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Crop Rotation and Tillage Effects on Phosphorus Distribution in the Central Great Plains

R. A. Bowman* and A. D. Halvorson

ABSTRACT

The fate and availability of soil P in the central Great Plains may become less predictable with less tillage and more intensive crop rotations that produce more crop residue and litter than conventional-till (CT) wheat (*Triticum aestivum* L.)–fallow (W-F). We need to evaluate these new systems relative to new P distribution patterns that may be occurring. We determined P changes in a Weld silt loam soil (fine, montmorillonitic, mesic aridic Paleustoll) in predetermined plots from a 5-year rotation–tillage experiment where 45 kg P ha^{-1} was applied in 1990, and 18 kg P ha^{-1} was applied to the wheat phase of the rotation thereafter. We determined changes in water-soluble P, resin-extractable P, total organic P, bicarbonate-extractable P, and phosphomonoesterase activity as a function of tillage and cropping intensity in soil from the 0- to 5-cm and 0- to 15-cm depths. Phosphorus concentration in wheat tops at an early stage was also determined to assess soil P availability. Generally, P availability indices increased significantly in the 0- to 5-cm depth with continuous cropping treatments compared with wheat–fallow treatments. The results suggest that under more intensive cropping systems P recycling through residue and litter could be an important mechanism resulting in additional plant-available P.

NEXT TO N, P is generally the most important soil nutrient for adequate grain production in a cereal-based cropping system (Sprague, 1964; Epstein, 1972; Ozanne, 1980). Its role in enhancing N-use efficiency and tillering in small grain is well documented (Olson and Dreier, 1956; Hanway and Olson, 1980). However, P sufficiency does not always exist in central Great Plains soils because of excessive wind erosion and, at times, high P-fixing calcareous soils. Soil test surveys in Colorado, Kansas, and Nebraska showed 73, 51, and 60%, respectively, of the soils are deficient in P (Potash and Phosphate Inst., 1994); consequently, N and P fertilization are frequently recommended for adequate grain yield for wheat and other small grain cereal production (Peterson et al., 1995; Rasmussen, 1995).

As cropping systems change from conventional winter wheat–summer fallow to less tillage and more intensive rotations, the fate and availability of P become less predictable because of a larger inorganic and organic P component from greater amounts of residue and litter maintained on the soil surface (O'Halloran et al., 1987). Phosphorus requirements may differ from that of the traditional system where preplant soil P sampling generally reflects the available P. However, in a more intensively cropped system where wheat may follow millet (*Panicum miliaceum* L.) (M) or pea (*Pisum* spp.) in the same year, the potential P contribution of the residue P from the millet or pea may not be assessed by traditional inorganic available P soil testing. A need exists, therefore, to evaluate P levels and distribution patterns that are occurring with these new cropping systems where the fallow period is reduced or eliminated, and residue and fertilizer P inputs are increased.

Previous P fertility studies were designed primarily to evaluate inorganic P availability at planting for a W-F system. Most of these studies evaluated differential P fertilization under N sufficiency (Fiedler et al., 1989; Stibbe and Kafkafi, 1973). Phosphorus needs for a specific crop in a defined climate, soil type, and cultural practice were obtained after two or more seasons. As a followup to these types of studies, availability of residual P with time was also assessed (Halvorson and Black, 1985; McCollum, 1991). Thus, P could be applied according to soil test needs, or a higher rate of P than needed might be applied to supply P longer than sufficiency or replacement requirement rates. This approach evaluated long-term availability of different placement methods, various sources of P, and timings of applications. However, these studies did not make allowances for the short-term potentially available P from the organic P as is common with NO_3–N credit from soil organic matter (SOM) content. Undoubtedly, this is because of the difficulties in assessing litter and SOM contribution to available P for the existing or following crop, and because of the sampling problems with banded P applications in no-till (NT) systems (Kitchen et al., 1990).

The general objectives of this multidisciplinary cropping systems project were to evaluate tillage and crop rotational effects on water- and fertilizer-use efficiencies, weed control, organic matter and residue changes, and on dry matter, grain, and forage yields. An ultimate objective of our cropping system research is to develop recommendations for cropping sequences with appropriate cultural practices that are both economically and environmentally sound.

