Phosphorus Extractability of Soils Amended with Stockpiled and Composted Cattle Manure

Final Report Submitted to
Texas Cattle Feeders Association
Amarillo, TX

Trust Fund Cooperative Agreement No. 58-6209-0-029

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June, 2004

EXECUTIVE SUMMARY

Soils are most often the resource used in the final assimilation of many agricultural waste products. The application of manure can have a beneficial influence on the soil condition by improving aggregation, increasing organic matter content, and supplying nutrients for plant growth. However manures should be applied to soils so that constituents in the waste do not exceed the soils capacity to adsorb or store them. Phosphorus in manure tends to be the most restrictive constituent because of the relatively large concentrations found in manure and because it is not very mobile in the soil which leads to surface accumulation and subject to offsite transport by runoff. In the Southern High Plains, confined cattle feeding operations generate large quantities of manure of which a large proportion is applied to agricultural soils. Knowledge of the influence of cattle manure applications on the soluble and extractable forms phosphorus in the soils of this region is critical in the development of practical nutrient management plans.

This study investigates the influence of soil characteristics, manure characteristics, and fertilizer application rates on the extractability of phosphorus in amended soils incubated under controlled environmental conditions. The Mehlich 3, Olsen ($NaHCO_3$), and Texas A&M (TAM) agronomic soil phosphorus tests were examined in this study because these extractants are used by the state extension soil testing laboratories of Oklahoma, New Mexico, and Texas, respectively, for making nutrient management recommendations. Changes in water extractable P in soils were also examined because it is an important quantity when considering offsite movement of P with runoff.

The increase in extractable P in soils amended with manures and synthetic fertilizers varied considerably with respect to P source, incubation time, extractant, and soil characteristics. The major summarized findings of this study follow.

- The fraction of total P added that became extractable after incubation varied widely among agronomic extractants. After an eight-week incubation period, P extraction efficiency of the Mehlich 3 extractant for all soils averaged 70% for scraped or stockpiled manure, 84% for composted manure, and 93% for a highly soluble fertilizer (KH_2PO_4). For the Olsen ($NaHCO_3$) extractant, the corresponding efficiencies averaged 47%, 49%, and 63%, respectively.
- The soils of this region are typically dominated by 2:1 clay mineralogy with a high base status and frequently calcareous. Under these conditions, soil calcium and calcium contained in manures and fertilizers were an important governing factor in regulation of soil P by depressing its solubility and extractability. Soluble organic acids and organic anions generated by or added with manures also appeared to play a role in governing P status in these soils.
- The calcareous soil was capable of immobilizing larger quantities of phosphorus then other soils investigated in this study. Accordingly, different management considerations will be required when manure is applied to calcareous soils. Scraped cattle manure maintained a higher level of water and $NaHCO_3$ extractable P as compared to a soluble synthetic fertilizer in a calcareous soil at the end of an eight week incubation period. Consequently, cattle manure might be advantageously used to improve the P availability to crops on calcareous soils.
- Soils amended with synthetic fertilizers had significantly greater water extractable P than soils amended with manures, especially after short, 1 week incubation periods.

- Increases in water extractable P relative to increases in agronomic soil test P were greatest for synthetic fertilizers as compared to composted or stockpiled manures. Consequently, the common agronomic soil extractants in the region cannot always be used to make reliable inferences about water extractable P, an important quantity when considering offsite movement of P with runoff. These inconsistencies could be overcome by applying both an agronomic and environmental soil test to P indexing systems so that both the soils capacity to supply P and readily soluble P are considered. An environmental soil test, such as water extractable P, would only need to be considered if the agronomic soil test value is “exceedingly” high.

Recommendations for estimating increases in extractable P resulting from cattle manure applications are provided in this document and should be considered only as a first approximation. Targeted field research looking at increases in extractable P after manure applications over the short and long term will need to be carried out in order to corroborate the relationships and improve estimates of changes in extractable P. It is hoped that the results of this study combined with further field research will allow for improved P management and permit more flexibility in planning manure applications thereby increasing its perceived and real value as a fertilizer.

R.C.S.

INTRODUCTION

In many regions dominated by animal-based agriculture, confined animal operations generate large quantities of manure in localized areas. In most cases, the only economically viable option for disposal is land application. Animal manures usually contain levels of phosphorus far in excess of that required by crops when applied to meet the nitrogen demand. Because of the nutrient imbalance between N and P, repeated applications of manures will lead to soil P enrichment and increased environmental risks associated with elevated concentrations of dissolved phosphorus in runoff.

In response to excessive P in surface waters, many state agencies have developed guidelines for manure applications aimed at reducing P in agricultural runoff. The strategies vary among states but typically employ a P-index approach or a soil P threshold to help delineate P loss vulnerability. A commonality among all P management strategies is the use of an agronomic soil P test to assess and monitor changes in the soil's P status and establish management guidelines aimed at reducing surface P loss (Sharpley et al., 2003). Agronomic soil P tests are often well-correlated with environmental soil tests such as water extractable P and in some cases with soluble P in runoff (Sims et al., 2002; Pote et al., 1996). However, these relationships may be altered when soils are amended with manure or fertilizer P. In recently amended soils, Sharpley et al. (2001) found that dissolved P in runoff was not related to Mehlich 3 extractable P but, rather, a function of the source and quantity of P applied. The characteristics and maturity of stockpiled manure and compost (Henry and Harrison 1996), competitive sorption between organic anions and phosphate (Hue 1991; Sharpley and Sisak 1997), soil characteristics, kinetics, and environmental conditions all may influence how much applied manure P is extractable during the first few months after an application. The amount of manure applied that becomes available to plants during a growing season is probably influenced by similar factors and mechanisms. For manure of fed cattle, plant availability of phosphorus within the first year after an application has been estimated as 60% (Iowa State University, 2003), 75% (Moffitt et al., 1999) and 90% (Zhang et al., 2003). The wide range in estimated P availability from manures is probably indicative of some degree of uncertainty regarding the turnover of manure phosphorus in soils and regional differences in prevailing soils and environmental conditions.

The objective of this study was to determine the influence of soil characteristics, manure characteristics (maturity), and application rates upon the extractability of phosphorus in amended soils incubated over time. The extractants of the state extension soil testing laboratories of Texas, Oklahoma, and New Mexico were used to facilitate interpretations based on each of their standardized soil analyses. Water and anionic resin extractable P in soils were also examined because they are important quantities when considering offsite movement of P with runoff.

MATERIALS AND METHODS

Five soils of the southern high plains were selected for use in the phosphorus extractability study (Table 1). The soils were collected from the Ap horizon (0 - 0.15 m) in fields with no recent (<5 years) history of organic (manure) fertilizer amendments. Bulk soil samples were air-dried, sieved (2 mm) and stored at -8° C until required for incubations. Selected properties of soils are provided in Table 2.

Table 1. Classification, location, and cropping history of soils used in the study.

Soil Series	USDA Classification	Location	Elevation m	Cropping history
Pullman	Fine, mixed, superactive, thermic Torrertic Paleustoll	Randall County TX 35° 11' 28" N 102° 04' 55" W	1169	Dryland wheat-sorghum-fallow rotation, no fertilizers.
Texline	Fine-loamy, mixed, superactive, mesic Calcidic Paleustoll	Hansford County TX 36° 10' 5.7" N 101° 13' 27.9" W	955	Soybeans followed by winter wheat planted in the fall, synthetic fertilizers as required.
Acuff	Fine-loamy, mixed, superactive, thermic Aridic Paleustoll	Lubbock County TX 33° 47' 43.1" N 102° 00' 50.1" W	1049	CRP for 10 years, no fertilizers.
Amarillo	Fine-loamy, mixed, superactive, thermic Aridic Pleustalf	Howard County TX 32° 16' 10" N 101° 29' 26" W	770	Dryland cotton, synthetic fertilizers.
Harney	Fine, smectitic, mesic Typic Argiustoll	Moore County TX 35° 51' 44.2" N 101° 53' 29.8" W	1107	Irrigated corn, synthetic fertilizers as required.

Bulk samples of manure and commercially produced composted manure were obtained from a beef cattle feed yard located near Amarillo, TX. Fresh manure was collected by hand from feedyard pens and dried in a 40° C convective oven overnight. Manure from a freshly scraped pen (Scraped Manure), a 'new' (~ 4 mo.) stockpile (New Stockpiled Manure), and an 'old' (> 1 year) stockpile (Old Stockpile Manure) were also collected from the same feed yard. Composted manure (Compost) was prepared with scraped manure in windrows that were periodically watered and mechanically aerated over a duration of two months. Additional organic amendments were not used in the production of the composted manure. Scraped, stockpiled and composted manures were allowed air dry to a water content sufficiently low enough to permit processing. Manures were ground by hand with a mortar and pestle to pass through a 0.5 mm sieve and stored at -8° C. Selected properties of manures used are provided in Table 3.

Incubation 1

A three-way factorial experiment was used to evaluate the influence of the temperature-moisture regime, fertilizer source, and phosphorus rate on P extractability in a Pullman soil. Eighty grams soil (oven-dry equivalent) were weighed into 100-ml plastic containers into which manures and inorganic fertilizer were added at rates of 0, 31.25, 62.5, 125, and 250 mg total P kg^{-1} soil. Unamended treatments were replicated six times and all other treatments were replicated three times. Inorganic fertilizer consisted of a solution of monocalcium phosphate $[Ca(H_2PO_4)_2]$, KNO_3, and NH_4NO_3 that supplied the nutrients N: P: K at ratios of 3.0 : 1.0 : 1.1. After addition of manure P sources (Fresh Manure, New Stockpile Manure, Old Stockpile Manure, and Compost) to containers, they were mixed with the soil using a glass rod. Soils were incubated

Table 2. Selected physical and chemical properties of soils.

Soil	Particle Size Distribution				pH	$CaCO_3$	NaOAc	NH_4OAc Extractable Bases					Total	Total	Mehlich 3
Series	sand	silt	fine clay	clay	1:01	Equiv.	CEC[†]	Ca	Mg	Na	K	Total	Carbon	Nitrogen	Phosphorus
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}		g kg^{-1}	cmole$_c$ kg^{-1}	——— cmole$_c$ kg^{-1} ———					g kg^{-1}	g kg^{-1}	mg kg^{-1}
Acuff	564	212	124	224	7.0		13.6	10.1	2.2	0.1	1.3	13.7	7.3	0.74	12.2
Amarillo	812	76	57	112	8.2	1	7.4	11.7[‡]	0.6	0.1	0.5	12.9	2.2	0.23	15.9
Harney	521	265	111	214	7.3		15.0	9.9	4.5	0.3	1.7	16.4	11.0	1.13	134.4
Pullman	172	447	147	381	6.8		27.5	18.0	5.6	0.2	2.1	25.9	10.2	1.00	43.7
Texline[§]	277	486	58	237	8.2	31	20.5						17.5	1.34	54.0

[†] CEC - Cation exchange capacity determined by saturation of exchange sites with Na^+ at pH 8.2.

[‡] Free carbonates are likely responsible for the larger than expected value of “exchangeable” Ca reported for the Amarillo soil.

[§] Extractable bases were not completed for the Texline soil because of the presence of significant quantities of free carbonates.

Table 3. Selected characteristics of manures used in the incubation experiments.

Manure	Total C	Total N	Total P	N:P Ratio	DRP ‡	Total Ca	Total Mg	Total K	Total Na	Total Fe	Total Mn
	g kg^{-1}	g kg^{-1}	g kg^{-1}		g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}
Fresh	463	27.5	4.53	6.07	0.325	19.1	5.28	9.6	4.70	242	148
Scraped	219	19.9	5.14	3.87	0.431	25.7	3.82	26.3	6.21	223	272
New Stockpile	188	25.3	8.40	3.01	0.361	29.5	5.59	31.4	7.34	257	359
Old Stockpile	168	19.4	6.26	3.10	0.445	29.8	4.46	28.0	6.01	250	302
Compost	147	17.4	6.26	2.78	0.489	28.5	4.72	32.4	7.20	243	376

[†] All concentrations are on dry matter basis and represent an average of five (C, N, P, and DRP) and two (Ca, Mg, K, Na, Fe, & Mn) replicates.

[‡] DRP - dissolved molybdate reactive phosphorus from a 1:10 extraction with deionized water.

under either i) a constant 25° C temperature regime or ii) a repeated wetted (1 week at 25° C, 33 kPa water content) and drying (1 week at 40° C) conditions. Water was replaced weekly for both incubation regimes to attain -33 kPa water content. Container lids were fitted loosely over samples incubating at 25° C to permit free air exchange. Lids were removed from sample containers incubating at 40° C. All incubations were initiated at the 25° C temperature regime and terminated nine-weeks later at the end of a 25° C regime. Incubated samples were then air-dried at 40° C in a convective oven, ground to pass through a 2-mm sieve, and stored at -8° C for later analyses.

Incubation 2

Five selected soils of the southern high plains region were amended with freshly scraped manure, composted manure, and inorganic fertilizer at five rates in triplicate and incubated under repeated wetted-drying conditions. Fertilizers were added to 70 g (oven-dry equivalent) soil in 100-ml plastic containers at rates of 0, 20, 40, 80, and 120 mg total P kg^{-1} soil. The inorganic fertilizer consisted of a solution of monopotassium phosphate [KH_2PO_4] and NH_4NO_3 that supplied nutrients N: P: K at ratios of 2.5 : 1.0 : 1.26. Unamended treatments were replicated six times and all other treatments were replicated three times. Amended soils were incubated under repeated wetted (25° C, -33 kPa water content) and drying (40° C) conditions as described for *Incubation 1*. Half the soil containers were incubated for only two days at 25° C and then transferred to the 40° C environmental chamber for 5 days (1 week duration). The remaining containers were incubated for eight weeks beginning with the 25° C temperature and terminating with one week in the 40° C drying regime (8 week duration). Upon termination of the 1 and 8-week incubations, samples were air-dried at 40° C in a convective oven, ground to pass through a 2-mm sieve, and stored at -8° C for later analyses.

Soil and manure analyses

Phosphorus was extracted from incubated soils with deionized water (2 g soil in 20 mL, shaken end over end for 30 minutes), Mehlich 3 extractant (Mehlich, 1984; 2 g soil in 20 mL, shaken end over end for 5 minutes), 0.5 *M* $NaHCO_3$ at pH 8.5 (Olsen et al., 1954; 1 g soil in 20 mL, shaken end over end for 30 minutes), and the Texas A&M extractant (TAM) consisting of 0.025 *M* EDTA, 1.0 *N* HCl, and 1.4 *M* NH4-OAc (Hons et al., 1990; 1 g soil in 20 mL, shaken end over end for 45 minutes). Water and 0.5 *M* $NaHCO_3$ soil suspensions were filtered through Whatman No. 42 filter paper and Mehlich 3 and Texas A&M suspensions were filtered through Whatman No. 2 filter paper. A strong base anion exchange resin (DOWEX SBR-C) polystyrene gel cross-linked with divynl benzene was used for resin extractions. This exchange resin has a P sorption capacity of 60 cmol kg^{-1} ($H_2PO_4^-$ replacing HCO_3^-), and selectivity coefficients of 5, 6, and 22 for PO_4^{-3}, HCO_3^-, and Cl^-, respectively. Resin extractions were completed using 0.4 mm mesh polyester bags containing 6 g resin each and previously washed with eight volumes of 0.5 *M* $NaHCO_3$ to saturate the exchange complex with HCO_3^-. The bags were rinsed twice with deionized water and permitted to air dry before use. Each resin bag was placed in a 100 ml bottle with 5 g soil and 50 mL of deionized water and shaken gently for 24 h at room temperature. Resin bags were then removed and rinsed with deionized water and eluted using 50 mL of 0.5 *N* HCl over a 16 hour period.

