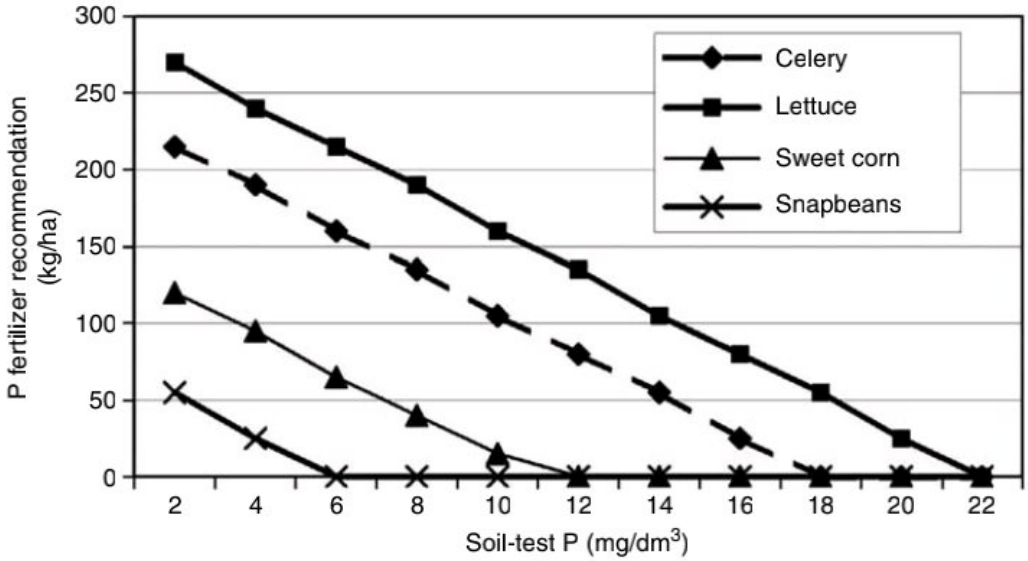

FIGURE 3.6 Fertilizer phosphorus recommendations for selected crops on Everglades Histosols. (Adapted from C.A. Sanchez, Soil Testing and Fertilizer Recommendations for Crop Production on Organic Soils in Florida. University of Florida Agricultural Experiment Station Bulletin 876, Gainesville, 1990.)

TABLE 3.4
Classifications for Soil Nutrient Tests and Yield Potential and Crop Response to Application of Phosphorus-Containing Fertilizers

Classification	Yield Potential and Need for Fertilizer
Very low	Very high probability of response to fertilizer. Crop-yield potential less than 50% of maximum. Deficiency symptoms possible. Highest recommended rate of fertilizer required
Low or poor	High probability of response to fertilizer. Crop yield potential 50 to 75%. No pronounced deficiency symptoms. Needs modest to high fertilizer application
Medium	Crop yield potential >75% without fertilizer addition. Low to modest rates of fertilizer may be required for economic maximum yield when yield potential high or for quality for high value crops
High	Very low probability of yield increase due to added fertilizer
Very High	No positive response to fertilizer. Crop may be affected adversely by fertilizer addition

Source: Adapted from B. Wolf, *Diagnostic Techniques for Improving Crop Production*. Binghampton, New York: The Hayworth Press Inc., 1996.

TABLE 3.5
General Guidelines for Interpreting the NaHCO3 Phosphorus Test for Fertilizing Vegetable Crops in California

Vegetable	Response Likely (mg/kg)	Response Unlikely (mg/kg)
Lettuce	<20	>40
Muskmelon	<8	>12
Onion	<8	>12
Potato (mineral soils)	<12	>25
Tomato	<6	>12
Warm-season vegetables	<5	>9
Cool-season vegetables	<10	>20

Source: Adapted from Soil and Plant Testing in California, University of California, Division of Agricultural Science Bulletin 1879 (1983). Modified based on personal communication with Husien Ajwa, University of California, Davis.

3.3 FACTORS AFFECTING MANAGEMENT OF PHOSPHORUS FERTILIZATION

3.3.1 Crop Response to Phosphorus

As noted in the previous section, the amounts of phosphorus applied to crops should be based ideally on a well-calibrated soil test. However, even at a given soil-test phosphorus level, the amount of phosphorus fertilizer required for economic-optimum yield often will vary with crop. Generally, fast-growing, short-season vegetable crops have higher phosphorus requirements than field and orchard crops. Many deciduous fruit crops infrequently respond to phosphorus fertilization even if soil tests are low (47). It is presumed often that surface soil tests fail to characterize the full soil volume where trees take up nutrients or the fact that trees take up nutrients over a considerable time period.

