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EFFECT OF CROPPING AND LOW-CHEMICAL INPUT SYSTEMS ON SOIL PHOSPHORUS FRACTIONS

S. H. Daroub[1], B. G. Ellis[1], and G.P. Robertson[2]

The adoption of alternative management practices has been shown to increase soil organic matter. However, the effect of adopting these practices on soil phosphorus (P), especially organic P, is not clear. We evaluated the effect of such practices—mainly no-tillage, zero and low-chemical input, organic-based, row crop agricultural systems—on soil P and compared them with conventional agriculture and perennial farming systems. We also compared soil P under conventional agriculture to an adjacent forest site and a never-tilled native successional community site in southwest Michigan. Sequential fractionation analysis of soil inorganic and organic P fractions showed that long-term conventional row crop agriculture resulted in a 79% reduction of NaOH-extractable organic P compared with adjacent forested sites. The calcium phosphate pool and the residual P fraction, however, increased under conventional agriculture compared with the forest site, probably because of fertilizer inputs. Adoption of no-tillage and low-chemical input systems with a winter leguminous cover crop in the rotation for 7 years did not increase organic P significantly in any of the fractions extracted from the annual cropping systems. However, organic P extracted by NaOH increased to 22.1% after adoption of continuous alfalfa for the same period compared with 11.4% extracted under conventionally tilled annual cropping systems. We conclude that continuous alfalfa can help restore soils to their native P fertility levels by taking up P from the stable residual fraction and transforming it into moderately labile organic P through root death. We found no evidence that low chemical input organic based systems are sustainable with regard to P as there is no evidence that organic P is accumulating as a result of the use of cover crops. Further investigation is warranted after these soils become P limiting and more years have passed under the same treatments. (Soil Science 2001;166:281–291)

Key words: Phosphorus fractions, organic P, tillage, low-input systems, deciduous forest, alfalfa, poplar, corn, soybean, wheat.

THE shift from conventional agriculture to farming systems that rely partly or fully on organic inputs will bring changes in the dynamics of organic matter turnover in soils and, subsequently, in the dynamics of phosphorus (P) in soils and its availability to crops. Conventional agriculture depends on the inputs of inorganic fertilizers and is concerned with the nutrition of the crops for one season. More organic matter-based farming systems use practices such as minimum tillage and winter cover crops to increase the soil organic matter content and supply nutrients through mineralization at the time when the plant requires it.

The effect of cultivation on soil organic matter stores of carbon (C), nitrogen (N) and P has been assessed by comparing cultivated soils with adjacent forested sites or never-tilled prairie soils. Carbon concentrations in the plow layer decrease rapidly when native soils are brought into cultivation and eventually, after many years, stabilize (Paustian et al., 1997). For example, Ellert

[1]Department of Crop and Soil Sciences, Michigan State University, East Lansing, MI 48824. Dr. Daroub is corresponding author. Current Address: University of Florida, EREC, Belle Glade, FL 33430. E-mail: sdaroub@mail.ifas.ufl.edu.

[2]Department of Crop and Soil Sciences, and Kellogg Biological Station, Michigan State University, Hickory Corners, MI 49060.

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and Gregorich (1996) compared soil C, N, and P stored in cultivated soils and in soils of adjacent forests or woodlots at 15 sites in Ontario, Canada. Compared with the forest soils, the surface layers of cultivated soils (averaged for the 15 sites) had 34% less C, 19% less N, and 24% more P. Increases in P storage were related to P fertilization. Total P content was 29% lower after 65 years of cropping in a wheat-wheat-fallow rotation compared with adjacent permanent pasture in Saskatchewan (Hedley et al., 1982). Continuous cultivation in Savannah Alfisols in Northern Nigeria caused large losses of organic P (Po) compared with a native site soil (Agbenin and Goladi, 1997). In the treatments investigated, Agbenin and Goladi discovered that the application of inorganic fertilizers did not mitigate Po losses; however, the addition of a combination of farmyard manure and inorganic fertilizers did help to maintain the fertility of the soil and reduce loss of Po.

Oberson et al. (1993, 1996) recently examined the effect of biological and conventional farming systems on soil P fractions and found that irrespective of the form of P applied in the different conventional and biological systems investigated, only inorganic P (Pi) fractions and residual Po differed by system. The conventional system received Pi fertilizer, whereas the biological systems received different proportions of manure and Pi fertilizer. Organic P extracted by $NaHCO_3$ or NaOH was not increased by any of the biological systems (Oberson et al., 1993). Although Po in these two fractions was independent of the farming system, the levels showed temporal fluctuations, indicating seasonal accumulation and mineralization processes (Oberson et al., 1996). Daroub et al. (2000) investigated the effect of long-term no-tillage (NT) management system on soil Pi and Po fractions in three soils in Michigan. They found that NaOH-extractable Po was higher at the 0- to 2-cm depth of a NT Kalamazoo soil compared with conventional tillage (CT) treatment, but they found no effect of tillage on microbial P in any of the three soils. They concluded that the effect of tillage on soil Pi and Po fractions was minimal and not consistent among the three soils investigated in their study. Furthermore, tillage had no effect on the fate of ^{33}P labeled soybean residues added to the three soils (Daroub et al., 2000).

No-tillage has been adopted widely for various reasons, one of which is to reduce soil erosion. Lesser amounts of P fertilizers are being added as more farmers become conscious of the negative effect of P on surface waters. In this context it is important to know if we can rely on mineralization of P from organic sources in the soil under low-input systems and, if so, what are the management practices that affect accumulation of Po. We hypothesize that the adoption of management practices such as no-tillage and the planting of winter leguminous crops in a crop rotation will increase organic C and Po in soils. Organic P pools would be higher under low-input organic based systems as well as under NT compared with conventional systems. The availability of P under these new systems will, therefore, be the same as in conventional systems receiving high P fertilization input. Because the soil investigated is not P limiting, it is not possible to test the second part of our hypothesis.