Manures were digested with sulfuric acid and hydrogen peroxide for determination of total P in digests (Richards, 1993). Dissolved molybdate reactive P (DRP) in manures was determined by shaking 2 g manure in 20 mL deionized water end over end for 30 minutes and filtering with a vacuum through a 0.45 μm membrane filter. Total elemental carbon and nitrogen in manures and soils were determined by dry combustion and subsequent thermal conductivity analysis of evolved gasses using an Elementar vario Max CN analyzer. Water contents of soils at -33 kPa were determined using pressure plate apparatus. Particle size distribution of soils was determined by wet sieving and the pipette method (Gee and Bauder, 1986). Calcite and dolomite content of soils were determined using a Chittick apparatus (Dreimanis, 1962). Cation exchange capacity was determined by the Na-OAc (pH 8.2) procedure of Rhoades (1982) and pH was measured using a 1:1 soil to water ratio. Dissolved molybdate reactive phosphorus in extracts and digests were determined using a modified colorimetric molybdate-blue method of Murphy and Riley (1962) in conjunction with an autoanalyzer (EPA, 1983). The Murphy and Riley (1962) method measures a portion of the acid-hydrolysable organic P in addition to all orthophosphate-P present in extracts.

Statistical analyses

Statistical analysis was completed using the general linear models procedure (SAS, 1999) to test for significant treatment effects. Orthogonal polynomial contrasts were used to test for linear, quadratic, and cubic trends between phosphorus application rate and soil test P. Linear regression was used to estimate the soil test P response (slope) to application rates (P extraction efficiency). Significant differences in linear trends between different fertilizer phosphorus sources, incubation regimes, incubation times, and soils were tested using mutually orthogonal linear regression contrasts of the interactions (Schabenberger and Pierce, 2002). Regression analyses were also used to study the relationships between P extracted by different soil tests.

RESULTS AND DISCUSSION

Extractable P increased with increasing P application rate for all treatments in both experiments (Figs. A1 to A8; Appendices). The trend of extractable P in response to applied P was highly linear ($P < 0.0001$) for all treatments and extractants. Orthogonal polynomial contrasts also yielded significant ($P < 0.05$) positive quadratic trends for all P sources with the TAM extractant (Fig. A3; Fig. A7) and for KH_2PO_4 with deionized water (Fig. A8). Hons et al. (1990) also obtained positive quadratic trends for the TAM extractant on non-calcareous soils. The Texline soil also exhibited a positive quadratic response ($P < 0.05$) to applied KH_2PO_4 with the $NaHCO_3$ extractant (Fig. A6). The efficiency of P extraction assuming a linear trend is presented in Tables A1 and A2 (Appendices) and summarized in Table 4. Efficiency of P extraction is essentially the slope of the linear regression of extractable P as a function of applied P. Analysis of variance for both incubations 1 and 2 (Tables A1 and A2) indicated highly significant main effects and two factor interactions among all extractants. Because of highly significant interactions and masked (crossed) effects, separate two-way analysis of variance was carried out to evaluate the influence of P source, incubation regime, time, and soil on the linear response of extractable P.

Resin extractable soil P results were highly variable which led to inconsistent and occasionally insignificant responses to applied P. Mixed and highly variable results with anion exchangeable resin extractions to assess P availability in soils has also been reported by other researchers (Griffin et al., 2003). Because of these difficulties, resin extractable P results are not presented throughout the remainder of this report.

Table 4. Summary of P extraction efficiencies for selected soils after an eight-week, wetted-drying incubation regime.

	Extractant		
Fertilizer Source	Mehlich 3	$NaHCO_3$	Water
	P Extraction Efficiency[†]		
	Pullman (clay loam)		
Composted Manure	0.81	0.50	0.085
Scraped & Stockpiled[‡]	0.67	0.45	0.089
KH_2PO_4	0.79	0.56	0.127
$Ca(H_2PO_4)_2$	0.66	0.44	0.112
Fresh Manure	0.50	0.42	0.060
	Texline (calcareous loam)		
Composted Manure	0.81	0.50	0.057
Scraped Manure	0.63	0.47	0.086
KH_2PO_4	0.85	0.33	0.053
	Amarillo (loamy sand)		
Composted Manure	0.88	0.56	0.080
Scraped Manure	0.73	0.48	0.112
KH_2PO_4	1.06	0.68	0.220
	Average (all soils)[§]		
Composted Manure	0.84	0.49	0.072
Scraped Manure	0.70	0.47	0.098
KH_2PO_4	0.93	0.63	0.203

[†] Phosphorus extraction efficiency is calculated as the slope of extractable P (mg kg^{-1}) as a function of application rate (mg kg^{-1}).

[‡] Average of scraped, new stockpiled and old stockpiled manure. Differences among these sources were either small or statistically insignificant.

[§] Average phosphorus efficiencies for the five soils investigated in the study (Incubation 2).

Incubation regime

Paired *t*-tests demonstrated that a wetted-drying incubation regime significantly ($P<0.001$) increased Mehlich 3 and water extractable P of unamended Pullman soil as compared to a constant temperature regime with minimal drying. A small but consistent increase in native extractable soil P following drying has also been reported for EDTA, $NaHCO_3$, deionized water, and resin extractions (Haynes and Swift, 1985; Pote et al., 1999; Turner and Haygarth, 2001; Turner and Haygarth, 2003). Potential mechanisms by which soil drying could augment extractable P include lysed microbial cells (Salema et al., 1982) and the disruption of organic matter coatings on clay surfaces by physical stresses induced by drying (Turner and Haygarth, 2003).

Differences in extractable P of unamended soils in response to incubation regime, however, were small in comparison to increases in extractable P in response to amendments. Efficiency of P extraction for both Mehlich 3 and water extractable P tended to be greater for manure P incubated under a constant temperature regime as compared to a wetted-drying regime (Tables A1 and A3). Decreased extractability of organic P under a wetted-drying regime may be a result of lower water contents that slow mineralization of organic P or hasten transformation of Ca-phosphates (Ca-P) to more insoluble forms.

Time

With few exceptions, differences between P extractability at 1 week and 8 weeks were dominated by significant ($P<0.05$) decreases with time for KH_2PO_4 amended soils (Table A5). Time dependence of extractabilities is characteristic of P soil chemistry and may be a consequence of intra-particle solid diffusion posing as a rate-limiting sorption or the precipitation of calcium phosphates (Ca-P) out of solution. The former process has principally been associated with oxides and hydroxides of Al and Fe (Van der Zee et al., 1989) that are of minor importance for the soils used in this study. Undoubtedly, the large decreases in P extractability over time for the KH_2PO_4 amended Texline was a result of precipitation of Ca-P on calcite (carbonate) surfaces and subsequent transformations to less soluble Ca-P (discussed in the next section). Lack of time dependence for TAM extractable P in the KH_2PO_4 amended Texline soil (Table A5) likely results from the acidic TAM extractant in conjunction with large solution:soil ratios and long shaking times that are sufficient to dissolve most of the precipitated Ca-P.

In contrast to KH_2PO_4-amended soils, significant changes in P extractability with time for soils amended with composted or scraped manure were more infrequent and resulted in P extractability increasing with time (Tables A2 and A5). Increased extractability with time of manure amended soils probably resulted from mineralization of P containing organic constituents (Dao and Cavigelli, 2003). Significant mineralization rates of organic carbon over the duration of the incubation period were only observed for the scraped manure (Fig. 1). Release of humic acids and organic anions by the decomposition process may also have (i) formed complexes with Ca (Ca-humate) thereby reducing solution Ca and increasing P solubility (Dalton et al. 1952, Moreno et al. 1960) and (ii) blocked or occupied sites of PO_4^{3-} sorption on the anion exchange complex (Kafkafi et al., 1988).

Soil

Soil type explained 56 to 62% of the variability of extractable Mehlich 3, TAM, and water P under incubation 2. Variability of $NaHCO_3$ extractable P due to soil class was less sensitive and accounted for only 31% of the total sum of squares. The effect of differences in native extractable soil P among soils on the analysis of variance can be removed by subtracting mean P

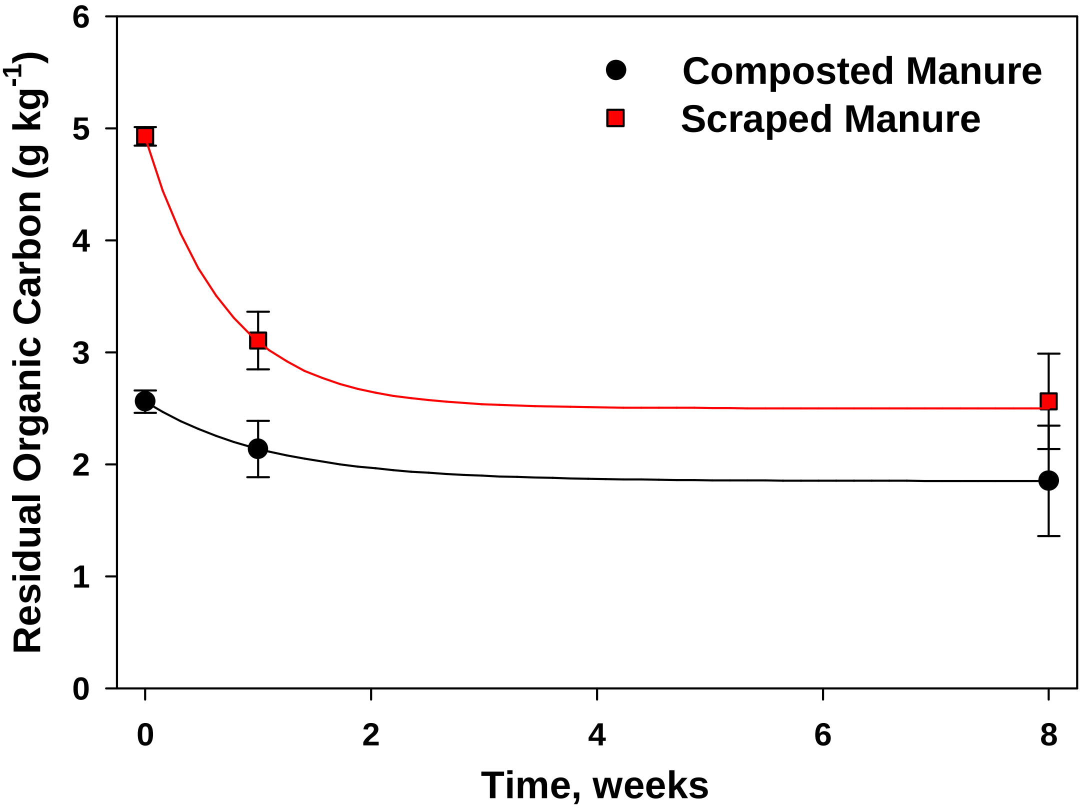

Fig. 1. Average residual organic carbon of soils amended with composted and scraped manure throughout the incubation period. Residual organic carbon is defined as the total organic carbon of amended soils less native organic carbon of unamended soils. Error bars represent ± 1 standard error.

extractability of unamended samples from amended samples to yield *net extractable phosphorus*. Repeating the analysis of variance using *net extractable P* resulted in percentages of soil sum of squares relative to the total sum of squares of approximately 2% for the Mehlich 3 and $NaHCO_3$ extractants and 11% for the TAM and water extractants. Thus, the initial P extractability of unamended soils accounted for a large proportion of the variability among soils. Moreover, the TAM and water P extractability were most sensitive to differences among soils.

Differences in the P extraction efficiency among soil types were significant principally for the TAM and water extractions (Table A7). Generally, differences in response to added P were less evident for the Mehlich 3 and $NaHCO_3$ extractants except for KH_2PO_4 amended soils. Texline, a calcareous soil, had significantly lower extractable Mehlich 3, $NaHCO_3$, and water P responses to added KH_2PO_4 as compared with non-calcareous soils. In contrast, the TAM extractant yielded recovery rates of 100% of added phosphorus in KH_2PO_4 and greater than extraction efficiencies (recovery rates) of the non-calcareous soils. As pointed out earlier, the TAM extractant seems particularly prone to dissolving a large proportion of Ca-P associated with calcite that, based on equilibrium considerations, would be the predominate fraction formed upon addition of orthophosphates to a calcareous soil.

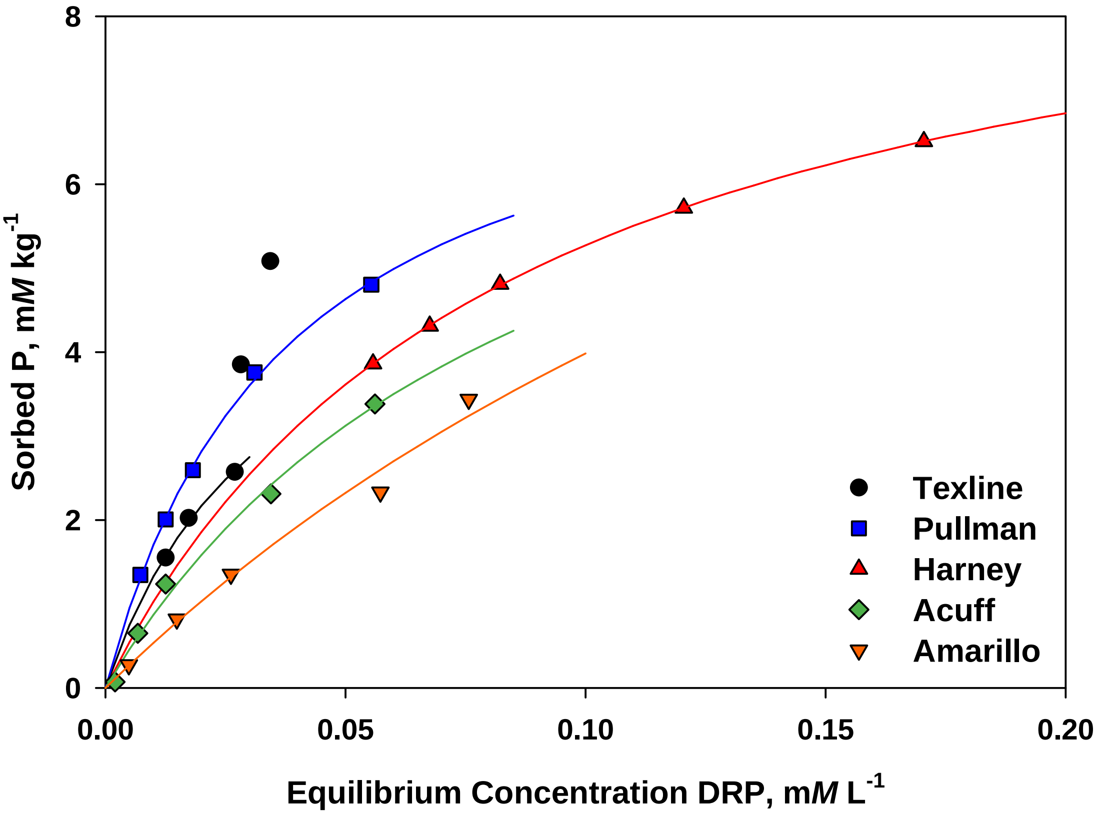

Fig. 2. Apparent sorption isotherms of orthophosphate-P in KH_2PO_4 amended soils after eight weeks. Each point represents the mean of three measurements. Lines represent the non-linear fits to the Langmuir Equation.

Water extractable P results for soils amended with synthetic fertilizer can be presented as sorption isotherms (Fig. 2). The isotherms were generated by fitting the Langmuir equation to eight-week water extractable P data and estimating previously sorbed P using a least-squares fit method. Note that equilibration time after P additions is eight weeks rather than the standard 24 hours. For non-calcareous soils amended with KH_2PO_4, P sorption increased with increasing CEC (Table 2) in the range of 0 to 0.2 m*M* L^{-1} of dissolved reactive P. The calcareous Texline soil appeared to approximate a Langmuir isotherm until an equilibrium concentration of 0.028 m*M* L^{-1} was attained, after which there was a large increase in retained P (Fig 2). Griffin and Jurinak (1973; 1974) demonstrated that a P concentration of 0.03 m*M* L^{-1} was sufficient to cause PO_4^{-3} sorption on calcite surfaces that was followed by heterogeneous precipitation of Ca-P and transformation to more stable, crystalline Ca-P phases. This mechanism is probably responsible for constraining solution P concentrations to low levels in the Texline soil.

