VERTICAL DISTRIBUTION OF PHOSPHORUS UNDER LONG-TERM CROPPING TRIALS

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INTRODUCTION

Historically, due to its high soil fixation rates and low solubility, phosphorus has not been considered an environmental menace, but years of over-application and the shift in American agriculture from small family farms to large corporate enterprises (McDowell et al., 2001; Sharpley et al., 2001) has led to phosphorus buildup and leaching in many soil types (Eghball et al., 1996; Lucero et al., 1995; Novak et al., 2000; Whalen and Chang, 2001). In addition, phosphorus accumulation in the upper soil profile can be exacerbated by conservation tillage with significant vertical stratification of nutrients occurring (Cruse et al., 1983; Holanda et al., 1998; Howard et al., 1999; Robbins and Voss, 1991; Scheiner and Lavado, 1998; Shear and Moschler, 1969). Because of these issues, the objective of this research was to examine the vertical distribution of phosphorus under the well-managed cropping systems established at the Wisconsin Integrated Cropping Systems Trials (WICST) in an attempt to determine the location of labile phosphorus and assess the potential negative environmental impacts based on the placement of the phosphorus.

SITE HISTORY

Prior to the establishment of the Arlington Agricultural Research Station in Arlington, Wisconsin, the 28 ha of land that is now the site of the WICST plots was privately held and farmed. Farmsteads were located at various sites near the current day location of the WICST site, but one farmhouse and the accompanying outbuildings occupied the easternmost portion of the site, next to US-51. Research station records for these fields began in 1961, and at that time the acreage was all farmed as alfalfa hay. Over the ensuing years, the land was divided into three fields and planted in a variety of crops including oats, alfalfa, and corn with various phosphorus applications ranging from 0 to 82 kg P ha^{-1}. The site also has a history of heavy manure application due to its close proximity to local dairies; however, because manure has often been considered a waste product and not a nutrient source, the application rates were not recorded. The WICST trial was initiated in 1990.

HYPOTHESES

***Bray-1 phosphorus soil test levels*:** The soil test phosphorus (STP) levels on all the plots were excessively high at the initiation of the trial and one goal in Best Management Practices was to bring these levels to optimum. It was hypothesized that the alfalfa-corn system (CS4) would have the highest levels of STP after 12 years of cropping due to the additions of manure and fertilizer, followed by the continuous corn treatment (CS1) since starter fertilizer, high in phosphorus, was applied annually. The corn-soybean rotation (CS2) would follow since P fertilizer was only added to the corn phase. It was anticipated that the rotational grazing (CS6) would follow due to the lack of added fertilizer, and simple recycling of the grazing and subsequent manure deposition. The rotation with lowest STP values would be CS3, which had no P fertilizer or manure additions, but annual removal of corn, soybeans and wheat + straw. (CS4>CS1>CS2>CS6>CS3).

***Vertical stratification*:** It was anticipated that two factors would be important in P-stratification: tillage and crop harvest. Considering primarily tillage, the greatest stratification would occur in the no-till systems (CS2 and CS6), followed by the high input, conventional tillage systems (CS1 and CS4) and then the low input conventionally tilled CS3. Looking at harvest management, it was thought that the removal of the forage in CS6 would lessen phytocycling compared to leaving the corn and soybean residue on the surface in CS2. By the same token, the alfalfa harvest would reduce P-enrichment of the soil surface compared to CS1 where corn stover was left on the field. (CS2>CS6>CS1>CS4>CS3)

***Soil sorption isotherms*:** It is thought that soils with high levels of STP, or having received high amounts of P inputs, would have lower sorption capabilities and greater soil solution phosphorus, presenting a situation where P leaching could potentially occur. Because of this, the cropping systems that still receive phosphorus inputs (either mineral or manure) would have a greater chance of exhibiting vertical P movement.

MATERIALS AND METHODS

Field Sampling: Duplicate soil cores, 45-mm in diameter (1 ¾") and 1-m depth, were obtained from each plot in five of six cropping systems in the fall of 2002 and again in the springs of 2003 and 2004 in repetitions 1 and 2. The systems sampled include: continuous corn, CS1; corn-soybean, CS2; corn-soybean-winter wheat-red clover, CS3; corn-alfalfa-alfalfa-alfalfa, CS4; and, pasture, CS6. The sampled plots were in the corn phase of each rotation in 2002, with the exception the rotational grazing system, and each followed their rotation sequence in 2003 and 2004. All the plots had been in their respective rotation for 12 years prior to sampling. Two sets of control cores were removed from center of the grass alleyways between plots 112 and 113 in repetition I and plots 206 and 207 in repetition II.

