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ANNEX 1

Comparative soil quality in maize rotations with high or low residue diversity

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Abstract

Differences in soil quality linked to differences in the diversity of residues returned to the soil were assessed in nine pairs of farm fields in central Michigan. To assure that management was the main difference in soil forming factors, sites were selected that mapped to the same soil series and were located as closely as possible. ANOVA using subsamples as replicates for all nine comparisons revealed significantly higher maize yield and total N for the high diversity sites, but significantly higher extractable P and mineralizable N/total C for the low diversity sites. Manuring history reported by farmers was difficult to reconcile with levels of C, N and extractable P. To account for manuring, comparisons were separated into two sets: those in which the ratio of extractable P in the high diversity site to the low diversity site was > 1 [high div P > low div P], and those in which that ratio was < 1 [low div P > high div P]. ANOVA using subsambles as replicates for the [high div P > low div P] set (5 X 2, n = 60), revealed significant improvements in 9 of 22 soil quality indices measured. Strong negative relationships were found between total C and bulk density and log(infiltration time), but these same relationships were strongly positive for extractable P. This suggests an antagonism between C and P; with high extractable P levels linked to higher bulk density and slower infiltration. The slopes of the regression lines differed significantly between the high and low diversity bulk density and infiltration time when data from all sites were considered together. Significantly different slopes were also found for the relationship between those two soil properties and the weight ratio (total C/extractable P) for the [high div P > low div P] set. This indicates that the high and low diversity data points originated from distinctly different populations. A similar pattern was found for microbial biomass, but correlations were lower and slopes did not differ. These results suggest a strong interaction between soil C and extractable P that is also influenced by residue diversity. A high residue diversity seems to permit additional accumulation of soil C, thus reducing the C:P ratio; this leads to improved soil quality by lowering bulk densities and increasing infiltration rates and microbial biomass.

Introduction

Management strategies to sustain or improve soil quality usually call for increasing the diversity of cropping by intercropping and using cover crops in rotations. Increasing the amount and diversity of residues returned by cover crops, intercrops, and manure can improve soil quality by protecting the soil and increasing organic matter. This can reduce soil erosion, increase water retention, and improve the efficiency of nitrogen utilization in the soil (Karlen et al. 1992). However, the poverty of species in cropping systems greatly restricts the potential for spatial diversity, and highlights the importance for temporal diversity in rotations.

It is now recognized that the linkage between plant diversity and the decomposers may be a keystone process in managed ecosystems (Swift and Anderson 1993). Because decomposition processes are regulated to a large extent by the physical and chemical properties of residues and exudates, a wide range in properties can result in a diversity of decomposition rates. This diversity in decomposition rates been hypothesized to directly control the availability of nutrients to plants and the stability of nutrient cycling in agricultural systems (Swift and Anderson 1993).

While it is thought that the robustness of agricultural systems can be improved by imitating the variety of natural ecosystems, little information is available about how diversity in crop rotations, and thus the mix of residues returned to the soil over several growing seasons, affects soil quality. The aim of this research was to utilize methods proposed for estimating soil quality to test whether diversity in residues returned to the soil during a single cycle in maize rotations can be linked to improvements in physical, chemical, and biological properties of soils.

Materials and Methods

In selecting sites for comparison, we attempted to minimize differences in soil forming factors except management. The candidate sites' histories of main and cover cropping and manuring were recorded for the years 1989-93 by interviewing farmers and extension agents. To verify that the potential paired sites were on the same soil series and had similar aspect and topographic position, we consulted soil survey maps and made observations in the field. Paired sites were selected that mapped to the same soil series and were located as closely as possible, although distances between them varied from 0.1 to 2 km (Table 1).

Diversity in residues returned to the soil was estimated by considering each crop and cover crop species, and manure applied, as one source of diversity. To be selected for comparison, field pairs were required to have a minimum difference of two points in residue diversity. Some experience in selecting and sampling sites had been gained in 1992 (Willson et al. 1993) Cropping and manuring histories were mostly reconstructed from farm records, but in some instances were based on memory. This led to selections being made in the field on the basis of information which was later discovered to be erroneous, and resulted in two comparisons that had differences of only one point. The selection process was often made difficult by the presence of extensive inclusions of other soil series in the mapped unit, the inability to match aspect and topographic position, the presence of features such as poorly drained spots in one field and not the other, etc. Moreover, the size of the areas of matching conditions was often surprisingly small due to restrictions due to the geometry of cropped fields, the patchiness of the soil series, and the need to work in the maize phase of the rotation.

Once a field pair was selected for study, three pairs of sampling stations were installed at each site. Stations were separated 6.8 m along the inter-row space, and the three station pairs were separated by 12 rows (approx. 10 m); study plots were thus ~0.01 ha. Sampling stations consisted of the area within 50 cm of the single-ring aluminum respirometer/infiltrometer (18 cm diameter X 15 cm height) installed ~ 7.5 cm deep in the center of the inter-row space. Sampling stations were located in the center of the inter-row because differences in the geometry of ridges, on which maize was generally planted, made matching the placement of the infiltrometer/respirometer difficult otherwise. Another reason for selecting the inter-row space was our interest in testing for the legacy of residues returned during the past five growing seasons; this effect would likely be less noticeable within the maize row. Inter-rows were selected only after considerable trial-and-error, and were generally non-wheel track rows, free from obvious disturbances such as fertilizer bands, etc.

Personnel were trained by conducting a trial run in a satellite maize field of the Living Field Laboratory (LFL, Kellogg Biological Station, Michigan) managed identically to one of the experimental treatments at the LFL. Measurements were taken in two locations in that field, which although separated by distance of ~40 m and on supposedly "uniform" soil, differed visibly in maize growth. Those measurements, which highlight spatial variability in soils, were used as controls for the nine comparisons (Tables 2-4).

Methods were as in Doran (1993); but in addition, we measured surface penetration resistance, and installed two additional double-ring infiltrometers (data not shown). Soil samples (0-20 cm), as well as other measurements, were taken from the inter-row area 30-50 cm from the respirometer/infiltrometer (e.g. sampling station). Samples were kept over ice in the field until transported to the laboratory, where portions to be used for measuring biological properties were stored at ~ 4 °C. Although some measurements were also made in soil samples in the field, only laboratory results are reported here. Soil properties were analyzed as follows: bulk density by pushing a small, bottomless aerosol can approximately 7.5 cm into the soil, and removing the soil quantitatively after measuring the length of head space; percent gravel by sieving (2 mm); texture by the hygrometer method; water-holding capacity by using pressure plates to determine water content in undisturbed soil cores at 30 kPa and in packed samples bulked from the six soil samples at each plot at 1.5 MPa; penetration resistance by using a Soiltest CL-700A pocket penetrometer (n = 6 at each station); depth of topsoil and of maize rooting by digging two small pits at each station; infiltration rate by measuring the time required for 2.5 cm of water added at once to enter the soil in the (single-ring) infiltrometer; inorganic N ($NO_3^+ + NO_2^- + NH_4^-$) by extracting with 2 M KCl and using automated colorimetry, mineralizable N by anaerobic incubation at 37 °C for 7 days; total C by high temperature combustion (Dohrmann DC 190); total N by the Kjeldahl procedure; extractable P by the Bray procedure; soil respiration by taking samples in the infiltrometer headspace after 1 h incubation and measuring CO_2 by gas chromatography; microbial biomass by measuring CO_2 evolved by 20 g subsamples of moist soil during 10 d following fumigation with chloroform; CO_2 evolved by unfumigated subsamples during the same period was used as a measure of respiration rate of the soil microbial biomass. The soil infiltration and respiration rate measurements were made in the early morning and repeated in the early afternoon 4-6 h after the first irrigation. Infiltration data were transformed to the $\log_{10}$, and microbial biomass C to the square-root form in order to obtain normal distributions for analysis. Statistical significance reported refers to the transformed data. Infiltration rates were calculated back from the transformed data. Maize yield was measured by hand-harvesting 6.8 m of row (n = 4) within each study site.

