PHOSPHORUS DYNAMICS IN SOILS RECEIVING CHEMICALLY TREATED DAIRY MANURE

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ABSTRACT

An incubation study was conducted with 3 soils (I, II, and III with 12, 66, and 94 mg/kg Bray-1 P), 4 manure treatments (1 untreated; 3 chemically [alum – Al; $FeCl_3$ - Fe, lime - Ca] treated) and 1 fertilizer (mono-calcium phosphate, MCP) treatment, at 2 rates (12.5 and 25 mg P/kg soil), and a control (no manure/fertilizer). Sub-samples were analyzed for water-soluble P (WSP) and Bray-1 P after each incubation period (1 d, 1 & 2 w, 1 and 3 months). Distribution of P among different fractions (soluble & exchangeable; Al-, Fe-, and Ca- bound; org-P; residual) was determined after 1 d reaction. WSP increased when soils received MCP and untreated or Ca-treated manure with the magnitude being proportional to the rate of P applied. WSP, however, decreased (compared to control) for soils II and III (high Bray-1 P) or increased slightly for soil I (low Bray-1 P) with application of Al or Fe-treated manure. WSP decreased sharply between 1 d and 1 or 2 w incubation and then remained relatively constant for up to 3 months. With respect to control, Bray-1 P increased for all treatment types and soils in proportion to the rate of P addition in the following order: MCP > Ca-treated > Al-treated ≥ untreated > Fe-treated > control. Within each treatment, Bray-1 P decreased between 1 d and 1 or 2 w and then increased gradually for up to 3 months. Addition of Al or Fe treated manure decreases P solubility with the effect being more pronounced in soils with high background P. On the other hand, application of Ca-treated manure or MCP increases both WSP and bio-available P.

INTRODUCTION

Deterioration of water quality of streams and lakes in the United States and worldwide through non-point source (NPS) pollution is a growing environmental concern (Sharpley et al., 1999). Runoff from agricultural lands is rich in nutrients [nitrogen (N) and phosphorus (P)], and hence, contributes significantly to NPS pollution. Currently, the focus is specifically on P additions through runoff from agricultural lands and urban areas (Moore and Miller, 1994; Sims et al., 2000). There is a greater concern in regions where sensitive water resources are located near concentrated livestock operations (Daniel et al., 1994; Sharpley et al., 1997). Concentrated livestock operations are very efficient producers of protein, but produce large volume of manure that is being distributed on less land, leading to a surplus of on-farm nutrients. This situation is especially true for P (Beegle and Lanyon, 1994). Numerous reports indicate build up of bio-available and water-soluble P in soils due to repeated long-term application of animal manure (Sharpley et al., 1993; Lucero et al., 1995). Future existence and expansion of these livestock operations depend on efficient recycling of nutrients within the farm. Due to changes in animal farm dynamics and impending P-based regulations, the available land resources for manure management, particularly near the farms, are going to be seriously stressed (Converse et al., 2000). Therefore, it is imperative to develop and implement practices that will help minimize nutrient loading in areas near the farm and export the excess nutrients off-farm.

Chemical treatment of animal manure with salts of Al, Fe, and Ca and polyacrylamide polymers appears capable of providing efficient solids and nutrients [<u>especially dissolved P</u>]

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separation (Moore and Miller, 1994; Vanotti and Hunt, 1999; Sherman, et al., 2000), thereby creating more options to manage P distribution over the landscape. P is known to interact strongly with the above chemicals, as a result of which it is likely to be converted into less water soluble and bio-available forms. There have been limited attempts to bridge the gaps between our knowledge of chemical treatment systems and the ultimate fate of nutrients when the treated manure is land applied. Most of the earlier investigations on chemical treatment have largely overlooked the interaction of treated manure with soils and the long-term stability of applied nutrients. Limited evidence available in the literature suggests that land application of chemically treated manure can reduce runoff P losses. Smith et al. (2001) reported a substantial decrease in runoff P losses from fields fertilized with swine manure treated with alum or $AlCl_3$. In a short-term (1 wk) incubation study, application of Al and Fe-treated dairy manure to a silt loam soil lowered water-extractable P compared to that obtained after the addition of untreated manure (Dao and Daniel, 2002). Soon and Bates (1982) showed that application of sewage sludge treated with $Ca(OH)_2$, alum or $FeCl_3$ to a near neutral loamy sand or loam soil increased both $NaHCO_3$-extractable P and soluble P of soils in the order of Ca-sludge >> Fe-sludge ≥ Al-sludge. However, results for application of untreated sewage sludge was not obtained and, hence, the effectiveness of chemical treatment cannot be determined.

The overall goal of this study is to investigate the interaction of P in chemically treated manure with soil. Specific objectives are to: (i) evaluate the impact of chemical treatment type on the stability of applied P in soils and (ii) determine the effect of incubation time, application rate, and background soil level on P dynamics in soils receiving chemically treated manure.