Our specific objective was to evaluate changes in selected P fractions associated with P availability among different cropping intensities and tillage practices. We compared changes in soil P concentrations because of tillage practices (CT, RT, and NT) and cropping intensities (C.I.), which is the ratio of crop to fallow on a land area basis. Thus, W-F is 0.5, W-corn (*Zea mays* L.) (C)-F is 0.67, W-C-M-F is 0.75, and W-C-M without fallow is 1.00. A C.I. of 1.00 is also referred to as continuous cropping. Within the cropping intensity, we compared rotations with wheat and fallow (the wheat phase was always fertilized with P), with continuous cropping rotations without wheat (no P fertilization). We also

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USDA-ARS, P.O. Box 400, 40335 City Road GG, Akron, CO 80720. Received 11 Sept. 1995. *Corresponding author (rbowman@lamar.colostate.edu).

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Abbreviations: AER-P, anion-exchange resin-extractable P; C, corn; C.I., cropping intensities; CT, conventional-till; EDTA, ethylenediaminetetraacetic acid; F, fallow; M, proso millet; NT, no-till; RT, reduced-till; SOM, soil organic matter; W, wheat.

Table 1. Selected soil physical and chemical properties of the test site at 0- to 15-cm depth, sampled in 1995.

Soil	Sod	W-F†	ACR‡
pH (0.01 M $CaCl_2$)	6.3	5.9	5.5
D_b, kg/m^3	1.20	1.38	1.38
Organic C, g/kg	0.90	0.72	0.76
Total N, mg/kg	0.09	0.07	0.07
$NaHCO_3$-P, mg/kg	12	22	24
Silt, %	20	16	18
Clay, %	22	16	18
Cation-exchange capacity, $cmol_c$/kg	16	13	14

† W-F: wheat–fallow.
‡ ACR is alternative crops to W-F.

determined P concentration in wheat tops at the 4 to 5 Feekes' stage on all wheat rotations (Bauer et al., 1983).

MATERIALS AND METHODS

Field plot research was initiated in 1990 at the USDA-ARS Central Great Plains Research Station near Akron, CO. The region receives an average of 420 mm of annual precipitation with about 80% occurring in April to September. The frost-free season is 139 d with average frost-free dates of 11 May to 28 September. Site elevation is about 1400 m.

The experiment was established on a Weld silt loam using a randomized complete block design with three replications. Selected physical and chemical soil properties are given in Table 1. Plot size for each treatment was 9.1 m by 30.5 m with a 15.2-m alleyway between each block of 30 adjacent treatments laid out in an east–west direction. Two adjacent blocks contained one replication (Fig. 1).

Subsets from three different tillage systems, NT, RT, and CT, and more than 20 different cropping sequences were established (Table 2). The NT system included residual herbicide application (atrazine [2-chloro-4-ethylamino-6-isopropylamino-s-triazine] and clomazone [2-(2-chlorophenyl)methyl-4, 4-dimethyl-3-isoxazolidi-none]) after wheat harvest (usually in late July to early August), and contact or burn-down herbicides (glyphosate [isopropylamine salt of N-(phosphonomethyl) glycine]) in the following spring and summer for weed escapes. Reduced-tillage (RT) was a combination of residual herbicides after harvest and two to three sweep tillage operations with minimal disturbance. Conventional tillage mixed the surface 5 to 10 cm of the soil five to seven times from wheat harvest to preplant wheat 14 mo after. Generally, a sweep plow was used in late July to early August, in early October, May, late June, and in August and September. Mulch treaders were used in fall and spring along with the sweeps to more effectively control grass weeds.

Table 2. Selected rotations were blocked to maximize physical proximity among tillage treatments, and cropping intensity: CT = conventional-till, RT = reduced-till, NT = no-till; cropping intensities reflect the fraction of the rotation in crops, i.e., wheat–fallow = 0.5, wheat–corn or wheat–millet = 1.0.

