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Soil phosphorus fractions after 111 years of animal manure and fertilizer applications

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Abstract Accumulated soil P in agricultural soils is a major source of soluble and particulate forms of P entering water resources and degrading water quality. However, few research sites are currently available to evaluate the long-term effects of different cropping systems and fertility practices on soil inorganic and organic P accumulation. The objectives of this study were: (1) to compare the forms and quantity of different inorganic and organic soil P fractions in plots on Sanborn Field, which has been cultivated for 111 years; and (2) to assess the use of standard soil test P extractants for determining changes in soil P dynamics over time. A modified sequential P extraction procedure was used to separate labile and stable inorganic and organic P pools from surface soils collected on Sanborn Field in 1915, 1938, 1962, and 1999 from plots in continuous corn, continuous wheat, continuous timothy, and a corn–wheat–clover rotation amended with either manufactured fertilizers, horse or dairy manure or receiving no fertilization since 1888. Additional samples were collected from a native grass prairie site of a similar soil series to estimate soil characteristics at Sanborn Field before initial cultivation in 1888. Observed accumulation of Bray-1 P among fertilizer and manure treatments was attributed to over-application of P due to unrealistically high yield goals for each cropping system. Long-term cultivation of Sanborn Field increased soil bulk density and lowered soil pH and total organic C compared with native prairie. Fertilization either by addition of manufactured fertilizer or manure significantly increased inorganic resin-P and inorganic NaOH-extractable P. Applications of animal manure also significantly increased most organic P fractions compared with the unfertilized treatment. The native prairie had a larger proportion of total P in organic forms compared with cultivated plots, especially in organic NaOH-extractable P, but no significant decreases in either residual or total P were observed due to cultivation. This study confirms that soil P availability in cropping systems that are amended with predominantly organic P amendments may differ from conventional cropping systems relying on manufactured P fertilizers. However, no direct evidence was found to support the hypothesis that any individual inorganic or organic soil P fraction has a better relationship than conventional soil test P extractants with plant P uptake under contrasting organic and conventional fertility practices.

Keywords Sanborn Field · Soil P pools · Cropping systems · Animal manure · Native prairie

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Introduction

Phosphorus (P) is an essential element for plant growth. Therefore, maintenance of adequate amounts of soil P through application of inorganic and/or organic P sources is critical for the long-term sustainability of cropping systems (Sharpley et al. 1994). However, accumulated soil P in surface soils from long-term and continuous agricultural fertilization is a major source of soluble and particulate forms of P contained in runoff that is entering water resources and degrading water quality throughout the USA (Daniel et al. 1998). Carpenter et al. (1998) estimate an average annual soil P accumulation rate from fertilizer applications in the USA and Europe of 22 kg of P ha^{-1}. In Missouri, approximately 31% of soil samples from agricultural fields submitted for analysis to the University of Missouri Soil and Plant Testing Laboratory in 1997 tested high or very high for soil test P (Manjula Nathan, personal communication, 1999). Growing public concern over the impact of agricultural sources of P on water quality has led to a reappraisal of traditional soil fertility recommendations and practices. However, few research sites are available for the evaluation of long-term effects of different cropping systems and fertility practices on soil inorganic and organic P accumulation.

Long-term application of animal manures and other organic amendments, which is often a major component of sustainable agricultural systems, may have several effects on soil P availability and losses. In general, such applications have been shown to increase soil total, available, and soluble P levels in both the surface and subsurface horizons, to reduce soil P adsorption capacity, and to increase rates of biologically-mediated turnover of organic P due to stimulation of microbial and enzyme activities (Sommers and Sutton 1980; Mozaffari and Sims 1994; Tiessen et al. 1994). Among the interrelated factors influencing the magnitude of these effects are the composition of the organic amendment (Nziguheba et al. 1998), the rate of application (Reddy et al. 1980), the soil type (Pote et al. 1999), climate, the method of application and incorporation, and the amount of reaction time with soil after application (Edwards and Daniel 1994).