The consistently greater P extraction efficiencies of KH_2PO_4 amended Harney as compared to Pullman soils was partly a result of the higher clay contents in Pullman, but the large amount of previously sorbed P of the Harney soil was probably responsible for the some of differences because additions occurred at positions along the isotherm where the magnitude of the slope was smaller (Fig. 2). Phosphorus extractabilities of KH_2PO_4 amended Amarillo soil were also significantly greater than extractabilities of the Acuff soil (Table A7) likely because of the extremely low clay contents of Amarillo fine sandy loam. Although significant differences exist among soils for P extractability, the isotherms generated for KH_2PO_4 do not approximate responses obtained for added manure P in a very predictable manner. These source × soil effects will be discussed in the next section.

Phosphorus source

Source by rate interactions were highly significant ($P<0.0001$) except the $NaHCO_3$ extractant of Incubation 1 (Tables A1 and A2) indicating that, for most scenarios, P extraction efficiencies differed among P sources. The P extraction efficiency obtained with the four extractants ranged from 18 to 52% greater for KH_2PO_4 amended Pullman soil (Incubation 2 at eight weeks) as compared to the $Ca(H_2PO_4)_2$ amended Pullman soil (Incubation 1 under a wetted-drying regime). In contrast to the isotherm of the KH_2PO_4 amended Pullman soil, isotherms obtained from the water extractable P data with $Ca(H_2PO_4)_2$ did not exhibit Langmuir type behavior above equilibrium solution concentrations of 0.05 m*M* (not shown). Calcium and magnesium saturation of exchange sites for the Pullman soil is high (~ 90%; Table 2) and only a small proportion of Ca^{2+} added with $Ca(H_2PO_4)_2$ would be adsorbed onto the exchange complex, with the remaining residing in the solution phase and therefore active in the formation of complexes and precipitates. Precipitation of Ca-P as dicalcium phosphate dihydrate and subsequent conversion to insoluble secondary calcium phosphates (e.g. octacalcium phosphate) (Bell and Black, 1970) during the incubation period probably depressed P extractability in $Ca(H_2PO_4)_2$ amended Pullman soil.

Mehlich 3 and TAM Phosphorus extractabilities of $Ca(H_2PO_4)_2$ amended Pullman soils were typically lower than corresponding soils amended with stockpiled and composted manure. Contrasts testing for differences between organic and inorganic P sources (Table A4) were highly significant for the Mehlich 3 extraction under the constant regime and for TAM extractions. Incompletely mineralized organic P and slower mineralization rates in stockpiled and fresh manures may have masked differences between organic and inorganic sources for Mehlich 3 extractable P under a drying-wetting regime. Monocalcium phosphate amended Pullman soil had significantly ($P<0.0001$) greater water P extractability as compared to manure amendments (Table A4) even though Mehlich 3 and TAM extractable P were greater for compost and manure (compare Fig. A4 with Figs. A1 and A2). Lack of significant differences between inorganic and organic source effects for the $NaHCO_3$ extractable P (Table A4) may result from limited extractability of Ca-P by HCO_3^-.

Mehlich 3 and TAM extractable P of Pullman soil amended with fresh manure were significantly ($P<0.0001$) less than P extractabilities of aged manure (compost and stockpiled manures) treatments (Table A4). Free sugars and polysaccharides present in fresh manure probably facilitated the observed prolific growth of fungi during the incubation period that immobilized a proportion of labile soil P. Fresh manures also contained some undigested feed that would have limited chemical extractability of P from the outset. Phosphorus extractabilities of the Pullman soil amended with new and old stockpiled manures were similar for all agronomic P tests (Mehlich 3, $NaHCO_3$, and TAM). Although significant differences were observed for the efficiency of water P extraction between new and old stockpiled manure, the differences in efficiency were small (<2.0%).

Mehlich 3 and $NaHCO_3$ extractable P of KH_2PO_4 amended soils were significantly ($P\leq0.0359$) greater than soils amended with organic sources (compost and scraped manure) except for the Pullman and Texline soils at eight weeks (Figs. A5 and A6; Table A6). As discussed earlier, the greater extractability of KH_2PO_4 amended soils may relate to the absence of Ca^{2+} in KH_2PO_4 that, with time, could slowly depress P extractability via the formation of relatively insoluble Ca-P. Although there were significant differences between organic and inorganic-amended TAM P extractabilities, KH_2PO_4 amended soils did not always have the greatest P extraction efficiencies. This may relate to the lower replacing ability of surface complexed PO_4^- for acetate in the TAM extractant as compared with F^- or HCO_3^- anions (Olsen et al, 1954; Thomas and Peaslee, 1973). Water extractable P was also significantly ($P<0.0001$) greater for KH_2PO_4 as compared to manure amended soils except for the Texline soil where extractable P was greatest for scraped manure at eight weeks (Fig. A8). Robbins et al. (2000) also observed greater 0.01 M $CaCl_2$ extractable P for a calcareous soil amended with manure as compared to monocalcium phosphate. Maintenance of greater water extractable P in calcareous soils by manures may be caused by coating of sorption sites with organic molecules that in turn reduce heterogeneous nucleation and crystal growth of Ca-P on the calcite surfaces (Suarez, 1977).

In most cases, compost amended soil exhibited greater agronomic (Mehlich 3, $NaHCO_3$, TAM) P extractabilities as compared to soil amended with scraped manure. However, at eight weeks, not all of the organic P in scraped manure may have been mineralized. Despite lower agronomic P extractabilities of scraped manure amended soils, water extractable P of scraped manure was significantly greater as compared to all compost amended soils. Adler and Sikora (2003) similarly found that immature (14 days) poultry compost had greater water extractable P than compost of greater maturity. These results may be related to the release of greater quantities of organic anions during the early decomposition phases of manure (Singh and Amberger, 1998) and consequently greater competition with PO_4^{3-} for sorption sites.

Besides phosphorus, amendments of cattle beef manure also add large quantities of principally inorganic calcium and magnesium (Table 3). As with $Ca(H_2PO_4)_2$, soluble Ca of manures added to neutral or slightly basic soils will combine with water soluble orthophosphates to form dicalcium phosphate dihydrate (DCPD; $CaHPO_4 \bullet 2H_2O$) as an initial reaction product. Inorganic calcium contained in manures added to soils has been shown to have a dominant role in regulating the readily available phosphorus pool (Siddique and Robinson, 2003). Organic anions may also block or compete with PO_4^{3-} for surface sites thereby leading to greater concentrations of solution P and eventual transformation to Ca-P. In the presence of organic molecules released as decomposition products of manures, however, large molecular weight organic acids can be adsorbed on the DCPD crystal surfaces and act as a new nuclei for DCPD crystals thereby inhibiting or delaying further hydrolysis to octacalcium phosphate and hydroxyapatite (Inskeep and Silvertooth, 1988; Grossl and Inskeep, 1991). Organic acids are also known to form complexes with Ca (Ca-humate) thereby reducing solution Ca:P ratios and shifting equilibrium Ca-P end products to more soluble forms (Dalton et al. 1952, Moreno et al. 1960). Low molecular weight organic anions originating from the manure can block or compete with phosphates for surface adsorption sites (e.g. Kafkafi et al., 1988), thereby decreasing PO_4^{3-} sorption and driving the formation of additional Ca-P. In addition, the relatively large amounts of magnesium added with the manure to the soil may also inhibit or delay DCPD hydrolysis to octacalcium phosphate (Bell and Black, 1970; Zhang et al., 1992). These mechanisms would suggest that manure amended soils tend to favor the formation of relatively large amounts of metastable or poorly crystalline Ca-P whereas soils amended with inorganic fertilizers tend to favor the retention of more phosphate on exchange sites and the formation of more insoluble Ca-P forms when sufficient Ca^{2+} is available (e.g. Toor and Bahl, 1999). Because acetic acid tends to selectively decompose soluble rather than insoluble Ca-P (Mehlich, 1984), this interpretation is corroborated by the greater 8-week Mehlich 3 extractable P for compost amended Pullman soil as compared to Pullman soil amended with inorganic P sources. In KH_2PO_4 amended soils with low clay contents (Acuff and Amarillo) and correspondingly lower Ca^{2+} status (Table 2), there was probably insufficient solution Ca^{2+} to drive equilibrium towards more insoluble Ca-P which led to greater Mehlich 3 extractabilities.

The similar or greater Mehlich 3 and TAM P extractablities of composted, scraped, and stockpiled manure amended as compared to $Ca(H_2PO_4)_2$ and KH_2PO_4 amended soils (noncalcareous) seem to be at odds with greater water extractablities of soils amended with these inorganic fertilizers. If the quantity and solubility of Ca-P is greater in manure amended as compared to $Ca(H_2PO_4)_2$ and KH_2PO_4 amended soils, then one would expect manure amended soils to have greater water extractable P. However surface adsorbed phosphate rather than Ca-P may be controlling orthophosphate concentrations in the water extracts. Throughout the eight-week incubation period after P additions, both soluble Ca-P and PO_4^{3-} weakly adsorbed to surface sites are probably governing equilibrium P concentrations in solution. But concentrations of P in the soil solution are diluted by 30 to 100-fold in water extractions and essentially set up a new concentration gradient that would drive dissolution of Ca-P and desorption of PO_4^{3-} from surface sites. However, for these short duration water extractions, soluble forms of Ca-P such as DCPD are probably not contributing much to solution P because of relatively slow dissolution rates of these minerals (Zhang et al., 1992). Greater saturation of surface sites by PO_4^{3-} combined with fast desorption rates during the extraction period may explain why greater water extractable P was obtained for soils amended with $Ca(H_2PO_4)_2$ and KH_2PO_4 as compared to manure amended soils. The net outcome of interactions of occurring in these soils upon addition of P demonstrated that the relationship between agronomic soil test P and water extractable P was strongly dependent on the fertilizer P source (Fig. 3; Figs. A9-A14). As compared to inorganic fertilizers, manure amended soils exhibited lower water extractable P at high agronomic soil test P values. Although agronomic tests can be well correlated with forms of soil P susceptible to runoff losses (Pote et al., 1996; Sims 2002), organic and inorganic P sources probably contributed to different soil P pools which led to source dependent relationships between agronomic and water soil test P. Griffin et al. (2003) also observed fertilizer source dependent relationships similar to these results.

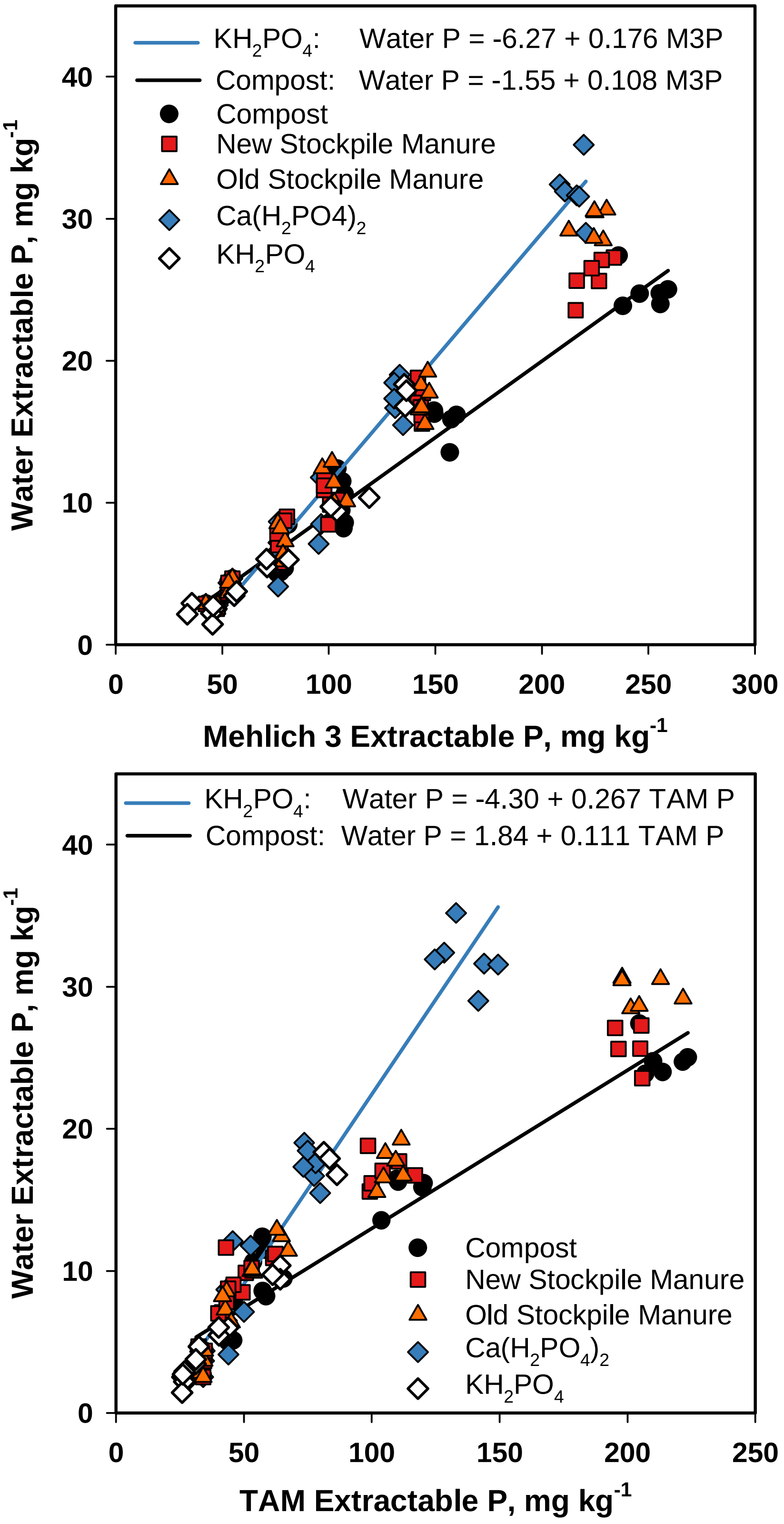

Fig 3. Trends in Mehlich 3 and TAM extractable P with water extractable P for different fertilizer sources. The abbreviation M3P represents Mehlich 3 extractable P.

SUMMARY AND IMPLICATIONS

The increase in extractable P in soils amended with manures and synthetic fertilizers varied considerably with P source, incubation time, extractant, and soil characteristics. Except for the TAM extractions and some water extractions, P extractability as a function of total P applied was linear over a wide range of application rates. This simplifies the description of the fertilizer efficiency as simply the fraction of total P added that becomes extractable after incubation. After an eight-week incubation period, Mehlich 3 P extraction efficiency for all soils averaged 70% for scraped or stockpiled manure, 84% for composted manure, and 93% for KH_2PO_4. For the Olsen ($NaHCO_3$) extractant, the corresponding efficiencies averaged 47%, 49%, and 63%, respectively. The linear relationship between P application rate and P extractability, however, tends to break down for the acidic extractants (Mehlich 3 and TAM) when initial P extractabilities become large (e.g. greater than 150 mg kg^{-1} Mehlich 3 extractable P). At these relatively high initial P extractabilities, fertilizer efficiencies were nearly 100% for the Harney soil.