Factor	Treatment†
Tillage	CT: W-F, F-W (Reps 1, 2, 3) RT: F-W, W-F (Reps 1, 2, 3) NT: W-F, F-W (Reps 1, 2, 3)
Cropping intensity	0.5: F-W (CT, RT, NT); W-F (CT, RT, NT) 0.67 to 0.75: F-W-C, C-M-F-W, W-M-F, F-W-M, F-W-M-C, W-M-C-F 1.0: W-M, M-W, M-W-C, W-C-M, C-M-W, W-C
Fallow–wheat	W-M-F, W-S-F, F-W-M, F-W (RT, NT), C-F-W, W-C-F (RT, NT)
Non-wheat	S-M, F-M-C, M-P, M-C, C-B, B-C, M-S, C-M

† W = wheat (*triticum aestivum* L.); C = corn (*Zea mays* L.); M = proso millet (*Panicum miliaceum* L.); F = fallow; S = sunflower (*Helianthus annuus* L.); B = black turtle bean (*Phaseolus vulgaris* L.).

All phases of a rotation were present every year. For example, these sequences ranged from continuous cropping with W-M or W-C-M, to 2- (W-F), 3- (W-C-F), and 4-yr (W-C-M-F) rotations with fallow. Crops included cool- and warm-season grasses, wheat and corn, and cool- and warm-season broadleaved crops, pea and sunflower (*Helianthus annuus* L.).

Cropping intensity as a treatment is a new concept and deserves additional clarification. Treatments with chemical rates and cultivars are straightforward in their statistical treatment. The evaluation of a specific rotation or sequence vs. a different rotation or other rotations is also straightforward. Cropping intensity creates some confounding since one crop in a wheat rotation may be substituted by another crop. Thus W-C-F and W-M-F, while representing different rotations, are assigned the same C.I. (two crops in 3 yr), and W-M and W-F, while representing 2-yr rotations, are assigned different C.I., because the former represents continuous cropping (W-M-W-M-W-M) and a C.I. of 1.0, and the latter (W-F-W-F-W-F) a C.I. of 0.5.

We deemed C.I. to be more important than an individual treatment in long-term cropping systems. The same C.I. generally has similar fertilization, tillage practices, pest control, and biological productivity (Bezdicek and Granatstein, 1989). If a designated crop cannot be planted because of bad weather, weed infestation, or water shortage, another similar crop can be substituted, and cropping intensity will remain the same. Thus, in some instances, sorghum [Sorghum bicolor (L.) Moench] can be substituted for corn, or sunflower for safflower (*Carthamus tinctorius* L.) in a manner analogous to flex- or risk-cropping management.

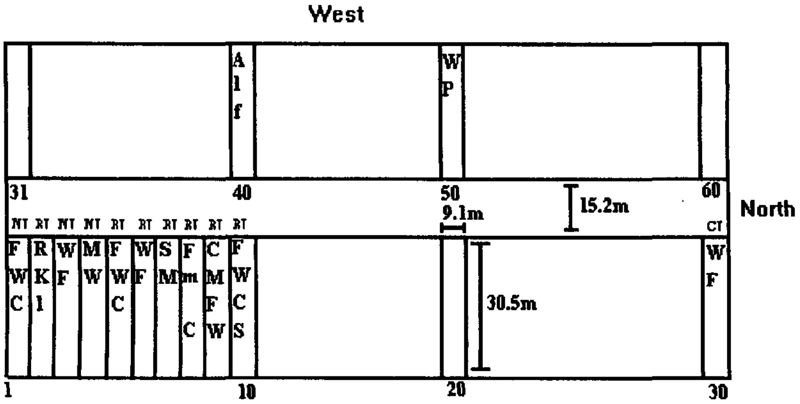

Fig. 1. Layout of experiment, replication 1 of 3; F is fallow, W is wheat, C is corn, M is proso millet, Alf is alfalfa (*Medicago sativa* L. subsp. *sativa*), P is pea, RK1 is risk plot (not part of experiment); CT is conventional-till, RT is reduced-till, NT is no-till.

Based on soil test and recommendations for dryland cropping for the area, 45 to 56 kg of N/ha was applied for wheat, and 78 to 90 kg for corn and sunflower. For P, 45 kg P/ha (0–45–0) was broadcast before planting. Following this blanket application in 1990 and 1991, 18 kg P/ha (11–52–0) was banded below the seed at wheat planting thereafter. No P was applied to the other non-wheat crops in the rotation. Soil samples were obtained in March 1995 at the 0- to 5-, and the 5- to 15-cm depths for all treatments plus the adjacent sod (same soil series). These depths were selected to evaluate stratification due to no- or reduced-till (0–5 cm), and to assess changes in the tillage depth (0–15 cm) for comparison with the WF conventional-till treatment. Soil samples were taken from five different areas to incorporate within- and between-rows sampling. All analyses were made for both depths on air-dried 2-mm screened samples. No attempt was made to exclude minute litter that passed through the screen.