Several studies have detailed the relative changes in soil organic and inorganic pools due to long-term cultivation (e.g., Hedley et al. 1982; Tiessen et al. 1983; Beck and Sanchez 1994). The relative distribution of soil inorganic and organic P pools may be influenced by initial soil chemical characteristics due to soil type (Tiessen et al. 1984), climate, and management practices. In general, long-term studies have observed a decline in organic P pools with continuous cultivation and no fertility inputs. For example, Beck and Sanchez (1994) examined soil inorganic and organic pools in a highly-weathered soil in Peru which had been cultivated for 18 years and found that the NaOH-extractable inorganic P pool acts as a sink for fertilizer P but that organic P pools were the primary source of plant-available P in the non-fertilized systems. They also found that crop yields were positively related to levels of available P measured by anion exchange resin and by NaOH-extractable organic P. NaOH-extractable organic P contains P associated with humic compounds and P adsorbed to Fe and Al oxides and, although it is more stable than bicarbonate-extractable organic P, it can be an important P source when the amount of labile inorganic P is small (Buresh et al. 1997). Therefore, traditional methods of measuring plant-available P may not be well correlated with plant uptake in agricultural systems with limited inputs, or primarily organic inputs, since these systems may utilize more stable forms of inorganic and organic P (Oberson et al. 1993; Beck and Sanchez 1994). For example, Oberson et al. (1993) speculated that the relatively larger residual organic P measured using the sequential extraction procedure for biological farming systems compared with conventional farming systems represented a reserve of soil P that could be rapidly transformed to available P due to greater phosphatase activity in the biological farming systems. However, sequential P extraction of long-term conventional agricultural systems receiving manufactured fertilizers also reveals changes in forms of inorganic and organic P which may contribute to P nutrition of crops and which are not measured by traditional tests for plant-available P (Richards et al. 1995).

Sanborn Field, located on the University of Missouri campus in Columbia, was established in 1888 and has provided researchers with an opportunity to examine the long-term effects of agricultural management practices on soil properties under different cropping systems (Buyanovsky et al. 1997). For example, after over 100 years of cultivation, plots receiving 13.4 Mg $ha^{-1}year^{-1}$ of animal manure had approximately 0.5% higher soil organic C levels, an average of 0.12 g cm^{-3} lower bulk density, and nine times the saturated hydraulic conductivity than an equivalent cropping system without manure (Anderson et al. 1990; Buyanovsky et al. 1997).

Estimated total amounts of soil P removed by crops on Sanborn Field over 100 years are dependent on crop rotation and are much larger than the soil-available P pools under the native prairie vegetation that existed prior to the first cultivation of Sanborn Field (Buyanovsky et al. 1997). Other researchers have examined the distribution of soil P in fertilized and unfertilized plots from Sanborn Field and observed no differences in P adsorption properties among fertilized and unfertilized plots (Kao and Blanchar 1973). However, an accumulation of total, plant-available, and inorganic soil P at depths 61–137 cm below the soil surface in fertilized plots was observed (Kao and Blanchar 1973). In a subsequent re-examination of this study, Blanchar and Conkling (1989) concluded that the comparatively higher subsoil P levels in the fertilized plots were due to depletion of native subsoil P in unfertilized plots and were not due to P leaching. However, research by Gantzer et al. (1991) found that all the topsoil was lost after 100 years of cultivation in the continuous corn plots of Sanborn field with slopes from 0.5% to 3%, suggesting that erosion may be a significant mechanism for soil P loss from Sanborn Field and may be dependent on crop rotation and fertilization practices.

The objectives of this study were: (1) to compare the form and quantity of different inorganic and organic soil P fractions in long-term cultivated plots under several cropping systems and fertility management regimes; and (2) to assess the use of standard soil test P extractants for determining changes in soil P dynamics over time.