The soils of this region are typically dominated by 2:1 clay mineralogy with a high base status and are frequently calcareous. Finer-textured soils with cation exchange capacities exceeding 15 m*M* kg^{-1} had lower extraction efficiencies as compared with their coarser-textured counterparts. Because of the relatively high base status of these soils, soil calcium was an important governing factor in regulation of soil P by depressing its solubility and extractability. Soluble organic compounds also appeared to play a role in governing P status in these soils. Since cattle manure adds both Ca and organic materials, the increase in soil extractable P resulting from manure amendments is not straightforward. Depressed extractabilities of $Ca(H_2PO_4)_2$ amended as compared to KH_2PO_4 amended Pullman soils, however, suggest that Ca is depressing P solubility. This would suggest that superphosphate fertilizers would increase extractable P in noncalcareous soils to a lesser extent than soluble fertilizers such as mono- or di-ammonium phosphate.

A sizeable proportion of soils in the Southern High Plains region are calcareous to the surface. These soils are capable of immobilizing larger quantities of phosphorus then other soils of the region and therefore require different management considerations and soil tests suited to dissolving only a small proportion of precipitated calcium phosphates. In the Texline soil, scraped manure maintained a higher level of water and $NaHCO_3$ extractable P as compared to KH_2PO_4 at the end of an eight week incubation period. Consequently, fed cattle manure might be advantageously used to improve the P availability to crops on calcareous soils.

A larger proportion of applied P was extracted from composted manures as compared to stockpiled and fresh manures with the acidic, agronomic extractants (Mehlich 3 and TAM). Incompletely mineralized organic P in scraped, stockpiled, and especially fresh manures is partly responsible for these lower efficiencies. Although ageing of manures (from stockpiles to compost) increased Mehlich 3 and TAM P extractability, it tended to decrease water extractable P. Soils amended with synthetic fertilizers generally had greater water extractable P than soils amended with manures, especially after short, 1 week incubation periods. Under field conditions, increase in soil P extractabilities after manure applications may vary because of differences in temperature and moisture regimes, incorporation depth, tillage practices, and sampling depth. However the water extractabilities for the relatively short incubation periods of this study are relevant because susceptibility of surface export of P by runoff is typically greatest immediately after fertilizer applications (Kleinman et al., 2002).

Increases in water extractable P relative to increases in agronomic soil test P were greatest for synthetic fertilizers (monocalcium and monopotassium phosphates) compared with composted or stockpiled manures. Consequently, common agronomic soil extractants in the region cannot always be used to make reliable inferences about water extractable P, an important quantity when considering offsite movement of P with runoff. These inconsistencies could be overcome by applying both an agronomic and environmental soil test to a P indexing systems so that both the soils capacity to supply P and readily soluble P are considered. An environmental soil test, such as water extractable P, would only need to be considered if the agronomic soil test value is "exceedingly" high.

ACKNOWLEDGEMENTS

This work was supported in part by the Texas Cattle Feeders Association, Amarillo, TX. We also gratefully acknowledge the assistance of Ms. Dayna Britten and Ms. Jourdan Bell for laboratory analyses, Ms. Kelly Attebury (USDA-NRCS, Lubbock, TX) and Dr. Scott vanPelt (USDA-ARS, Big Spring, TX) for help in acquiring soil samples, and Dr. Tony Provin (TAES, College Station, TX) for providing details of the TAM extraction method.

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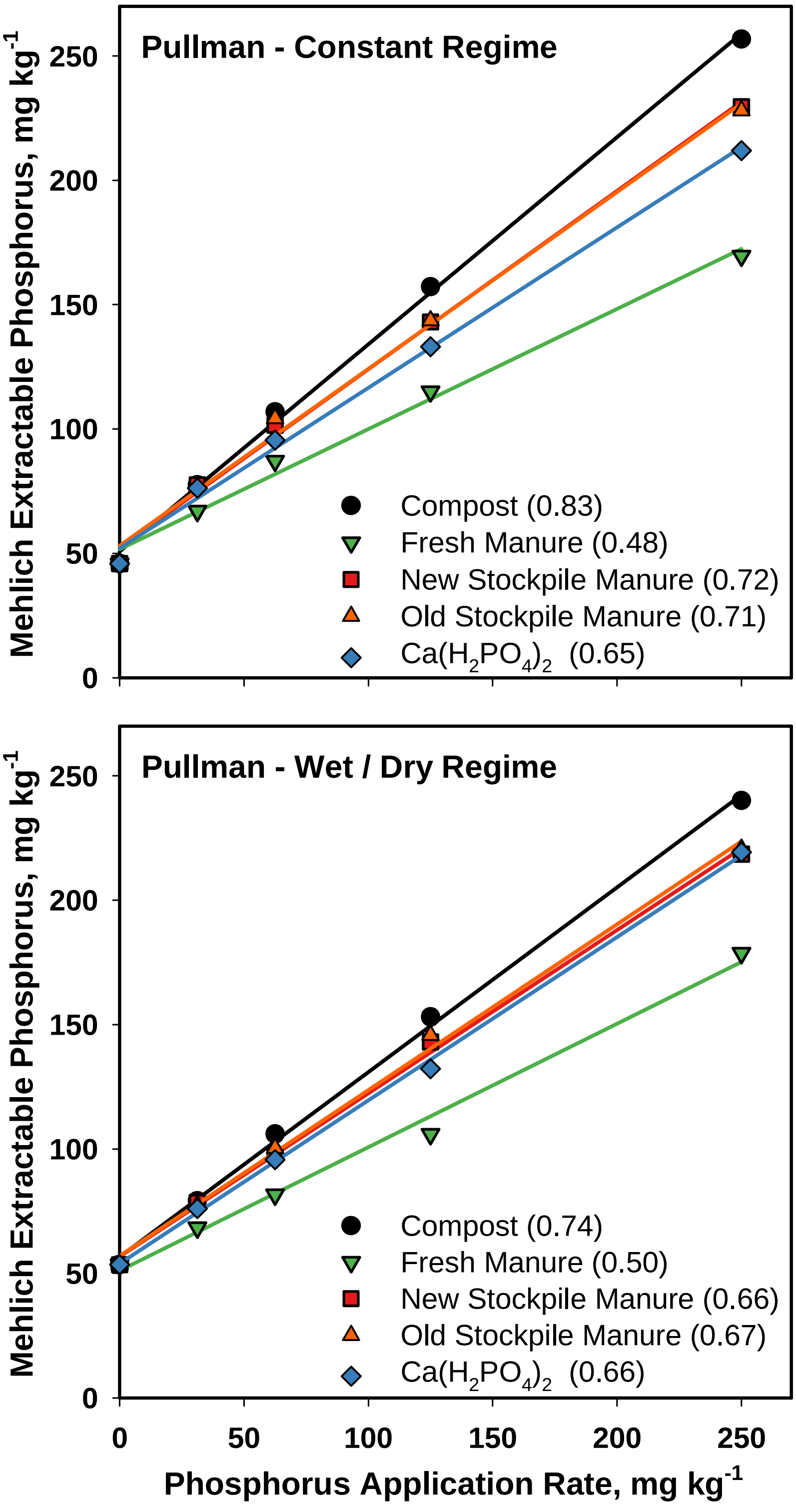


Figure A1. Effect of P application rate, P source, and incubation regime on Mehlich 3 extractable P. Efficiency of each P source shown in parenthesis.

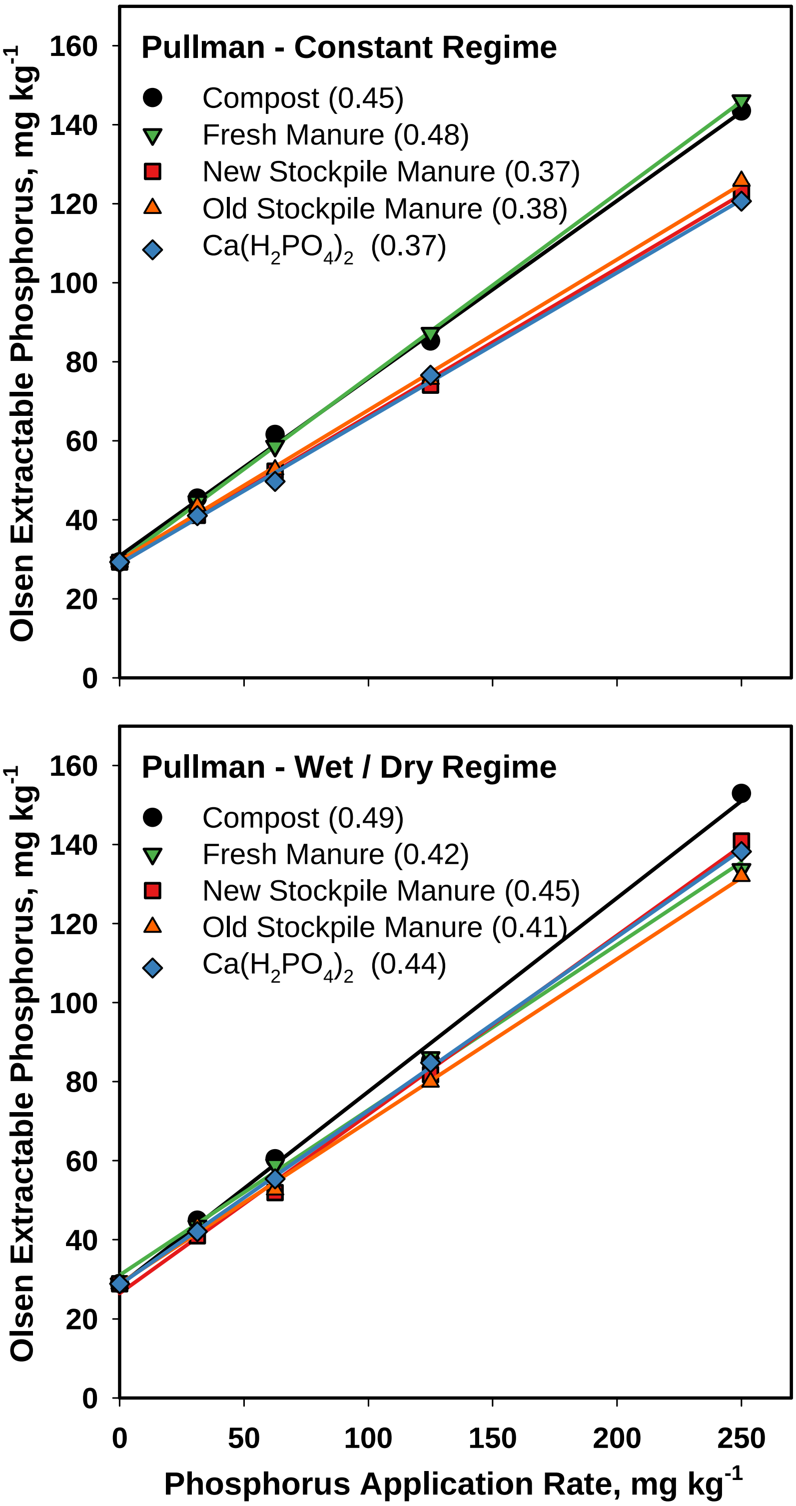


Figure A2. Effect of P application rate, P source, and incubation regime on Olsen (0.5 *M* $NaHCO_3$) extractable P. Efficiency of each P source shown in parenthesis.

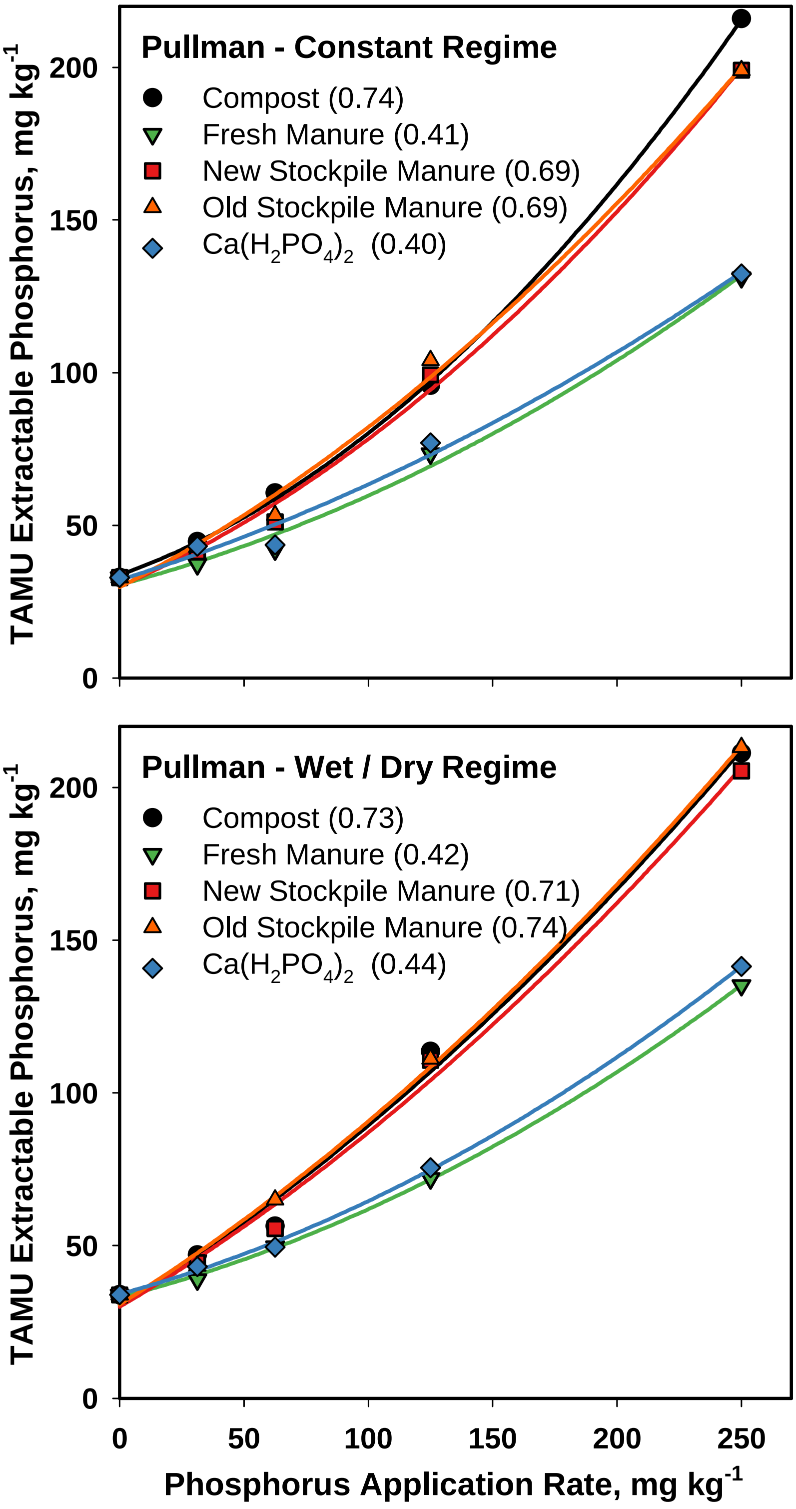


Figure A3. Effect of P application rate, P source, and incubation regime on TAMU extractable P. Efficiency of each P source shown in parenthesis.