Four soil P parameters were selected for analysis based on immediate P availability (water-soluble; Fox, 1981), seasonal P availability (resin-extractable) (Stevenson, 1986), and potential P availability (organic P and phosphatase activity) (Dalal, 1977). Water-soluble P was determined by shaking 2 g of soil with 20 mL of distilled water for 5 min (Olsen and Sommers, 1980). Anion-exchange resin-extractable P (AER-P) was determined by equilibrating in 100 mL of distilled water, 1 g of soil with bicarbonate-impregnated strips overnight, followed by removal of P from the strips with 0.5 *M* HCl (Cooperband and Logan, 1994). Labile organic P was determined from the increase in bicarbonate-extractable P after persulfate oxidation. Total organic P was determined with hot basic Na_2EDTA (Bowman and Moir, 1993), and the phosphomonoesterase activity essentially according to Tabatabai (1980). Inorganic P in extracts was determined colorimetrically (Watanabe and Olsen, 1965).

Phosphorus concentration in wheat tops (whole plant) at the 4 to 5 Feekes' stage was also determined to assess early soil P availability. A comparison was made among P concentrations for cropping intensities where equal amounts of fertilizer P were applied.

Statistics

Main treatments were tillage (CT, RT, NT), cropping intensity (0.5, 0.67 and 0.75, 1.00) and P-fertilizer treatments (wheat and fallow) with no-P-fertilizer treatments (continuous cropping without wheat). Phosphorus results from treatments were subjected to analysis of variance for mean differences (P = 0.10 by LSD) among tillage practices, cropping intensities, and fallow–wheat and non-wheat rotations.

RESULTS AND DISCUSSION

Not all treatments showed significant differences. Data for all P parameters for the 5- to 15-cm depths were not significantly different among tillage treatments and cropping intensities. Tillage at all depths, when assessed for the same cropping intensity (0.50), was insignificant. However, when assessed with other cropping intensities, tillage at the 0- to 5-cm depth was significant because of the confounding from cropping intensities greater than 0.50, which were all either in reduced- or no-till treatments. Data were not presented for tillage since significance was confounded by cropping intensity.

Significant differences were observed as cropping intensity increased (Table 3). Generally, the greatest increases in P parameters were obtained with continuous cropping (C.I. = 1.0). Water-soluble P was significantly higher with continuous cropping than with wheat–fallow even though the latter generally received more P fertilization than the former. This water-soluble P pool represents the immediately available P pool for microbes and plants, and is also a sink for P from the mineral and organic pools (Olsen and Khasawneh, 1980; Anderson, 1980). Average results for continuous cropping at the 0- to 5-cm depth were about 30% higher than results for treatments with fallow (C.I. < 1.0) (Table 3). This significance remained for the 0- to 15-cm depth. Apparently, under continuous cropping, soil P at deeper depths was taken up and deposited at the soil surface through residue and litter production. Stubble and stover can leach nutrients during the late spring and summer (Tukey, 1970), thereby enriching the surface soil P pool. Additionally, residue and litter in contact with the soil can slowly decompose, releasing more organic and inorganic P (Birch, 1961; Dormaar, 1990).

Table 3. Effects of cropping intensity (crops/rotation) on measures of soil P for 0- to 5- and 0- to 15-cm depths.

Cropping intensity	Depth	Water-soluble	AER-P†	TPo‡	Pase Act§
	cm	mg L^{-1}	—— g m^{-3} ——		mmol kg^{-1} h^{-1}
0.5	0–5	1.00b¶	30.5b	117c	379b
0.67–0.75		1.04b	30.5b	127b	378b
1.00		1.33a	42.5a	141a	435a
0.5	0–15	0.73b	27.1a	119a	320a
0.67–0.75		0.81b	28.5a	118a	299a
1.00		1.04a	31.2a	112a	342a

† AER-P is anion-exchange resin extractable P.