Materials and methods

Soil sample collection from Sanborn Field and Tucker Prairie

Soil samples were collected to a depth of 20 cm using a stainless steel push probe on 4 October 1999 from long-term cropping system plots located at Sanborn Field in Columbia, Missouri. Plots measure 30.6 m length by 9.5 m width and are separated by a 1.5 m-wide grass border. Cropping systems sampled include continuous corn (*Zea mays* L.), continuous wheat (*Triticum aestivum* L.), a corn–wheat–red clover (*Trifolium pratense* L.) rotation, and continuous timothy (*Phleum pratense* L.). Plots have been unamended or amended with manufactured fertilizers based on soil test recommendations for Missouri or 13.4 Mg (wet weight basis) ha^{-1} horse or dairy manure since 1888. Based on analyses initiated in 1990, dairy manure applied to Sanborn Field has had an average moisture content of 792±70 g kg^{-1} and a nutrient content of 18.6±4.4 g kg^{-1} total N, 3.9±5.3 g kg^{-1} total P, and 9.1±6.7 g kg^{-1}

Table 1 Yield goals, fertilizer nutrient applications and average grain and forage yields in selected periods for Sanborn Field

Period	Crop	Yield goal ($t\ ha^{-1}\ year^{-1}$)	Fertilizer nutrients applied			Grain or forage yields[a]		
			N	P	K	None	Fertilizer	Manure
			($kg\ ha^{-1}\ year^{-1}$)			($t\ ha^{-1}\ year^{-1}$)		
1888–1949[b]	Corn (grain)	5.0	141	21	76	1.4±0.9	2.7±1.3	2.3±1.3
	Wheat (grain)	2.7	92	14	62	1.4±1.1	1.3±0.7	1.3±0.6
	Clover (forage)	6.7	143	17	121	1.5±0.9	6.9±2.9	3.2±3.0
	Timothy (forage)	6.7	–	–	–	2.4±1.5	–	5.5±2.2
1950–1989[c]	Corn (grain)	11.3	187	31	134	1.3±1.4	6.4±2.6	4.0±2.6
	Wheat (grain)	2.7	85	11	63	0.8±0.7	2.7±0.8	2.4±1.1
	Clover (forage)	NA	NA	NA	NA	4.0±2.0	8.2±4.2	7.1±3.7
	Timothy (forage)	NA	–	–	–	2.3±1.2	–	6.5±2.8
1990–1999[d]	Corn (grain)	11.3	233	0	0	1.5±1.1	7.5±1.8	4.0±1.8
	Wheat (grain)	4.7	92	16	24	1.1±0.7	2.3±1.6	2.2±1.0
	Clover (forage)	9.4	0	22	157	4.5±1.8	3.2±3.0	9.6±4.6
	Timothy (forage)	9.0	–	–	–	2.2±1.0	–	6.0±2.4

[a] Average annual grain or forage yields over selected period ±1 SD
[b] Crop residues removed after harvest. Horse manure with bedding applied for manure treatment. Fertilizer was not applied to the timothy cropping system
[c] Crop residues returned after harvest. Dairy manure applied for manure treatment. Information not available (NA) regarding yield goals for clover and timothy during this period. Fertilizer was not applied to the timothy cropping system. For clover, P and K fertilizer were added based on soil test recommendations and information on specific rates were not recorded
[d] Crop residues returned after harvest. Dairy manure applied for manure treatment. N, P and K fertilizers added based on soil test recommendations. Numbers presented are averages over years of actual fertilizer applied. Fertilizer was not applied to the timothy cropping system

total K. Horse manure applied prior to the 1940s contained a relatively larger proportion of bedding material compared with dairy manure. All manure was broadcast-applied in the fall and manufactured fertilizers in the spring. Fertilizer P was applied as crude-grade acid phosphate or normal superphosphate (70–87 g P kg^{-1} fertilizer) up to the 1940s, and subsequently triple superphosphate (200 g P kg^{-1} fertilizer) was applied (Buyanovsky et al. 1989) Rock phosphate (131–157 g P kg^{-1} fertilizer) was also applied sporadically to fertilized plots. All plots considered in this study were tilled using a moldboard plow and then were disked twice before planting. Table 1 summarizes the major changes in yield goals and fertilizer sources since 1888.