MATERIALS AND METHODS

An incubation study was conducted with 3 soils (I, II, and III with 12 [low], 66 [high], and 94 [excessive] mg/kg Bray-1 P, respectively), 4 manure treatments (1 untreated; 3 chemically [alum – Al; $FeCl_3$-Fe, lime-Ca] treated), and 1 fertilizer (mono-calcium phosphate, MCP, $Ca(H_2PO_4)_2$) treatment, at 2 application rates (low equivalent to 12.5 mg P/kg soil and high equivalent to 25 mg/kg), and a control (no manure/ferilizer application) at constant moisture (50% water holding capacity) and temperature (25 ^{o}C). Triplicate samples are being incubated for 8 different time periods (1 d, 1 and 2 weeks, 1, 3 and 6 months, and 1 and 2 years). Three surface (0-15 cm) Plano silt loam soils (fine, silty mixed, mesic Typic Agriudoll) varying in Bray-1 P were collected from the University of Wisconsin (UW) Arlington Agricultural Research Station, Arlington, WI. Soil samples were air-dried and then gently ground to pass a 2-mm sieve. Selected physico-chemical characteristics of soils, analyses performed by the UW Soil and Plant Analysis Laboratory (SPAL), Madison, WI, are shown in Table1.

Table 1. Selected physico-chemical characteristics of soils used in this study.

		Texture			**Bray-1 P**	**Total**		
	pH (1:1.3)	sand (%)	silt (%)	clay (%)	(mg/kg)	P (mg/kg)	N (%)	OC (%)
Soil I	6.81	13	65	22	12	422.5	0.23	2.41
Soil II	6.80	15	62	23	66	549.4	0.22	2.42
Soil III	6.82	10	67	23	94	697.2	0.23	2.60

Chemically Treated Manure Preparation:

Chemically treated manure samples were prepared using solution conditions and optimum dosage as determined in our previous study (Karthikeyan et al., 2002). Diluted liquid dairy manure (total solids = 0.8%) was treated with alum $[Al_2(SO_4)_3.18H_2O]$, ferric chloride

[$FeCl_3$] or lime [CaO] using a PHIPPS & BIRD PB-900™ programmable jar tester with 2 min. rapid mixing at 100 rpm followed by 15 min. slow mixing at 30 rpm and finally a settling period of 30 min. Chemical dosages applied were 8 mM Al from alum, 8 mM Fe from $FeCl_3$ and 20 mM Ca from CaO. After sedimentation, the clear supernatant was siphoned out and the sludge was transferred into a 1 L beaker and stored in a refrigerator at 4 °C. After 24 h the clear solution on top of the beaker was siphoned out again and the resultant sludge was stored at 4 °C for further analysis and for use in the incubation experiment. Treated and untreated manure samples were analyzed for total solid [TS], total organic carbon [TOC], total N [TN], total P [TP], and dissolved reactive P [DRP] following standard procedures (APHA, 1992). P analysis was performed in our laboratory using a Lachat Autoanalyzer [Zellweger Analytics, Milwaukee, WI] and standard molybdate-based colorimetric methods at a wavelength of 880 nm (Murphy and Riley, 1962). Electrical conductivity (EC) and pH of treated or untreated manure were measured using a Accumet AR-50 pH/conductivity meter. Total elemental analysis was performed using ICP (UW SPAL). Important characteristics of treated and untreated manure are listed in Table 2.

Table 2. Physico-chemical characteristics of untreated and chemically treated manure.

Sample ID*	**pH**	**EC**	**TS**	**TOC**	**TP**	**TN**	**DRP**	**Ca/P**	**Al/P**	**Fe/P**	**Mg/P**
		mS/cm	%	%	mg/kg	mg/kg	mg/kg	molar ratio			
UM	8.49	13.7	3.2	1.06	300	955.8	64.3	2.73	0.07	0.05	2.85
ATM	6.92	5.00	2.0	0.70	197	774.6	0.0	2.04	4.01	0.05	1.68
ITM	7.97	5.36	2.2	0.74	217	814.9	0.0	1.97	0.08	3.55	1.68
LTM	7.79	3.95	6.7	1.58	561	903.8	194.3	10.11	0.09	0.07	2.49

*UM = untreated manure, ATM=Al-treated manure, ITM=Fe-treated manure, and LTM=Ca-treated

Incubation Experiment:

Soil for each treatment (75 g) and all incubation times (1800 g) was transferred into a large plastic bowl. Two-third of the water required (based on 50 % water holding capacity) was initially added to the soil and mixed thoroughly to form a uniform soil-water mixture. Appropriate amount of untreated or treated manure was diluted with the remaining portion of water and spread uniformly on the soil and then thoroughly mixed. For fertilizer treatment, MCP was dissolved in water and the solution was then mixed thoroughly with the soil. Treated soil mixtures were then transferred into 125 mL PP jars. Weight of the jar plus treated soil was recorded for moisture control throughout the experiments. Jars were covered with para-film, perforated for air circulation, and incubated in a constant temperature chamber at 25 °C. Moisture content of the soil was kept constant by periodically weighing the jars and adding DI water to compensate for evaporative losses. After each incubation period, corresponding soil samples were air-dried, gently crushed to pass a 2 mm sieve and stored for further analysis.