After removal, cores were stored intact in plastic capped liners (Giddings Machine Company Inc., Windsor, Colorado; www.soilsample.com) at 4º C until processing. Cores were processed individually by sectioning into 1-cm intervals for the first 40 cm and then 5-cm intervals for the next 40 cm. The remaining 20 cm of the core were not analyzed. Samples were air-dried and hand-ground for analysis. This resulted in forty-eight samples from each core.

Laboratory Experiments: Labile phosphorus was extracted by the Bray P-1 dilute acid extraction (Bray and Kurtz, 1945) as modified by Avila-Segura et al. (2004) for use with a microplate reader and analyzed by the ascorbic acid method (Avila-Segura et al., 2004; Murphy and Riley, 1962).

Soil sorption isotherms were created using the techniques of Graetz and Nair (2000) as modified for a microplate reader by Avila-Segura et al. (2004). Specific samples were chosen by using profiles of the Bray P-1 with depth. Solutions were analyzed by the ascorbic acid method (Murphy and Riley, 1962) and plotted using the Langmuir equation. As soil sorption is nonlinear, the data were fit to this equation using the nonlinear optimizing routine "Solver" (Microsoft Excel 2000) to minimize the sum of squares of the residuals (Barrow, 1978). The fitted data were graphed and inspected to assure that local minima were avoided. Equilibrium P concentration and the P buffer capacity were analytically calculated from the fitted parameters.

RESULTS AND DISCUSSION

Three or four cores from each plot of the five cropping systems in repetitions 1 and 2, plus a control set were analyzed (i.e., approximately one core per plot per year). The mean P-levels and standard error bars per plot are shown in Figures 1 and 2. The control cores were too dissimilar to simply average, so all four cores are represented in Figure 2b. Because all the samples were analyzed in 1-cm and 5-cm increments, the analytical results were also mathematically combined and then averaged to create "bulk samples". This allowed us to compare cores in a manner consistent with current soil testing procedures, (i.e., samples taken in 15-cm increments).

Cropping System Cores: The phosphorus profiles for the various cropping systems (Figures 1 and 2) suggest chromatography columns, with considerable vertical stratification. There is a general trend of high surface phosphorus content decreasing with depth to low mid-range concentrations and then increasing concentration at depths of 40-cm and greater. Initial surface soil (0 to 1-cm depth) P levels range from 35 mg P kg^{-1} soil to 155 mg P kg^{-1} soil and the results from the 15-cm depth range from 20 mg P kg^{-1} soil to 147 mg P kg^{-1} soil.

Control Cores: The WICST organizers neither set aside a location for a control nor did they archive sufficient samples to depth at the onset of the trial in 1989, because the intent of the research was to compare cropping systems and not to explicitly track soil changes from their start point in time. In an effort to determine a background phosphorus profile, it was decided that the 2.4-m alleyways between the existing plots were the best potential locations. These grass alleyways are not used for vehicular traffic and spillage of fertilizer is minimal. In order to further reduce edge effects, the chosen locations were adjacent to the pasture plots that only receive depositional manure from the grazing heifers.

Four cores were removed from each of the two locations. Unfortunately, due to the inherent heterogeneity of the site, these profiles were not entirely comparable (Figure 2b); controls B and C had similar profiles that started with approximately 140 mg P kg^{-1} and average plow layer Bray P-1 values from 110 to 140 mg P kg^{-1}. Controls A and D had very similar profiles, with surface Bray P-1 levels near 90 mg P kg^{-1} and average plow layer values of approximately 50 mg P kg^{-1} soil. Although the initial P levels differ, both sets of cores have surface phosphorus values that are approximately 30 mg P kg^{-1} greater than the mean of the entire 15 cm plow layer. This type of heterogeneity has been shown to be common in heavily manured fields.

Bray P-1 Concentrations to Depth

Because current soil testing methods composite soil cores over a greater area with lesser resolution, the values obtained for this study were mathematically averaged to provide a comparison. Table 1 shows the results of the current research for the combined samples (0 to 15 cm, 16 to 30 cm, and 31 to 60 cm) for each cropping system and the difference from the controls. For simplicity, the similar controls were averaged (i.e., A & D and B & C) and the results are shown accordingly.