‡ TPo is total soil organic P.

§ Phosphomonoesterase activity: mmol p-nitrophenol released kg^{-1} soil h^{-1}.

¶ Means followed by the same letter or no letter within a column are not significant (LSD $P = 0.10$).

Results for resin-extractable P also showed continuous cropping treatments to be significantly higher than treatments with fallow in the rotation, but only at the 0- to 5-cm depth. Generally, resin P gives a good measure of the amount of P available for the growing season (Sibbesen, 1977), and could be regarded as analogous to a capacity factor (labile pool) with the water-soluble P (intensity factor) reflecting the immediately plant-available pool. Resin-extractable P is highly correlated with soil testing indices such as the bicarbonate and weak acid procedures (Hislop and Cooke, 1968). Because it simulates root P desorption, it is used as a phytoavailability soil test (Yang et al., 1991). Again the increased AER-P in the topsoil for the continuous cropping system was related partially to nutrient released from residue and litter, and probably to surface soil P protection from wind erosion as the summer fallow was eliminated.

For total organic P, the data showed a direct relationship with cropping intensity at the 0- to 5-cm depth (Table 3). There were a 20 and a 10% increases, respectively, with continuous cropping and 3-yr and 4-yr cropping, compared with the 2-yr W-F cycles. As P and N fertilization increased with greater C.I., residue and litter contained more P for release and subsequent enrichment of the SOM (Sharpley, 1985). Total organic P

Table 4. Soil P in the 0–5 cm depth as affected by P fertilization systems.

Cropping system	Depth	Water-soluble	AER-P†	Tpo‡	Pase§
	cm	mg L^{-1}	g m^{-3}		mmol kg^{-1} h^{-1}
Fallow-wheat (+P)	0–5	1.20a¶	32.0a	113a	330a
Non-wheat crops (no P)	0–5	1.48a	45.0b	117a	346a

† AER-P is anion-exchange resin extractable P.
‡ TPo is total soil organic P.
§ mmol p-nitrophenol released kg^{-1} soil h^{-1}.
¶ Means followed by the same letter or no letter within a column are not significant (LSD $P = 0.10$).

content was probably a function of residue, litter, and SOM produced by these plant materials with time. Part of this pool, therefore, was potentially available for crop use within a relatively short time, as shown by the water-soluble and resin-extractable P data.

The phosphatase activity was significantly higher at the 0- to 5-cm depth for continuous cropping only (Table 3). This measurement is used to show the potential of the soil to mineralize labile organic P, and is an indirect way to assess the potential for plant-available P from the soil organic matter (Sharpley, 1985). The importance of this pool in grasslands is documented (Dormaar, 1972; Halm et al., 1972); however, its importance in intensively cropped systems has only recently been addressed, and should become more important as we shift toward less summer fallow and greater residue production.

Since only the wheat phase of the rotation was fertilized, soil P from non-wheat rotations (these were all in continuous cropping) came primarily from P in the surface residue and litter and from soil residual sources (Table 4). Water-soluble P and total organic P were not different, but resin-extractable P was significantly higher for the non-wheat crops even though these crops received no additional P fertilization for 4 to 5 yr. The W-F systems during the 5-yr period received P fertilization two (W-C-F) or three (W-F) times.

Phosphorus redistribution due to cropping intensities was reflected in the labile P pools extracted in bicarbonate (Table 5). Labile organic P was significantly higher in the more intensified cropping systems (C.I. > 0.50). The total P extracted in bicarbonate showed no difference for C.I. of 0.5 and 0.67. The continuous cropping (C.I. = 1.00), however, was significantly higher than both. This total pool is probably more meaningful than either inorganic P or organic P singly, since residue P or labile soil organic P can be readily converted (through mineralization) to inorganic P. While some of this P is attributable to fertilizer P, a significant portion may also be attributable to recycled P from residues.

Table 5. Soil bicarbonate-extractable organic (Po) and total P (Pt) (0–5 cm) as affected by cropping intensity.