Phosphorus extraction and determination:

Water-soluble P: 2 g of soil was extracted with 20 mL of DI water. The suspension was shaken for 1 hr in a 40 mL centrifuge tube. At the end of shaking period, supernatant pH was measured and the suspension was centrifuged for 10 min at 10000 rpm and then passed through a 0.45-µm filter. P concentration and EC were measured in the filtrate using the methods described earlier.
Bray and Kurtz P-1: 1.5 g of soil was extracted with 15 mL of extracting solution [0.025 M HCl + 0.03 M NH_4F] (Bray and Kurtz, 1945). The suspension was shaken for 5 min. in a 40 mL centrifuge tube, after which it was centrifuged for 10 min. at 10000 rpm and then passed through 0.45-µm filter. P concentration in the filtrate was determined using the methods described earlier.
Sequential extraction of P: A modification of the fractionation scheme used by Nair et al. (1995) was followed to determine P distribution in different pools for each soil as a function of the treatment type. 2 g of air-dried soil sample was sequentially extracted with 20 mL of 1 M NH_4Cl

(adjusted to pH 7.0; 2 h shaking), 20 mL of NH_4F (pH=8.2; 1 h shaking), 0.1 M NaOH (17 h shaking), and 0.5 M HCl (24 h shaking). The corresponding P fraction extracted by NH_4Cl, NH_4F, NaOH, and HCl has been defined as soluble/loosely bound (Psenner and Pucsko, 1988), Al-bound, Fe-bound, and Ca-bound, respectively. Residual P represents the fraction that is not readily removed by the above extractants and is considered recalcitrant and primarily organic in nature. After each extraction step, the suspension was centrifuged for 15 min. at 15000 rpm and filtered (0.45-μm). Residual P was determined by ashing 0.5 g of the previously extracted soil for 2 h and then solubilizing it with 6 M HCl (Anderson, 1976). Inorganic P (ortho-phosphate) in the various extracts was determined using the methods described earlier. A portion of the NaOH extract was also digested by HNO_3-H_2SO_4 digestion procedure (APHA, 1992) to determine the total NaOH-soluble P, which is the sum of of NaOH-soluble inorganic plus organic P.

RESULTS AND DISCUSSION

Soil pH:

Soil pH varied between 6.85 and 7.65 depending on the treatment type and incubation time, with the former exerting a greater influence. Application of Ca-treated manure increased soil pH (compared to control) under all conditions in proportion to the application rate. With the addition of Ca-treated manure, pH initially decreased slightly between 1 d and 1 w and then remained relatively constant (7.3 to 7.5) for up to 3 months. The initial decrease is likely to be due to nitrification of existing NH_4^+ in the treated manure. Effect of other treatment types on soil pH was dependent on the rate and incubation time. After 1 d incubation, pH in soils receiving manure was higher than that in control. Soil pH, however, dropped sharply between 1 d and 1 or 2 w to values lower than that in control. After 1 or 2 w of incubation, pH in soils receiving untreated or Al and Fe-treated manure remained relatively constant [around neutral] or increased slightly with time. Application of MCP lowered the pH values than those obtained in controls.

Water-soluble P:

As shown in Figures 1 and 2, water-soluble P (WSP) levels are influenced by treatment type, manure application rate, initial soil P level and incubation time. Under all experimental conditions, fertilizer treatment resulted in the highest concentration of WSP. Despite the differences induced by the above variables, a common overall trend with time can be observed. WSP decreased sharply between 1 d and 1 to 2 w and then remained relatively constant or increased gradually up to 3 months. The extent of initial reduction in WSP was controlled by treatment type and application rate with maximum values obtained for the higher rate of untreated manure for all the soils. The initial reduction can be attributed to the reaction of soluble P in untreated or Ca-treated manure or MCP with the mineral components in soils or to the interaction between free Al or Fe in Fe and Al-treated manure (molar ratio of Al/P and Fe/P in Al and Fe-treated manure is 4.01 and 3.55, respectively - Table 2) with soil P via adsorption and/or precipitation. Increase in WSP at longer reaction times could be due to mineralization of organic P and desorption/dissolution from soil colloids and solid phases induced by change in soil pH.

Chemical treatment type effects are manifested differently in soil I (low Bray-1 P level) as compared to soils II and III (high and excessive Bray-1 P levels). Application of untreated and treated manure increased WSP (compared to “control,” which had no manure application and, hence, no fresh P input) from soil I. The magnitude of increase was, however, smaller for application of Fe and Al-treated manure and larger for MCP, Ca-treated and untreated manure and was proportional to the rate of P applied. WSP levels for both application rates followed the particular order: MCP > Ca-treated >> untreated > Al-treated > Fe-treated > control. Increase in WSP due to manure addition to soils has been reported by several researchers (Vivekanandan and Fixen, 1990; Graetz et al.,1999). For soils II and III (high and excessive background P), only application of MCP, Ca-treated and untreated manure increased WSP. Addition of Al and Fe -treated manure decreased WSP levels below those obtained in control samples and were particularly effective at the higher application rates. Our results indicate that treatment with $FeCl_3$ is more effective than with alum in lowering P solubility. Smith et al. (2001) and Dao and Daniel (2002) also reported a significant decrease in soluble P levels in runoff or in soil water extracts after mixing chemically treated (alum, $AlCl_3$ or $FeCl_3$) swine or dairy manure with soils. Our findings highlight the potential of chemical treatment of manure with Al and Fe salts to stabilize P in soils, especially those with high or excessive background levels. WSP from soils II and III is about 1-1.5 order of magnitude larger than that in soil I ("control" in Fig. 1b vs. that in Fig. 1a). Consequently, application of Al- or Fe- treated manure is more effective in lowering WSP from soils II and III than from soil I.