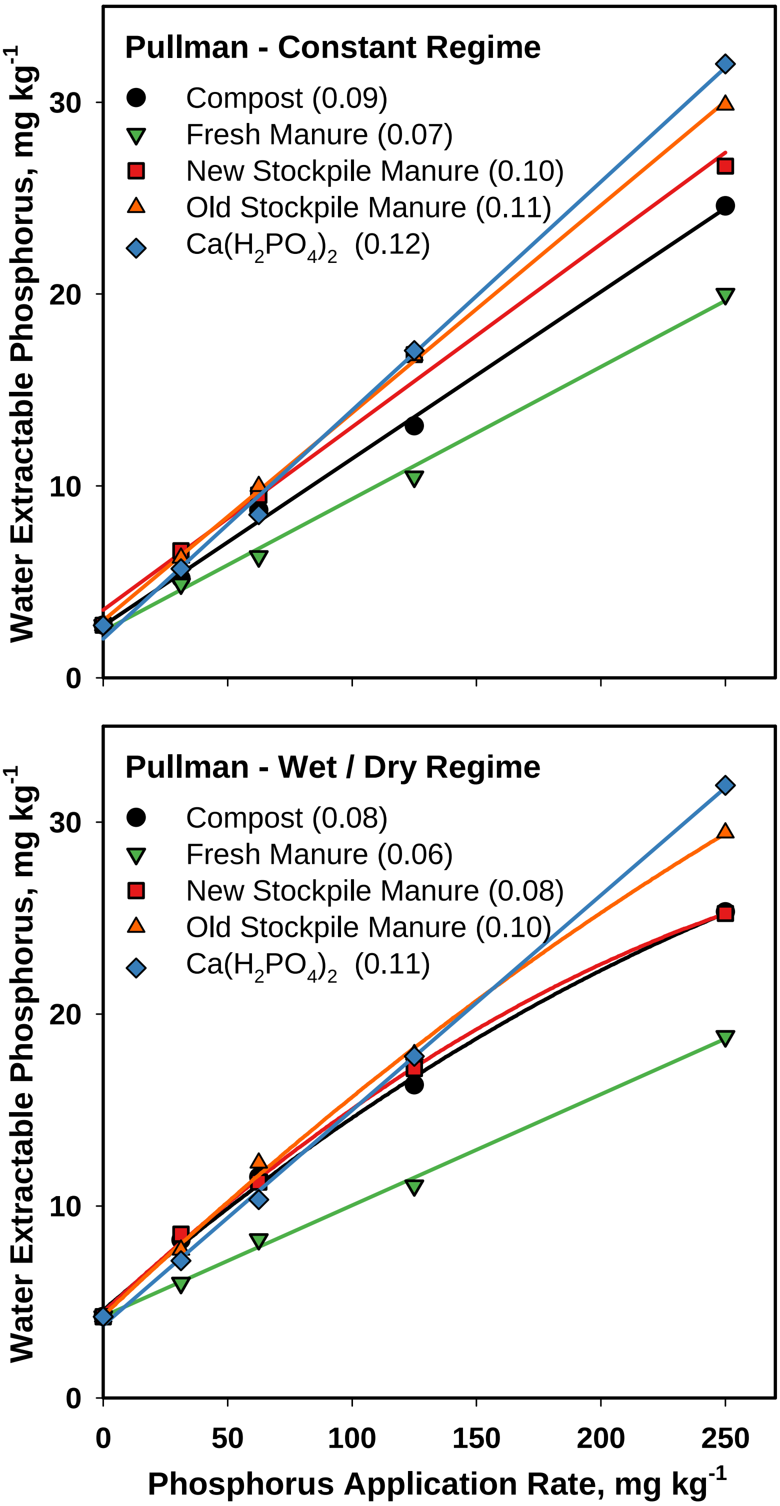


Figure A4. Effect of P application rate, P source, and incubation regime on water extractable P. Efficiency of each P source shown in parenthesis.

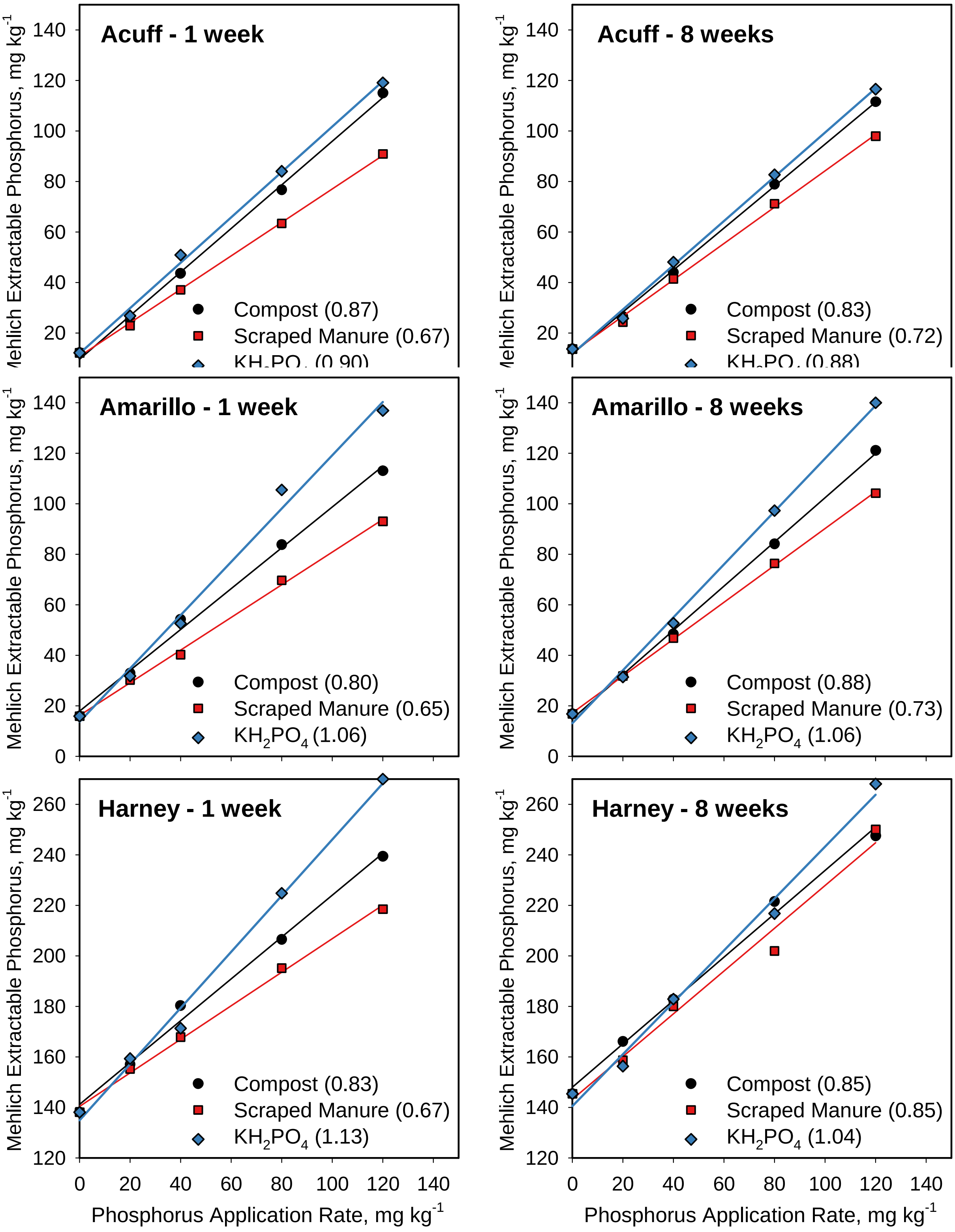
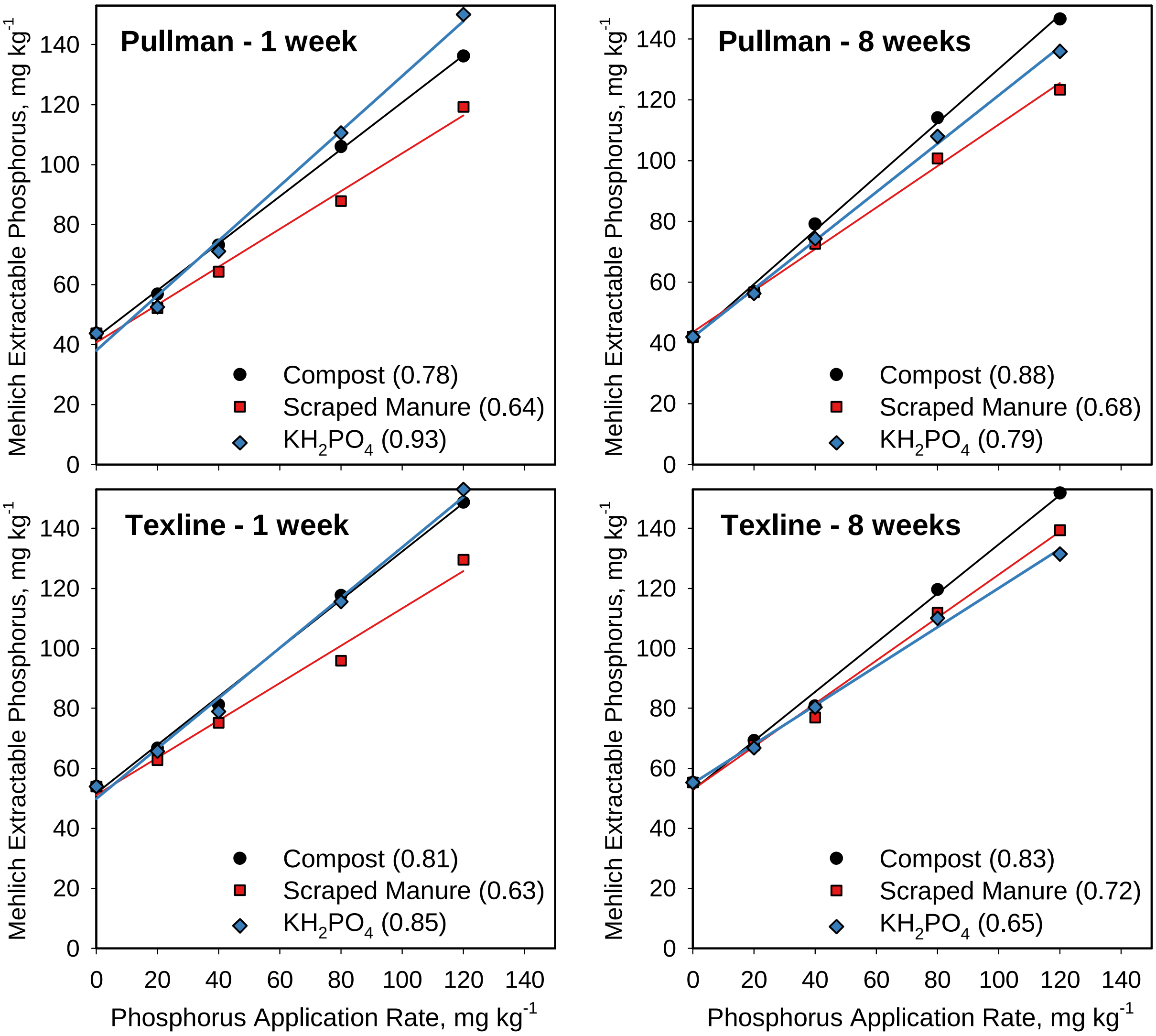


Figure A5. Effect of P application rate, P source, and incubation time on Mehlich 3 extractable P. Efficiency of each P source shown in parenthesis.



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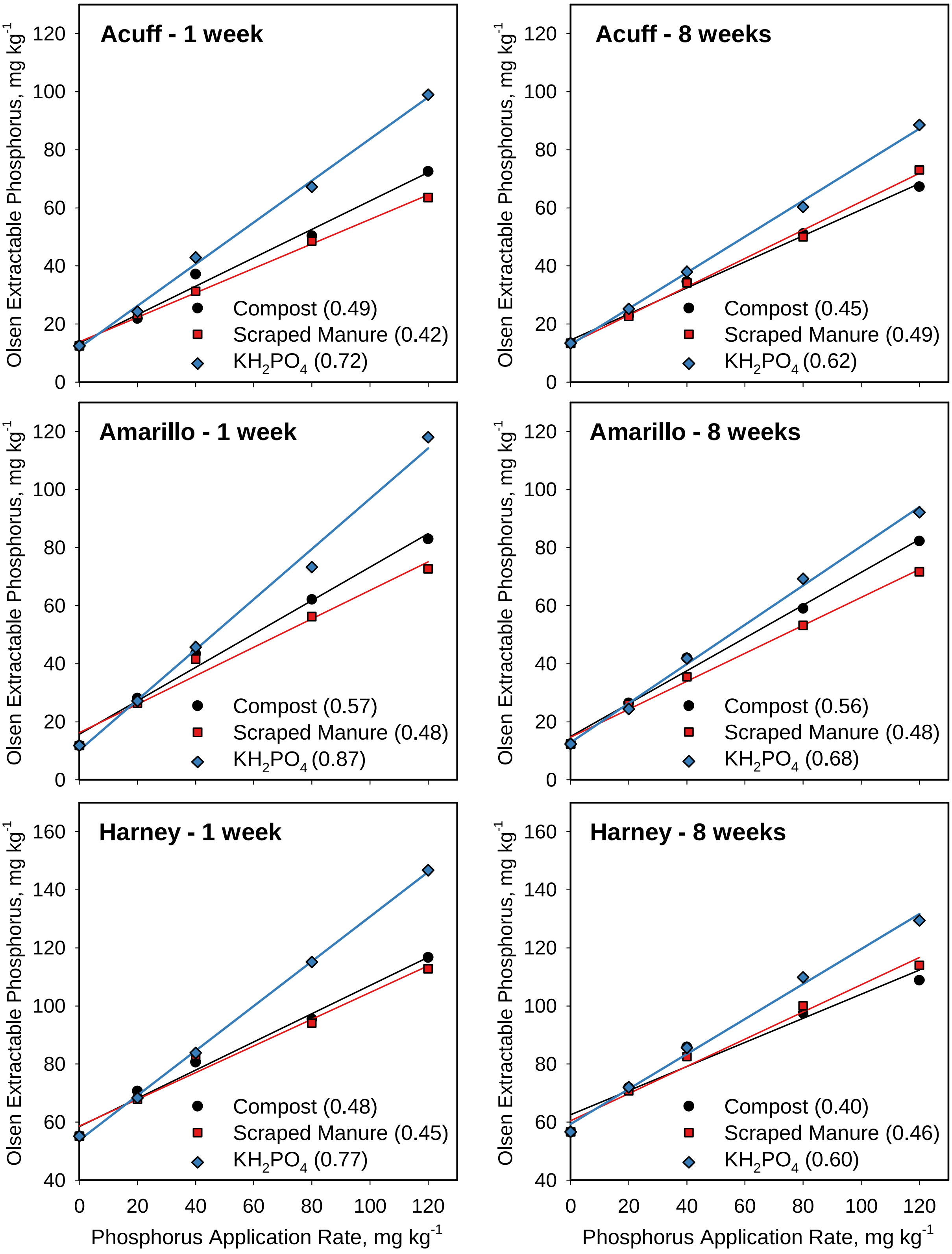

Figure A6. Effect of P application rate, P source, and incubation time on Olsen (0.5 *M* $NaHCO_3$) extractable P. Efficiency of each P source shown in parenthesis.