Cropping intensity	NaHCO$_3$-P Po	NaHCO$_3$-P Pt
	mg kg^{-1}	
0.5	11.8b	48.1b
0.67–0.75	15.2a	49.7b
1.00	15.8a	61.7a
Sod	6.0	17.0

Phosphorus concentration was determined in young wheat plants (Feekes 4–5) to assess whether more soil available P in the continuous cropping plots resulted in greater P concentration in the plant (Table 6). Cropping systems with wheat for the same rotation length received the same amount of P fertilizer; however, the 2-yr rotation had cropping intensities of 0.50 (W-F) and 1.00 (W-M, W-C), while the 3-year rotation had intensities of 0.67 (W-C-F) and 1.0 (W-C-M, W-C-oat (*Avena sativa* L.) In both instances, the wheat in the continuous cropping systems contained significantly greater P concentrations than the wheat with fallow in rotations. Wheat samples were taken in early April to minimize major growth and biomass differences.

It would appear that greater amounts of soil P are redistributed from the lower depths through residue and litter in these intensively cropped systems than the W-F system. For this reason, the various P indices were, generally, significantly greater at the 0- to 5-cm depth in the continuous cropping systems than in the W-F systems even though the W-F rotations on average received more P fertilization. The effects of this increased cover on water storage and use, coupled with adequate N fertilization, may have provided the impetus for greater soil P deposited on the soil surface.

CONCLUSION

The concept of assessing changes in P or other nutrient content on the basis of cropping intensity is new. However, as we start to emphasize more cropping sequences with no- or minimum-till, specific treatments may be important in the short term, but less important in the long term than the amount of time a site or treatment is in cover and fallow. Even though this new approach may create some confounding since one crop may substitute for a similar one, crop residue will generally increase to a new equilibrium with greater cropping intensity, which should result in more nutrient release in the topsoil. Additionally, in the long term, more residue and soil organic matter should also result in better soil physical properties, which should promote greater water infiltration and less erosion. However, we still need to conduct experiments with less or no additional fertilizer P inputs (except for starter P, which is generally recommended even with adequate P levels) in our con-

Table 6. Phosphorus concentration in young wheat plants (Feekes' 4–5) as a function of rotation length for the same P fertilization rate.

2-yr rotation† Crops	P	3-yr rotation‡ Crops	P
	mg kg^{-1}		mg kg^{-1}
W-F (CT)	2.76b	W-C-F (RT)	2.65ab
W-F (NT)	2.40b	W-C-F (NT)	2.49b
W-M	3.11a	W-C-M	2.81a
W-C	3.00a	W-C-Oat§	2.80a

† All 2-yr rotations were fertilized the same (once every 2 yr).
‡ All 3-yr rotations were fertilized the same (once every 3 yr).
§ Oat: *Avena sativa* L.

tinuous cropping systems with wheat to evaluate this new equilibrium, and the role of residue and organic P in helping to maintain adequate yields.

REFERENCES

Anderson, G. 1980. Assessing organic phosphorus in soils. p. 411–431. *In* F.E. Khasawneh et al. (ed.) The role of phosphorus in agriculture. ASA, Madison, WI.

Bauer, A., D. Smika, and A.L. Black. 1983. Correlation of five wheat growth stage scales used in the Great Plains. AAT-NC-7. USDA-ARS. U.S. Gov. Print. Office, Washington, DC.

Bezdicek, D.F., and D. Granatstein. 1989. Crop rotation efficiencies and biological diversity in farming systems. Am. J. Altern. Agric. 4:111–119.

Birch, H.F. 1961. Phosphorus transformation during plant decomposition. Plant Soil 15:347–366.

Bowman, R.A., and J.O. Moir. 1993. Basic EDTA as an extractant for soil organic phosphorus. Soil Sci. Soc. Am. J. 57:1516–1518.

Cooperband, L.R., and T.J. Logan. 1994. Measuring in situ changes in labile soil phosphorus with anion-exchange membranes. Soil Sci. Soc. Am. J. 58:105–114.

Dalal, R.C. 1977. Soil organic phosphorus. Adv. Agron. 29:83–117.

Dormaar, J.F. 1972. Seasonal pattern of soil organic phosphorus. Can. J. Soil Sci. 52:107–112.

Dormaar, J.F. 1990. Effect of active roots on the decomposition of soil organic materials. Biol. Fertil. Soils 10:121–126.

Epstein, E. 1972. Mineral nutrition of plants: Principles and perspectives. John Wiley & Sons, New York.