Application of Ca-treated manure, on the other hand, increased WSP in all the 3 soils, since WSP in Ca-treated manure was significantly higher than that in untreated or Al- or Fe-treated manure (Table 2). In addition, a very high Ca/P ratio of 10.11 in Ca-treated manure could have promoted the formation of amorphous Ca-P mineral phases. However, these mineral phases are usually more soluble in neutral to slightly acid soils as compared to Fe and Al phosphates (Lindsay, 1979). Also, the high organic acid content in manure is capable of inhibiting the crystallization of the freshly precipitated Ca-P solids (Grossl and Inskeep, 1991; Harris et al., 1994). Lime treatment of liquid dairy manure is, therefore, a suitable management option for manure application on acid to neutral soils low in bio-available P. Since the initial total and bio-available P content is lower in soil I compared to the other two soils, increase in WSP was relatively greater in soil I.

Bray-1 P:

Effect of treatment type, manure application rate and incubation time on Bray-1 P for soils I, II and III is indicated in Figures 3 and 4. Application of manure, treated manure, or fertilizer increased Bray-1 P concentration of all soils for up to 3 months. This increase was proportional to the application rate for all treatments except for application of Fe-treated manure to soils with high initial soil P level (soils II and III). The magnitude of increase for each application rate was in the order of: MCP > Ca-treated > Al-treated ≥ Untreated > Fe-treated ≥ control. Interestingly, when soil II received Fe-treated manure at the higher application rate, its Bray-1 P was lower than that in control (no P input) after 3 months (Fig. 3b). Higher Bray-1 P levels in soils receiving Ca or Al treated manure compared to those applied with untreated or Fe-treated manure can be attributed to the nature of the extractants used (0.03 M NH_4F+ 0.025 M HCl), which reacts more strongly with Ca-P and Al-P.

Bray 1-P decreased between 1 d and 1-2 weeks for all the treatments and soils used. It then increased with a decreasing gentle slope for up to 3 months. The initial decrease is due to the reaction of soluble P in manure/fertilizer with the mineral components in soils or the interaction between free Al, Fe, or Ca in treated manure with soil P via adsorption and/or precipitation. Subsequent increase in Bray-1 P could have been caused by the mineralization of organic P and/or desorption or dissolution of inorganic P influenced by changes in soil pH. Application of Fe-treated manure is highly effective in decreasing water-soluble and Bray-1 P. On the other hand, soils receiving lime-treated had elevated levels of water-soluble and Bray-1 P. Application of Al-treated manure is more effective in lowering water-soluble P.

Phosphorus Fractionation:

Distribution of soil P among various fractions, as influenced by treatment type, after 1 d incubation is shown in Table 3. For all soils, irrespective of treatment type, residual P was the dominant fraction. Although the concentration (mg P/kg soil) in the residual fraction was

Table 3. Effect of treatment type on P fractionation after one day incubation.

Treatment	Exch-P		Al-P		Fe-P		Org-P		Ca-P		Residual		Total
	(mg/kg)	(%)	(mg/kg	(%)	(mg/kg)	(%)	(mg/kg)	(%)	(mg/kg	(%)	(mg/kg)	(%)	(mg/kg)
	Soil I												
Cont.	0.81	0.20	6.54	1.59	33.03	8.05	56.74	13.84	28.21	6.88	285.52	69.45	452.63
M-L	0.89	0.23	8.83	2.31	37.30	9.75	56.23	14.70	29.24	7.64	250.19	65.37	426.84
M-H	1.19	0.29	10.67	2.62	38.53	9.46	55.76	13.66	29.76	7.30	272.06	66.68	453.29
ATM-L	1.05	0.27	8.27	2.11	34.92	8.91	58.03	14.77	27.54	7.02	262.76	66.92	435.84
ATM-H	1.18	0.30	12.09	3.03	41.65	10.47	51.62	12.94	27.87	6.99	265.40	66.28	444.62
ITM-L	1.12	0.30	6.29	1.71	36.39	9.93	52.99	14.44	26.28	7.18	243.92	66.43	408.00
ITM-H	1.20	0.32	7.59	2.01	44.12	11.70	48.33	12.82	27.67	7.33	248.51	65.82	420.40
LTM-L	1.43	0.39	7.72	2.10	34.97	9.54	45.46	12.32	25.93	7.06	252.23	68.60	406.24
LTM-H	1.99	0.52	12.49	3.29	43.00	11.33	41.45	10.87	30.39	7.99	251.24	65.99	423.67
Average	1.21	0.31	8.94	2.31	38.21	9.90	51.85	13.37	28.10	7.27	259.09	66.84	430.17
	Soil II												
Cont.	2.50	0.48	46.27	8.94	89.43	17.30	89.87	17.37	50.88	9.84	238.30	46.08	610.22
M-L	3.60	0.68	52.34	9.83	87.20	16.38	95.43	17.86	50.93	9.54	244.96	45.72	630.95
M-H	4.50	0.80	56.91	10.16	88.90	15.86	104.40	18.63	53.86	9.62	251.59	44.93	663.01
ATM-L	2.67	0.50	51.12	9.62	85.38	16.07	94.55	17.80	54.84	10.33	242.56	45.67	627.31
ATM-H	2.86	0.51	54.56	9.63	92.45	16.33	88.16	15.55	53.64	9.47	275.27	48.51	664.15
ITM-L	2.59	0.49	43.91	8.31	93.81	17.74	86.89	16.43	60.37	11.40	241.79	45.64	625.22
ITM-H	2.44	0.43	45.29	8.07	98.04	17.44	104.45	18.53	61.44	10.94	250.57	44.59	666.12
LTM-L	4.21	0.79	52.89	9.96	83.42	15.71	88.66	16.70	57.51	10.83	244.29	46.00	626.55
LTM-H	6.40	1.22	58.98	11.23	85.24	16.26	96.03	18.33	59.94	11.43	218.71	41.53	627.49
Average	3.53	0.66	51.36	9.53	89.32	16.57	94.27	17.47	55.93	10.38	245.34	45.41	637.89
	Soil III												
Cont.	4.55	0.76	61.73	10.27	123.21	20.49	67.37	11.21	74.87	12.46	269.48	44.82	711.80
M-L	6.04	0.99	63.58	10.46	114.35	18.81	81.31	13.39	74.26	12.22	268.16	44.13	720.86
M-H	8.03	1.29	68.43	11.02	103.93	16.73	92.08	14.82	77.11	12.42	271.46	43.71	737.57
ATM-L	4.79	0.81	63.17	10.64	106.17	17.91	81.80	13.76	78.27	13.18	259.85	43.70	705.45
ATM-H	4.91	0.80	71.66	11.62	115.62	18.75	73.45	11.90	78.08	12.66	272.92	44.27	731.21
ITM-L	4.76	0.81	60.29	10.27	111.06	18.93	86.48	14.73	80.05	13.64	244.28	41.61	701.12
ITM-H	4.65	0.74	62.23	9.95	117.60	18.78	86.36	13.81	84.07	13.42	271.44	43.29	744.65
LTM-L	7.00	1.19	68.57	11.66	109.53	18.62	77.50	13.16	80.38	13.67	245.53	41.70	702.85
LTM-H	10.77	1.79	76.96	12.80	102.36	17.07	85.31	14.17	81.06	13.49	244.50	40.68	719.76
Average	6.17	1.02	66.29	10.97	111.54	18.46	81.30	13.44	78.68	13.02	260.85	43.10	719.47