Three soil samples were collected per plot by separating each plot into three 10 m sections and bulking 20 subsamples per section. Bulk density was determined to a depth of 20 cm using the core method and a Uhland core sampler (Blake and Hartge 1986). Three additional composite soil samples were collected over an area of approximately 10 ha to a depth of 20 cm from Tucker Prairie, a virgin, mixed-grass prairie site located approximately 24 km east of Columbia, containing a similar soil association to that of Sanborn Field. This site has been utilized to estimate initial soil characteristics at Sanborn Field before cultivation, since soil samples from Sanborn Field are not available from before 1914 (Brown and Breight 1989; Wagner 1989). The primary soil series present at both Sanborn Field and Tucker Prairie is the Mexico silt loam. A more in-depth discussion of the soil morphology, particle size distribution, and clay mineralogy throughout the soil profile of Sanborn Field can be found in Miles and Hammer (1989). All soil samples were air-dried, ground in a hammer-mill, and passed through a sieve with 2-mm diameter openings.

Additional soil samples from the same plots were selected from stored samples taken to a depth of 20 cm in 1915, 1938, and 1962. These soils had been air-dried, ground, and passed through a sieve with 0.425–2 mm diameter openings, before storage in sealed glass containers.

Soil analysis

Air-dried samples were analyzed for total P and soil inorganic and organic P fractions using a modified sequential extraction procedure developed by Hedley et al. (1982) and modified by Beck and Sanchez (1994). Briefly, this method uses a series of increasingly stronger chemical extractants to separate labile and stable inorganic and organic P pools. The extractants used, in order, were anion exchange resin (Dowex 1-X8 converted to bicarbonate form), 0.5 M $NaHCO_3$, 0.1 M NaOH, 0.1 M NaOH + sonication, 1 M HCl, and a concentrated H_2SO_4 digestion at 360°C for 3 h. The sequential analytical procedure, the associated P fraction, and its proposed functional role in soil are described in Fig. 1.

Resin-extractable P has been associated with plant-available P and $NaHCO_3$-extractable P with labile inorganic and organic P (Okalebo et al. 1993). NaOH extracts moderately labile organic P and partially dissolves inorganic iron and aluminum phosphates. Sonication of NaOH extracts promotes extraction of inorganic and organic P physically protected in aggregates (Hedley et al. 1982). The HCl extractant dissolves P minerals and possible fertilizer reaction products (Okalebo et al. 1993).

Dissolved organic P in $NaHCO_3$, NaOH, and NaOH + sonication extracts was digested in the autoclave (103.4 kPa, 121°C for 1.5 h) using acidified ammonium persulfate oxidation (Environmental Protection Agency 1971). All inorganic P extracts or organic P digests were analyzed colorimetrically using a Lachat QuikChem 8000 analyzer and the ascorbic acid method (Lachat Instruments 1996). Samples were also analyzed for soil test P using the Bray P1 extractant (Bray and Kurtz 1945). Soil pH was measured in water (soil:water w/v) and soil total organic C was determined using a heated dichromate oxidation method (Nelson and Sommers 1975).

Data analysis

Analysis of variance (ANOVA) for evaluating the effects of years, cropping systems, and fertility treatments on soil P fractions were determined by PROC GLM (SAS Institute 1988). The multiple comparison test used was Fisher's (protected) LSD at a 0.05 significance level. Annual P uptake among cropping systems on Sanborn Field were calculated using estimates of tissue P concentration for each crop and grain and forage yields recorded since 1888. Pearson product moment linear correlations were calculated using PROC CORR (SAS Institute 1988).