In this paper, we assess the impact of land use change on soil Pi and Po fractions in:

1) Long-term conventional row crop agriculture;
2) Alternative management systems, including NT and organic based systems imposed for 7 years; and
3) Perennial cropping systems imposed for 7 years.

MATERIALS AND METHODS

Site Description

The Kellogg Biological Station (KBS) Long-term Ecological Research (LTER) site was established at Hickory Corners, MI, to increase our understanding of ecological phenomena in agricultural and row crop ecosystems (Robertson et al., 1997). This site was established in 1988 and is part of the national LTER network. The KBS LTER main experimental site is a 60-ha site that has been subdivided into seven different 1-ha cropping systems, each replicated in one of six blocks, with an eighth never-tilled system nearby (Table 1). Four of these cropping systems are annual crop rotations, two are perennial, and two are successional systems in native vegetation. Before the establishment of the KBS LTER, this site had been in corn-soybean rotation under CT for the last 50 years with regular inputs of fertilizers and pesticides.

The annual crop rotation in Treatments 1 and 2 from 1989 to 1994 was corn (*Zea Mays* L.)-soybean (*Glycine Max* L.). Wheat (*Triticum aestivum* L.) was introduced into the rotation in 1995. These two treatments receive standard levels of agrochemical inputs (inorganic fertilizers and herbicides), with Treatment 1 moldboard

TABLE 1

Description of the cropping systems at the KBS LTER site

Treatment no.	Abbreviation	Description
1	CT	Corn-Soybean-Wheat; standard level of agrochemical inputs; Conventional tillage, moldboard plowed (n = 6 reps).
2	NT	Corn-Soybean-Wheat; standard level of agrochemical inputs, No-till management (n = 6).
3	Low-input	Corn-Soybean-Wheat; chemical inputs only to control outbreak pests; moldboard plowed; Winter leguminous cover crop (n = 6).
4	Zero-input	Corn-Soybean-Wheat; no chemical inputs at any time; moldboard plowed; Winter leguminous cover crop (n = 6).
5	Poplar	Poplar trees planted on a 10 year rotation cycle (n = 6)
6	Alfalfa	Continuous alfalfa (n = 6)
7	Native; tilled	Native successional community; historically tilled, but abandoned after spring plowing in 1989 (n = 6).
8†	Native; never-tilled	Native successional community; Never plowed (n = 4).
DF†	Forest	Native deciduous forest; old growth (n = 3)

†Treatment not part of the randomized block design.

plowed and Treatment 2 under NT management. Fertilizer inputs in both treatments, applied in the corn phase, were 123 kg N ha^{-1} in 1989 and 1991 and 84 kg N ha^{-1} and 90 kg K ha^{-1} in 1993. In 1995, 56 kg N ha^{-1} was applied for the wheat crop. No fertilizers are applied in the soybean phase of the rotation. Treatments 3 and 4 have been in wheat-corn-soybean rotation since 1989, and they are both organic based, low-chemical input systems with a winter leguminous cover crop planted in the rotation. Treatment 3, which receives chemical inputs only to control outbreak pest populations and to provide an initial pulse of N at planting, received 28 kg N ha^{-1} in 1990 (corn), 90 kg K ha^{-1} in 1993 (corn), and 34 kg N ha^{-1} in 1995 (wheat). Treatment 4 received no chemical inputs at any time. The cover crop planted was hairy vetch (*Vicia villosa Roth*) in 1989, 1990, 1992, and 1993 and Mammoth red clover (*Trifolium pratense*) in 1995. The cover crop is generally planted in late summer or early fall and mowed before planting of the next crop in the spring to provide nitrogen for the next crop in rotation. In 1991 and 1994, wheat was seeded in early winter and harvested mid-summer the following year with no cover crops planted those years.

The perennial systems include fast growing *Populus* clones (trees) planted on a 10-year rotation cycle (Treatment 5) and continuous alfalfa (*Medicago Sativa* L.) (Treatment 6). Potassium fertilizers were applied to the alfalfa crop starting in 1991 and continued every year thereafter. The rates are variable, ranging from 392 kg K ha^{-1} in 1991 to 52 kg K ha^{-1} in 1995. Treatment 7 is a native successional community, abandoned after spring plowing in 1989. Treatment 8, a never-plowed site with a native successional community cut from forest in 1960, is 200 m from the others and serves as an historical control for soil organic matter studies.

Each plot contains a permanent set of five sampling stations that are designated locations in the field where most of the sampling takes place. Soil cores (2.5 cm diameter) are taken north of each station flag to a depth of 25 cm. Two cores are taken at each station. An equal number of cores are taken within a row and between rows for the row crops. In non-cropped systems, cores are taken at 10-cm intervals. All cores from each plot are composited into one sample. Phosphorus fertilizers have not been applied to any of these plots since the establishment of the LTER because soil P tests were high. All plots are 100 m × 100 m on the same Kalamazoo (fine-loamy, mixed, mesic, typic Hapludalf) - Oshtemo soil series (coarse-loamy, mixed, mesic, typic Hapludalf). Selected properties of the Kalamazoo soil in the Ap horizon are: pH 5.5; clay content 190 g kg^{-1}; sand content 430 g kg^{-1}; CEC 8.4 cmol(+) kg^{-1}; organic carbon 12.85 g kg^{-1}; total N 1.31 g kg^{-1}. Selected properties of the Oshtemo soil in the Ap horizon are: pH 5.7; clay content 140 g kg^{-1}; sand content 590 g kg^{-1}; CEC 7.1 cmol(+)kg^{-1}; organic carbon 9.7 g kg^{-1}; total N 1.04 g kg^{-1}.