There is considerable variability in phosphorus response among species of vegetable crops (66–70). For example, lettuce generally shows larger responses to phosphorus than most other vegetable crops including cucurbit and brassica species. Furthermore, genetic variation in response to phosphorus within species also exists. For example, Buso and Bliss (71), in sand culture experiments found that some butterhead types of lettuce (*Lactuca sativa* L.) were less efficient than other types under phosphorus-deficient regimes. However, the magnitude of this variation is usually small compared to the uncertainties and natural variation in soil-test-based phosphorus fertilizer recommendations. Generally, field experiments show that lettuce has a similar response to phosphorus regardless of cultivar or morphological type (72,73). As shown by the data presented in Figure 3.7, a similar soil-test phosphorus index level of 22 mg dm^3 was required for maximum yield regardless of lettuce type (73).

Mechanisms of phosphorus-utilization efficiency have been classified into three broad classes including (a) secretion or exudation of chemical compounds into the rhizosphere, (b) variation in the geometry or architecture of the root system, and (c) association with microorganisms (74). Future opportunities for improving phosphorus-utilization efficiency in crops through genetic manipulation of traits exist (75).

In conclusion, as available data permit, soil-test recommendations for phosphorus should be customized by crop. However, at present, soil-test-based recommendations are generally not sufficiently sensitive to allow recommendations to accommodate the more subtle genetic variation among cultivars within crop species.

TABLE 3.6
Phosphorus Fertilizer Recommendations for Various Vegetable Crops on Sandy Soils in Florida Based on the Mehlich 1 Soil Test

Soil Test P (mg/kg)	<10	10–15	16–30	31–60	>60
Classification	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Crop	**P Fertilizer Recommendation (kg/ha)**				
Bean	60	50	40	0	0
Beet	60	50	40	0	0
Broccoli	75	60	50	0	0
Brussel sprouts	75	60	50	0	0
Cabbage	75	60	50	0	0
Carrot	75	60	50	0	0
Cauliflower	75	60	50	0	0
Celery	100	75	50	0	0
Corn, sweet	75	60	50	0	0
Cucumber	60	50	40	0	0
Eggplant	75	60	50	0	0
Endive	75	60	50	0	0
Escarole	75	60	50	0	0
Kale	75	60	50	0	0
Lettuce	75	60	50	0	0
Muskmelon	75	60	50	0	0
Mustard	75	60	50	0	0
Okra	75	60	50	0	0
Onion/bulb	75	60	50	0	0
Onion/leek	60	50	40	0	0
Onion/bunching	60	50	40	0	0
Parsley	75	60	50	0	0
Pea	40	40	30	0	0
Pepper, bell	75	60	50	0	0
Potato	60	60	30	0	0
Potato, sweet	60	50	40	0	0
Pumpkin	60	50	40	0	0
Radish	60	50	40	0	0
Spinach	60	50	40	0	0
Squash	60	50	40	0	0
Strawberry	75	60	50	0	0
Tomato	75	60	50	0	0
Turnip	75	60	50	0	0
Watermelon	75	60	50	0	0

Source: Adapted from G. Hochmuth and E. Hanlon, IFAS Standarized Fertilization Recommendations for Vegetable Crops. Fla. Coop. Ext. Serv. Circ. 1152, 1995.

3.3.2 Soil Water

Phosphorus availability is affected by soil water conditions. Soil water affects soil reactions governing the release and diffusion of phosphorus in the soil solution and ultimately the positional availability of phosphorus relative to root growth. Generally, maximum availability of phosphorus for most crops has been associated with a soil water tension of about 1/3 bar (76).