Fiedler, R.J., D.H. Sander, and G.A. Peterson. 1989. Fertilizer phosphorus recommendations for winter wheat in terms of method of application, soil pH, and yield goal. Soil Sci. Soc. Am. J. 53: 1282–1287.

Fox, R.L. 1981. External phosphorus requirements of crops. p. 223–239. *In* R.H. Dowdy et al. (ed.) Chemistry in the soil environment. ASA Spec. Publ. 40. ASA and SSSA, Madison, WI.

Halm, B.J., J.W.B. Stewart, and R.H. Halstead. 1972. The phosphorus cycle in a native grassland ecosystem. p. 571–586. *In* Isotopes and radiation in soil plant relationships including forestry. Publ. STI/PUB 292. IAEA, Vienna.

Halvorson, A.D., and A.L. Black. 1985. Long-term dryland crop responses to residual phosphorus fertilizer. Soil Sci. Soc. Am. J. 49:928–933.

Hanway, J.J., and R.A. Olson. 1980. Phosphorus nutrition of corn, sorghum, soybeans, and small grains. p. 681–692. *In* F. E. Khasawneh et al. (ed.) The role of phosphorus in agriculture. ASA, Madison, WI.

Hislop, J., and I.J. Cooke. 1968. Anion-exchange resin as a means of assessing soil phosphate status. A laboratory technique. Soil Sci. 105:8–11.

Kitchen, N.R., J.L. Havlin, and D.G. Westfall. 1990. Soil sampling under no-till banded phosphorus. Soil Sci. Soc. Am. J. 54: 1661–1665.

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umprabuult. Agron. J. 83:77–85.

O'Halloran, I.P., J.W.B. Stewart, and E. deJong. 1987. Changes in P forms and availability as influenced by management practices. Plant Soil 100:113–126.

Olsen, S.R., and F.E. Khasawneh. 1980. Use and limitations of physical-chemical criteria for assessing the status of phosphorus in soils. p. 361–410. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Olsen, S.R., and L.E. Sommers. 1980. Phosphorus. p. 403–430. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA Madison, WI.

Olson, R.A., and L. Dreier. 1956. Nitrogen, a key factor in fertilizer phosphorus efficiency. Soil Sci. Soc. Am. Proc. 20:509–514.

Ozanne, P.G. 1980. Phosphate nutrition of plants — A general treatise. p. 559–589. *In* F. E. Khasawneh et al. (ed.) The role of phosphorus in agriculture. ASA, Madison, WI.

Peterson, G.A., D.G. Westfall, L. Sherrod, R. Kolberg, and D. Poss. 1995. Sustainable dryland agroecosystem management. Tech. Bull. 95-1. Agric. Exp. Stn., Colo. State Univ., Fort Collins, CO.

Potash and Phosphate Inst., 1994. Soil test summaries: P, K, and pH. Ref no. 323044/94174. Better crops plant food 78:14–17.

Rasmussen, 1994. Are present-day wheat varieties more sensitive to phosphorus deficiency? Better crops plant food 78:14–15.

Sharpley, A.N. 1985. Phosphorus cycling in unfertilized and fertilized agricultural soils. Soil Sci. Soc. Am. J. 49:905–911.

Sibbesen, E. 1977. A simple ion-exchange resin procedure for extracting plant-available elements from soil. Plant Soil 46:665–669.

Sprague, H.B. 1964. Hunger signs in crops. David McKay Co., New York.

Stevenson, F.J. 1986. Cycles of soil C, N, P, S, and micronutrients. John Wiley & Sons, New York.

Stibbe, E., and U. Kafkafi. 1973. Influence of tillage depths and phosphorus fertilizer application rates on the yields of annual cropped winter-grown wheat. Agron. J. 65:617–620.

Tabatabai, M.A. 1980. Soil enzymes. p. 903–947. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.

Tukey, H.B. 1970. The leaching of substances from plants. Annu. Rev. Plant Physiol. 21:305–332.

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts. Soil Sci. Soc. Am. J. 29:677–678.

Yang, J.E., E.O. Skogley, S.J. Georgitis, B.E. Schaff, and A.H. Ferguson. 1991. Phytoavailability soil test: Development and verification of theory. Soil Sci. Soc. Am. J. 55:1358–1365.