For the current research, in the 0 to 15 cm plow layer, the mean Bray P-1 levels of all cropping system cores are vary when compared to the control cores with most showing some

drawdown of P. The actual ranking of soil test levels did not exactly match our hypothetical ranking, as there was one difference. Cropping system 4, the corn-alfalfa system, has the highest average phosphorus value (due to heavy manuring), followed by CS1 (continuous corn with high-P starter fertilizer every year), followed by the fertilizer-free CS6 (pasture), CS2 (corn-soybean with high-P fertilizer every other year), and CS3 (corn-soybean-winter wheat-red clover). It was hypothesized that CS2 would be ranked higher than CS6, but that was not the case. It is possible that less phosphorus is removed from the pasture system then the corn-soybean system causing a greater amount of phosphorus to remain in the soil profile.

In the zone below the plow layer, 16 to 30 cm, average P values are still high to excessively high when compared to soil test recommendations for Wisconsin in every system except CS3. In the 31 to 60 cm zone, all soil test phosphorus levels are lower than in the upper profile. The highest value was found in CS2, 35.7 mg kg^{-1}, with the control B & C following having a P concentration of 29.7 mg kg^{-1}. The level of phosphorus in control A & D at this depth is similar with the other plots, but the P level in control B & C is higher than the remaining systems suggesting that the crop rooting system is extracting P from these depths more consistently than in those check plots.

The second half of Table 1 shows the difference in Bray P-1 concentrations between each system and two controls, with negative values denoting depletion of soil phosphorus. As shown, P levels have been lowered in the upper 15 cm for all five cropping systems studied. This decrease is greatest for CS3, which does not receive any fertilizer and lowest for CS4, which receives manure additions twice throughout each four year rotation. The subsoils (16 to 30 cm) also have been depleted of soil P with the greatest removal again in CS3.

Table 1. Mean Bray P-1 at three combined depths with the values having been mathematically averaged.

Soil Depth	**CS1**	**CS2**	**CS3**	**CS4**	**CS6**	**Control**	
Plot Number	*109 & 204*	*108 & 206*	*102 & 212*	*113 & 210*	*112 & 207*	*A & D*	*B & C*
cm			------- mg P kg^{-1} -------				
0-15	60.6	31.3	29.1	77.1	42.1	50.5	122
16-30	57.7	37.8	28.9	50.7	45.0	38.8	149
31-60	13.6	20.2	14.2	16.8	13.7	10.6	29.7
Difference from controls A & D							
0-15	10.1	-19.3	-21.4	26.5	-8.4	–	–
16-30	18.8	-1.0	-9.9	11.9	6.2	–	–
31-60	3.0	9.5	3.6	6.2	3.0	–	–
Difference from controls B & C							
0-15	-61.6	-90.9	-93.1	-45.1	-80.1	–	–
16-30	-91.1	-111	-120	-98.1	-104	–	–
31-60	-16.0	-9.5	-15.5	-12.9	-16.0	–	–

Vertical Stratification in the Root Zone

The range of phosphorus concentrations with depth, from high to low to high again, reveals that vertical stratification is present in the majority of cropping systems at the WICST at Arlington. Figure 3 shows the Bray P-1 phosphorus distribution in the upper 30 cm of each plot and Table 2 shows the average concentration of Bray P-1 phosphorus over three different depth

intervals commonly sampled for soil testing for agriculture and environmental purposes. Of the plots sampled, 109 (continuous corn), 113 (corn-alfalfa), 210 (corn-alfalfa), and 112 (pasture) have the greatest stratification, with their surface P concentrations ranging from approximately 75 to 125 mg P kg^{-1} soil and the phosphorus concentrations at 30 cm depth between 15 and 20 mg P kg^{-1} soil. Cropping system one, plot 204 and CS6, plot 207 show stratification to a lesser degree, with surface concentrations between 55 and 70 mg P kg^{-1} soil and the deeper depths again around 15 to 20 mg P kg^{-1} soil. CS6-207 shows most of the stratification for its profile in the upper five centimeters, whereas the other profiles have a more gradual decline in phosphorus levels from the surface to 30-cm deep. Of the stratified systems, CS3 (corn-soybean-winter wheat-red clover) has the least stratification, with the surface soil for both plots containing approximately 35 to 40 mg P kg^{-1} soil and the 30-cm soil containing about 15 mg P kg^{-1} soil. Cropping system 2 (corn-soybean) did not show stratification in the top 20 cm most likely because it was conventionally tilled for the first four years of production. Although not directly associated with vertical stratification, all of the systems show a slight increase of phosphorus between 12 and 14 cm, which is likely a mechanical effect from the old plow layer.