Cont. - Control
M-L - untreated manure (low)*
M-H - untreated manure (high)*
ATM-L - Al-treated manure (low)
ATM-H - Al-treated manure (high)
ITM-L - Fe-treated manure (low)
ITM-H - Fe-treated manure (high)
LTM-L - Ca-treated manure (low)
LTM-H - Ca-treated manure (high)
*low and high correspond to manure application rates

comparable for the three soils, a significantly higher percentage of P could not be extracted from soil I (lowest total P content, Table 1) compared to soils II and III. These soils were obtained from the same farm and as shown in Table 1 possess similar textural properties, N and organic carbon content, and pH but have different background P levels. Manure and fertilizer application during several years of agricultural production activities have resulted in higher total P content in soils II and III, as well as P distribution in other fractions. Accumulation of P in soils II and III resulted in an increase in soluble and exchangeable P (2-3 times), Al-P (4-5 times), Fe-P (1.5-2 times), org-P (1-1.5 times) and Ca-P (1.3-2 times). However, there was no increase in residual P indicating that P added to soil through fertilizer and manure contributes mostly to Al-P and to a lesser degree to the other fractions. Tran and N'dayegamiye (1995) report similar results from a long-term trial involving manure and fertilizer application on an eastern Quebec silt loam soil.

The amount of P added to the soils in our incubation experiments (12.5 - 25 mg/kg) constitutes a small portion when compared to their background total P level (422.5 - 697.2 mg P/kg). Therefore, the effect of treatment type on total soil P or its distribution among different fractions will not be significant, and in some cases can be expected to be masked by the experimental error. Application of manure or treated manure impacted only the soluble and exchangeable P fractions in all soils and Al-P content in soil I. Soluble and exchangeable P fraction (0.2 to 0.76 % of total P) increased with manure application, but only the addition of untreated or Ca-treated manure resulted in a proportional increase with application rate. The overall increase in soluble P followed this particular order: Ca-treated > untreated > Al-treated ≥ Fe-treated. Compared to control (no manure application), the Al-P content of soil I exhibited a slight increase for high rates of untreated, Al-treated and Ca-treated manure addition. Soils II and III have a much higher percentage of P associated with Al and, therefore, an appreciable increase in Al-P was not obtained with manure addition.

Acknowledgments:
Financial support for this project provided by the Wisconsin Fertilizer Research Program is gratefully acknowledged.