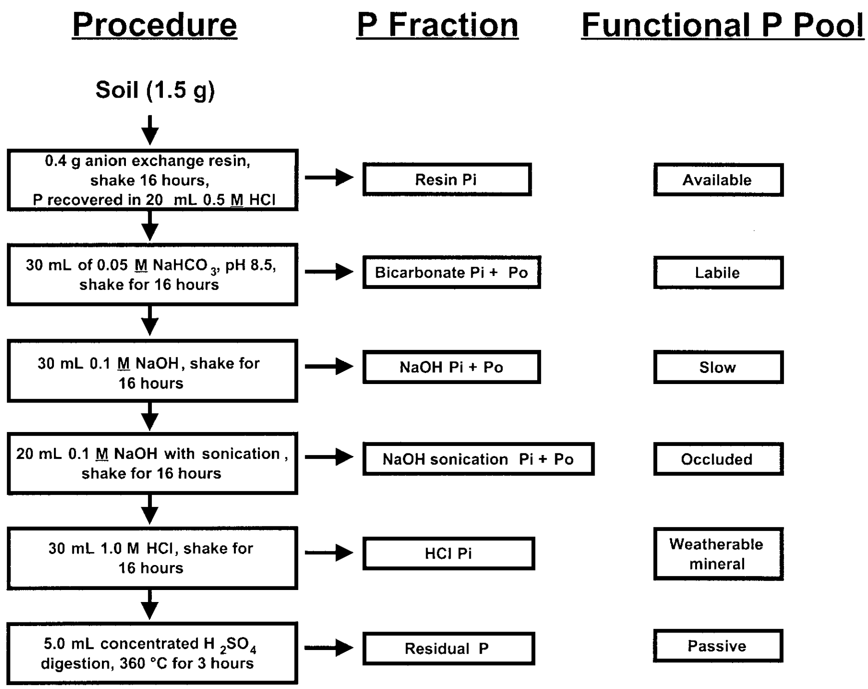

Fig. 1 Sequential P extraction procedure and functional significance of extracted soil P fractions (*Pi* inorganic P, *Po* organic P) (Adapted from Okalebo et al. 1993)

Results and discussion

P fertilization and soil P accumulation

Yield goals for grain and forage crops on Sanborn Field increased from the cropping period of 1888–1949 to the cropping period of 1990–1999, corresponding to changes in crop genetics, fertilizer sources, and other developments in agricultural technology (Table 1). Higher rates of N, P and K fertilizer were applied on fertilizer-treated plots to meet the higher yield goals based on University of Missouri soil test recommendations. However, average crop yields observed on fertilizer- and manure-treated plots during the three selected periods were below yield goals, especially for the grain crops (Table 1), suggesting a possible consistent over-application of nutrients due to unrealistically high yield goals. Over-application of P fertilizers and animal manure containing P is the leading cause of soil P accumulation in agricultural soils (Sharpley et al. 1995).

The accumulation of soil Bray-1 P in cropping systems under different soil fertility treatments over time on Sanborn Field is shown in Fig. 2. The Bray-1 extractant is used as the standard soil test P extractant for agricultural soils in the state of Missouri and several other states in the North Central Region of the USA (Frank et al. 1998). Under Missouri soil test recommendations, soil Bray-1 P values greater than 20–22.5 mg P kg^{-1} are above the level required for optimal P growth response (Buchholz 1992). By 1915, soil Bray-1 levels were significantly higher in the fertilized and manure treatments under all cropping systems compared with the unfertilized control treatment (Fig. 2). The unfertilized control treatment also showed a general decrease in soil Bray-1 P from 1915 to 1999, possibly due to crop removal.