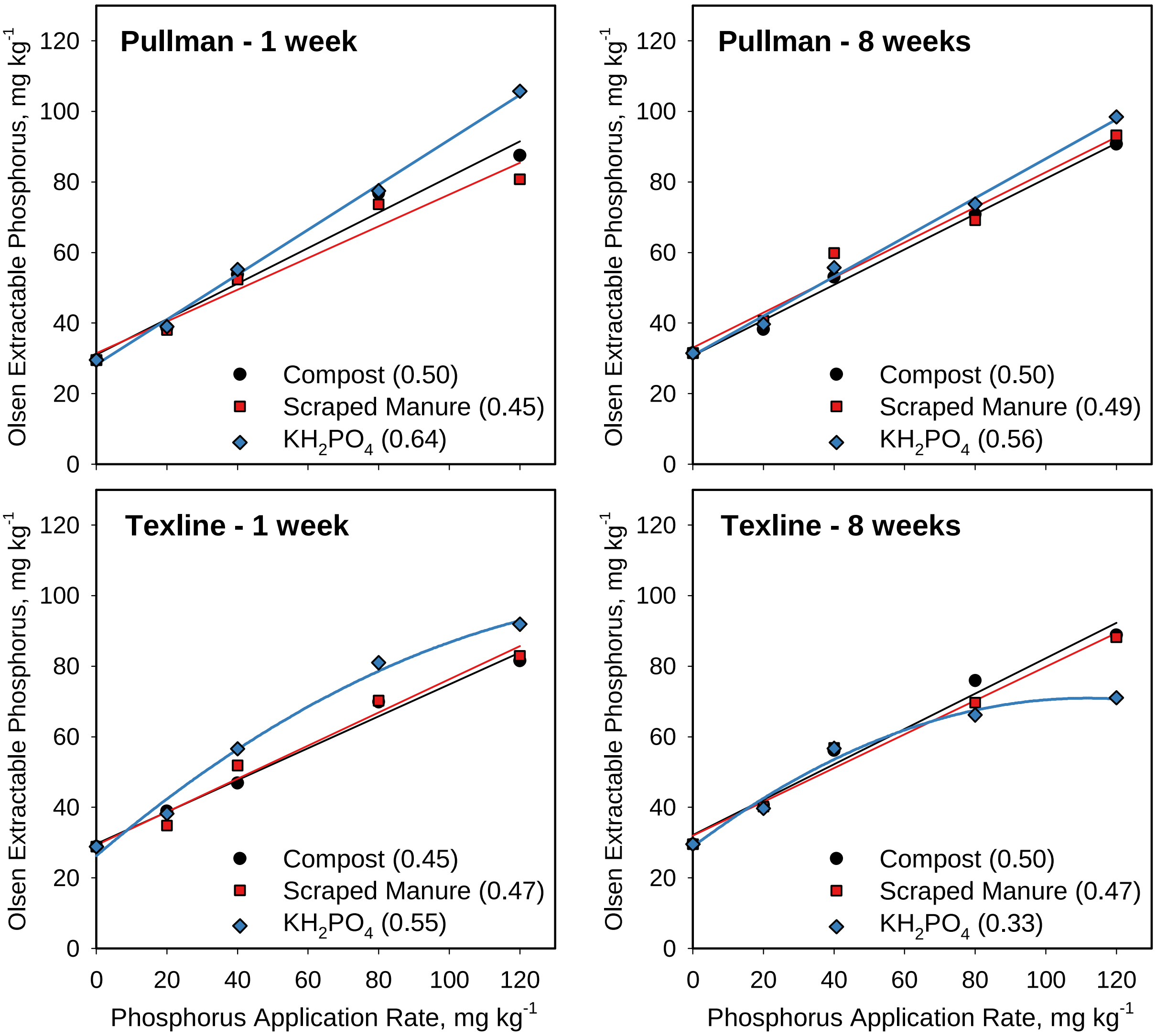

Figure A6. (Cont.) Effect of P application rate, P source, and incubation time on Olsen ($NaHCO_3$) extractable P. Efficiency of each P source shown in parenthesis.

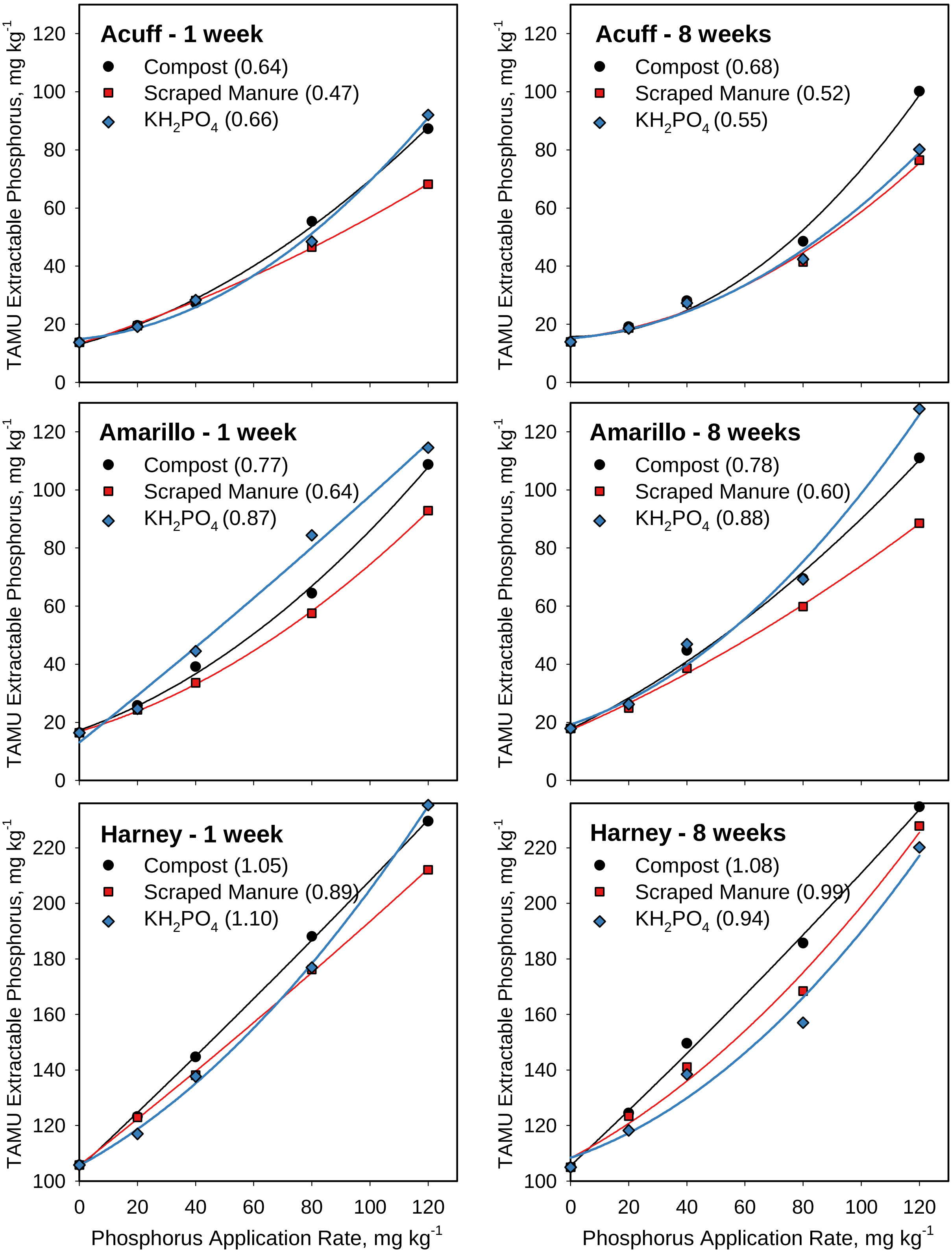

Figure A7. Effect of P application rate, P source, and incubation time on TAMU extractable P. Efficiency of each P source shown in parenthesis.

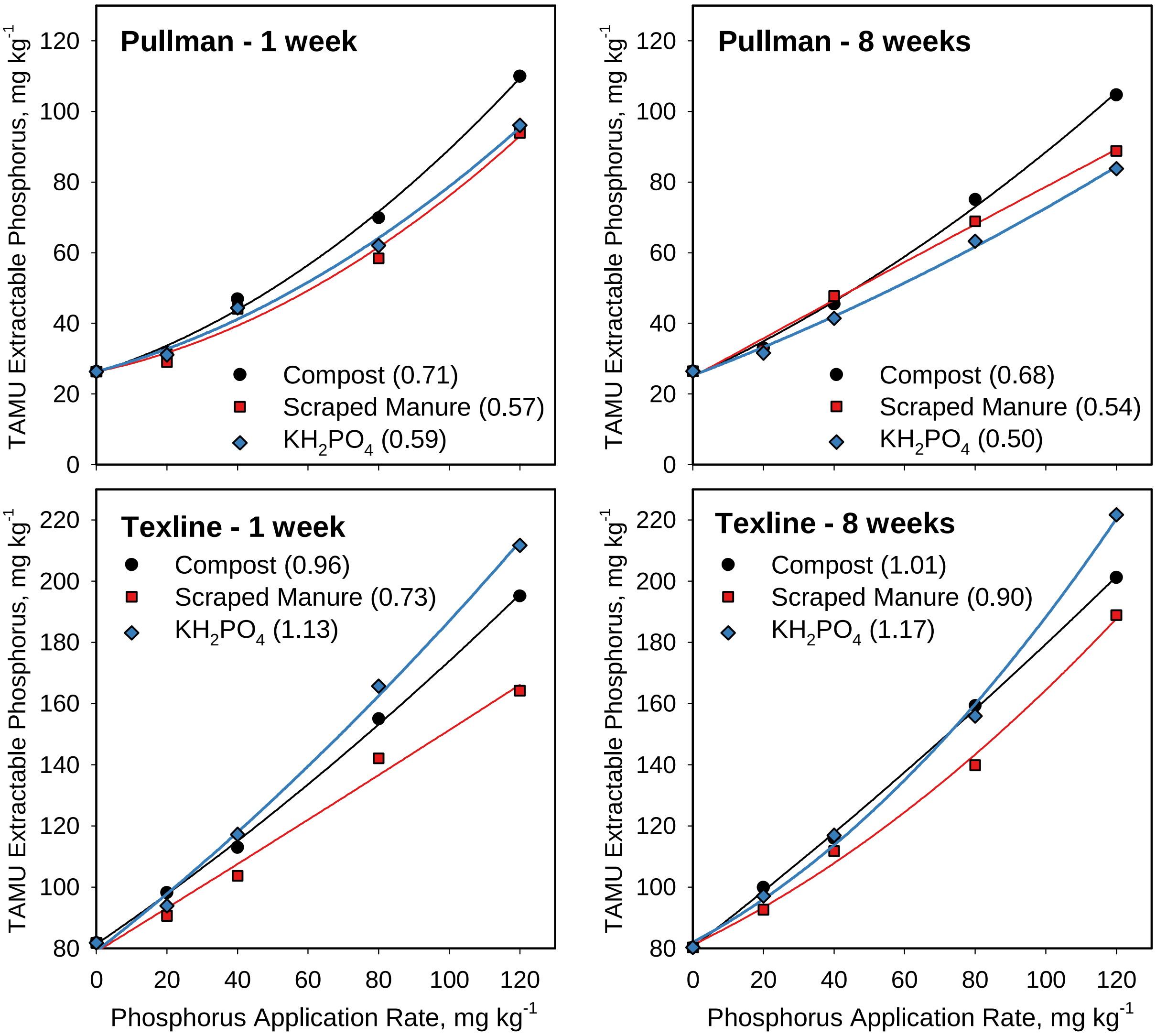

Figure A7. (Cont.) Effect of P application rate, P source, and incubation time on TAMU extractable P. Efficiency of each P source shown in parenthesis.

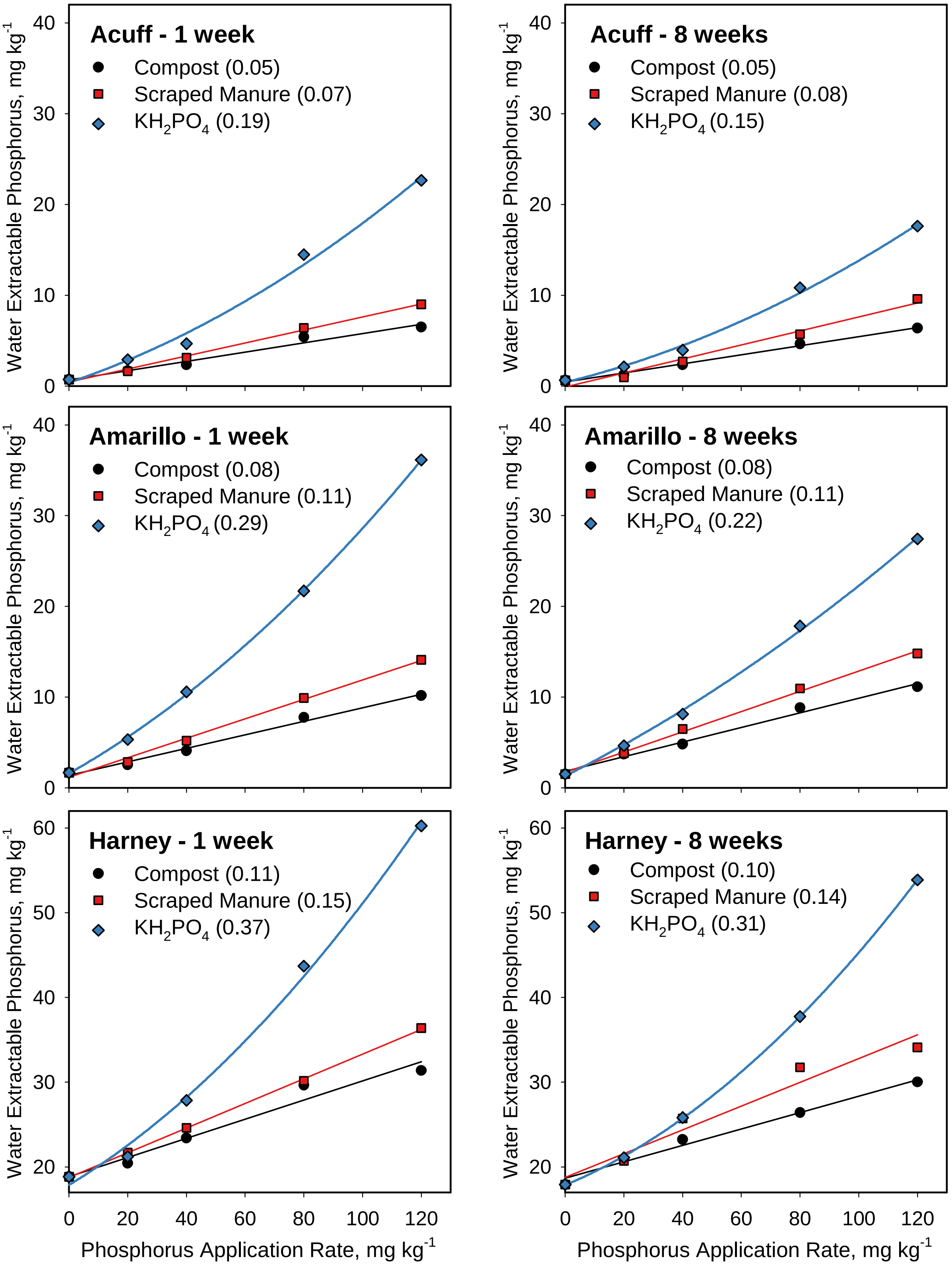

Figure A8. Effect of P application rate, P source, and incubation time on water extractable P. Efficiency of each P source shown in parenthesis.