The actual estimates of stratification did not match the hypothetical ranking. It was thought that the no-till systems 2 (corn and soybeans) and 6 (pasture) would have the greatest stratification and the more frequently tilled systems 1 (continuous corn), 4 (corn and alfalfa) and 3 (organic grain) would have the least stratification. In this study when comparing the average stratification for each cropping system using the 0 to 5/5 to 15 cm ratio, the greatest stratification occurred in CS6 followed by CS3, CS4, CS1, and CS2. It is likely that CS2 has the least amount of stratification due to modest P additions and high P off take as corn and soybean grain. This net removal of phosphorous has masked the natural tendency for this no-till system to create a stratified P profile in the soil.

Table 2. Average Bray P-1 values for three different depth intervals commonly sampled for soil test phosphorus. Max/Min is equal to the maximum P concentration from 0 to 5 cm and minimum equals the lowest concentration from 26 to 30 cm. Mean denotes the average of the plow layer (0 to 15 cm).

Core	CS1		CS2		CS3		CS4		CS6	
Interval	109	204	108	206D	102	212	113	210	112	207
cm	---------- mg kg^{-1} ----------									
0 – 5	82.0	54.9	33.1	27.1	38.0	36.4	90.3	96.6	79.0	42.3
5 – 15	73.6	39.7	34.3	29.3	25.1	25.1	55.3	82.4	41.8	23.8
15 – 30	32.6	18.8	14.5	18.7	14.4	11.7	22.5	22.2	21.8	19.8
Max/Min	5.6	4.3	4.0	3.9	4.3	4.9	10.3	7.5	8.4	4.5
Max/Mean	1.1	1.3	1.1	1.2	1.4	1.3	1.5	1.2	1.7	2.3
0–5/5–15	1.1	1.4	0.97	0.92	1.5	1.4	1.6	1.2	1.9	1.8

There are likely causes for the stratification shown in this research: first, the systems are minimally tilled and so P inputs from fertilizer and manure are left to slowly infiltrate the soil profile, and second, these systems leave copious amounts of plant tissue as crop residue on the soil surface after harvest. Upon decomposition, this plant matter releases phosphorus (that was mined from deeper in the soil profile) back into the soil at the surface and so this phytocycling of nutrients will cause greater stratification.

Because this site was under conservation management prior to the beginning of the WICST and vertical stratification was found in the untilled control, this is assumed to be the starting condition. Twelve years of tillage and nutrient extractions have not only maintained the vertical stratification but somewhat amplified it. The original goals of the Wisconsin Integrated Cropping Systems Trials included intentional drawdown of high phosphorus concentrations and reduction of erosion using conventional tillage methods. According to current Wisconsin soil test recommendations, the P levels for the plow layer in each of the cropping systems are still excessively high for corn, alfalfa, wheat, and managed pasture (>30 ppm P) as well as soybeans (>20 ppm P) and red clover (>25 ppm P) (Kelling et al., 1998). These values are based on bulk soil samples for the plow layer, but phosphorus levels in conservation tillage systems are known to become stratified with depth due to the lack of mixing (Cruse et al., 1983; Holanda et al., 1998; Howard et al., 1999; Robbins and Voss, 1991; Scheiner and Lavado, 1998; Shear and Moschler, 1969). It is difficult to compare stratified systems with recommendations based on conventional soil testing methods because the act of taking composite soil samples from a soil that does not display P homogeneity means that the values obtained are highly dependent upon the depth of sampling. In essence, composite sampling on a stratified system gives a weighted average that only truly represents the phosphorus level at one soil depth within the entire sampling zone. In stratified systems, the greatest amount of soil P is at the most vulnerable location for loss by soil erosion and the true P value for crop requirements is not determined. This shows that new testing methods are needed for these systems, to determine both plant nutritional needs and runoff potential.

Soil Sorption Isotherms

Phosphorus sorption research was conducted on a subset of soil samples from the larger collection of cores with the depths selected based on inflection points from the Bray P-1 to depth curves (Figures 1-2). Results of the phosphorus sorption/desorption protocol (Avila-Segura et al., 2004; Nair et al., 1984) were fit to a form of the Langmuir equation written as:

$$S - S_0 = k_l S_{\max} \frac{C}{1 + k_l C},$$

where S is the sorbed P, S_0 is the initial sorbed P, k_l is the Langmuir constant, C is the soil solution concentration, and S_{max} is the P sorption maximum. Figure 4 and Table 3 show the isotherms and the fitted and calculated parameters for each interval of a selected core from CS1, plot 109. The data for the remaining cores are not presented here.