In addition to the main site experiment, the KBS LTER site has associated with it an unmanaged forested site, replicated three times in the larger KBS landscape. The forested site is an old-growth native deciduous forest that shares a soil series with the main experimental site. The replications are in three different portions of the KBS landscape within 1000 m of the agronomic plots. Two of the forests host old growth vegetation, while the third was apparently cut around 90 years ago. Within the forest site is a 1-ha sampling area laid out in a manner similar to plots of the main experimental site. These individual plots each contain a permanent set of five sampling stations, at which most within-plot sampling is performed.

Soil Sampling and Analysis

Soils were sampled from the different treatments in July 1995. The four annual cropping systems were in the wheat phase of the crop rotation. All of the six replications were sampled at the 0- to 25-cm depth. The soils were air dried and ground to pass a 0.25-mm (60-mesh) sieve and stored at room temperature. Soils were extracted for P using the fractionation procedure developed by Hedley et al. (1982). Briefly, 0.5 g dry soil was weighed into a 50-mL centrifuge tube, 30 mL of water was added, and 0.4 g Dowex 1×8–50 anion exchangeable resin in HCO_3 form in a nylon mesh bag was added and the tube shaken for 16 h. Resin P was eluted from the bag with 0.5 *N* HCl. The residual soil was then extracted sequentially with 0.5 *N* $NaHCO_3$, 0.1 *N* NaOH, 0.1 *N* NaOH with sonication, and 1 *N* HCl. Each of these extractions was shaken for 16 h, with the tube then centrifuged at 12,096 *g* for 10 min. The solution was then decanted and frozen until analysis. Finally, the soil was digested with sulfuric acid and hydrogen peroxide for determination of residual P. All analyses in the laboratory were done in duplicate.

Inorganic P in all fractions was analyzed by the method of Murphy and Riley (1962) using an automated flow injection analyzer after adjusting the pH of the extracted solutions (Olsen and Sommers, 1982). Total P was measured in the $NaHCO_3$, NaOH, and NaOH with sonication extracts, after digesting the samples with sulfuric acid and ammonium persulfate on a hot plate (USEPA, 1978), and analyzed with the same method as above. Organic P was obtained as the difference between total P and Pi in these three fractions. Organic C data were obtained from the KBS-LTER database for treatments sampled on August 29, 1994. Organic C was determined by dry combustion using a Carlo Erba CN analyzer (Nelson and Sommers, 1982). Total P was measured on separate selected samples from the different treatments (total of 29 samples) after digestion with nitric and perchloric acids (Olsen and Sommers, 1982) to determine the extraction efficiency of the fractionation procedure, which ranged from 99.7 to 106% of total P in the soil.

Resin extractable Pi is considered to be the P most biologically available to plants (Amer et al., 1955; Sibbesen, 1977). The $NaHCO_3$ extractable Pi and Po fractions are also readily available pools (Bowman and Cole, 1978; Tiessen et al. 1984). The NaOH extractable Pi is thought to be associated with amorphous and some crystalline Al and Fe phosphates (Williams et al., 1980) and is moderately labile (Ryden et al., 1977). More stable forms of Po are extracted with NaOH (Tiessen et al., 1984). Phosphorus released on sonication with NaOH extraction provides an estimate of physically protected Pi and Po (Hedley et al., 1982). The HCl extraction provides an estimate of P bound as calcium phosphate (Williams et al., 1980). Residual P in the soil not extracted by the previous chemical agents contains Pi and Po that is resistant to decomposition. The extracted P fractions do not correspond exactly to soil P pools (Daroub et al., 2000). However, because it is more meaningful to relate the P fractions to P pools in the soil, we assigned extracted P fractions to P pools described in the literature. We realize that this assumption has limitations, and the various fractions may indicate different availability in different soils.

Statistical Analysis

Statistical analyses were performed using General Linear Models (PROC GLM) procedures (SAS Institute, 1998). A two-way analysis of variance for Treatments 1 to 7 in the randomized block design of the main site was conducted for the P fractions extracted, and the F-test was considered significant at the 0.05 probability level. Other analyses were performed using PROC T-TEST for differences between means and PROC CORR for the correlation analysis, as appropriate. Since the never-tilled and the forest treatments are not part of the randomized block design for the main LTER site, the differences between these two treatments and CT were evaluated by a *t*-test between the means.

RESULTS

Long-term Cropping Effect

The differences between the never-tilled and the forest treatments evaluated by a *t* test between the means are presented in Table 2. Total P concentration in the CT treatment was 25% lower

TABLE 2

Inorganic phosphorus (Pi) and organic phosphorus (Po) fractions under conventional tillage, deciduous forest, and the never-tilled native successional community treatments

P Fraction	P pool	CT	DF	Never-tilled	Difference (CT-DF)		Difference (CT-Never-tilled)	
		-------- mg kg^{-1}---------			-- mg kg^{-1} --	%†	-- mg kg^{-1} --	%†
Inorganic P								
Resin-Pi	Labile	29	32	16	−3	−11	13	78
Bic-Pi	Labile	17	23	15	−6	−26	2	12
NaOH-Pi	Al-P & Fe-P	98	100	110	−2	−2	−12	−11
SNaOH-Pi	Physically protected	8	5	7	3**	67	1	21
HCl-Pi	Ca-P	76	39	56	37**	95	20*	35
Sun Pi		227	199	204	28	14	23	11
Organic P								
Bic-Po	Labile	15	39	24	−24**	−61	−9	−36
NaOH-Po	Moderately labile	55	263	166	−208***	−79	−111***	−67
SNaOH-Po	Physically protected	6	7	0	−1	17	6*	
Sum Po		76	310	190	−234***	−75	−114**	−60
Residual	Pi and Po resistant to decomposition	171	120	116	51*	42	55	47
Total P (Sum of fractions)		474	629	510	−155§	−25	−36	−7

*, **, *** Significant differences at the 0.05, 0.01, and 0.001 probability level, respectively.