The dissolution of fertilizer phosphorus and all amorphous and mineral phosphorus compounds in the soil depends on soil water. Furthermore, under anaerobic conditions, the reduction of ferric

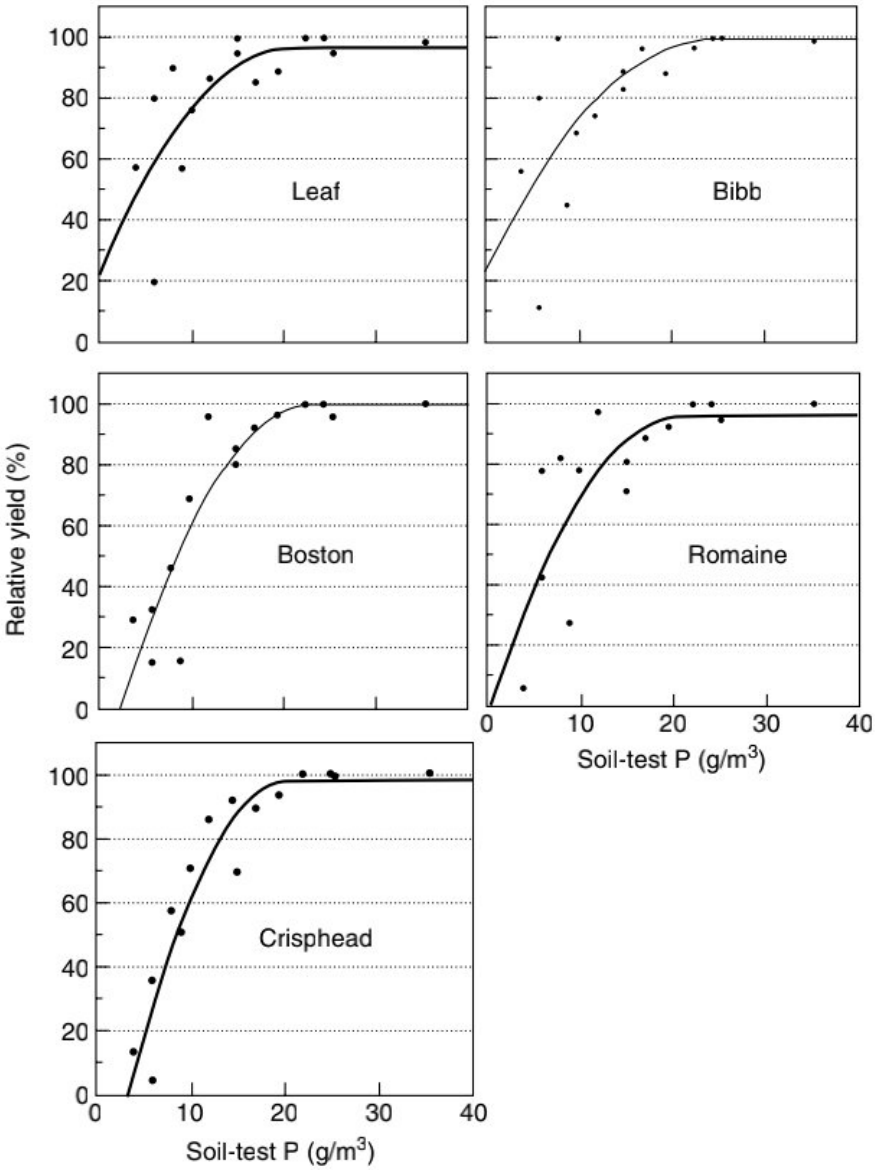

FIGURE 3.7 Response of five lettuce types to soil-test phosphorus. (Adapted from C.A. Sanchez and N.M. El-Hout, *HortScience* 30:528–531, 1995.)

phosphates to ferrous phosphates might result in additional increased phosphorus solubility (77,78). Nevertheless, it is the general view that with the exception of aquatic crops, excessive water resulting in poor aeration would actually restrict phosphorus uptake by crops in spite of this enhanced solubility. However, Bacon and Davey (79), using trickle irrigation in an orchard, noted increased phosphorus availability during and immediately after each irrigation and noted that available phosphorus decreased rapidly as soil moisture declined below field capacity. These authors attributed this increased phosphorus availability to the reduction of amorphous iron phosphates in anaerobic micro-sites.

The volume of soil that is occupied by water affects the cross-sectional area through which phosphorus can diffuse (80). Thus, the lower the soil moisture, the more tortuous the path of diffusion and the greater the likelihood of contact with soil constituents that render phosphorus insoluble.

Under most conditions, phosphorus is applied near the soil surface. Thus, during dry periods in nonirrigated production systems, crops largely draw soil moisture from lower soil depths, and phosphorus deficiencies can arise (81). This condition is generally not a problem in irrigated production systems where root growth extends to near the soil surface.