Results and Discussion

Soils were generally of medium texture and density, non-saline (EC $\leq$ 0.1 dSm^{-1}, data not shown), slightly acid to neutral, and fertile (Tables 2-4). Even though the sites were selected such that they mapped to the same soil series, textures differed significantly in two of the nine comparisons. Gravel content, which significantly affects soil water relations, also differed in several comparisons. Nonetheless, the quality of the nine comparisons seems reasonably good.

The six sampling-station measurements were used to compare within-site means by the paired comparison t-test, and variances by the F-test (Tables 2-4). Some significant differences in means and variances were found for nearly all indices. Only the means of total C and N, mineralizable N, and extractable P, and the variances of pH and extractable N differed in the majority of comparisons. Few patterns could be discerned in these within-site comparisons. Nevertheless, the majority of significant differences in means lay in the direction of improved soil quality for the fields receiving a high diversity of residues. Overall, significantly higher variances were about evenly divided between high and low diversity fields. Except for lower pH, the means of the controls were similar to the average soil properties for the nine comparisons (Table 5). Of 22 indices measured, the controls differed significantly in six, while the average for the nine comparisons was eight.

At some sites, high and variable concentrations of extractable N and P, and mineralizable N, were encountered. In the case of N, this may have been due to unintentionally sampling near fertilizer bands. But the high concentrations of extractable P were likely due to long-term manuring, which in some cases may have occurred more than five growing seasons before our study. It was difficult to reconcile manuring history reported by farmers with levels of C, N, or extractable P. Spatial variability in manure application may explain the high variability in concentrations of extractable P found at some sites.

When means were compared across sites by ANOVA in a 9 X 2 block design (n = 18), no significant differences were found between high- and low-diversity farming systems (not shown). The data were then analyzed in a similar 9 X 2 ANOVA, but using a procedure that treats subsamples as replicates (n = 108). The use of subsamples as replicates in paired comparisons of soil quality has been criticized (Wardle 1994). Pseudoreplication cannot be avoided in comparing adjacent farm fields, but interpretation by making simple comparisons can be justified (Reganold 1994). The ANOVA procedure revealed significantly higher maize yield and total N for the high diversity sites, but significantly higher extractable P and mineralizable N/total C for the low diversity sites (Table 5). This suggests that past manuring may have confounded this ANOVA. Note that in at least three comparisons, one field received manure much more frequently than its neighbor (Table 1, comparisons 2,4, and 5).

To account for manuring, comparisons were separated into two sets: those in which the ratio of extractable P in the high diversity site to the low diversity site was > 1 [high div P > low div P], and those in which that ratio was < 1 [low div > high div P]. ANOVA using subsambles as replicates for the [high div P > low div P] set (5 X 2, n = 60), revealed significant improvements in 9 of 22 soil quality indices measured (Table 5). In contrast, the only significant difference found for the [low div P > high div P] set (4 X 2, n = 48) was faster infiltration after irrigation associated with low input diversity. Of course, significant differences in extractable P cannot be counted in either of these two analyses because that was how the comparisons were selected. These results revealed an interaction between manuring (i.e. high levels of extractable P) and residue diversity which strongly influenced soil quality.

Strong negative correlations were found between soil C concentration (and thus N) and bulk density, log(infiltration time), mineralizable N, and microbial C (Table 6). On the other hand, extractable P was strongly positively correlated with soil bulk density and log(infiltration time) in the high diversity sites, but these relationships were meaningless for the low diversity sites. Moreover, for extractable P, the slopes of the high and low diversity lines for both bulk density and log(infiltration time) differed significantly ($P \leq 0.05$, Table 7), indicating that these originated from distinctly different populations. Thus, soil quality appears to improve with soil C concentration; but it decreases as extractable P increases for the high diversity sites, and has no effect in the low diversity sites.

Examination of the soil C scattergrams showed the population of high diversity data points was slightly shifted towards a higher soil C content relative to the low diversity data points (not shown). Interestingly, the highest soil C concentrations were recorded in the high diversity side of comparison 2, which did not receive manure during the period under study. To account for this shift, soil properties were correlated with the weight ratio of total C/extractable P. The behavior of this index combined aspects of both C and P (Tables 6 and 7). For example, soil C seems to be unequivocally related to soil microbial biomass, but the ratio total C/extractable P correlates weakly with both microbial biomass and specific microbial respiration (qCO_2). A significant difference in the slopes of high vs. low diversity lines was also discovered for the relationships between the ratio total C/extractable P and both bulk density and log(infiltration time) for the [high diversity P > low diversity P] set (Table 7). Again, this indicates that these originated from different populations and underscores the complex interaction between soil C, extractable P, and residue diversity.

Examination of the relationship between soil C and the ratio total C/extractable showed that this index generally trended higher as soil C increased (not shown). This suggests that C accumulates faster than extractable P, and thus dilutes the ostensibly negative effect of extractable P on soil quality. Interestingly, for the high diversity sites of the [Low diversity P > High diversity P] set, this trend was lower. This may explain how these sites differed from the other high diversity sites, and may justify segregating them.

Results presented here indicate that increased diversity of residues returned to the soil during a single rotation cycle resulted in improved soil quality by increasing total soil C and N. This in turn apparently led to lower bulk densities and higher infiltration rates and microbial biomass. This effect seemed to be counteracted by high levels of extractable P in the soil. In contrast, a low diversity of residues did not result in improvement in soil quality even though soil C and extractable P concentrations were similar to those of the high diversity sites. Our results are generally consistent with those of Reganold et al. (1993), who compared conventional and biodynamic farms in New Zealand. The biodynamic farms, which likely used manure and cover crops to a greater extent than the conventional farms, had significantly lower bulk density and thicker topsoil, as well as higher soil C and N. However, in contrast to our results, they also reported higher soil respiration, mineralizable N and ratio of mineralizable N to C in the biodynamic farms. Results presented here support the hypothesis that a higher resource variety (in conjunction with resource amount) can improve the availability of nutrients as well as the stability of nutrient cycling by increasing soil organic matter and microbial biomass and improving soil tilth.

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References

Doran, J. 1993. On-farm measurement of soil quality indices—bulk density, soil water content, water-filled pore space, EC, pH, NO_3-N, infiltration, water holding capacity, and soil respiration. Unpublished ms. 11 pp.

Karlen, D. L., N. S. Eash, and P. W. Unger. 1992. Soil and crop managements effects on soil quality indicators. American Journal of Alternative Agriculture 7:48-55.

Reganold, J. P., A. S. Palmer, J. C. Lockhart, and A. N. Macgregor. 1993. Soil quality and financial performance of biodynamic and conventional farms in New Zealand. Science 260:344-349.

_______ 1994. Statistical analyses of soil quality. Science 264:282-83

Swift, M. J., and J. M. Anderson. 1993. Biodiversity and ecosystem function in agricultural systems. pp. 15-41 *In:* E.-D. Schulze and H. A. Mooney (eds.) Biodiversity and Ecosystem Function. Ecological Studies: Analysis and Synthesis. Vol. 99. Springer-Verlag, Berlin. 525 pp.

Wardle, D.A. 1994. Statistical analyses of soil quality. Science 264:281-82.

Willson, T.C., E. Franco-Vizcaíno, C. M. McGrath, M.E. Jones and R. R. Harwood. 1993. Microbial activity and soil quality: A comparsion of high and low diversity farming systems in Michigan. Agronomy Abstracts, p. 263.