Values for S_{max} varied among plots (data not shown), but within a core (Table 3), tended to be similar or increase with depth, which is consistent with the findings of Mozaffari and Sims (1994). The largest sorption maximums were located at the deepest soil intervals, for multiple reasons: first, there are more sorption sites in this zone due to lower phosphorus levels; second, clay content is higher in the subsoil and sorption is correlated with the clay content (Mozaffari and Sims, 1994); third, the fitted functions were less precise due to the steepness of slope; and fourth, S_{max} is an extrapolation of the data beyond the range of data points toward a saturating concentration of phosphorus. It is important to note that there was little correlation between the S_{max} values and Bray P-1 phosphorus concentrations, a finding that agrees with results from Eghball et al. (1996), who found no correlation between adsorption maximums and available phosphorus concentrations at different soil depths.

Table 3. Fitted and calculated parameters using the Langmuir equation for P sorption data for CS1, plot 109.

Cropping System	Depth	SSE	k_l	S_{max}	S_0	pH	C_0	$dS/dC\|_{C=C_0}$	r^2
	cm			mg P kg^{-1}			mg P L^{-1}		
CS1 – 109	6	4.78	0.50	201	-34.2	6.00	0.407	69.7	0.998
	12	5.23	0.48	189	-28.4	5.33	0.367	65.7	0.997
	19	69.0	1.14	203	-31.9	6.00	0.163	165	0.974
	24	139	1.39	205	-28.8	6.32	0.117	212	0.954
	30	857	3.00	244	-41.1	6.32	0.068	506	0.776
	40-45	337	8.32	355	-129	6.20	0.068	1201	0.929
	55-60	488	9.90	384	-136	6.00	0.055	1588	0.899
	70-75	665	4.13	273	-57.2	5.39	0.064	707	0.841

The phosphorus adsorption strength, k_l, tended to increase with depth and the equilibrium phosphorus concentrations, C_0, defined here as the concentration at which no phosphorus is sorbed or desorbed from solution, decrease with depth within a core. Finally, the buffer capacity of the soil, calculated from the fitted sorption isotherm at the equilibrium phosphorus concentration, i.e., *dS/dC* at C_0, increases with depth within each core, particularly below 20 cm. The highest soil solution P values are associated with soil samples with the lowest buffer capacity and the highest Bray P-1 concentrations. There is the potential for leaching within these systems; however, at this time, the deeper soils are fully capable of sorbing the excess P that may slip below the upper root zone, thereby keeping vertical migration to a minimum.

CONCLUSIONS

The soil profiles presented here all resemble chromatography columns and all the cores within a plot have similar Bray P-1 profiles to depth. These results show the intentional drawdown of phosphorus, starting in 1989, has been successful and continued management will bring the phosphorus levels to optimum for Wisconsin soils (between 10 and 25 mg kg^{-1}). The majority of the soil profiles presented did not show phosphorus leaching to depth, but the soil sorption data shows that the potential exists. Phosphorus added at the soil surface, through both fertilizer additions and crop residue decomposition, will slowly infiltrate and migrate downward through the nutrient-rich surface soil, which has limited sorption sites, to the more nutrient-poor soil below where sorption sites are abundant, thereby limiting the leaching potential. Further analysis of these samples using the Hydrus 1-D modeling program will shed more light on the movement of P through both leaching and phytocycling.

Finally, vertical stratification is present in these systems, including the control cores, and the current management practices are amplifying this stratification by adding nutrients at the soil surface without incorporation by tillage. This practice is localizing high concentrations of phosphorus at the soil surface; the area most susceptible to runoff. Because current soil sampling methods composite soil from multiple cores to a depth of 15-cm, a stratified system would give a value for runoff potential that would be lower than the actual P concentration at the surface and so new soil sampling techniques are needed for systems that exhibit vertical stratification.