3.3.3 Soil Temperature

Soil temperature affects reactions that govern the dissolution, adsorption and diffusion of phosphorus. Although sorption and desorption generally occur concurrently, an increase in soil temperature increases kinetics of reactions (82) and enables more rapid equilibration among nonlabile, labile, and solution phosphorus pools, resulting in more rapid replenishment of solution phosphorus as phosphorus is taken up by crops. Sutton (83) concluded that most of the effect of temperature on available phosphorus was due to inorganic reactions, since the effect occurred too rapidly to be explained by microbial mineralization.

Soil temperature also has the potential to affect root uptake of phosphorus. With excised corn roots in solution culture experiments, Carter and Lathwell (84) reported that absorption increased as temperature was increased from 20 to 40°C. The effects of temperature on soil reactions may be more important than effects on plant physiology. Singh and Jones (85) noted that changes in temperature had a more pronounced effect on the phosphorus nutrition of Boston lettuce in soil culture than in solution culture.

In production systems where crops are seeded and harvested over the same time interval each year, soil temperature is unlikely to substantially confound soil-test-based fertilizer recommendations for phosphorus. However, in crop production situations where planting and harvesting are extended over seasonal changes, such as many vegetable production systems, temperature changes can affect the amount of fertilizer required for maximum production. Lingle and Davis (86) reported that tomatoes seeded in cool soils showed a larger growth (dry mass) response to phosphorus than those seeded in warm soils. Locascio and Warren (87) noted that tomato (*Lycopersicon esculentum* Mill.) growth increased with applications up to 550 kg P/ha at 13°C but only to 140 kg P/ha at 21 or 30°C. Research has shown that the phosphorus rate required for maximum production of lettuce in deserts increased as temperatures during the growing season decreased (88,89). Lettuce produced in the desert of southwestern United States is planted every day from September through January and is harvested daily from November through April with mean soil temperatures ranging from 4 to 18°C. As illustrated in Figure 3.8, soil-test levels for phosphorus requirement for maximum lettuce yield decreased as mean soil temperature during the growing season increased.

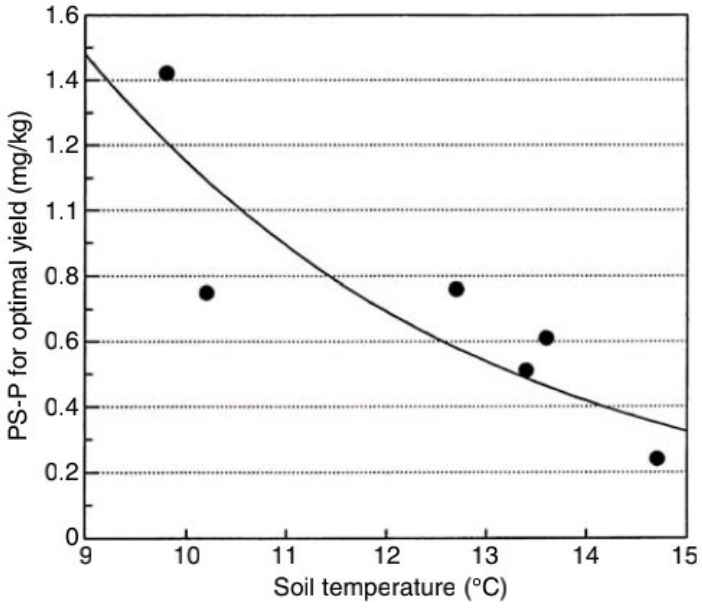

FIGURE 3.8 Soil test phosphorus level using phosphorus sorption (PS-P) required for maximum yield of lettuce as affected by soil temperature. (Adapted from Gardner and Sanchez, unpublished data.)

3.3.4 Sources of Phosphorus

Most phosphorus-containing fertilizers are derived from mined phosphate rock. In some unique production situations on acidic soils, phosphate rock can be used directly as a phosphorus source. Most cropping systems show the best response to water-soluble phosphorus fertilizers. Water-soluble phosphorus fertilizers are produced by reacting phosphate rock with sulfuric or phosphoric acid (90). Ammonium phosphates are made by passing anhydrous ammonia through phosphoric acid. This production includes diammonium phosphate and monoammonium phosphate.