†Difference % = [(CT-DF)/DF)]*100

‡Difference % = [(CT-Never-tilled)/Never-tilled)]·100.

§Significant at the 0.1 probability level.

than in the forest treatment, primarily because of a decrease in the Po fraction (Table 2). Inorganic P increased by 14%, residual P by 42%, and Po decreased by 75% in the CT treatment compared with the forest treatment (Table 2). The increases of P were mainly in the calcium phosphate (Ca-P) pool, and the residual fraction and the decrease of Po were in both the labile and moderately labile pools.

Similar changes were observed when CT was compared with the native never-tilled treatment (Table 2). Inorganic P increased by 11%, mainly in the Ca-P pool, and the residual fraction increased by 47% in the CT treatment compared with the never-tilled site. The decrease in Po under CT compared with the never-tilled native vegetation was 60%, mainly in the moderately labile pool.

Effect of Cropping Systems Imposed for Seven Years

There were no significant differences in any of the Pi, Po, or the residual fractions when the annual cropping systems (Treatments 1 through 4) were compared (Figs. 1 and 2). The data in the graphs are calculated as percent of total P in each treatment to allow comparisons between the different treatments. Absolute concentrations of total P, sum Pi, sum Po, and residual P are presented in Table 3. The adoption of NT and the planting of winter cover crops for 7 years did not increase Po significantly when compared with the CT treatment, although trends of increased Po were apparent. The effect of the alfalfa perennial system on soil P was more apparent than the effect of annual cropping systems. Significant differences were observed in Po in the NaOH and the residual fractions in alfalfa when compared with CT (Fig. 2). Organic P extracted by NaOH comprised 22.1% of total P under alfalfa compared with 11.4% extracted in the CT and 12.5% in the NT. There was a decrease in the residual fraction in the alfalfa treatment both in total content (Table 3) and as percentage of total P (Fig. 2).

No significant differences were observed in any of the Pi and Po fractions in the poplar treatment compared with CT. Organic P extracted by NaOH was significantly higher, and residual P significantly lower, in the historically tilled native successional community (Treatment 7) compared with CT (Fig. 2).

Correlation Analysis

A simple linear correlation matrix analysis between selected P fractions and organic C is

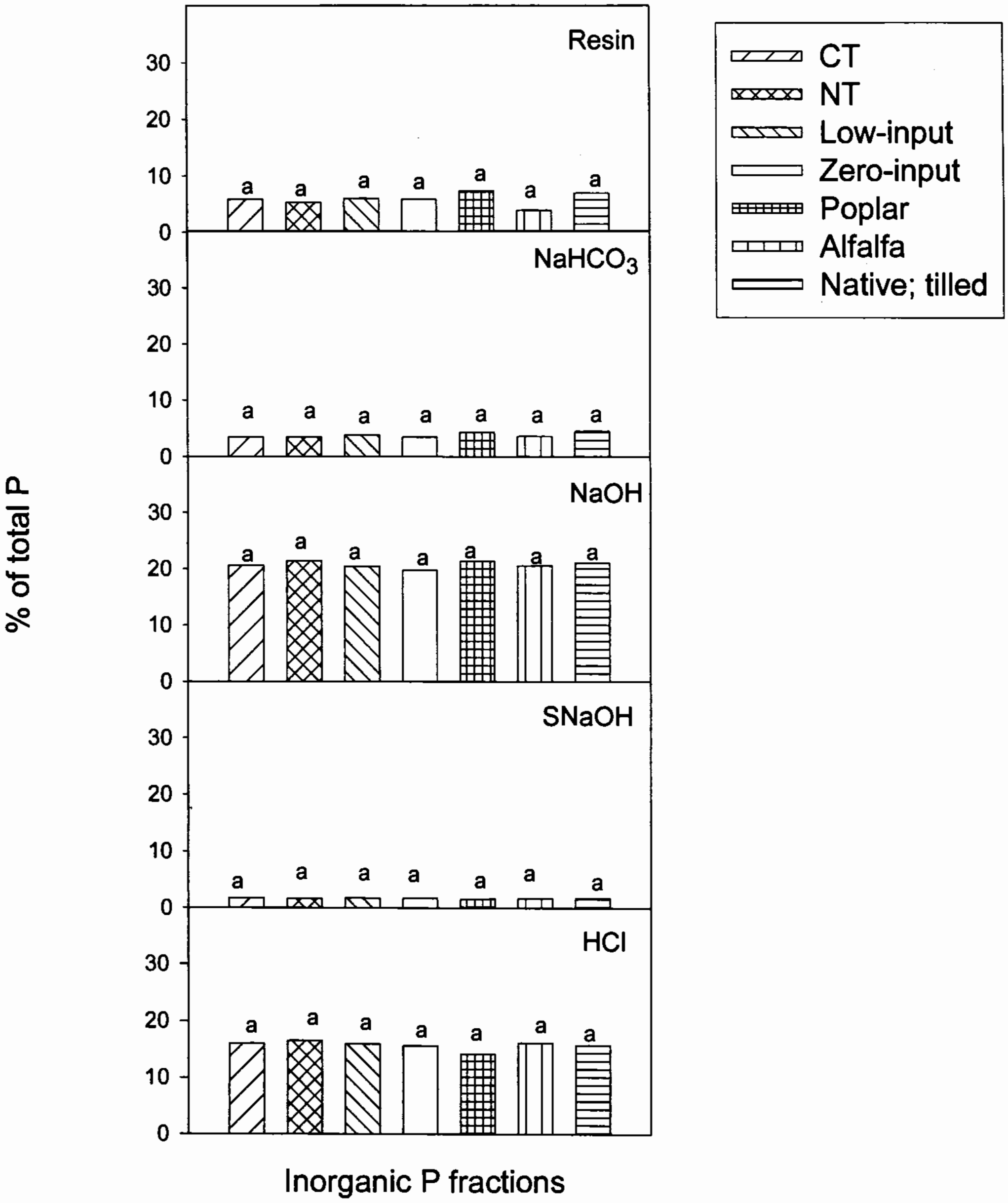

Fig. 1. Distribution of P in the inorganic fractions in the different treatments. For complete description of the treatments see Table 1. Significant differences at the 0.05 level between treatments for each fraction are designated by different letters.