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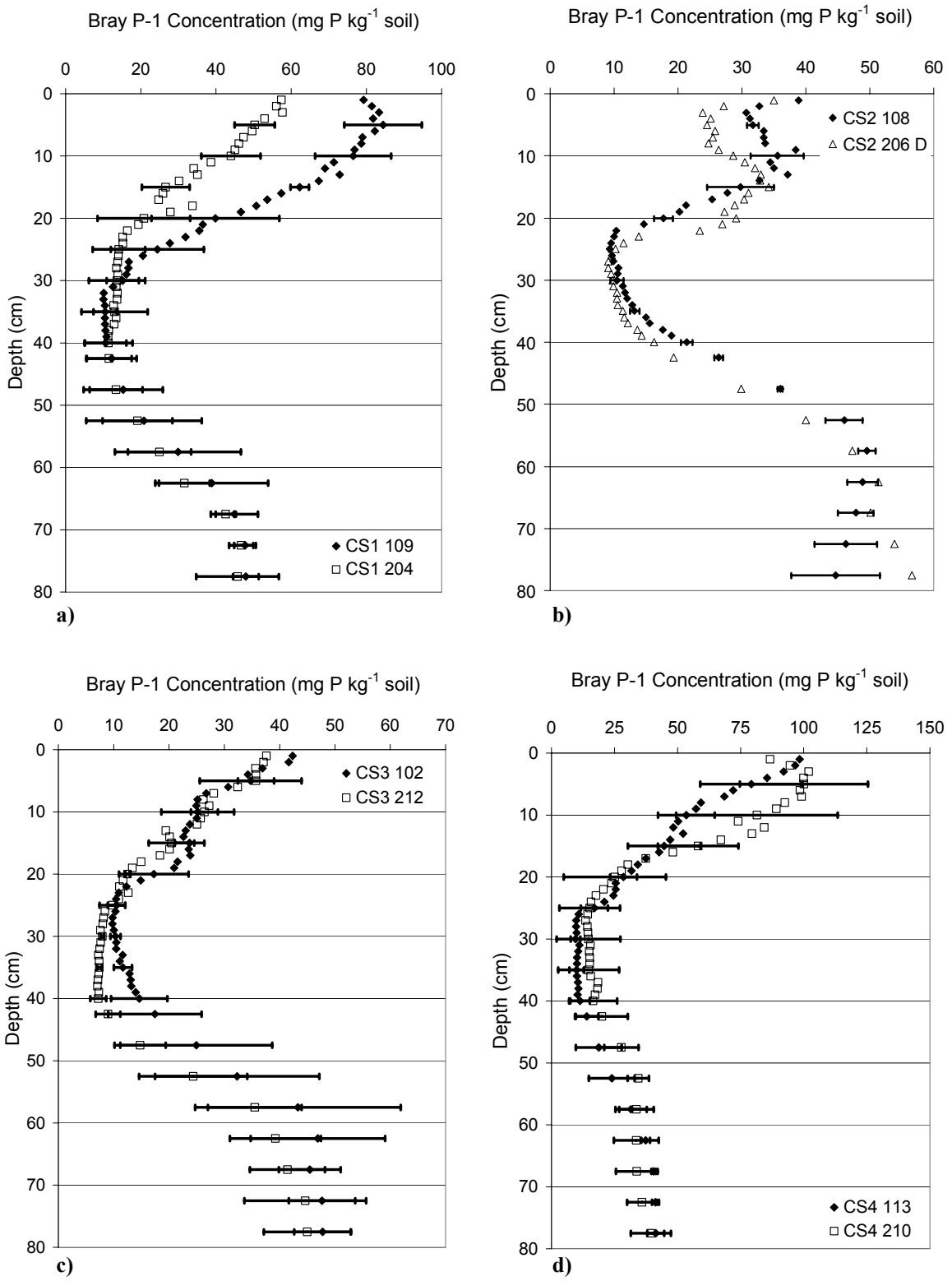

Figure 1. Average concentrations of Bray P-1 (mg P kg^{-1}) to depth for four cropping systems at the WICST Arlington, Wisconsin site: a) CS1, plots 109 and 204; b) CS2, plots 108 and 206; c) CS3, plots 102 and 212; d) CS4, plots 113 and 210. Standard error bars represent the standard deviation from the average of the three cores evaluated for each plot.