The agronomic effectiveness of phosphorus fertilizers was reviewed by Engelstad and Terman (91). Most crops require readily available phosphorus, and most soluble sources perform similarly. However, in some situations the ammonium phosphates produce phytotoxicity (92), and their use is often discouraged when high amounts of phosphorus are required. For example, for economic reasons, diammonium phosphate typically is broadcast applied for lettuce production in the southwestern desert, but its use is discouraged when broadcast rates are high or when phosphorus fertilizer is banded near the plants.

Soluble, dry fertilizers and solution fertilizers perform similarly under many production systems. However, there are some unique production situations where solution sources may present logistical advantages. Often solution sources are easier to use in band placement or point-injection technologies. Generally, solution sources would be utilized in application with irrigation water.

In conclusion, under most conditions, cost considerations, available application technologies, and the potential for phytotoxicity are the major determining factors influencing the selection of sources of phosphorus fertilizers.

3.3.5 Timing of Application of Phosphorus Fertilizers

Overwhelming evidence indicates that for annual crops, phosphorus fertilizers should largely be applied preplant. Phosphorus moves to plant roots primarily by diffusion, and young seedlings of most annual crops are very sensitive to phosphorus deficits. Furthermore, yields of some crops often fail to recover fully from transitory phosphorus deficits (93).

Grunes et al. (94) showed that the proportion of fertilizer phosphorus absorbed by sugar beets (*Beta vulgaris* L.) decreased as the time of application was delayed. Lingle and Wright (95) reported that muskmelons (*Cucumis melo* L.), which showed large responses to phosphorus at seeding, showed no response to sidedressed phosphorus fertilization. Sanchez et al. (96) reported that a preplant phosphorus deficit in lettuce could not be corrected by sidedressed fertilization. Preplant broadcast or band applications are usually recommended for annual crops.

3.3.6 Placement of Phosphorus Fertilizers

The literature contains many accounts recording the positive effects of applying phosphorus fertilizer to a localized area, usually near the plant roots, as opposed to a general soil broadcast application. Reviews on the subject of fertilizer placement should be consulted for detailed information (97,98). Localized placement of phosphorus fertilizers might include row, band, or strip placement.

It is generally presumed that a localized or band application reduces fertilizer contact with the soil thereby resulting in less phosphorus sorption and precipitation reactions and, thus, enhanced availability to crops. However, for soils with a high phosphorus-fixing capacity, where phosphorus is relatively immobile, placement of the fertilizer where root contact is enhanced may be an equally or more important mechanism than restricting fixation (99–101).

The relative benefits of localized placement of phosphorus fertilizers are neither constant nor universal across crop production situations. This fact is illustrated by a series of experiments that the author conducted to improve phosphorus fertilizer use for vegetable crops produced on Histosols (102,103). The amount of phosphorus required for lettuce production could be reduced by at least 50% if phosphorus was banded instead of broadcast (Figure 3.9). However, band placement was not a viable strategy for improving phosphorus-use efficiency for celery under the