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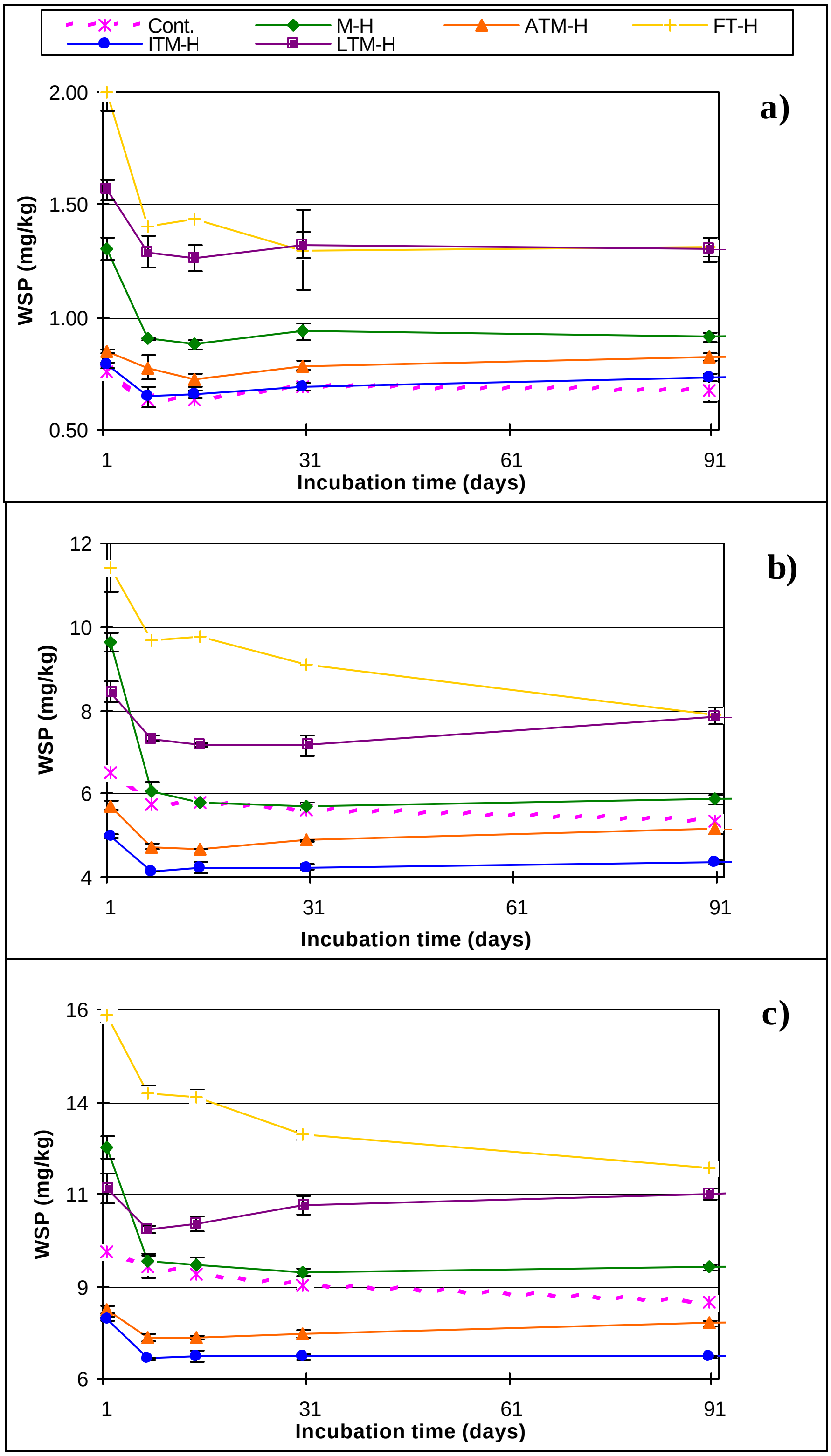

Figure 1. Effect of treatment type on water-soluble P (WSP) for soil I (a), soil II (b), and soil III (c) at the higher manure application rate. [Cont.-control; M-H – manure-high*; ATM-H – Al-treated manure-high; ITM-H – Fe-treated manure-high; LTM-H – Ca-treated manure-high; FT-H - MCP-high; *high corresponds to manure application rate].