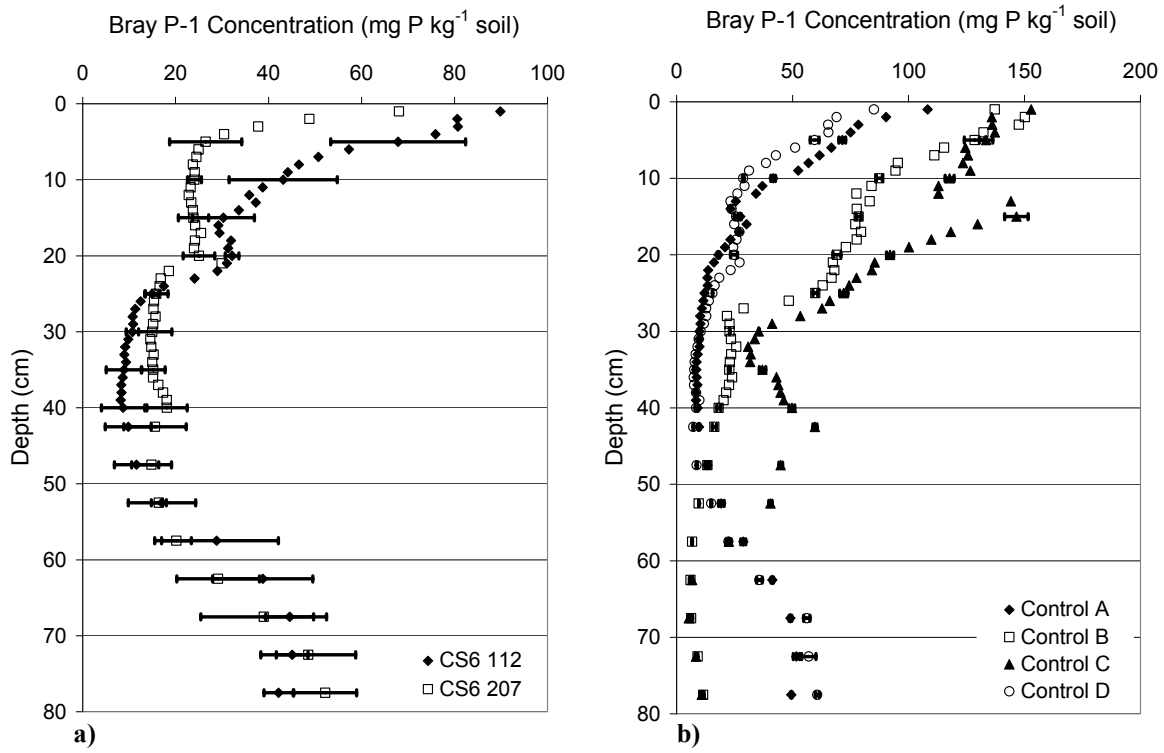

Figure 2. Average concentrations of Bray P-1 (mg P kg^{-1}) to depth for one cropping system and hypothetical control plots at the WICST Arlington, Wisconsin site: a) CS6, plots 112 and 207; b) four control cores removed from the alleyway between existing plots. Standard error bars represent the standard deviation from the average of the three cores evaluated for each plot.