Brown and Breight (1989) compared Bray-1, Bray-2, and Mehlich 3-extractable soil P in archived samples from 1915 to 1980 collected from among the cropping systems and fertilization treatments at Sanborn Field, and also observed a continuous decrease in extractable P in unfertilized plots. In that study, plots receiving animal manure showed an initial marked decline followed by a continuous increase in extractable P, which was attributed to the early use of horse manure with a high proportion of bedding. An additional effect on extractable and organic soil P may have occurred after 1950 due to the initiation of incorporation of straw and stalks after cropping (Buyanovsky et al. 1997).

Other factors affecting the fate of applied P in Sanborn Field include the effects of long-term cultivation on soil physical, chemical and biological properties. A comparison of soil bulk density of soil samples collected in 1999 to a depth of 20 cm indicates a significant increase in bulk density in cultivated plots on Sanborn Field compared with that of a native prairie soil that possibly reflects the same general soil properties that occurred at Sanborn Field before cultivation (Table 2). In addition, both fertilizer and manure treatments had significantly lower soil bulk density compared with the control treatment when continuous corn or wheat were grown (Table 2). These differences in bulk density were also observed by Anderson et al. (1990) and may also be a result of differential soil erosion removing the surface soil among the cropping systems (Gantzer et al. 1991). Soil pH was significantly higher in plots receiving fertility treatments, probably because of the periodic lime applications added to those plots. Fertility treatments also signif-

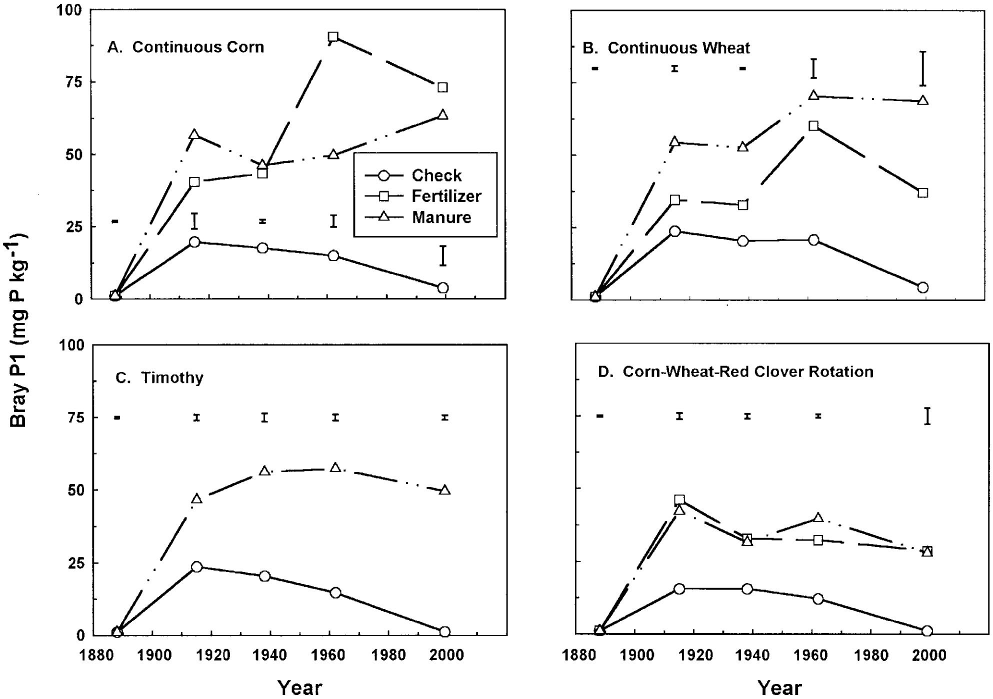

Fig. 2 Soil Bray 1-extractable P after 111 years of fertility treatments in Sanborn Field for **A** continuous corn, **B** continuous wheat, **C** timothy, and **D** a corn–wheat–red clover rotation. The soil test P values for 1888 are estimates based on soil collected from Tucker Prairie in 1999. *Bars* indicate $LSD_{(0.05)}$ values at each sampling time with the exception of 1888, for which the *bar* represents ±1 SD