presented in Table 4. We grouped the treatments according to management history into annual cropping systems (Treatments 1 through 4), perennial cropping systems (Treatments 5 and 6), and unmanaged sites (Treatments 8 and DF). The objective of this analysis was to identify the stable P fractions that may limit the pool size of labile Pi as described by Crews (1996). Correlation analysis does not identify cause and effect but merely indicates that a relationship exists. In the annual cropping systems, the labile Pi pool (Resin-Pi and Bic-Pi) was correlated significantly with NaOH-Pi (Al-P and Fe-P pool) and HCl-Pi (Ca-P pool). In addition, Bic-Pi correlated with Bic-Po and NaOH-Po. In the perennial cropping systems, Resin-Pi was correlated with residual P

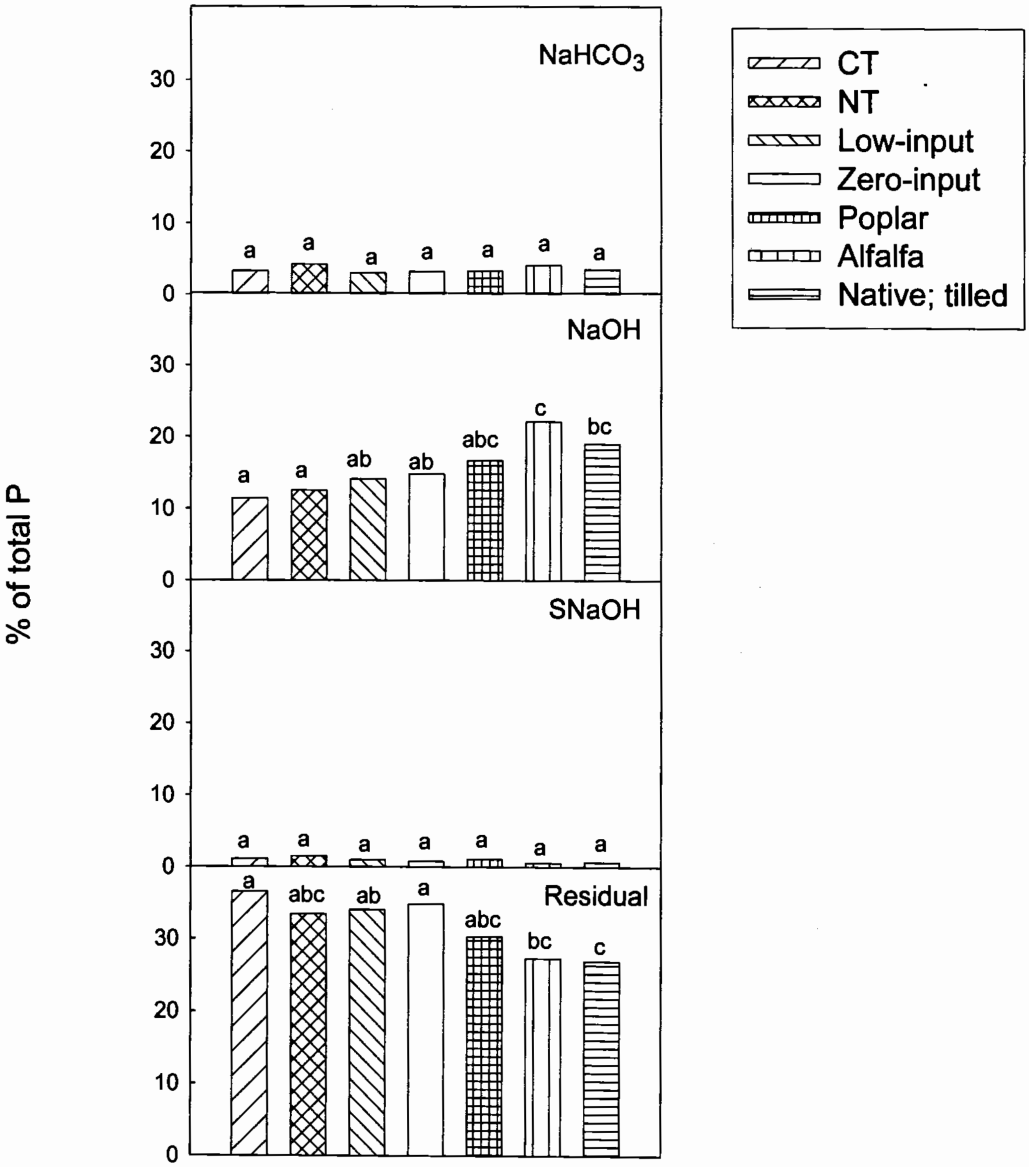

Fig. 2. Distribution of P in the organic and residual fractions in the different treatments. For complete description of the treatments see Table 1. Significant differences at the 0.05 level between treatments for each fraction are designated by different letters.

whereas Bic-Pi correlated with NaOH-Pi. In the unmanaged sites, labile Pi was strongly correlated with Bic-Po, NaOH-Po, and organic C.

