FINAL REPORT

CHARACTERIZATION OF MILORGANITE® 6-2-0 BIOSOLIDS RELATING TO PHOSPHORUS POTENTIAL FOR SOIL WATER MOVEMENT

EXECUTIVE SUMMARY

2008

George A. O'Connor, PI
Sampson Agyin-Birikorang
Matt Miller
Sarah Chinault

EXECUTIVE SUMMARY

Concern that phosphorus (P) from land-applied biosolids can contribute to accelerated eutrophication of surface waters has led to increasingly stringent regulation of land-based recycling programs. Regulators are implementing P-based nutrient management tools, like the P-index, to reduce non-point source P pollution. The complexity of P-indices varies greatly among states, and many state P-indices do not account for environmental risk differences among P-sources. If biosolids are shown to represent less environmental P risk than fertilizers and manures, state P-indices should incorporate factors that acknowledge the unique P release characteristics of biosolids.

P-based nutrient management mandates P-source application rates based on crop P demands (P-based rates). Biosolids are usually applied to meet crop nitrogen (N) demands (N-based rates), and mandating the much smaller P-based application rates (typically ≤ 2 Mg ha^{-1}) could severely constrain land-based recycling programs. Biosolids application rates in excess of fertilizer-P recommendations are justified if biosolids-P is less agronomically effective (phytoavailable) than fertilizer-P; thus, determining the plant availability of biosolids-P relative to fertilizer-P is critically important. The overall objective of this project was to utilize laboratory characterizations, rainfall simulation studies, and greenhouse studies to characterize the environmental risk and agronomic effectiveness of a variety of biosolids (including Milorganite). Additional isotherm studies were also conducted to investigate the potential of Milorganite to act a P sorbent and to reduce solution P concentrations supplied by inorganic fertilizers.

The details of the various experiments conducted are attached:

1) An electronic copy (.pdf file) of a recent MS thesis by Matt Miller (*The long-term lability of biosoids-P*)
2) Recent publications by Chinault and O'Connor (*Phosphorus release from a biosolids-amended sandy Spodosol*), Agyin-Birikorang and O'Connor (*Evaluating phosphorus loss from a Florida spodosol as affected by P-source application*), and Alleoni et al. (*Runoff and leachate losses of phosphorus in a sandy Spodosol amended with biosolids*)
3) Summary reports for the P sorption/desorption isotherm and rainfall simulation studies.

This executive summary presents the results and conclusions of these studies in an abbreviated form.

Laboratory Characterizations

The physical and chemical properties of several biosolids produced and/or marketed in Florida, including Milorganite, were determined (Tables ES-1 and ES-2). Of particular interest were biosolids percent water extractable P (PWEP) values, which describe the fraction of total P that is water soluble. Brandt et al. (2004) suggested that biosolids PWEP values are useful indicators of environmental P loss potential, and found that the PWEP values for conventional biosolids are less than fertilizers, manures, and biosolids produced with biological P removal (BPR) processes. The Milorganite PWEP value (0.58%) is substantially less than the PWEP value for triple super phosphate (TSP) fertilizer (85%; Table ES-2). Biosolids phosphorus saturation index (PSI) is the molar ratio of oxalate extractable-P to oxalate extractable iron (Fe) and aluminum (Al). Elliott et al. (2002) suggested that biosolids PSI values qualitatively gauge the P leaching potential of biosolids, and that biosolids with PSI values ≤ 1.1 pose minimal environmental P risk. Both the PWEP and PSI values for Milorganite (Table ES-2) suggest that Milorganite is a low environmental P risk biosolids. A detailed description of the laboratory characterizations is found in Chinault (2007).

Table ES-1. Selected chemical and physical properties of several biosolids produced and/or marketed in Florida and TSP fertilizer.