Table 2 Selected soil characteristics of fertility plots in Sanborn Field (1999 samples)

Crop	Fertility treatment	Bulk density (g cm^{-3})	pH (water)	Organic C (g kg^{-1})
Corn	None	1.49	5.21	7.3
	Fertilizer	1.34	5.98	11.7
	Manure	1.35	6.25	12.6
Wheat	None	1.50	4.77	8.2
	Fertilizer	1.36	6.14	12.1
	Manure	1.35	6.04	15.1
Corn-Wheat-Red clover	None	1.41	5.54	11.7
	Fertilizer	1.42	6.14	14.4
	Manure	1.33	5.59	15.2
Timothy	None	1.32	5.48	14.4
	Manure	1.23	6.06	19.1
Native Prairie	None	1.01	5.26	23.6
	$LSD_{(0.05)}$	0.11	0.26	3.2

icantly increased soil organic C compared with unfertilized plots, possibly as a result of higher residue inputs, although all cultivated plots had significantly lower organic C than the native prairie (Table 2). Extensive research concerning the fate of native prairie soil organic C in Sanborn Field after long-term cultivation under different cropping systems has been presented by Wagner (1991).

P fractions

The results of sequential P fractionation of the soil samples collected in 1999 from Sanborn Field and Tucker Prairie are given in Table 3. Addition of fertilization, either in the form of fertilizers or manure, significantly increased resin P_i among all cropping systems at Sanborn Field compared with the unfertilized controls and the native prairie site. With the exception of the corn–wheat–clover rotation, long-term application of fertilizer and manure also significantly increased NaOH-extractable P_i, a more slowly-available P fraction than resin P_i and $NaHCO_3$-P_i. Richards et al. (1995) observ-ed significant increases in resin P_i, $NaHCO_3$-P_i, and NaOH-P_i with 10 years of P fertilizer applications for continuous corn production in southern Ontario, Canada. In contrast, this study did not observe significant increases in $NaHCO_3$-P_i, with long-term application of fertilizer, but did find significant increases in $NaHCO_3$-P_i with applications of manure in the continuous corn and wheat cropping systems (Table 3). In addition, long-term application of manufactured fertilizers did not significantly increase organic P fractions and residual P compared with the plots receiving no amendments or to the native prairie site. Contributing factors to the lack of increased

Table 3 Inorganic (P_i) and organic (P_o) sequential P fractions from Sanborn Field and Tucker Prairie (1999)

Crop	Fertility treatment	Inorganic P (P_i)				Organic P (P_o)				Residual P	Total P
		Resin	Bicarb	NaOH	NaOH + Sonic	HCl	Bicarb	NaOH	NaOH + Sonic		
		mg P kg^{-1} soil									
Corn	None	3.0	18.4	19.4	14.4	1.2	22.5	30.8	7.7	111	228
	Fertilizer	54.1	54.8	75.8	39.3	24.7	36.6	103.9	3.2	149	541
	Manure	55.5	181.2	148.6	40.9	23.2	23.0	148.6	40.9	154	676
Wheat	None	3.8	3.3	29.4	19.7	1.5	53.5	50.6	7.2	109	278
	Fertilizer	35.3	34.4	80.2	16.8	83.0	52.3	73.3	10.5	114	500
	Manure	47.7	82.6	198.3	41.0	21.1	76.0	135.0	0.6	154	756
Corn-Wheat-Red clover	None	5.0	6.4	15.4	6.8	8.8	30.3	69.0	11.4	55	208
	Fertilizer	27.1	39.3	44.6	11.6	87.7	36.3	67.7	12.3	89	416
	Manure	21.3	40.7	44.5	16.3	167.2	59.7	82.2	20.1	86	538
Timothy	None	4.3	14.8	21.0	7.2	14.5	41.8	62.5	7.2	72	253
	Manure	41.7	51.4	114.9	22.9	143.2	69.3	99.1	12.0	104	659
Native Prairie	None	4.0	6.5	21.8	9.6	6.5	59.6	176.5	7.4	35	327
	$LSD_{(0.05)}$[a]	8.2	50.3	40.7	10.9	123.8	42.1	82.9	14.1	NS	309