DISCUSSION

Long-term Cropping Effect

For 50 years prior to 1988, when the LTER treatments were imposed, the cropping system on the main site was corn-soybean rotation under CT with standard inputs of fertilizers and pesticides. Therefore, we evaluated the long-term impact of conventional row-crop agriculture on P by comparing the CT treatment with standard levels of agrochemical inputs with the never-tilled native successional community site and the deciduous forest. Long-term high input CT resulted in a 25% decrease in total P in surface soils

TABLE 3

Sum of inorganic P (Pi) fractions, sum of organic P (Po) fractions, and residual and total P and organic C in the different treatments

Treatment	Sum Pi†	Sum Po‡	Residual P	Total P	Organic C
	mg kg^{-1}				g kg^{-1}
CT	227 ± 19§	76 ± 14	171 ± 13	473 ± 34	8.06 ± 0.68
NT	229 ± 9	85 ± 6	159 ± 14	473 ± 9	9.44 ± 0.79
Low-input	244 ± 27	95 ± 22	164 ± 7	504 ± 43	9.48 ± 0.47
No-input	225 ± 14	91 ± 12	167 ± 8	483 ± 11	9.00 ± 0.39
Poplar	251 ± 18	110 ± 16	155 ± 11	516 ± 25	10.39 ± 1.28
Alfalfa	221 ± 13	129 ± 8	131 ± 6	481 ± 22	11.42 ± 0.45
Native; tilled	266 ± 15	124 ± 12	142 ± 5	532 ± 21	10.85 ± 0.84
Native; never-tilled	204 ± 15	190 ± 8	116 ± 25	510 ± 35	19.66 ± 0.86
Forest	199 ± 18	310 ± 44	120 ± 13	629 ± 69	24.80 ± 0.63

†Sum Pi = Sum of inorganic P extracted in the resin, bicarbonate, NaOH, NaOH after sonication, and HCl fractions.

‡Sum Po = Sum of organic P extracted in the bicarbonate, NaOH, and NaOH after sonication fractions.

§Means with standard errors (n = 6 for the first seven treatments, n = 4 for the native never-tilled treatment, and n = 3 for the forest treatment).

compared with adjacent deciduous forest. All of the decrease occurred in the organic P fraction.

These results are similar to those found by Tiessen et al. (1982), who compared three cultivated soils with adjacent uncultivated prairie soils. Total P concentrations in the cultivated soils in the Tiessen et al. (1982) study were reduced by 12% in the clay and silt loam textured soils and by 29% in their sandy loam soil. They report that losses in the heavier textured soils were caused by organic fraction losses, whereas losses in the sandy loam soil were caused by both organic and inorganic losses. Hedley et al. (1982) reported that of the total P lost by comparing a cultivated soil to an adjacent permanent pasture, 22% of the P was in extractable organic forms and 52% was in stable forms, and the rest was Pi. Soil P is lost primarily from the organic fraction until this fraction is depleted sufficiently to allow the dissolution of apatites to occur (Tiessen et al. 1982).

The increases in inorganic and residual P fractions in our soil are an indication of the high amounts of fertilizers and manure applied before 1988. No detailed record on fertilizer input before 1988 is available, and, therefore, no mass balance sheet could be constructed for the site. However, the increase in Pi caused by fertilizer application is documented in the literature. For example, Ellert and Gregorich (1996) found that total P concentrations increased 24% in the surface layers of 15 cultivated sites compared with adjacent forests or woodlands in Ontario. The increases in P storage were attributed to fertilization. Increases in Pi in our soil were in the stable fractions (HCl and residual) and not in the labile fractions (resin and bicarbonate) because P fertil-

TABLE 4

Correlation matrix between labile P fractions and selected P fractions and organic C in the different cropping systems groups according to management.

	Annual Cropping Systems†		Perennial Cropping Systems‡		Unmanaged sites§	
Variable	Resin-Pi	Bic-Pi	Resin-Pi	Bic-Pi	Resin-Pi	Bic-Pi
Bic-Pi	0.633**		0.616*		NS	
NaOH-Pi	0.506*	0.864***	NS	0.683*	NS	NS
HCl-Pi	0.657**	0.757***	NS	NS	NS	NS
Bic-Po	NS	0.418*	NS	NS	0.915*	NS
NaOH-Po	NS	0.527**	NS	NS	0.942**	NS
Residual P	NS	NS	0.610*	NS	NS	NS
Carbon	NS	NS	NS	NS	0.829*	NS

†Annual Cropping Systems: Treatments 1, 2, 3, and 4 (n = 23).

‡Perennial Cropping Systems: treatments 5 and 6 (n = 11).

§Unmanaged sites: treatment 8 and DF (n = 6).

*, **, *** Significant at $P \leq 0.05, 0.01, 0.0001$

NS = Not significant.

izers were last applied in 1988. Increases in P due to past applications of fertilizers show up in stable pools as a result of fixation reactions that P undergoes in the soil with time.

Effect of Cropping Systems Imposed for Seven Years

We found no significant differences in organic P among the four annual cropping systems. This may be because not enough time had passed at the time of sampling for these different treatments to diverge; only 7 years had passed since the adoption of these management systems, and trends of increased Po content were apparent in both of the organic based rotations (Fig. 2). However, it is not certain that these treatments will show any significant differences in organic P even after additional years in the same rotation. Paniagua et al. (1995) investigated the distribution of P pools as affected by the addition of organic amendments for 10 years on a maize and bean rotation on a tropical volcanic soil. They found no differences in the size of the P pools as a result of the addition of organic amendments.

Another possible explanation for the lack of differences among our annual cropping systems is that organic P is so rapidly mineralized during the growing season that no significant increases in total P are apparent. In a study of biological and conventional farming systems, Oberson et al. (1993) found no differences in organic P fractions under biological farming systems imposed for 13 years compared with conventional systems. However, Bic-Po showed temporal fluctuations, where levels were higher and diverged between treatments in the spring (March and April sampling) and those in summer sampling where they went back to base levels. This indicates seasonal accumulations and mineralization in this fraction (Oberson et al., 1996). In addition, NaOH-Po and total residual P levels fluctuated during the year, indicating that P in these fractions might be involved in short-term transformations (Obesron et al., 1996). Measuring Po several times during the year to monitor temporal variations as affected by the different treatments might be a better way to detect differences.