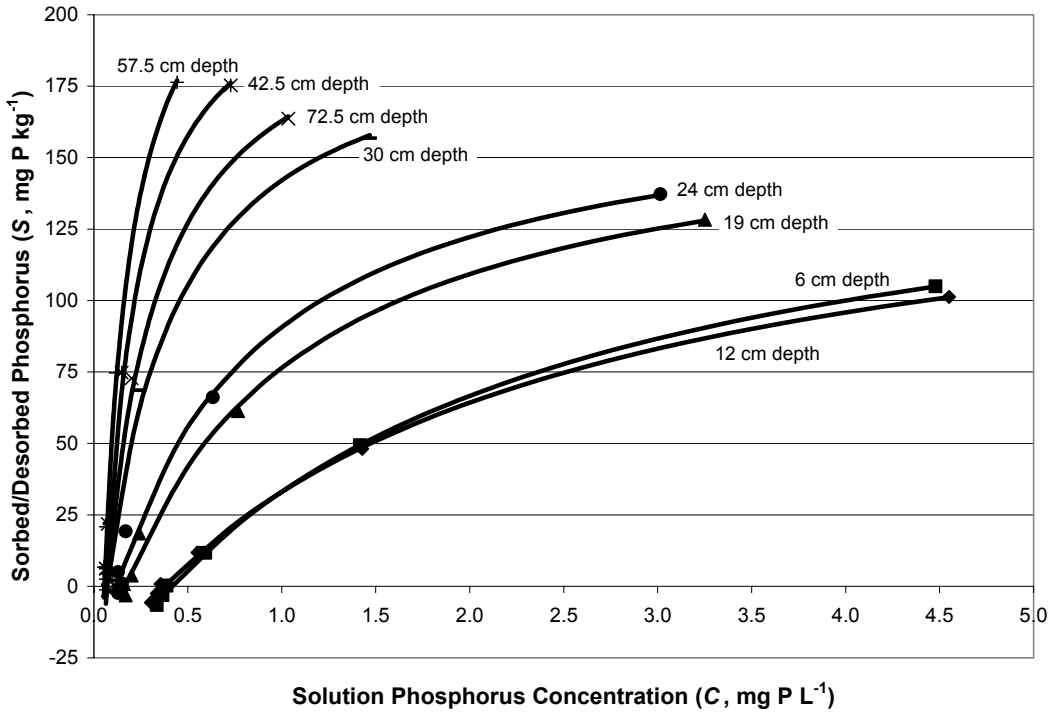

Figure 3. Langmuir sorption isotherms for CS1, plot 109 at eight depth intervals.

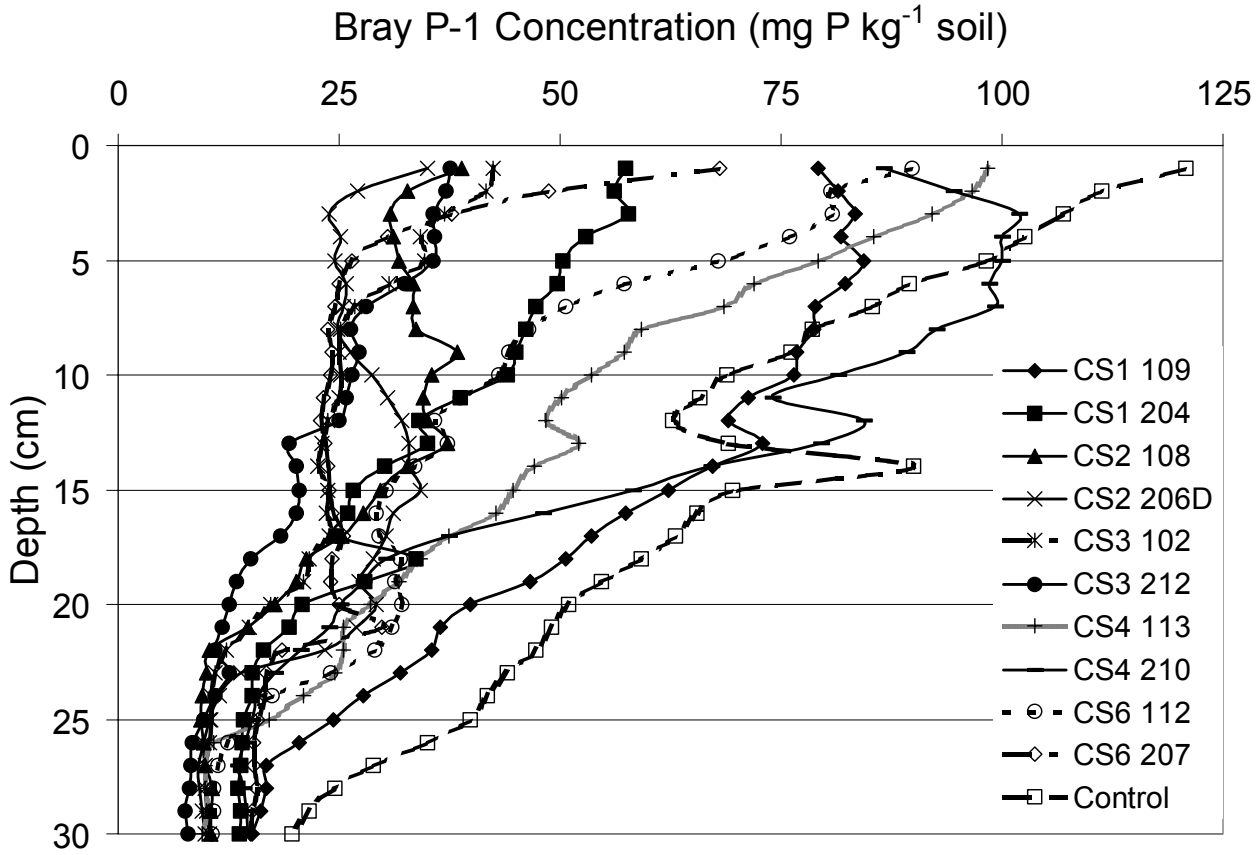

Figure 4. Vertical phosphorus stratification at the Wisconsin Integrated Cropping Systems Trial as shown by the Bray P-1 concentrations (mg P kg^{-1} soil) to depth.