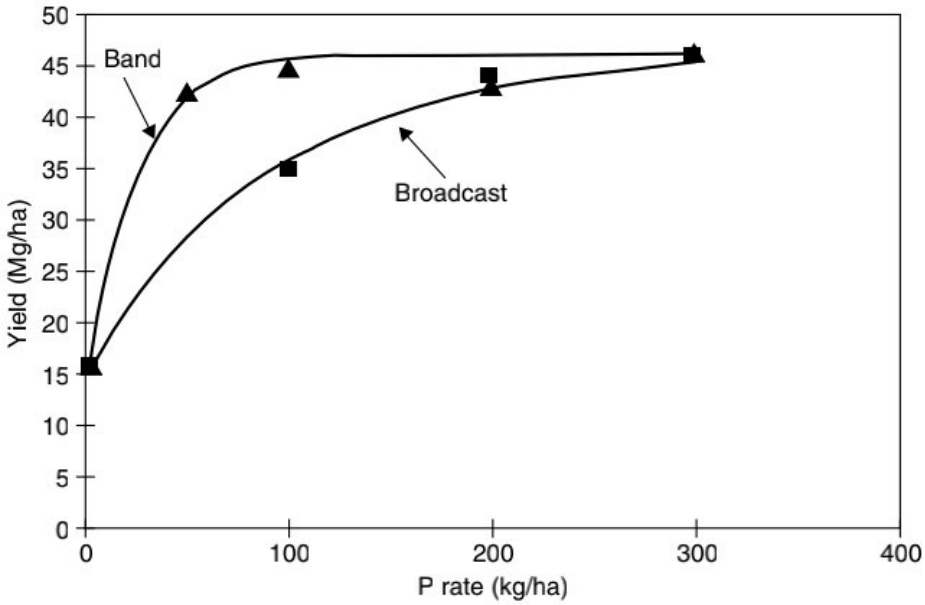

FIGURE 3.9 Marketable yield of lettuce as affected by phosphorus rate and placement. (Adapted from C.A. Sanchez et al. *J. Am. Soc. Hortic. Sci.* 115:581–584, 1990.)

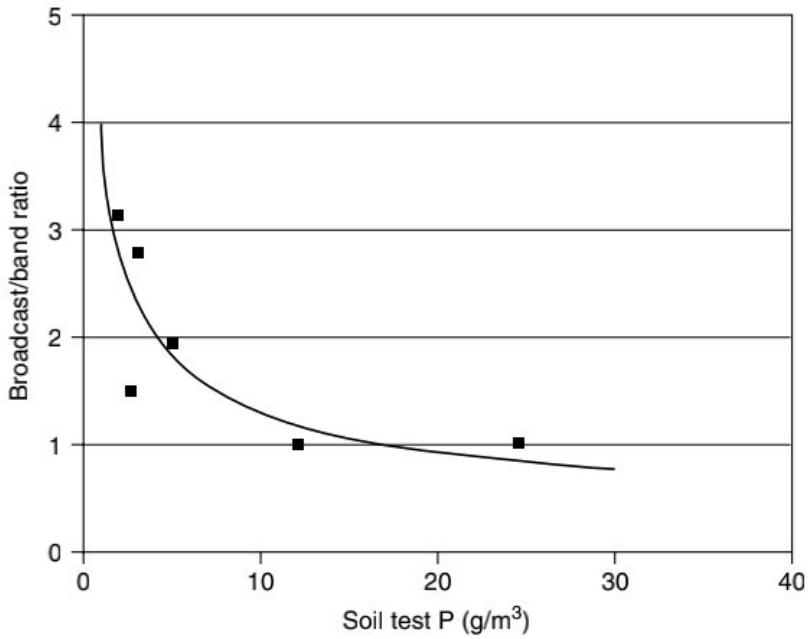

FIGURE 3.10 Relative efficiency of broadcast to banded phosphorus for sweet corn as affected by soil-test phosphorus level.

existing production system. For sweet corn (*Zea mays rugosa* Bonaf.), the relative efficiency of banded to broadcast phosphorus depended on soil-test level (Figure 3.10). The relative efficiency was greater than 3:1 (band:broadcast) at low soil-test phosphorus levels but approached 1:1 as soil-test phosphorus approached the critical value. Others have reported a relationship between the relative efficiency of the localized placement of phosphorus and soil-test levels (105–107). Many factors including crop root morphology, length of crop growing season, soil chemical and physical characteristics, and crop cultural practices interact to influence the relative crop response to broadcast or band fertilization.

3.3.7 Foliar-Applied Phosphorus Fertilization

Foliar fertilization with phosphorus is generally not practiced to the extent that it is done with nitrogen and micronutrient fertilizers although a limited amount of fertilizer phosphorus can be absorbed by plant foliage. Silberstein and Witwer (108) tested various organic and inorganic phosphorus-containing compounds on vegetable crops. They generally observed small responses in plant growth, but some compounds caused injury at phosphorus concentrations as low as 0.16%. They concluded that orthophosphoric acid was the most effective foliar phosphorus fertilizer evaluated. Barrel and Black (109,110) reported that several condensed phosphates and some phosphate fertilizers containing phosphorus and nitrogen could be applied at 2.5 to 3 times the quantity of orthophosphate without causing leaf damage. Yields of corn and soybeans (*Glycine max* Merr.) were higher with tri-polyphosphate and tetra-polyphosphate than with orthophosphate.

Teubner (111) reported that although about 12% of the phosphorus in the harvested plant parts of some field-grown vegetable crops could be supplied through multiple foliar sprays, foliar phosphorus fertilization did not increase total phosphorus absorbed or crop yields. Upadhyay (112) reported that the yield of soybeans were highest when all fertilizer phosphorus was soil-applied, intermediate where 50% of the phosphorus was soil-applied and 50% foliar-applied, and lowest where all the phosphorus was foliar-applied.