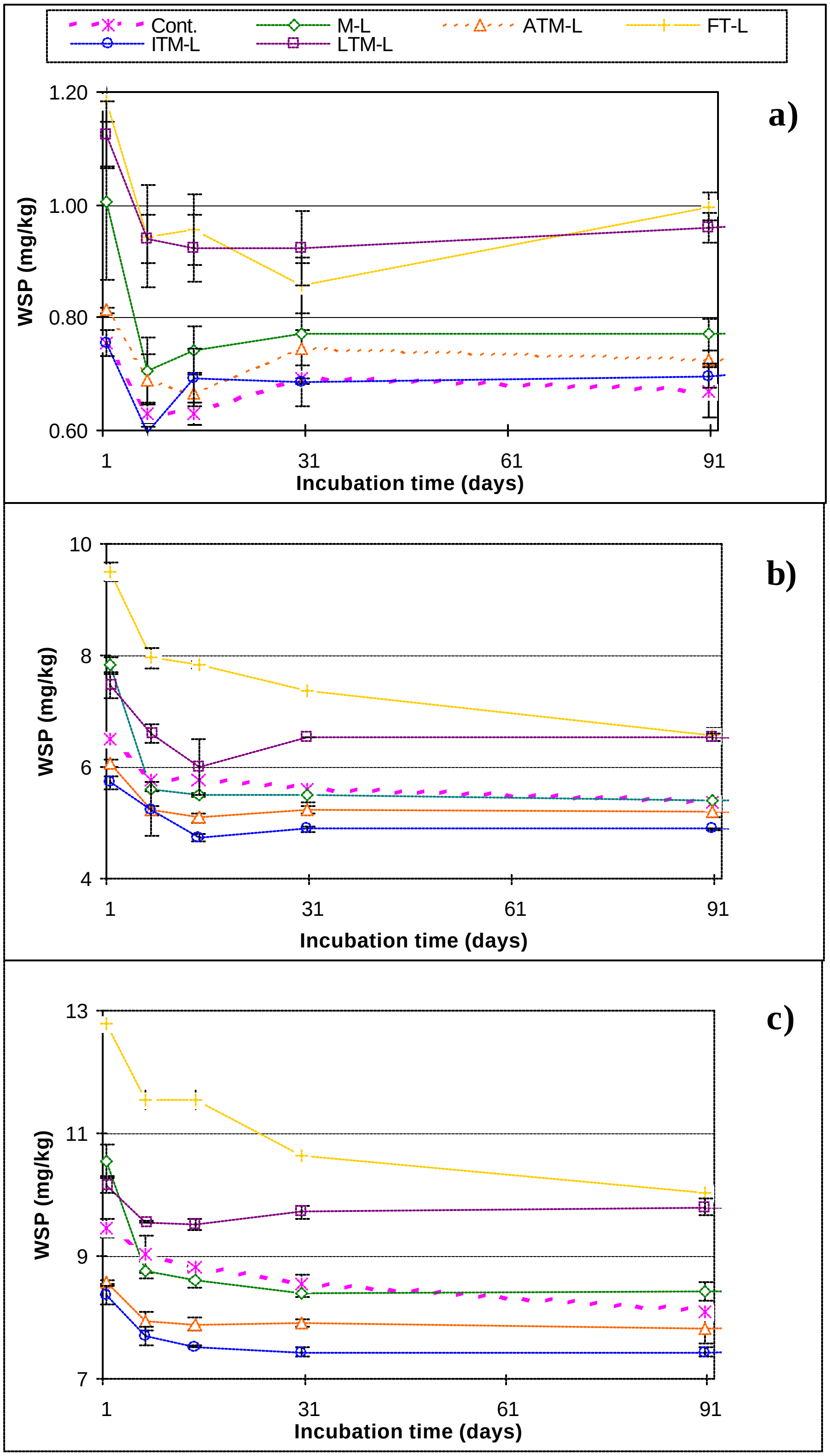

Figure 2. Effect of treatment type on water-soluble P (WSP) for soil I (a), soil II (b), and soil III (c) at the lower manure application rate. [Cont.-control; M-L – manure-low*; ATM-L – Al-treated manure - low; ITM-L – Fe-treated manure - low; LTM-L – Ca-treated manure-low; FT-L - MCP-low; * low corresponds to manure application rate].