Table 1. Landscape and soil characteristics, and 1989-1993 history of cropping and manuring of study sites in south central Michigan.

Comparison	Landscape position	Distance between study sites (~ m)	Soil series (% slope)	Cropping	Cover crops	Manure ~ Mg ha^{-1}	Residue diversity
Control	Nearly level	40	Kalamazoo sl 0-2%	A A A A M	— — — — — —	— — — — — —	2
1 high	S shoulder, small knoll	200	Spinks ls 0-6%	Tr S M S M	— — — — — —	— 25 — 25 —	4
1 low	S shoulder, small knoll		Spinks ls 0-6%	M M M M M	— — — — — —	25 25 — — —	2
2 high	Nearly level bottom	200	Capac l 0-3%	M M S W M	cl — — cl cl	— — — — — —	4
2 low	Nearly level bottom		Capac l 0-3%	M M M M M	— — — — — —	25 25 25 25 25	2
3 high	Nearly level	100	Capac l 0-3%	M M S W M	cl — — cl cl	— — — — — —	4
3 low	Nearly level		Capac l 0-3%	M S W M M	— — — — — —	— — — — — —	3
4 high	Rolling, midslope	100	Marlette fsl 2-6%	M S M S M	cl — — — —	— — 25 — —	4
4 low	Rolling, midslope		Marlette fsl 2-6%	M M M M M	— — — — — —	25 25 25 25 25	2
5 high	Nearly level	1000	Capac l 0-3%	M S W M M	— — cl cl cl	— — — — — —	4
5 low	Nearly level		Capac l 0-3%	A A A M M	— — — — — —	25 25 25 25 —	3
6 high	Small undulations	150	Ithaca l 0-3%	C W M S M	— — — — — —	— — — 25 —	5
6 low	Small undulations		Ithaca l 0-3%	M M S M M	— — — — — —	— — — — — —	2
7 high	Nearly level	2000	Kalamazoo sl 0-2%	M M W M M	— — cl — —	25 — 25— —	4
7 low	Small undulations		Kalamazoo sl 2-6%	M M M M M	— — — — — —	— — — — — —	1
8 high	Small undulations	1000	Capac l 0-3%	M B C W M	— — — cl —	25 25 25 — —	6
8 low	Small undulations		Capac l 0-3%	M M M M M	— — — — — —	25 25 25 — —	2
9 high	S shoulder, small knoll	400	Marlette fsl 2-6%	A W M S M	og v — — v	— 12.5— — —	7
9 low	S shoulder, small knoll		Marlette fsl 2-6%	W F M S M	— — cl — —	— — — — — —	5

M = Maize, S = Soybeans, A= Alfalfa, W =Wheat, Tr = Triticale, B = Beans, C = cucumbers, F = Fallow, cl = clover, og = orchard grass, v = vetch. Manure was generally from on-farm dairy or hog operations, and it was assumed that the type applied did not change from year to year. Capac: fine-loamy, mixed, mesic Aeric Ochraqualfs. Ithaca: fine, mixed, mesic, Glossaquic Hapludalfs. Kalamazoo: fine-loamy, mixed, mesic Typic Hapludalfs. Marlette: fine-loamy, mixed, mesic Haplic Glossudalfs. Spinks: sandy, mixed, mesic Psammentic Hapludalfs.

Table 2. Comparisons of soil physical properties in maize fields with high or low diversity of residues returned to the soil during 1989-93. Values are means (standard error of the mean); n = 6, except as noted. Differences between means were tested by the paired-comparison procedure, and variances were compared by the F-test.

Soil property	Comparison																			
	Control[a]		1		2		3		4		5		6		7		8		9	
			High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Texture[b] (%gravel-sand-silt-clay)	cl (1-26 44-30)	l (15-42 33-25)	ls (2-86 7-7)	ls (2-87 7-6)	cl (1-40 24-35)	scl (1-53 18-29)	scl (16-49 21-29)	scl (4-51 23-26)	sl (10-67 23-10)	sl (6-66 24-11)	scl (3-45 27-28)	scl (3-53 25-22)	scl (8-46 22-31)	scl (1-52 21-27)	sl (1-58 25-17)	sl (6-56 26-18)	cl (6-39 33-29)	sl (6-54 28-18)	sl (17-64 20-16)	sl (10-58 23-19)
Bulk density[c]	1.05 (0.02)	1.25** (0.04)#	1.38 (0.01)	1.43# (0.02)*	1.01 (0.04)	1.03 (0.04)	1.06 (0.01)	1.29* (0.06)**	1.26 (0.01)	1.25 (0.02)#	1.15 (0.04)	1.29 (0.07)	1.25 (0.03)	1.23 (0.04)	1.44 (0.04)	1.40 (0.03)	1.29** (0.03)	1.15 (0.02)	1.27 (0.04)	1.20 (0.03)
Water holding capacity[d]	1.90# (0.06)	1.25 (0.18)#	0.98 (0.13)	1.02 (0.08)	2.29 (0.39)	1.69 (0.19)	1.20 (0.28)	1.34 (0.19)	2.48 (0.26)	2.20 (0.29)	1.52 (0.12)	1.51 (0.15)	1.10 (0.22)	1.49* (0.22)	1.99* (0.33)	1.38 (0.30)	1.72 (0.17)	2.36# (0.17)	2.18* (0.21)	1.00 (0.17)
Penetration resistance[e]	0.9 (0.2)	1.0 (0.3)	wet ~0	wet ~0	0.9 (0.3)*	0.5 (0.1)	0.7 0.1)	2.4* (0.5)***	1.9 (0.2)	1.1 (0.4)	1.9 (0.1)	1.8 (0.3)*	0.4 (0.1)	0.8** (0.1)	0.9 (0.3)	1.5 (0.3)	1.1* (0.2)	0.6 (0.1)	1.0 (0.2)	0.7 (0.1)
A horizon depth[f]	nd[i]	nd[i]	26 (0.5)	29# (0.8)	26 (0.9)	31* (1.4)	30 (1.1)	28 (0.8)	25 (0.3)	23 (1.0)*	29 (0.3)	28 (0.6)	25 (0.7)	24 (1.7)#	30* (0.6)	27 (0.7)	26 (1.0)	24 (0.7)	22 (0.4)	24*** (0.5)
Maize rooting depth[f]	25 (2.0)	26 (1.5)	23 (0.5)	23 (0.5)	22 (0.7)	22 (1.8)#	25 (2.1)	23 (1.2)	20 (0.5)	23# (1.1)	23 (0.9)	25** (0.9)	25 (0.7)	24 (1.7)#	28** (0.8)	22 (1.1)	23 (0.9)	21 (0.9)	20 (0.5)	23** (0.4)
Infiltration rate[g]	3.67** (0.45)	0.17 (0.04)	0.40** (0.05)	0.10 (0.01)	23.2 (6.01)	11.4 (3.04)	17.5* (3.10)**	0.60 (0.38)	1.74 (0.65)	3.65 (1.92)	7.82 (1.78)	12.2 (5.56)#	0.99 (0.36)	1.29 (0.60)	0.33 (0.15)	0.32 (0.11)	0.94 (0.40)	3.33 (0.88)	1.84 (0.32)	1.22 (0.31)
Infilt. rate after irrigation[h]	0.43 (0.19)	0.88 (0.31)	0.37 (0.04)	0.28 (0.2)***	9.41 (4.26)	7.24 (2.54)	3.42* (1.19)#	0.08 (0.05)	0.91 (0.44)	1.66 (0.92)	2.95 (1.01)	7.39 (3.26)	0.29 (0.12)	0.34 (0.15)	0.10 (0.03)	0.14 (0.07)	0.13 (0.06)	0.19 (0.10)	0.26 (0.07)	0.44 (0.16)

[a]Trial comparison at Living Field Laboratory, Kellogg Biological Station, MI., on "uniform" soil with same cropping history during previous five years; [b] bulk sample n = 1; [c] 0-7.5 cm depth; [d] cm in upper 20 cm soil; [e] surface, kg cm^{-2}; [f] cm; [g] cm min^{-1}, 2.5 cm H_2O (falling head); [h] cm min^{-1}, 2.5 cm H_2O 4-6 h after first irrigation (falling head); [i] not determined; #, *,**,*** significantly different at the 0.10, 0.05, 0.01, and 0.001 levels, respectively (symbols arbitrarily placed on the higher value).