Some research suggests that phosphorus in combination with other nutrients might delay senescence and increase yields, but results are inconsistent. Garcia and Hanway (113) reported that foliar applications of N, P, K, and S mixtures during seed filling seemed to delay senescence and increase yield in soybean and the complete mixture produced greater yields than foliar sprays where the mixture was incomplete. Subsequent work with soybeans by others ranged from no-yield response (114) to yield reduction (115) for foliar mixtures containing phosphorus. Similar negative responses have been obtained with other crops. Harder et al. (116,117) observed temporary decrease in photosynthesis and a decrease in grain yield of corn (*Zea mays* L.) receiving foliar N, P, K, and S. Batten and Wardlaw (118) reported that applying monobasic ammonium phosphate to the flag-leaf of phosphate-deficient wheat (*Triticum aestivum* L.) delayed senescence but failed to increase grain yield.

Because only a modest portion of the crop's total phosphorus requirement can be met by foliar application and foliar fertilization does not produce consistent positive responses where residual soil phosphorus or soil-applied fertilizer phosphorus is sufficient, foliar fertilization with phosphorus is seldom recommended as a substitute for soil fertilization practices.

3.3.8 Fertilization in Irrigation Water

Although application of fertilizer in irrigation water (fertigation) is a common practice with mobile nutrients such as nitrogen, it is less common with phosphorus because of concerns about efficiency of utilization. Owing to the soil reactions discussed in a previous section, it is often presumed that much of the phosphorus applied with water will be tied up at its point of contact with the soil. Nevertheless, there are some situations where fertigation is a viable and economical means of delivering phosphorus for crop production.

The downward movement of phosphorus in soil is influenced strongly by soil texture as shown in the laboratory (119,120) and field experiments (121,122). In one study, sprinkler-applied phosphorus moved to a depth of approximately 5 cm in a clay loam soil and to approximately 18 cm in a loamy sand (121). On a basin surface-irrigated Superstition sand that received 91 cm of water, phosphorus moved to a depth of 45 cm (123).

Phosphorus source seems to be another important factor affecting phosphorus movement in soils and thus the efficacy of fertigation. Stanberry et al. (124), using radioautographs to trace P32 movement in Superstition sand, noted that phosphorus from phosphoric acid and monocalcium phosphate moved vertically across the length of the photographic film (20 cm) compared to dicalcium phosphate and tricalcium phosphate, which showed negligible movement. Lauer (122)

reported that sprinkler-applied monoammonium phosphate, urea phosphate, and phosphoric acid showed similar movement in soils. However, ammonium polyphosphate penetrated only to 60 to 70% of the depth of the other sources. Rauschkolb (125) reported that glycerophosphate moved slightly farther than orthophosphate when injected through a trickle-irrigation system but phosphorus from both sources moved a sufficient distance into the root zone such that phosphorus availability was adequate for tomatoes. O'Neill (126) reported that orthophosphoric acid applied in the irrigation water for trickle-irrigated citrus (*Citrus* spp. L.) was delivered to a greater soil volume than triple superphosphate applied directly below the emitter. The phosphoric acid also lowered the pH of the irrigation water sufficiently to eliminate clogging problems associated with the precipitation of phosphorus in the irrigation lines.

In established perennial crops such as citrus or deciduous fruits, fertigation is often a viable means of phosphorus delivery, regardless of the method of irrigation, because tractor application and incorporation would likely cause root damage and broadcast application would not necessarily be more efficient than fertigation. For fast-growing annual crops, where most phosphorus should be applied preplant, fertigation might not result consistently in production benefits compared to band application but might be economical or even necessary depending on the opportunities and constraints of the irrigation delivery system. Bar-Yosef et al. (127) noted no difference between broadcast and drip-injected phosphorus for sweet corn on a sandy soil. Carrijo et al. (128) reported that phosphorus applied through the irrigation system was more efficient than preplant incorporation for tomato produced on sandy soils testing low in phosphorus. Reports that phosphorus fertigation sometimes produced positive responses have been attributed to band-like effects where phosphorus is delivered in or close to the root zone and not widely mixed with the soil (128,129). Overall, the efficacy of phosphorus fertigation depends on soil texture, phosphorus source, irrigation method and amount, and cropping system utilized.

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