We attribute the increase in Po under alfalfa cropping in our soils to the turnover of the extensive alfalfa root system. The increase was about 53 ppm, which adds up to more than over 100 kg P ha^{-1} for the upper 15 cm of the soil. The soils were sampled in July during the growing season, when labile Po is expected to be high because of root death. Organic P would probably be lower in the spring after some mineralization has occurred. We suspect that alfalfa cropping is transforming the residual Pi in the soil into Po through assimilation of P in the roots and then root death. Alfalfa root biomass manually sampled in October 1996 on subplots of the LTER experiment averaged 3.55 Mg ha^{-1} (Rasse et al., 1999). In addition crown residues and other soil-incorporated debris added 2.17 Mg ha^{-1} of biomass to the soil, adding to the 5.72 Mg ha^{-1} of residues. Reported alfalfa root biomass in the literature is variable. Lory et al. (1992) reports 3.22 Mg ha^{-1} of alfalfa root biomass sampled at a depth of 0 to 35 cm. Blumenthal and Russelle (1996) sampled 17-month-old alfalfa plants and reported up to 7.85 Mg ha of root biomass in the top 35 cm. If we are to assume a 0.2% P content of the residues sampled at LTER, the total P contribution per year would be 11.44 kg P ha^{-1}. Over 6 years (1989 to 1994), the total value is 68.6 kg P ha^{-1} (85.8 kg P ha^{-1} over 6 years if a 0.25% P is assumed for residues). Measured alfalfa biomass in 1988 was low, so it was not taken into account for the above calculation. Unfortunately, the content of P in the roots was not measured throughout the course of the experiment, but the calculations show clearly that our conclusions regarding increased Po content caused by alfalfa roots are reasonable.

The residual P content decreased under alfalfa cropping, which suggests that alfalfa is able to take up P from this stable pool. The P content in the stable pool is believed to be mostly apatites and, in part, very stable Po. Residual P has been shown to have seasonal variation, which indicates possible short-term P transformations (Oberson et al., 1996). Alfalfa may be tapping into the residual P not only for P but for Ca released through apatite dissolution as well. Crews et al. (1996) found a highly significant correlation between labile P fractions (Resin-Pi and Bic-Pi) and HCl extractable Pi in traditional Mexican agroecosystems of maize-bean-squash/alfalfa rotation, which is consistent with the hypothesis that HCl extractable P constitutes an important P source for alfalfa. In that same experiment, P fractionation analysis was performed on original soils and on soils that were cropped with alfalfa. Compared with the original soils, alfalfa plants depleted the HCl fraction significantly in four of the nine soils used (Crews, 1996). In our experiment, the residual P fraction decreased with continuous alfalfa cropping, and the resin and residual fractions were significantly correlated in the perennial cropping systems (Table 4). We concluded, therefore, that continuous alfalfa cropping can help to restore native organic P levels in this soil by transforming residual stable P forms into organic forms. In practical terms, P may be in a more available form to the next crop in rotation. This adds to the benefits of using alfalfa in crop rotations as alfalfa improves soil N due to the high amounts of N_2 fixed by perennial alfalfa (Fox and Piekielek, 1988; Peterson and Russelle, 1991)

Although the poplar treatment did not show any significant difference in any of the fractions extracted, trends of increased NaOH-Po and decreased residual P were observed. The historically tilled native treatment with no harvested plants had higher percentages of Po compared with CT after 7 years of abandonment and no cultivation. Tiessen et al. (1992) found that 8 to 10 years of bush fallow were sufficient to re-establish fertility levels similar to the original uncultivated sites in subsistence farming systems in semi-arid northeastern Brazil with no fertilizer inputs.

Correlation Analysis of Soil P Fractions and Organic Carbon

We found a significant correlation between the labile Pi pool fractions, resin-Pi and Bic-Pi in the annual cropping systems ($r = 0.63$) and in the perennial cropping systems ($r = 0.62$) (Table 4). A similar significant correlation ($r = 0.5$) was found between resin-Pi and Bic-Pi in 168 soils representing eight orders in the United States (Tiessen et al., 1984).

Correlation analysis shows clearly the relationship shift between labile P (resin-Pi and Bic-Pi) and other P fractions when annual row-crop agriculture and unmanaged sites are compared. In the annual cropping systems, the labile pool was correlated with the NaOH-Pi fraction and the HCl fraction, which suggests that it may be replenished by these two fractions. Using path analysis, Zhang and Mackenzie (1997) concluded that NaOH-Pi was the major source of Bic-Pi in inorganic systems. In our unmanaged sites, the never tilled native successional community site and the deciduous forest site, resin-Pi was correlated with organic P fractions (Bic-Po and NaOH-Po) and organic C, with no significant correlation to any of the Pi fractions. Using correlation analysis calculated for 168 samples, Tiessen et al. (1984) showed dependence of Po forms on organic matter and that the accumulation of organic C results in an increase in extractable Po forms at the expense of Pi.

CONCLUSIONS

The use of fractionation analysis for soil P may not be adequate for tracking differences induced by annual cropping systems over a short period of time. However, this methodology was able to show differences in P fractions when land under native vegetation for many years is brought into cropping as well as differences under systems that add a lot of residues, such as alfalfa, to the soil. Long-term conventional agriculture of the Kalamazoo soil for 50 years resulted in a decrease in Po and an increase in Pi and residual P in the surface 25 cm of soil when compared with adjacent deciduous forest. The adoption of low-input, organic based annual cropping systems and NT for 7 years did not result in an increase in any of the soil Po fractions. Continuous alfalfa, on the other hand, resulted in an increase in NaOH-Po and a decrease in residual P when compared with CT corn-soybean-wheat rotation. Continuous alfalfa can restore soils to their native P fertility level by transforming stable residual P into moderately labile Po extracted by NaOH. We conclude that NT or planting of winter cover crops did not lead to the accumulation of Po or affect soil Pi and Po fractions in this soil after 7 years of adopting these practices. This study offers no support to the hypothesis that adoption of certain management practices such as no-till and organic based low-input systems could be sustainable with regard to soil P.