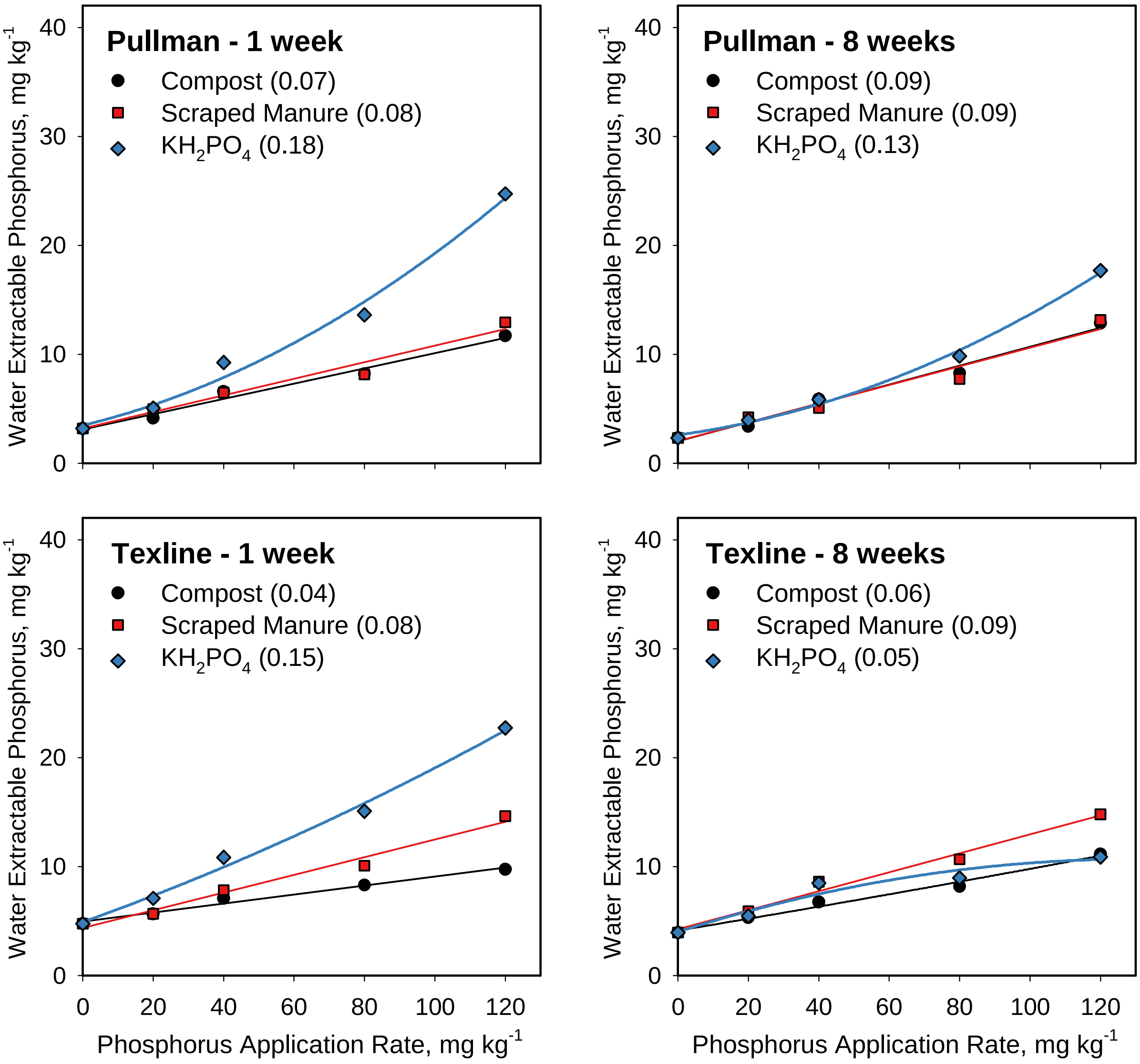

Figure A8. (Cont.) Effect of P application rate, P source, and incubation time on water extractable P. Efficiency of each P source shown in parenthesis.

Table A1. Efficiency of P extraction and analysis of variance for P sources used for Incubation 1.

P Source	Regime	Mehlich 3	$NaHCO_3$	TAMU	Water
		Efficiency of P Extraction			
Compost	Constant	0.832	0.450	0.741	0.087
	Wet / Dry	0.743	0.490	0.734	0.082
Fresh Manure	Constant	0.483	0.466	0.411	0.069
	Wet / Dry	0.496	0.418	0.415	0.058
New Stockpile Manure	Constant	0.717	0.374	0.690	0.095
	Wet / Dry	0.656	0.447	0.706	0.082
Old Stockpile Manure	Constant	0.710	0.381	0.689	0.108
	Wet / Dry	0.666	0.411	0.739	0.100
$Ca(H_2PO_4)_2$	Constant	0.645	0.368	0.408	0.119
	Wet / Dry	0.657	0.440	0.436	0.112
Mean		0.661	0.425	0.597	0.091
Effect:	**df**		$P > F$		
Rate	4	<0.0001	<0.0001	<0.0001	<0.0001
P Source	4	<0.0001	0.0004	<0.0001	<0.0001
Regime	1	0.8720	0.0776	<0.0001	<0.0001
P Source × Rate	16	<0.0001	0.3839	<0.0001	<0.0001
Regime × Rate	4	<0.0001	0.2772	0.1861	0.0007
P Source × Regime	4	0.0189	0.1942	0.4618	0.1117
P Source × Regime × Rate	16	<0.0001	0.8451	0.0889	0.9969

Table A2. Efficiency of P extraction and analysis of variance for P sources used for Incubation 2.

Soil	Time	Source	Mehlich 3	$NaHCO_3$	TAMU	Water
	Weeks		Efficiency of P Extraction			
Acuff	1	Compost	0.869	0.488	0.639	0.051
		Scraped	0.665	0.419	0.465	0.072
		KH_2PO_4	0.900	0.720	0.656	0.193
	8	Compost	0.835	0.447	0.685	0.050
		Scraped	0.722	0.489	0.517	0.079
		KH_2PO_4	0.880	0.621	0.550	0.148
Amarillo	1	Compost	0.804	0.568	0.771	0.075
		Scraped	0.646	0.482	0.645	0.108
		KH_2PO_4	1.060	0.871	0.869	0.292
	8	Compost	0.879	0.560	0.785	0.080
		Scraped	0.729	0.476	0.600	0.112
		KH_2PO_4	1.057	0.676	0.880	0.220
Harney	1	Compost	0.829	0.479	1.049	0.113
		Scraped	0.666	0.452	0.892	0.146
		KH_2PO_4	1.126	0.772	1.101	0.366
	8	Compost	0.852	0.402	1.075	0.095
		Scraped	0.852	0.461	0.988	0.139
		KH_2PO_4	1.039	0.597	0.940	0.307
Pullman	1	Compost	0.785	0.501	0.712	0.070
		Scraped	0.638	0.445	0.571	0.076
		KH_2PO_4	0.928	0.640	0.589	0.177
	8	Compost	0.885	0.503	0.682	0.087
		Scraped	0.679	0.495	0.540	0.086
		KH_2PO_4	0.794	0.560	0.500	0.127
Texline	1	Compost	0.812	0.450	0.961	0.041
		Scraped	0.634	0.470	0.734	0.080
		KH_2PO_4	0.848	0.547	1.130	0.148
	8	Compost	0.825	0.496	1.014	0.057
		Scraped	0.722	0.473	0.901	0.086
		KH_2PO_4	0.652	0.333	1.173	0.053
Means		Compost	0.837	0.489	0.837	0.072
		Scraped	0.695	0.466	0.685	0.098
		KH_2PO_4	0.928	0.634	0.839	0.203
Effect:		**df**	$P > F$			
Rate		4	<0.0001	<0.0001	<0.0001	<0.0001
Soil		4	<0.0001	<0.0001	<0.0001	<0.0001
P Source		2	<0.0001	<0.0001	<0.0001	<0.0001
Time		1	<0.0001	0.0758	0.2705	<0.0001

Table A2. (Cont.)

		Mehlich 3	$NaHCO_3$	TAMU	Water
Effect:	**df**	*P* > *F*			
Soil x Rate	16	<0.0001	<0.0001	<0.0001	<0.0001
P Source × Rate	8	<0.0001	<0.0001	<0.0001	<0.0001
Time × Rate	4	0.8722	<0.0001	0.0018	<0.0001
Soil × P Source	8	<0.0001	<0.0001	<0.0001	<0.0001
Soil × Time	4	0.0055	0.0022	0.0726	0.0113
P Source × Time	2	<0.0001	<0.0001	0.0002	<0.0001
P Source × Soil x Rate	32	0.0008	<0.0001	<0.0001	<0.0001
Time × Soil × Rate	16	0.3333	0.0025	<0.0001	0.1584
Time × P Source × Rate	8	0.0004	<0.0001	0.0234	<0.0001
Time × Soil × P Source	8	0.8470	0.0195	0.5154	0.0019
Time × P Source × Soil × Rate	32	0.6969	0.3094	0.0266	0.0786

Table A3. Level of significance for linear regression contrasts testing for differences between regime × rate interactions (H_0: efficiency of P extraction for the two regimes are equivalent).

Source	Mehlich 3	$NaHCO_3$	TAMU	Water
	P > F			
Compost	<0.0001	0.0308	0.865	0.3073
Fresh Manure	0.4516	0.08	0.6355	0.0162
New Stockpiled Manure	<0.0001	0.2998	0.2545	0.0021
Old Stockpiled Manure	0.0039	0.0663	0.0009	0.0428
$Ca(H_2PO_4)_2$	0.2437	0.0438	0.1507	0.3311

Table A4. Level of significance for linear regression contrasts testing for differences between source × rate interactions (H_0: efficiency of P extraction for the two groups of fertilizer sources are equivalent).

Contrast H_0:†	Regime	Mehlich 3	$NaHCO_3$	TAMU	Water
		P > F			
Organic = Inorganic	Constant	0.0004	0.1099	<0.0001	<0.0001
	Wet / Dry	0.0977	0.8762	<0.0001	<0.0001
Aged = Fresh	Constant	<0.0001	0.0473	<0.0001	<0.0001
	Wet / Dry	<0.0001	0.1096	<0.0001	<0.0001
Composted = Stockpiled	Constant	<0.0001	0.0357	0.0331	0.0008
	Wet / Dry	<0.0001	0.0143	0.6361	0.0396
Old Stockpile = New Stockpile	Constant	0.6062	0.8442	0.9878	0.0093
	Wet / Dry	0.4023	0.1821	0.2089	0.0007

† Groups of fertilizer sources are as follows: Organic = {Compost, Fresh Manure, New Stockpile Manure, Old Stockpile Manure}; Inorganic = {$Ca(H_2PO_4)_2$}; Aged = {Compost, New Stockpile Manure, Old Stockpile Manure}; Fresh = {Fresh Manure}; Stockpiled Manure = {New Stockpile Manure, Old Stockpile Manure}.

Table A5. Level of significance for linear regression contrasts testing for differences between time × rate interactions (H_0: efficiency of P extraction at 1 day = efficiency of P extraction at 8 days).

Soil	Source	Mehlich 3	$NaHCO_3$	TAMU	Water
		P > *F*			
Acuff	Compost	0.3287	0.2009	0.0847	0.7707
	Scraped Manure	0.0157	0.0010	0.1069	0.0989
	KH_2PO_4	0.4771	<0.0001	<0.0001	<0.0001
Amarillo	Compost	0.0414	0.8152	0.7505	0.3971
	Scraped Manure	0.0031	0.7968	0.3090	0.6244
	KH_2PO_4	0.8515	0.0061	0.5995	0.0002
Harney	Compost	0.8268	0.0007	0.6600	0.2115
	Scraped Manure	0.1056	0.7036	0.2500	0.7071
	KH_2PO_4	0.4140	<0.0001	0.0173	0.0001
Pullman	Compost	0.0450	0.9414	0.3790	0.0032
	Scraped Manure	0.3642	0.2446	0.4020	0.2329
	KH_2PO_4	0.0405	0.0034	0.0024	<0.0001
Texline	Compost	0.7686	0.2519	0.4599	0.0020
	Scraped Manure	0.0524	0.6755	<0.0001	0.2988
	KH_2PO_4	0.0002	<0.0001	0.3395	<0.0001

Table A6. Level of significance for linear regression contrasts testing for differences between source × rate interactions (H_0: efficiency of P extraction for the two groups of fertilizer sources are equivalent).

Contrast H_0:†	Soil	Time	Mehlich 3	$NaHCO_3$	TAMU	Water
		Weeks	$P > F$			
Compost = Scraped	Acuff	1	<0.0001	0.0100	<0.0001	<0.0001
		8	<0.0001	0.0808	<0.0001	<0.0001
	Amarillo	1	<0.0001	0.0759	0.0459	0.0196
		8	<0.0001	0.1159	0.0001	0.0002
	Harney	1	0.1463	0.1798	0.0465	0.0107
		8	0.9061	0.0498	0.1359	0.0024
	Pullman	1	0.0027	0.2102	<0.0001	0.5443
		8	0.0018	0.8749	<0.0001	0.8300
	Texline	1	0.0004	0.5270	0.0003	0.0049
		8	0.0143	0.4922	0.0237	<0.0001
Organic = Inorganic	Acuff	1	<0.0001	<0.0001	0.0042	<0.0001
		8	<0.0001	<0.0001	0.0013	<0.0001
	Amarillo	1	<0.0001	<0.0001	0.0040	<0.0001
		8	<0.0001	0.0020	<0.0001	<0.0001
	Harney	1	0.0007	<0.0001	0.0797	<0.0001
		8	0.0359	<0.0001	0.0313	<0.0001
	Pullman	1	<0.0001	0.0002	0.0566	<0.0001
		8	0.8024	0.0072	<0.0001	<0.0001
	Texline	1	0.0039	0.0014	<0.0001	<0.0001
		8	0.0019	<0.0001	<0.0001	0.0002

† Groups of fertilizer sources are as follows: Organic = {Compost, Scraped Manure}; Inorganic = {KH_2PO_4}.

Table A7. Level of significance for linear regression contrasts testing for differences between soil × rate interactions (H_0: efficiency of P extraction for the two groups of soil classes are equivalent).

Contrast H_0:†	Source	Time	Mehlich	$NaHCO_3$	TAMU	Water
		weeks		*P* > *F*		
Calcareous = Non-Calcareous	Compost	1	0.6823	0.0612	0.0002	<0.0001
		8	0.3367	0.4325	<0.0001	0.0008
	Scraped	1	0.5073	0.5634	0.0419	0.0232
		8	0.5412	0.7908	<0.0001	0.0048
	KH_2PO_4	1	0.0074	<0.0001	<0.0001	<0.0001
		8	<0.0001	<0.0001	<0.0001	<0.0001
Harney = Pullman	Compost	1	0.2694	0.6550	<0.0001	<0.0001
		8	0.6362	0.0056	<0.0001	0.1791
	Scraped	1	0.4649	0.7549	<0.0001	<0.0001
		8	0.0069	0.2687	<0.0001	<0.0001
	KH_2PO_4	1	0.0061	<0.0001	<0.0001	<0.0001
		8	<0.0001	0.2836	<0.0001	<0.0001
Low CEC = High CEC	Compost	1	0.4720	0.1961	<0.0001	<0.0001
		8	0.6373	0.0242	0.0004	<0.0001
	Scraped	1	0.9475	0.9294	<0.0001	0.0030
		8	0.3294	0.9397	<0.0001	0.0007
	KH_2PO_4	1	0.4245	<0.0001	0.0256	0.0079
		8	0.1544	0.0269	0.6670	<0.0001
Acuff = Amarillo	Compost	1	0.2852	0.0402	0.0192	0.0022
		8	0.4305	0.0003	0.1388	0.0002
	Scraped	1	0.7884	0.0399	0.0027	0.0008
		8	0.8440	0.7831	0.0065	<0.0001
	KH_2PO_4	1	0.0350	<0.0001	<0.0001	<0.0001
		8	0.0010	0.1776	<0.0001	<0.0001

† Soil classes are: Calcareous = {Texline}; Non-Calcareous = {Acuff, Amarillo, Harney, Pullman}; Low CEC (< 15 $cmol_c\ kg^{-1}$) = {Amarillo, Acuff}; High CEC (> 15 $cmol_c\ kg^{-1}$) = {Harney, Pullman}.