Table 3. Comparisons of soil chemical properties in maize fields with high or low diversity of residues returned to the soil during 1989-93. Values are means (standard error of the mean) n = 6. Differences between means were tested by the paired-comparison procedure, and variances were compared by the F-test.

Soil property	Control[a]		Comparison 1		2		3		4		5		6		7		8		9	
			High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
pH[b]	5.2 (0.1)	5.4 (0.1)	6.5# (0.04)	5.8 (0.1)***	6.9 (0.1)	7.1* (0.1)	6.3 (0.2)**	6.5 (0.1)	5.9 (0.1)#	5.7 (0.03)	6.4 (0.2)	6.3 (0.1)	6.1 (0.1)	5.8 (0.1)	5.6 (0.2)*	6.1 (0.1)	5.8 (0.2)***	6.8 (0.03)	5.8 (0.1)	5.9 (0.2)
Total C[c]	43.7** (1.27)	34.6 (1.50)	29.0 (1.33)	33.8# (2.38)	80.1 (3.55)	74.1 (4.20)	52.0 (1.96)	56.5 (2.33)	51.8 (6.17)*	42.5 (1.88)	42.9 (1.44)	58.2** (3.10)	49.8# (3.10)	46.6 (2.61)	50.5** (2.85)	32.9 (2.05)	61.9 (2.42)	55.8 (1.75)	30.6 (1.46)	34.7# (2.27)
Total N[c]	4.27** (0.11)	3.28 (0.14)	1.99 (0.11)	2.69* (0.11)	9.81# (1.0)	7.52 (0.51)	5.57 (0.14)	5.47 (0.17)	4.31 (0.36)*	3.94 (0.12)	4.00 (0.17)	5.91*** (0.24)	5.51# (0.40)#	4.34 (0.17)	4.82* (0.17)	3.29 (0.16)	5.65 (0.14)	5.24 (0.25)	3.02 (0.12)	3.43** (0.08)
C:N ratio	10.3 (0.3)	10.6 (0.3)	14.7 (1.0)	12.6 (0.8)	8.4 (0.6)	9.9* (0.3)	9.4 (0.3)	10.3* (0.2)	11.9 (0.7)#	10.8 (0.3)	10.8 (0.4)	9.9 (0.5)	9.1 (0.2)	10.7*** (0.3)	10.5 (0.5)	10.0 (0.4)	10.9 (0.2)	10.7 (0.5)	10.1 (0.2)	10.2 (0.6)
Extractable N[d]	70.3 (8.5)	59.5 (7.0)	43.5 (2.9)	292* (65)***	83.5* (5.2)	59.4 (6.3)	369# (155)***	23.2 (1.7)	37.1 (7.2)*	45.0 (2.0)	54.0 (12.3)	335 (190)***	98.1 (21)	73.1 (25)	42.9 (2.4)	35.7 (9.6)**	131# (35)***	51.3 (4.7)	42.0 (4.9)	153* (30)**
Mineralizable N[d]	51.2 (2.1)	44.2 (3.6)	31.0 (2.0)	186* (56)***	61.7# (6.4)	52.9 (5.0)	102 (33)***	47.2 (2.9)	67.4 (10)	79.1 (11)	33.1 (1.2)	159# (59)***	41.7 (2.0)	33.9 (4.0)	77.8* (6.8)	50.7 (3.5)	46.9 (5.1)	49.3 (3.4)	45.5* (2.8)#	34.6 (1.2)
Extractable P[de]	163# (11)	157 (10)	758* (46)	675 (28)	260 (27)	192 (30)	140# (11)	124 (11)	380 (33)	1510*** (132)**	163 (5)	188 (15)*	267* (11)	172 (19)	806* (143)***	208 (21)	277 (46)	578** (61)	84.9 (14)	278*** (17)

[a]Trial comparison at Living Field Laboratory, Kellogg Biological Station, MI, on "uniform" soil, same cropping history during previous five years; [b]1:1 soil:H_2O; [c]Mg ha^{-1}; [d]kg ha^{-1}; [e]Bray 1; #, *, **, *** significantly different at the 0.10, 0.05, 0.01, and 0.001 levels, respectively (symbols arbitrarily placed on the higher value).

Table 4. Comparisons of soil biological properties and economic yield in maize fields with high or low diversity of residues returned to the soil during 1989-93. Values are means (standard error of the mean); n = 6, except as noted. Differences between means were tested by the paired-comparison procedure, and variances were compared by the F-test.

Soil property	Control[a]		1		2		3		4		5		6		7		8		9	
			High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Soil respiration[b]	40.8 (3.46)	33.4 (6.21)	17.2 (2.60)	13.9 (7.82)*	23.8 (3.03)	30.4 (4.45)	42.4 (9.16)	29.7 (5.55)	32.8 (6.06)	27.8 (7.25)	1.98 (6.52)	34.8# (10.7)	39.9 (6.81)	60.3# (10.9)	27.7 (3.77)	31.1 (3.15)	37.1 (6.64)	27.1 (4.83)	64.2 (7.94)#	45.7 (3.08)
Soil resp. after irrigation[b]	24.7 (3.98)	18.6 (4.55)	10.8 (2.50)	8.83 (3.28)	10.6 (1.94)	15.7# (2.02)	17.9 (3.28)	13.9 (4.61)	8.58 (3.16)	6.68 (1.58)	3.08 (1.00)	32.4** (5.27)**	6.21 (0.30)	6.86 (1.23)**	29.6* (5.29)**	15.0 (1.19)	15.4 (3.51)	11.4 (2.30)	12.5 (0.93)	11.0 (2.84)
Microbial biomass C[c]	1.40 (0.10)	1.27 (0.14)	1.07 (0.15)	1.27 (0.20)	2.20# (0.09)	1.88 (0.10)	1.61 (0.25)	1.55 (0.15)	1.13 (0.10)	1.33 (0.16)	1.46 (0.05)	1.81# (0.15)*	1.01# (0.09)#	0.84 (0.04)	1.30*** (0.08)	0.88 (0.07)	1.38 (0.13)	1.62 (0.07)	1.06 (0.07)	0.95 (0.06)
Microbial respiration[b]	25.7 (5.54)	30.2 (5.63)	35.8 (7.89)	51.2 (9.10)	36.5* (6.9)***	14.3 (1.02)	17.5 (4.25)	16.7 (2.37)	8.86 (1.95)	14.8 (2.23)	17.8 (5.05)**	21.2 (0.85)	14.3 (5.79)	12.6 (4.08)	32.1 (8.50)	15.7 (3.88)	21.9 (5.27)	26.6 (4.87)	11.6 (4.68)*	8.69 (1.74)
Specific respiratory activity[e]	0.75 (0.13)	1.03 (0.21)	1.50 (0.34)	2.09 (0.65)	0.70# (0.14)**	0.32 (0.03)	0.44 (0.05)	0.44 (0.04)	0.31 (0.06)#	0.45# (0.03)	0.49 (0.12)*	0.50 (0.03)	0.75 (0.41)	0.64 (0.23)	1.03 (0.28)	0.79 (0.24)	0.67 (0.13)	0.70 (0.14)	0.44 (0.17)	0.40 (0.09)
Cmic/Ctotal[f]	3.22 (0.26)	3.72 (0.43)	3.77 (0.57)	3.81 (0.65)	2.77 (0.16)	2.58 (0.21)	3.17 (0.58)	2.79 (0.33)	2.37 (0.45)	3.15 (0.44)	3.42 (0.08)	3.16 (0.35)**	2.02 (0.15)	1.85 (0.19)	2.58 (0.04)	2.69 (0.18)**	2.23 (0.19)	2.93# (0.15)	3.51 (0.27)	2.74 (0.37)
Mineralizable N/ Total C[g]	1.17 (0.04)	1.30 (0.13)*	1.07 (0.06)	6.84 (2.9)***	0.77 (0.07)	0.72 (0.07)	1.91 (0.6)***	0.84 (0.04)	1.39 (0.29)	1.83 (0.21)	0.77 (0.02)	2.84 (1.2)***	0.85# (0.06)	0.73 (0.09)	1.57 (0.15)	1.55 (0.08)	0.75 (0.07)	0.89 (0.07)	1.51* (0.13)#	1.01 (0.05)
Maize yield[ch]	nd[i]	nd[i]	5.56 (0.02)	7.35# (0.46)	10.8* (0.46)	8.90 (0.65)	11.1** (0.10)	5.84 (0.70)	10.7 (0.58)	10.1 (0.39)	11.1* (0.36)	6.48 (1.10)	10.3 (1.37)	9.74 (0.79)	8.23 (0.46)	7.15 (0.53)	10.3 (0.16)	10.7 (0.33)	5.48 (0.50)	8.22* (0.49)