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REFERENCES

Agbenin, J. O., and J. T. Goladi. 1997. Carbon, nitrogen and phosphorus dynamics under continuous cultivation as influenced by farmyard manure and inorganic fertilizers in the savanna of northern Nigeria. Agric. Ecosyst. Environ. 63:17–24.

Amer, F., D. R. Bouldin, C. A. Black, and F. R. Duke. 1955. Characterization of soil phosphorus by anion exchange resin adsorption and P^{32}-equilibration. Plant Soil 4:391–408.

Blumenthal, J. M., and M. P. Russelle. 1996. Subsoil nitrate uptake and symbiotic dinitrogen fixation by alfalfa. Agron. J. 88:909–915.

Bowman R. A., and C. V. Cole. 1978. An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Sci. 125:95–101.

Crews, T. E. 1996. The supply of phosphorus from native, inorganic phosphorus pools in continuously cultivated Mexican agroecosystems. Agric. Ecosyst. Environ. 57:197–208.

Daroub, S. H., F. J. Pierce, and B. G. Ellis. 2000. Phosphorus fractions and fate of phosphorus-33 in soils managed under plowing and no-tillage. Soil Sci. Soc. Am. J. 64:170–176.

Ellert, B. H., and E. G. Gregorich. 1996. Storage of carbon, nitrogen, and phosphorus in cultivated and adjacent forested soils of Ontario. Soil Sci. 161: 587–603.

Fox, R. H., and W. P. Piekielek. 1988. Fertilizer N equivalence of alfalfa, birdsfoot trefoil, and red clover for succeeding corn crops. J. Prod. Agric. 1: 313–317.

Hedley, M. J., J. W. B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and laboratory incubations. Soil Sci. Soc. Am. J. 46:970–976.

Lory, J. A., M. P. Russelle, and G. H. Heichel. 1992. Quantification of symbiotically fixed nitrogen in soil surrounding alfalfa roots and nodules. Agron. J. 84:1033–1040.

Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36.

Nelson, D. W., and L. E. Sommers. 1982. Total carbon, organic carbon, and organic matter. *In* Methods of Soil Analysis, Part 2, 2nd Ed. A.L. Page et al. (eds.). Agron. Monogr. No. 9. ASA , Madison, WI, pp. 539–577.

Oberson A., J. M. Besson, N. Maire, and H. Sticher. 1996. Microbiological processes in soil organic phosphorus transformations in conventional and biological cropping systems. Biol. Fert. Soils 21: 138–148.

Oberson A., J. C. Fardeau, J. M. Besson, and H. Sticher. 1993. Soil phosphorus dynamics in cropping systems managed according to conventional and biological agriculture methods. Biol. Fert. Soils 16: 111–117.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorus. *In* Methods of Soil Analysis, Part 2, 2nd Ed. A.L. Page et al. (eds.). Agron. Monogr. No. 9. ASA, Madison, WI, pp. 403–430.

Paniagua, A., M. J. Mazzarino, D. Kass, L. Szott, and C. Fernandez. 1995. Soil phosphorus fractions under five tropical agroecosystems on a volcanic soil. Aust. J. Soil Res. 33:311–320.

Paustian, K., H. P. Collins, and, E. A. Paul. 1997. Management controls of soil carbon. *In* Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. E.A. Paul et al. (eds.). CRC Press, Boca Raton, FL, pp. 15–49.

Peterson, T. A., and M. P. Russelle. 1991. Alfalfa and the nitrogen cycle in the corn belt. J. Soil Water Conserv. 46:229–235.

Rasse, D. P., A. J. M. Smucker, and O. Schabenberger. 1999. Modifications of soil nitrogen pools in response to alfalfa root systems and shoot mulch. Agron. J. 91:471–477.

Roberston, G. P., K. M. Klingensmith, M. J. Klug, E. A. Paul, J. R. Crum, and B.G. Ellis. 1997. Soil resources, microbial activity, and primary production across an agricultural ecosystem. Ecol. App. 7: 158–170.

Ryden, J .C., J. R. McLaughlin, and J. K. Syers.1977. Mechanisms of phosphate sorption of soils and hydrous ferric oxide gels. J. Soil Sci. 28:72–92.

SAS Institute. 1998. SAS Statistical Guide, Version 7. SAS Institute, Cary, NC.

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

Tiessen, H., J. W. B. Stewart, and J. R. Bettany. 1982. Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorus in grassland soils. Agron. J. 74:831–835.

Tiessen H., I. H. Salcedo, and E. V. S. B. Sampaio. 1992. Nutrient and soil organic matter dynamics under shifitng cultivation in semi-arid northeastern Brazil. Agric. Ecosyst. Environ. 38:139–151.

Tiessen H., J. W. B. Stewart, and C. V. Cole. 1984. Pathways of phosphorus transformations in soils of differing pedogenesis. Soil Sci. Soc. Am. J. 48: 853–858.

U.S. Environmental Protection Agency (USEPA). 1978. Methods for Chemical Analysis of Water and Wastes. USEPA, Washington, DC.

Williams, J. D. H., T. Mayer, and J. O. Nriagu. 1980. Extractability of phosphorus from phosphate minerals common in soils and sediments. Soil Sci. Soc. Am. J. 44:462–465.

Zhang, T. Q., and A. F. Mackenzie. 1997. Changes of soil phosphorus fractions under long-term corn monoculture. Soil Sci. Soc. Am. J. 61:485–493.