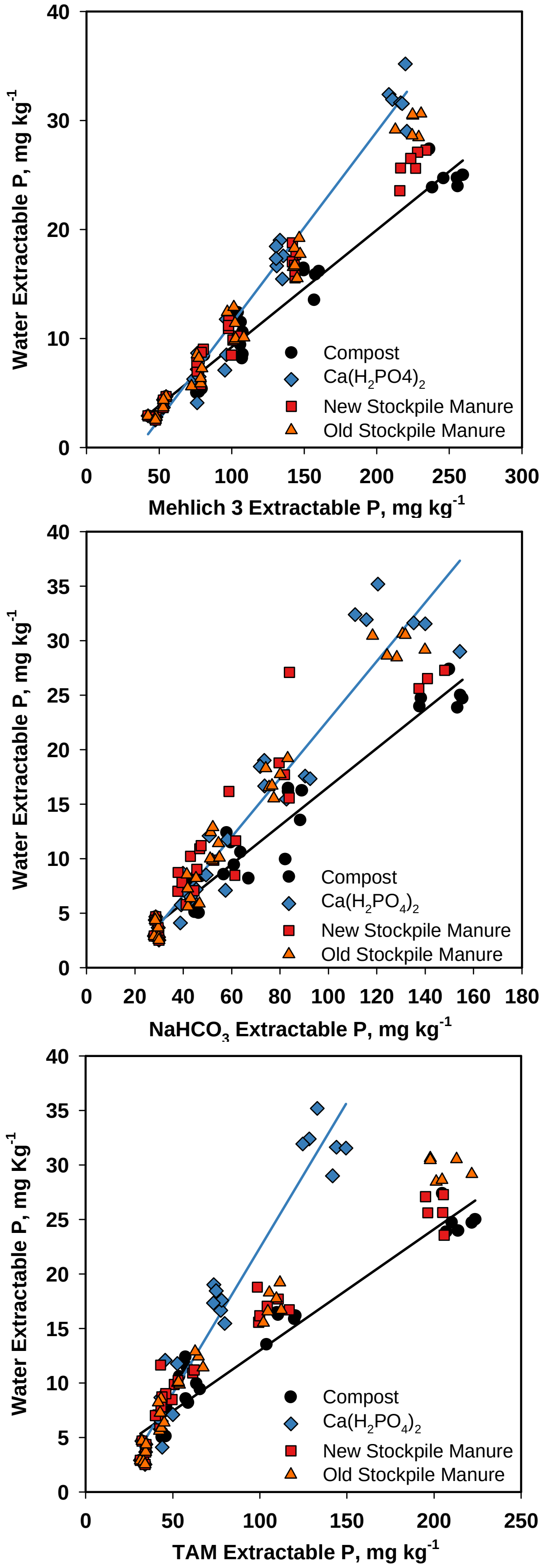

Figure A9. Relationships between dissolved reactive P and agronomic soil test P for Pullman soil (Incubation 1).

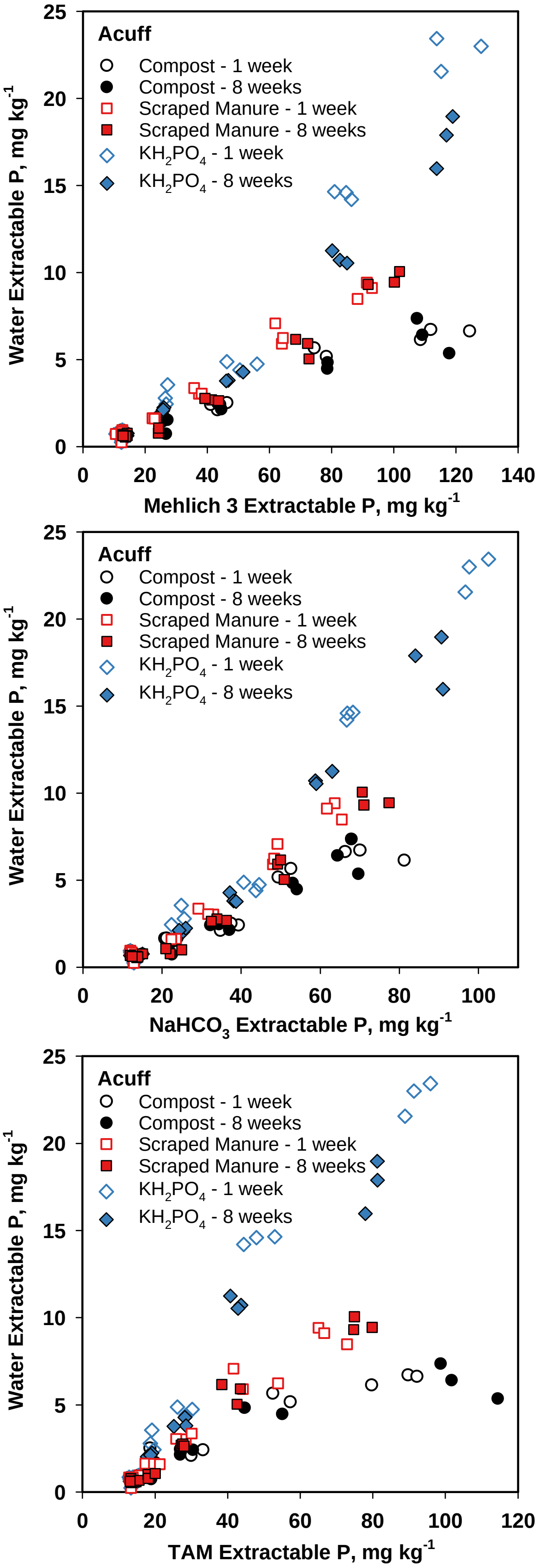

Figure A10. Relationships between dissolved reactive P and agronomic soil test P for the Acuff soil.

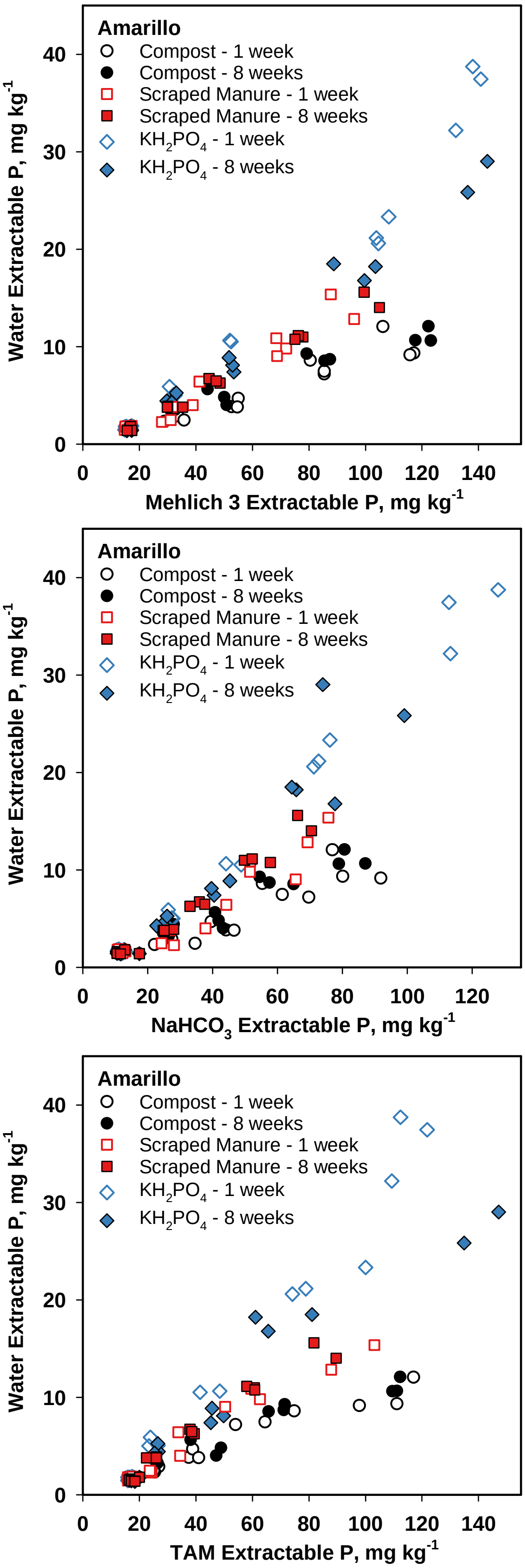

Figure A11. Relationships between dissolved reactive P and agronomic soil test P for the Amarillo soil.

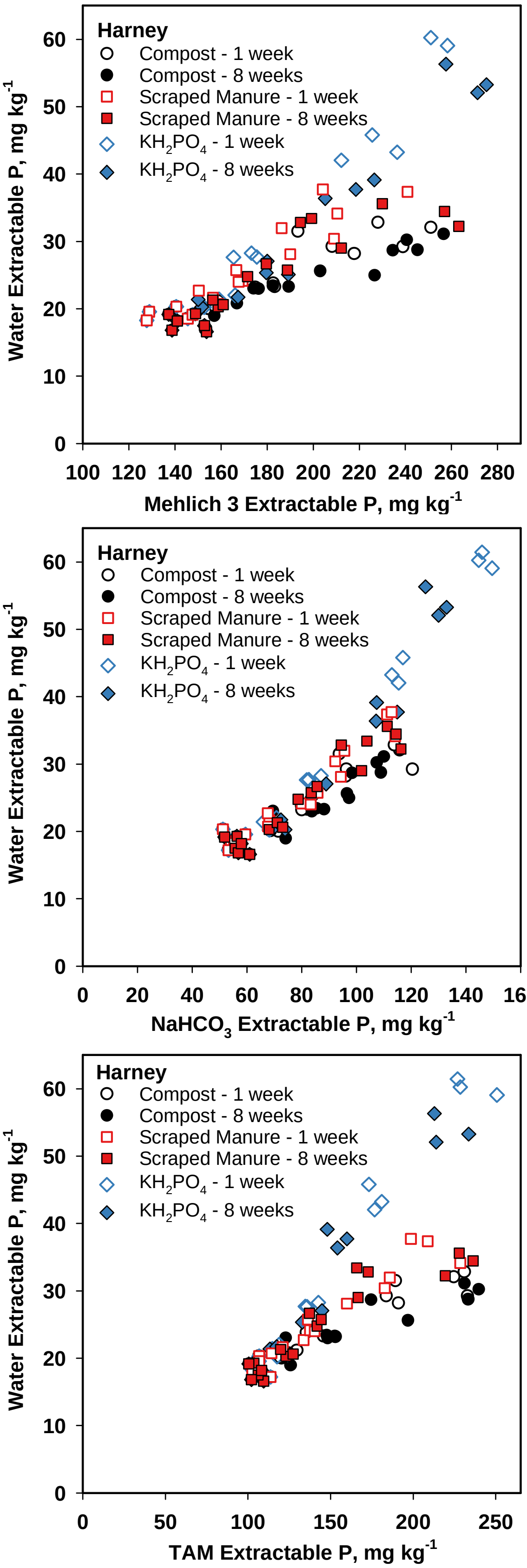

Figure A12. Relationships between dissolved reactive P and agronomic soil test P for the Harney soil.

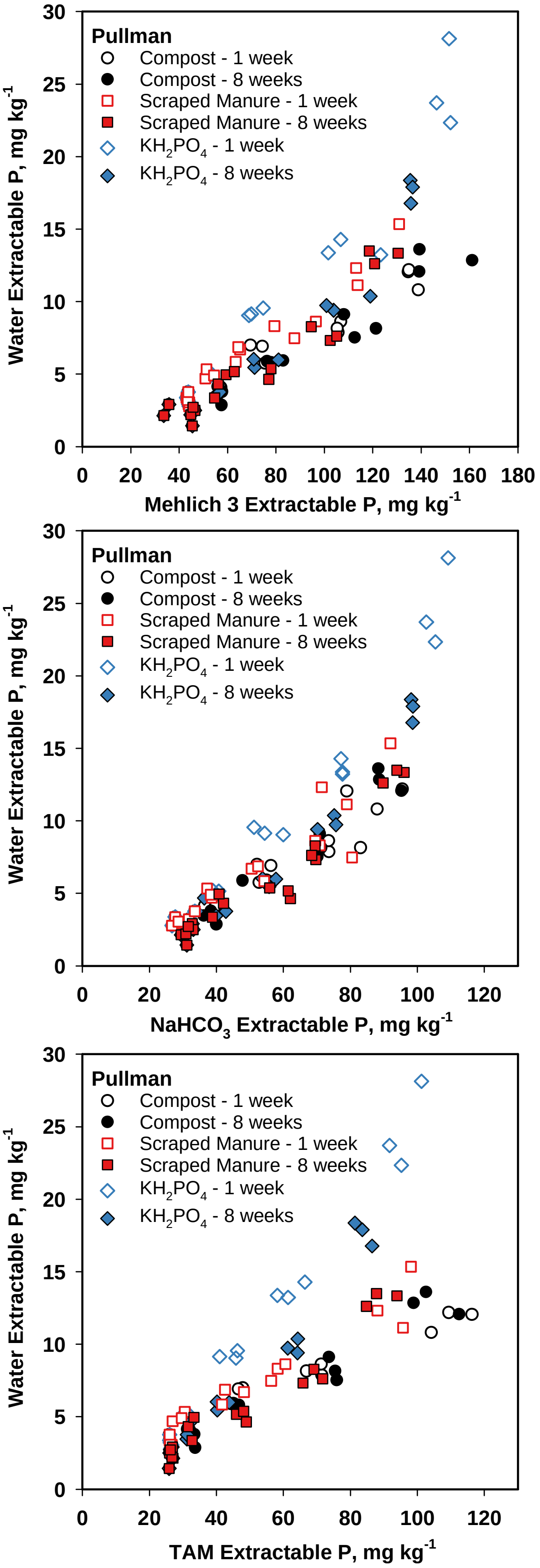

Figure A13. Relationships between dissolved reactive P and agronomic soil test P for the Pullman soil (Incubation 2).

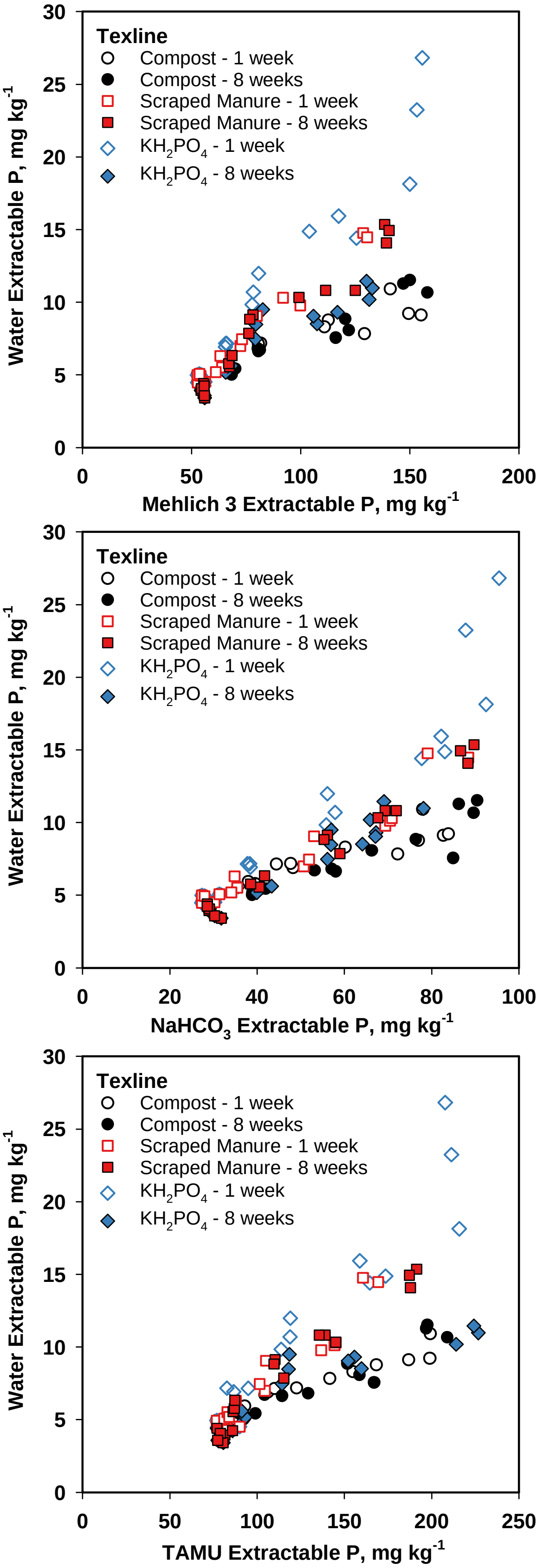

Figure A14. Relationships between dissolved reactive P and agronomic soil test P for the Texline soil.