[a] Least significant difference at P<0.05; NS not statistically significant

Table 4 Correlation coefficients among extracted P fractions and estimated P uptake

P fraction	Fertility treatment		
	Fertilizer	Manure	No added fertility
Inorganic P fractions			
Resin	0.56	–0.35	0.10
Bicarb	0.55	–0.28	–0.08
NaOH	–0.06	–0.51[a]	–0.06
NaOH + Sonic	0.37	–0.21	0.11
HCl	0.28	0.30	–0.08
Organic P fractions			
Bicarb	0.18	–0.19	–0.33
NaOH	0.13	–0.42	–0.19
NaOH + Sonic	–0.04	0.07	–0.28
Other			
Bray1	0.33	–0.52[a]	–0.06
Residual	0.09	–0.18	–0.16
Total	0.30	–0.31	–0.27

[a] r values are significantly correlated at the 0.05 probability level; n = 12 for fertilizer treatment and n = 16 for each of the manure and no-added-fertility treatments

organic P fractions in manufactured fertilized plots on Sanborn Field may have been the continuous use of conventional tillage in plot preparation and the practice of removing all crop residues before 1950.

Long-term application of animal manure generally resulted in significant increases in most inorganic and organic P fractions and total P compared with the unfertilized treatment (Table 3). The NaOH-P_i extract appeared to be more responsive than the resin-P_i extract to manure applications compared with added fertilizer. An exception to this relationship was under the corn–wheat–red clover rotation, in which the HCl-P_i extract was more effective in extracting added manure P.

The native prairie site had a larger proportion of total P in organic forms compared with the cultivated plots, especially in the NaOH-P_o extract (Table 3). Hedley et al. (1982) observed a decrease in residual and total P in cultivated plots compared with permanent pasture plots, which they attributed to the effects of tillage and differences in residue management. However, long-term cultivation of the native prairie originally present at Sanborn Field did not result in a significant decrease in either residual or total P. Total P levels on Sanborn Field appeared to be most affected by fertility treatment and not by cropping system.

Results of correlating estimated plant P uptake with extracted P fractions by fertility treatment for the four years considered in this study are shown in Table 4. In general, the plant P uptake did not show a strong correlation with sequential P fractions, Bray-1 P, or total P with the exceptions of NaOH-P_i (r= –0.51*) and Bray-1 P (r= –0.52*) when manure was applied (Table 4). These results indicate that plant response on Sanborn Field is probably influenced by several interacting soil, plant, and climatic factors besides P deficiency.

Conclusions

The results of this study confirm that long-term cropping systems and fertility practices significantly alter the amounts and proportions of labile and stable soil P pools compared with the initial native prairie soil. A major factor affecting the accumulation of soil P in Sanborn Field has been the use of unrealistically high yield goals, leading to over-fertilization. Changes in management which have occurred over the 111-year cropping history of Sanborn Field have also had a significant impact on soil P, including changes in crop residue management and applied animal manure composition. This study also provides evidence that long-term manure applications have significantly different effects than applications of manufactured fertilizers on soil inorganic and organic P pools and both labile and more stable P pools are increased by long-term manure applications. This result supports previous studies that have suggested that soil P availability dynamics in cropping systems that receive predominantly organic P amendments may differ from conventional cropping systems relying on manufactured P fertilizers. However, no direct evidence could be found to support the hypothesis that any individual soil P fraction, such as NaOH-P_i or P_o, had a better relationship than conventional soil test P extractants, such as the Bray-1 extractant, with plant P uptake under contrasting fertility practices over 111 years of cultivation.

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