[a] Trial comparison at Living Field Laboratory, Kellogg Biological Station, MI., on "uniform" soil, same cropping history during previous five years; [b] kg CO_2-C ha^{-1} day^{-1}; [c] Mg ha^{-1}; [e] (soil microbial respiration/soil microbial biomass) X1000; [f] %; [g] X1000; [h] n = 4; [i] not determined, but yield averaged 8.53 Mg ha^{-1} at adjacent LFL experimental trials under the same management; #, *,**,*** significantly different at the 0.10, 0.05, 0.01, and 0.001 levels, respectively (symbols arbitrarily placed on the higher value).

Table 5. Comparison of soil properties in maize-based rotations with high or low diversity of residues returned to the soil, analyzed by two-way ANOVA procedures using subsamples as replicates.

Soil property	All nine comparisons			High diversity P > Low div P (Comparisons 1,2,3,6,7)			Low diversity P > High div P (Comparisons 4,5,8,9)		
	High div.	Low div.	Ratio	High div.	Low div.	Ratio	High div.	Low div.	Ratio
Bulk density 0-7.5 cm depth, g cm^{-3}	1.24	1.25	0.99	1.23	1.28#	0.96	1.24	1.22	1.02
Penetrability, kg cm^{-2}	0.97	1.47	0.66	0.57	1.03**	0.55	1.47	2.02	0.73
Maize rooting depth, cm	23.1	22.9	1.01	27.5	28.0	0.98	21.4	23.1	0.93
A horizon depth, cm	26.5	26.2	1.01	24.6*	22.7	1.08	25.3	24.0	1.05
Water holding capacity, cm	1.72	1.54	1.12	1.51	1.39	1.09	1.98	1.72	1.15
Infiltration rate, cm min^{-1}	2.15	1.72	1.25	2.21*	0.95	2.33	2.03	3.65	0.56
Infiltration rate after irrigation, cm min^{-1}	0.69	0.47	1.47	0.81*	0.27	3.00	0.56	0.89*	0.63
pH	6.0	6.0	1.00	6.1	6.0	1.02	5.9	6.0	0.98
Total C, Mg ha^{-1}	49.8	48.3	1.03	52.3#	48.8	1.07	46.8	47.8	0.98
Total N, Mg ha^{-1}	4.96#	4.65	1.07	5.41**	4.53	1.19	4.50	4.57	0.98
C:N ratio	10.6	10.6	1.00	10.6	10.9	0.97	10.6	10.5	1.01
Extractable N, kg ha^{-1}	100	119	0.84	128	96.7	1.32	66.1	146	0.45
Mineralizable N, kg ha^{-1}	56.3	75.4	0.75	62.7	74.0	0.85	48.2	77.2	0.62
Extractable P, kg ha^{-1}	359	436#	0.82	409***	237	1.71	235	545***	0.43
Soil respiration, kg C ha^{-1} day^{-1}	31.2	31.9	0.98	30.2	30.4	0.99	32.6	33.7	0.97
Soil respiration after irrigation	13.2	13.6	0.97	15.8	12.7	1.24	9.70	13.9	0.70
Microbial biomass C, Mg ha^{-1}	1.36	1.35	1.01	1.37#	1.22	1.12	1.21	1.31	0.92
Microbial respiration, kg C ha^{-1} day^{-1}	21.8	20.1	1.08	24.3	19.1	1.27	14.9	16.7	0.89
Specific microbial respiration (X1000)	0.70	0.70	1.00	0.80	0.78	1.03	0.53	0.54	0.98
$C_{microbial}/C_{total}$, %	2.87	2.86	1.00	2.70	2.58	1.05	2.71	2.77	0.98
Available N/C_{total} (X1000)	1.11	1.81*	0.61	1.11	1.94#	0.57	1.11	1.63	0.68
Maize yield, Mg ha^{-1}	9.29*	8.28	1.12	9.23*	7.76	1.19	9.42	8.91	1.06

#, *, **, *** significantly different at the 0.1, 0.05, 0.01, and 0.001 levels, respectively (symbols arbitrarily placed on larger value).

Table 6. Correlation coefficients for the relationships between selected soil properties and total carbon, extractable phosphorus, and the weight ratio of total carbon to extractable phosphorus (n = 54).

Soil property	Total Carbon (mg/kg)		Extractable Phosphorus (mg/kg)		Total C/Extractable P	
	High diversity	Low diversity	High diversity	Low diversity	High diversity	Low diversity
Bulk density	–0.63***	–0.66*	+0.55***	+0.02	–0.60***	–0.28*
Penetrability	+0.19	<0.01	–0.26	–0.21	+0.15	+0.45***
Corn rooting depth	–0.01	+0.06	+0.30*	–0.04	–0.28*	+0.04
A horizon depth	+0.24	+0.38**	+0.24	-0.37**	–0.15	+0.50**
Water holding capacity	+0.23	+0.32***	–0.08	+0.33*	+0.17	–0.09
Log(time to infiltrate 2.5 cm H2O)	–0.57***	–0.49***	+0.45***	–0.08	–0.57***	–0.11
Log(time to infiltrate after irrigate)	–0.49***	–0.39***	+0.26	–0.09	–0.32*	–0.07
Total C	—	—	–0.21	+0.15	—	—
Total N	+0.92***	+0.97***	–0.22	–0.20	+0.37**	+0.61***
Extractable N	+0.21	–0.13	–0.22	–0.08	+0.31*	–0.02
Mineralizable N	+0.48***	+0.40**	+0.13	+0.45**	+0.05	+0.04
Extractable P	–0.21	+0.15	—	—	—	—
Soil respiration	–0.14	+0.10	–0.24	–0.20	+0.24	+0.21
Soil respiration after irrigation	–0.02	+0.15	+0.23	–0.35*	–0.09	+0.34*
Microbial biomass C	+0.68***	+0.69***	–0.25	–0.01	+0.41**	+0.36**
Microbial respiration	+0.20	–0.07	+0.39**	+0.09	–0.13	–0.25
Specific microbial respiration	–0.22	–0.31*	+0.55***	–0.10	–0.42**	–0.33**

*, **, *** significant at the 0.05, 0.01, and 0.001 levels, respectively.