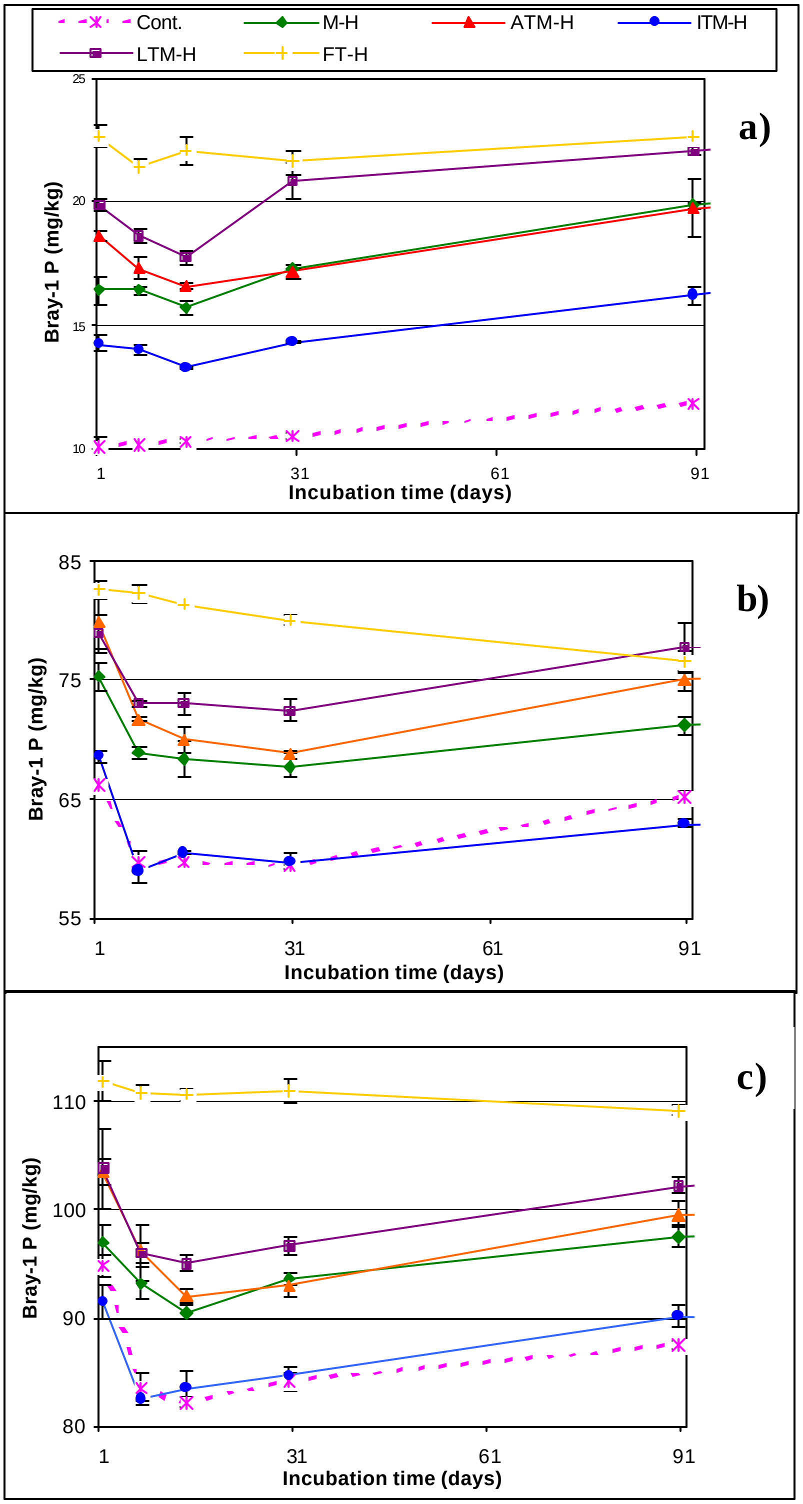

Figure 3. Effect of treatment type on Bray-1 P for soil I (a), soil II (b), and soil III (c) at the higher manure application rate. [Cont.-control; M-H – manure-high*; ATM-H – Al-treated manure-high; ITM-H – Fe-treated manure-high; LTM-H – Ca-treated manure-high; FT-H - MCP-high; *high corresponds to manure application rate].

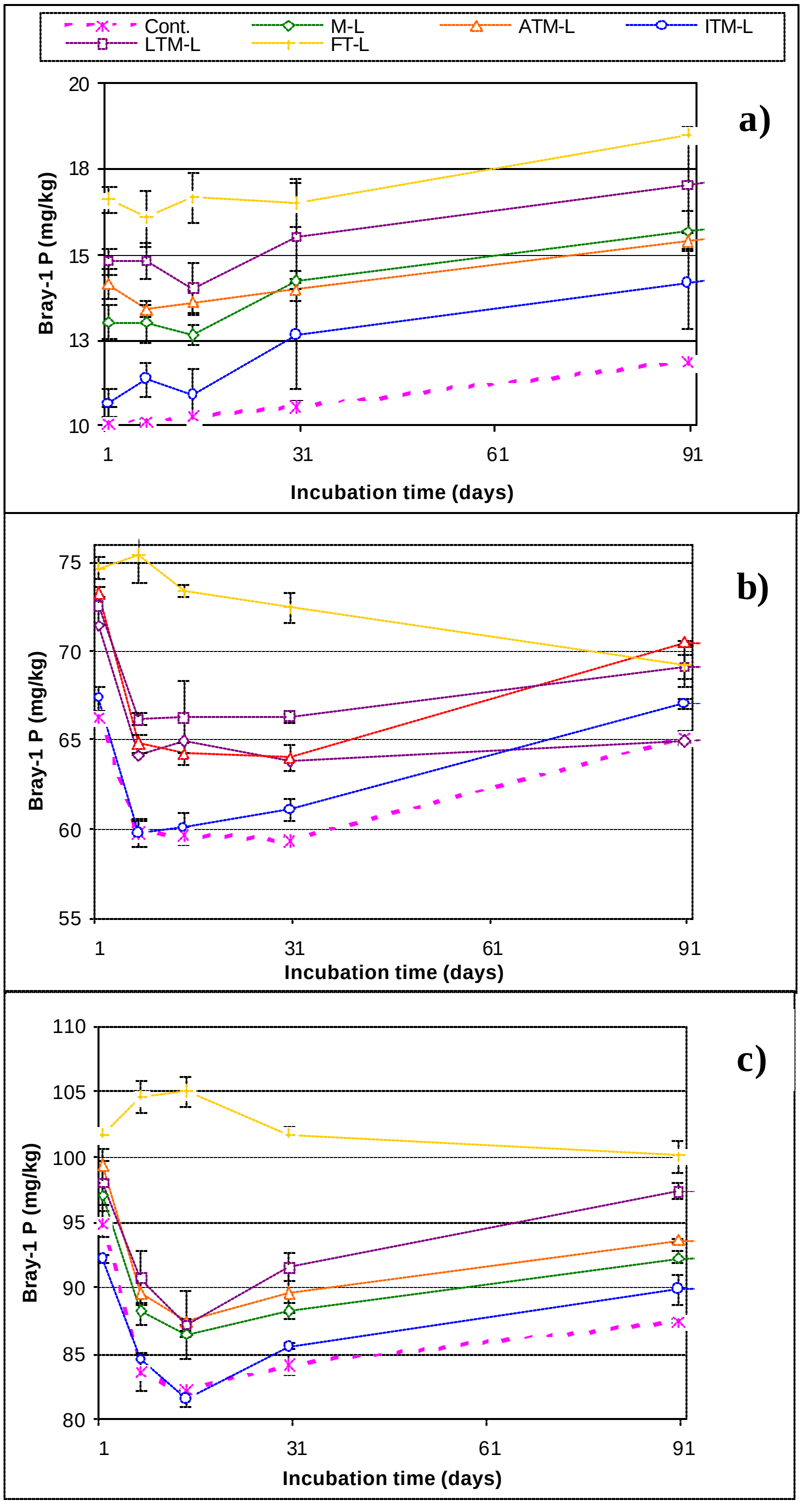

Figure 4. Effect of treatment type on Bray-1 P for soil I (a), soil II (b), and soil III (c) at the lower manure application rate. [Cont.-control; M-L – manure-low*; ATM-L – Al-treated manure - low; ITM-L – Fe-treated manure - low; LTM-L – Ca-treated manure-low; FT-L - MCP-low; * low corresponds to manure application rate].