Table 7. Correlation coefficients, and 95% confidence limits of the slope of the line, between extractable phosphorus, the weight ratio (Total C/ Extractable P) and soil bulk density or infiltration time.

		Bulk density			Log(time to infiltrate 2.5 cm H_2O)		
	n	lower	upper	r	lower	upper	r
Extractable P (mg/kg)							
All high diversity	54	+0.00074	+0.00182	+0.55***	+0.00231	+0.00808	+0.45***
All low diversity	54	–0.00034	+0.00038	+0.02	-0.00278	+0.00156	–0.08
High div P > Low div P (High div)	30	+0.00120	+0.00252	+0.74***	+0.00283	+0.01100	+0.56**
High div P > Low div P (Low div)	30	–0.00010	+0.00263	+0.34	–0.00579	+0.01100	+0.12
Low div P > High div P (High div)	24	–0.00128	+0.00122	–0.01	–0.00357	+0.01000	+0.21
Low div P > High div P (Low div)	24	–0.00030	+0.00032	+0.02	–0.00156	+0.00222	+0.08
Total C/Extractable P							
All high diversity	54	–0.00091	–0.00041	–0.60***	–0.00441	–0.00188	–0.57***
All low diversity	54	–0.00049	–0.00001	–0.28*	–0.00213	–0.00092	–0.11
High div P > Low div P (High div)	30	–0.00141	–0.00091	–0.87***	–0.00671	–0.00395	–0.83***
High div P > Low div P (Low div)	30	–0.00089	–0.00023	–0.55**	–0.00377	–0.00070	–0.26
Low div P > High div P (High div)	24	–0.00031	+0.00036	+0.03	–0.00191	+0.00180	–0.02
Low div P > High div P (Low div)	24	–0.00032	+0.00041	+0.05	–0.00369	+0.00053	–0.31

*, **, *** significant at the 0.05, 0.01, and 0.001 levels, respectively.

Figure Legends

Figure 1. Relationships between soil extractable phosphorus (0-20 cm) and bulk density (0-7.5 cm). Slopes followed by the same **letter** are not significantly different ($P \leq 0.05$).

Circles: All high diversity, (BD) = 1.12 + 0.00128**a** X (extP), r = 0.55*** (pictured).

Triangles: All low diversity, (BD) = 1.25 + 0.00002**b** X (extP), r = 0.02NS (pictured).

High div P > Low div P (High div): (BD) = 1.02 + 0.00186**a** (extP), r = 0.74***, n = 24.

High div P > Low div P (Low div): (BD) = 1.19 + 0.00127**ab** X (extP), r = 0.34NS, n = 30.

Low div P > High div P (High div): (BD) = 1.25 – 0.00003**ab** X (extP), r < 0.01NS, n = 24.

Low div P > High div P (Low div): (BD) = 1.22 + 0.00001**b** X (extP), r = 0.02NS, n = 24.

Figure 2. Relationships between soil extractable phosphorus (0-20 cm) and Log(infiltration time in seconds). Slopes followed by the same **letter** are not significantly different ($P \leq 0.05$).

Circles: All high diversity, (Log time) = 1.37 + 0.00519**a** X (ext P), r = 0.45***, n = 54 (pictured).

Triangles: All low diversity, (Log time) = 2.00 – 0.00061**b** X (extP), r = 0.08 NS, n = 54 (pictured).

High div P > Low div P (High div): (Log time) = 1.07 + 0.00674**a** X (extP), r = 0.56**, n = 30.

High div P > Low div P (Low div): (Log time) = 2.01 + 0.0026**ab** X (extP), r = 0.12 NS, n = 30.

Low div P > High div P (High div): (Log time) = 1.64 + 0.0033**ab** X (extP), r = 0.21NS, n = 24.

Low div P > High div P (Low div): (Log time) = 1.56 + 0.0003**b** X (extP), r = 0.08NS, n = 24.

Figure 3. Relationships between the weight ratio (total C/extractable P) and bulk density. Slopes followed by the same **letter** are not significantly different ($P \leq 0.05$).

Circles: All high diversity, (BD) = 1.39 – 0.00066**a** X (totC/extP), r = 0.59***, n = 54.

Triangles: All low diversity, (BD) = 1.31 –0.00025**ab** X (totC/extP), r = 0.28*, n = 54.

High div P > Low div P (High div): (BD) = 1.46 – 0.00116**c** X (totC/extP), r = 0.87***, n = 30 (pictured).

High div P > Low div P (Low div): (BD) = 1.43 – 0.00056**ab** X (totC/extP), r = 0.55**, n = 30 (pictured).

Low div P > High div P (High div): (BD) = 1.24 + 0.00003**b** X (totC/extP), r = 0.03NS, n = 24.

Low div P > High div P (Low div): (BD) = 1.22 + 0.00004**b** X (totC/extP), r = 0.05NS, n = 24.

Figure 4. Relationships between the weight ratio (total C/extractable P) and bulk density. Slopes followed by the same **letter** are not significantly different ($P \leq 0.05$).

Circles: All high diversity, (Log time) = 2.56 – 0.00315**ab** X (totC/extP), r = 0.57***, n = 54.

Triangles: All low diversity, (Log time) = 2.07 – 0.00060**a** (totC/ extP), r = 0.11NS, n = 54.

High div P > Low div P (High div): (Log time) = 2.90 – 0.00533**b** X (totC/extP), r = 0.83***, n = 30 (pictured).

High div P > Low div P (Low div): (Log time) = 2.61 – 0.00153**a** X (totC/extP), r = 0.26NS, n = 30 (pictured).

Low div P > High div P (High div): (Log time) = 1.86 – 0.00009**a** X (totC/extP), r = 0.02NS, n = 24.

Low div P > High div P (Low div): (Log time) = 1.85 – 0.00158**a** X (totC/extP), r = 0.31NS, n = 24.

Fig. 1.

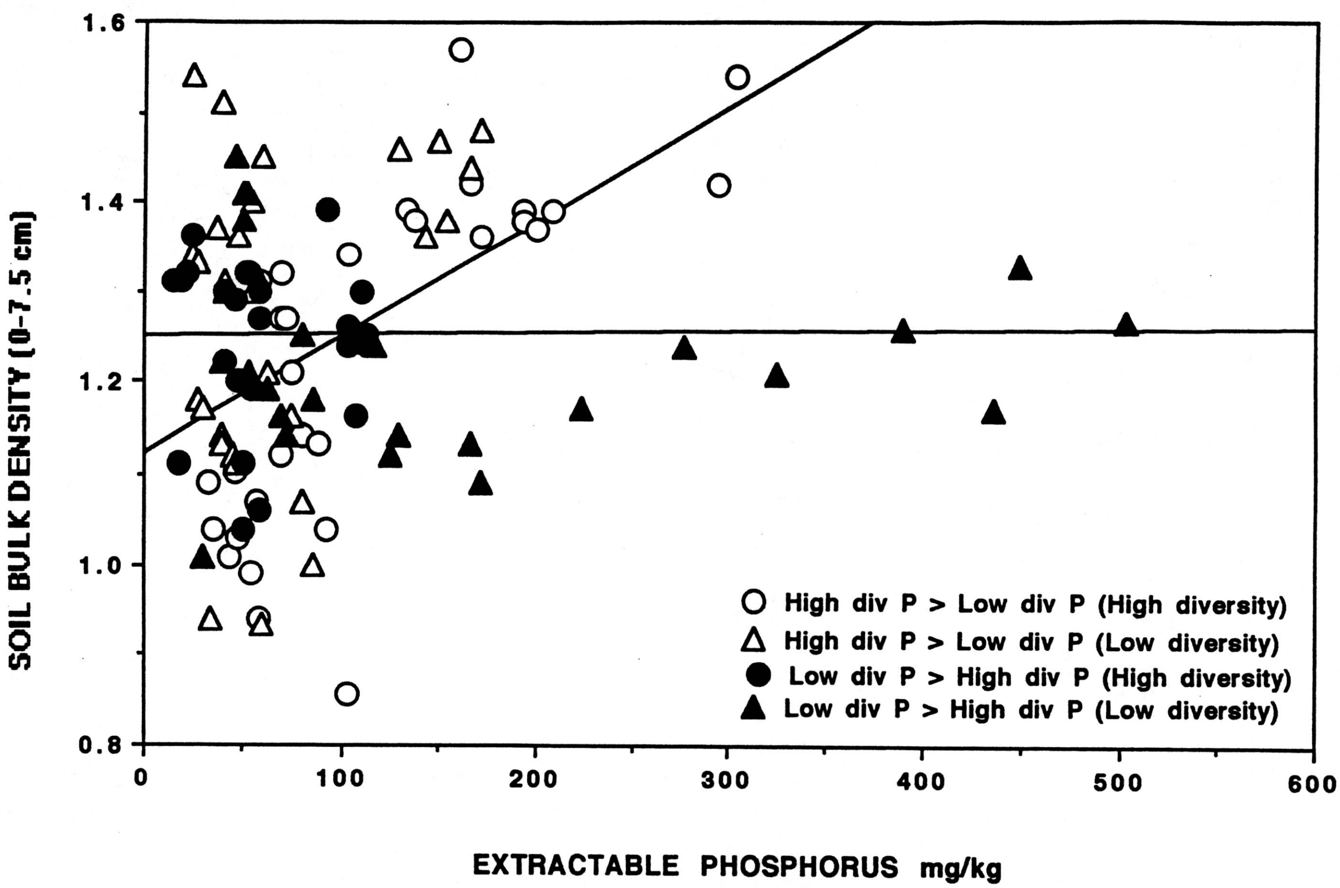
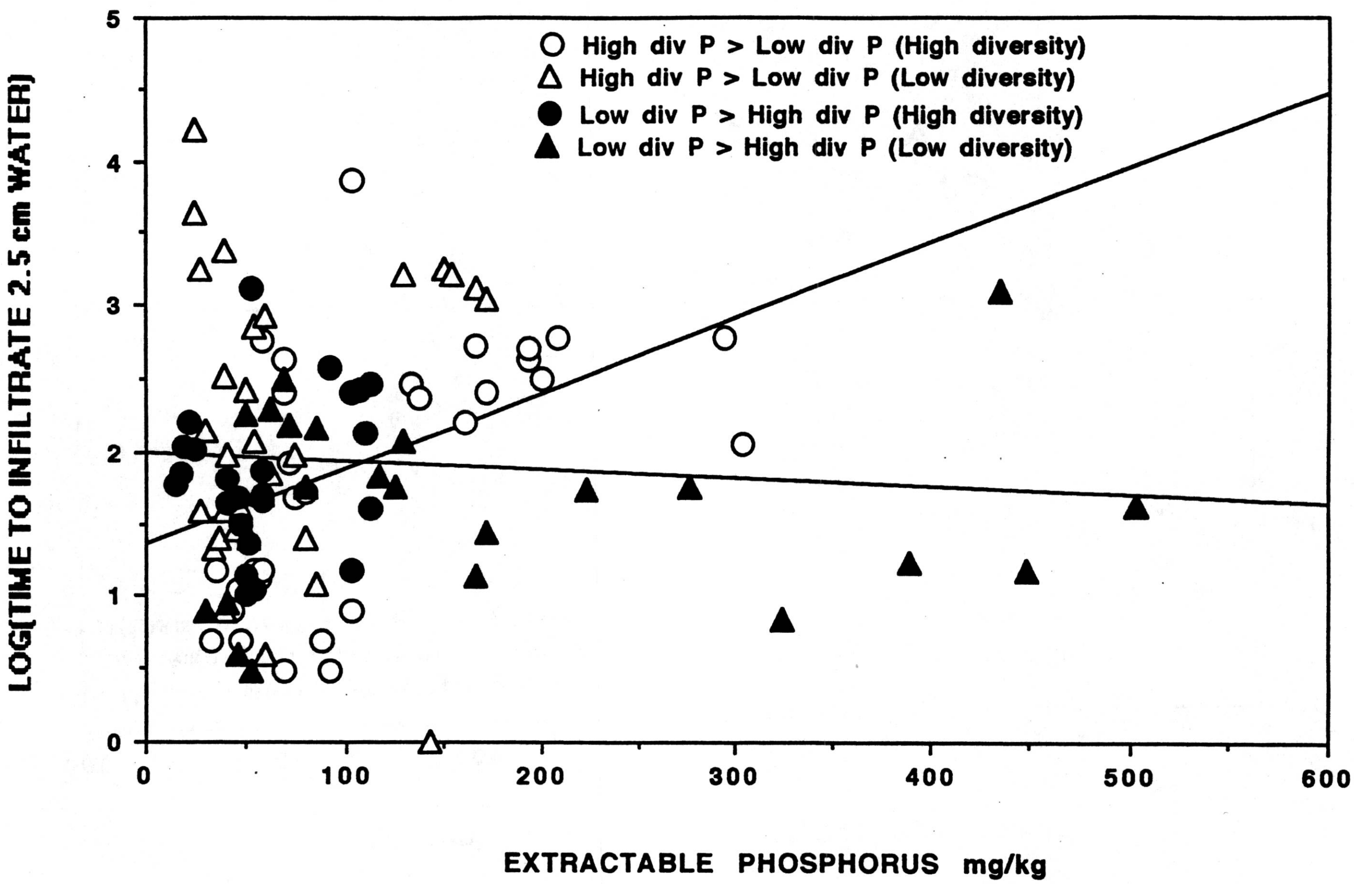
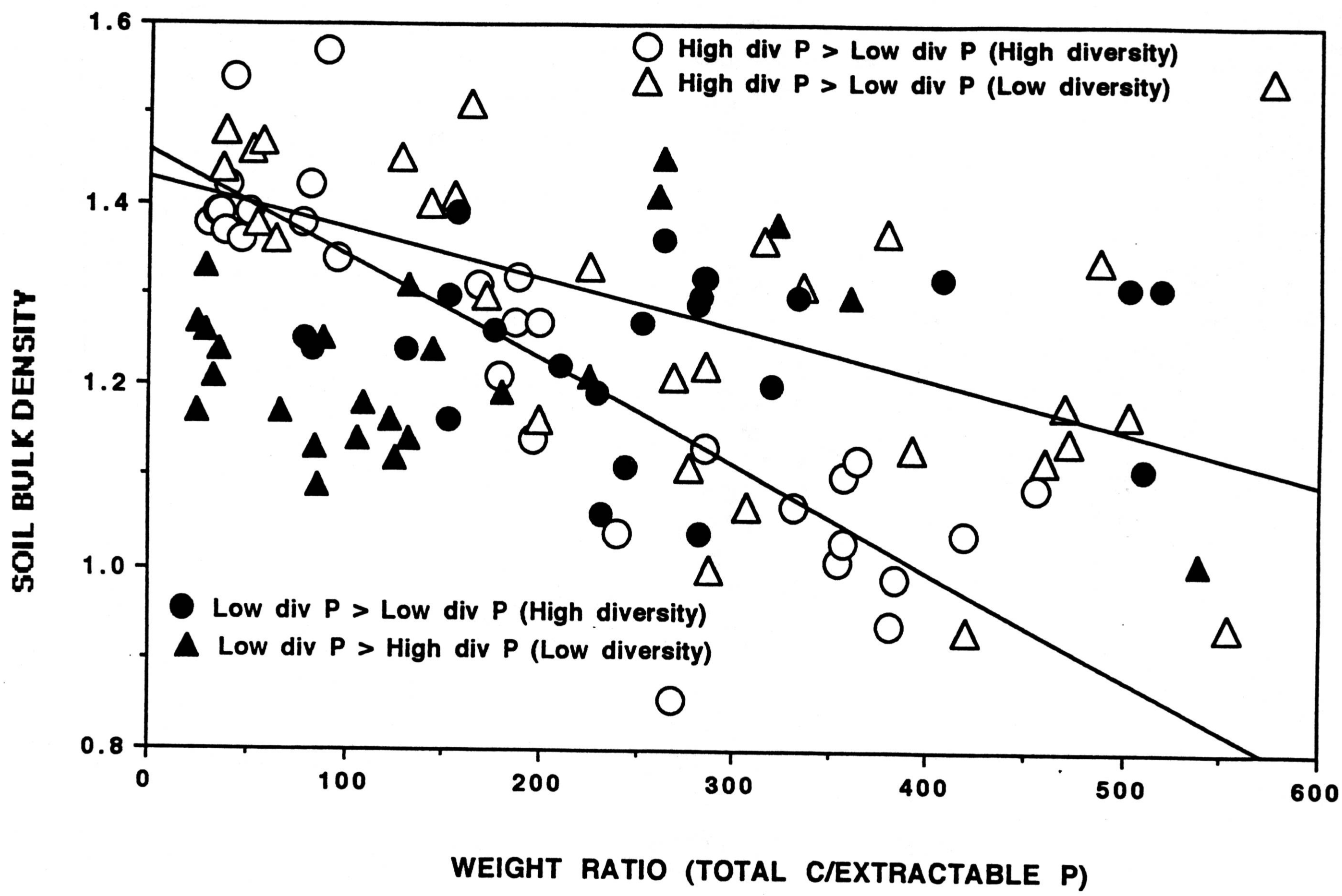

1.6
1.4
1.2
1.0
0.8
SOIL BULK DENSITY (0-7.5 cm)
0
100
200
300
400
500
600
EXTRACTABLE PHOSPHORUS mg/kg
High div P > Low div P (High diversity)
High div P > Low div P (Low diversity)
Low div P > High div P (High diversity)
Low div P > High div P (Low diversity)

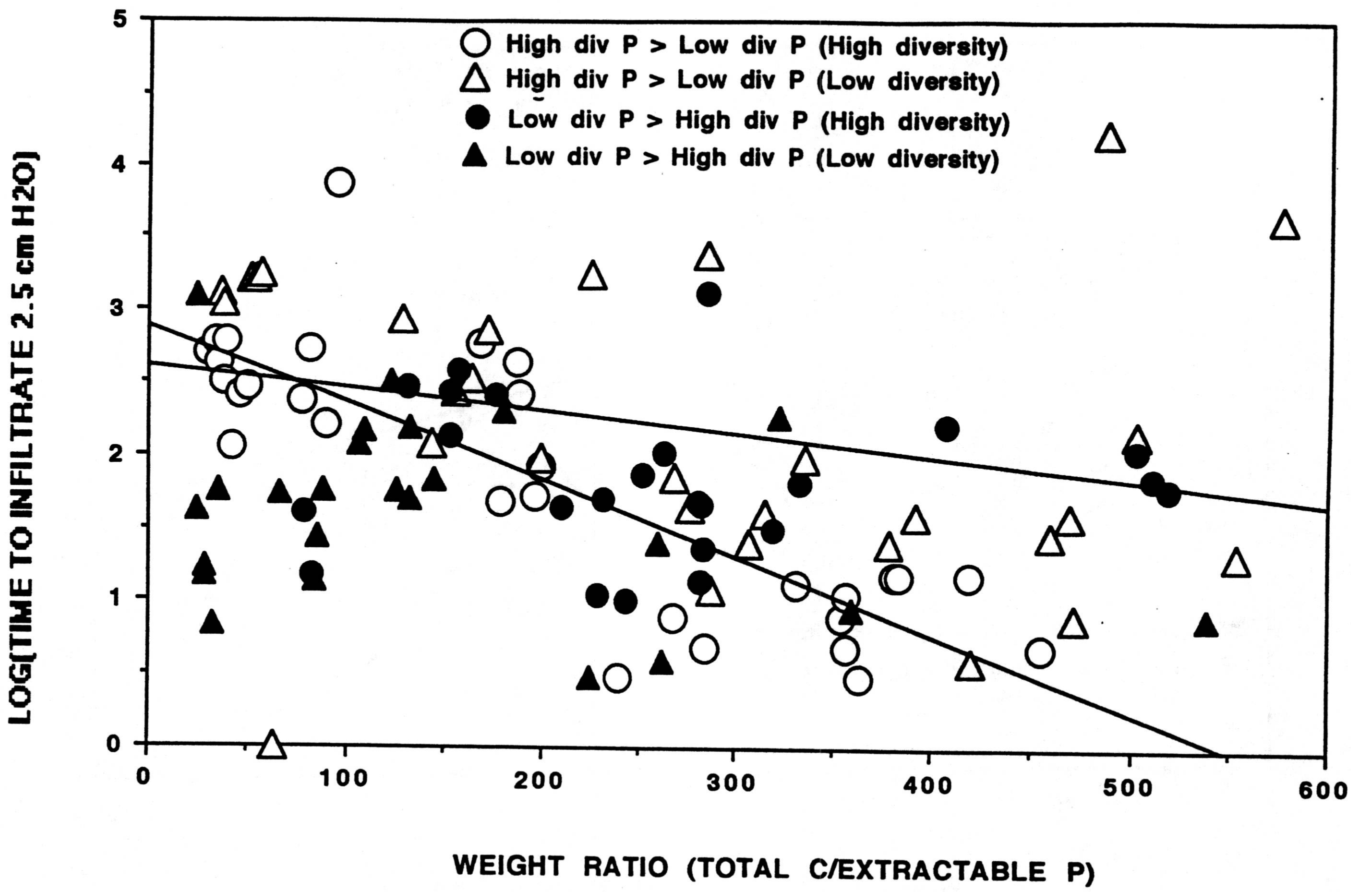
Fig. 2



High div P > Low div P (High diversity)
High div P > Low div P (Low diversity)
Low div P > High div P (High diversity)
Low div P > High div P (Low diversity)
LOG(TIME TO INFILTRATE 2.5 cm WATER)
EXTRACTABLE PHOSPHORUS mg/kg
0
1
2
3
4
5
0
100
200
300
400
500
600



High div P > Low div P (High diversity)
High div P > Low div P (Low diversity)
Low div P > Low div P (High diversity)
Low div P > High div P (Low diversity)
SOIL BULK DENSITY
1.6
1.4
1.2
1.0
0.8
0
100
200
300
400
500
600
WEIGHT RATIO (TOTAL C/EXTRACTABLE P)



High div P > Low div P (High diversity)
High div P > Low div P (Low diversity)
Low div P > High div P (High diversity)
Low div P > High div P (Low diversity)
LOG(TIME TO INFILTRATE 2.5 cm H2O)
WEIGHT RATIO (TOTAL C/EXTRACTABLE P)
0
1
2
3
4
5
0
100
200
300
400
500
600