Material	C	N Average	N Producer[‡]	C to N ratio	Solids	LOI	pH	EC	Fe	Al	Ca
	--------------g kg^{-1}	----------			------%	-----		us cm^{-1}	---------g kg^{-1}	---------	
Milorganite	360	60	60	6.0	95	72	6.3	2900	38	9.0	15
Milorganite Greens Grade	370	62	60	5.9	95	74	6	3630	45	6.1	19
Broward County*	390	53	69	7.3	13	74	7.9	3570	16	6.6	39
Jacksonville*	390	57	60	6.8	20	76	8.2	3170	11	7.1	24
GreenEdge	350	50	52	7.0	93	71	6.9	2600	15	8.4	25
Lakeland Glendale	170	30•	24	5.7	35•	17	12•	6200	2.2•	3.16•	310•
Lakeland Northside*	380	59	70	6.4	3	75	8.5	6550	4.5	11	22
Baltimore	300	43	52	7.1	87	61	5.9	2300	60	24	15
Clay Fleming	340	55	44	6.2	2	69	7.8	245	51	9.0	13
Clay Miller	350	54	ND	6.3	19	64	9.3	932	6.6	6.8	119
Orange County South*	380	60	71	6.3	11	76	7.8	2750	5.4	5.6	24
Orange County East Cake*	430	70	82	6.2	16	84	5.9	2700	2.2	7.7	17
Orange County East Dry	430	70	ND	6.2	95	84	5.9	1069	1.9	7.5	17
Tampa	410	56	52	7.4	96	76	7.1	743	8.8	8.8	42
West Palm Beach Compost	420	16	ND	26	64	56	6.5	2200	UK	UK	UK
Disney Compost*	410	28	22	15	66	77	5.7	5190	14	1.7	16
Pinellas Cake	310	43	54	7.3	24	68	7.5	1173	27	15	27
Pinellas Dry	320	48	62	6.8	92	69	6.9	1157	28	19	35
Tallahassee Smith	430	65	41	6.6	98	20	5.9	1673	8	13	26
Orlando City*	280	42	51	6.6	20	49	13	7730	2.6	3.5	159
Boca Raton*	370	62	50	6.0	13	76	7.5	3390	12	6.4	25
GRU*	400	64	62	6.2	5	80	6.4	1108	7.7	5.5	14
Ocala	ND	ND	ND	ND	93	ND	5.9	1833	11	9.8	20
TSP	ND	ND	ND	ND	92	21	5.9	ND	16	10	140

[a]Producer-supplied data. [b]LOI = loss on ignition. [c]Data from Brandt and Elliott, 2005. [d]NP = not provided. [e]ND = not determined.
[f]TSP data from O'Connor et al. (2004). Bolded materials used in glasshouse study.

Table ES-2. Selected measures of P for several biosolids produced and/or marketed in Florida and TSP fertilizer.

Material	Total P Determined	Total P Producer	Fe-Strip P	WEP	PWEP	Oxalate Extractable P	Oxalate Extractable Al	Oxalate Extractable Fe	PSI
	g kg^{-1}				%	g kg^{-1}			
Milorganite	21	23	0.08	0.12	0.58	16	1.2	25	1.0
Milorganite Greens Grade	20	23	ND	0.19	0.85	15	1.4	24	1.0
Broward County	20	19	0.08	1.3	6.7	18	6.0	5.0	2.0
Jacksonville	15	20	0.05	0.31	2.0	13	10	5.0	1.2
GreenEdge	17	19	0.12	0.19	1.1	13	5	13	1.0
Lakeland Glendale	11†	ND	ND	0.08†	0.92†	1.9	0.4	0.4	2.7
Lakeland NS	29	29	0.35	14	47	22	3.2	8.3	2.0
Baltimore	23	27	ND	0.04	0.15	21	12	52	0.5
Clay Fleming	31	18	ND	0.47	1.4	32	8.1	52	0.8
Clay Miller	16	ND	ND	0.04	0.23	4.2	1.4	1.8	1.6
Orange County South	23	30	0.14	4.8	21	23	5.0	4.4	2.9
Orange County East Cake	20	23	0.34	8.0	41	17	1.3	3.1	4.1
Orange County East Dry	23	23	1.4	2.7	11	22	4.5	1.1	3.8
Tampa	21	25	0.29	0.07	0.29	17	5.6	6.0	1.8
West Palm Beach Compost	7.9	ND	ND	0.71	8.1	9.1	1.8	6.5	1.6
Disney Compost	11	27	0.95	0.02	8.4	11	7	20.0	0.6
Pinellas Cake	31	41	ND	0.27	0.78	30	11	12	1.6
Pinellas Dry	33	41	0.11	0.16	0.44	27	14	32	0.8
Tallahassee Smith	21	31	ND	1.4	6.1	19	6.5	5.2	1.8
Orlando City	17	20	0.003	0.04	0.23	13	1.7	2.4	NA
Boca Raton	26	39	0.02	3.9	15	33	14	7.3	2.1
GRU	31	48	1.7	7.9	26	21	6.4	3.7	2.1
Ocala	21	28	0.74	0.63	3	20	11	5.6	1.5
TSP	190	210	ND	170	85	186	11	6.8	NA

[a]Producer supplied data. [b]WEP = water-extractable P. [c]PWEP = (WEP/biosolids-TP*100). [d]PSI = phosphorus saturation index = [moles of oxalate-extractable P/(moles of oxalate extractable Fe + Al)]. [e]ND = not determined. [f]Data from Brandt and Elliott, 2005. [g]NA = not applicable. Bolded materials used in glasshouse study.

A laboratory incubation study was conducted to confirm the P release differences suggested by the laboratory characterizations, and to determine the P leaching risk (environmental lability) of biosolids. The laboratory incubation study utilized an unvegetated, sandy Florida soil (Immokalee fine sand) with minimal capacity to retain P so that the P leaching characterization represented a "worst-case" scenario. Periodic leaching continued until the data suggested "ultimate" P leaching risks were characterized.

Overall, conventional biosolids posed less P leaching risk than TSP fertilizer; however, the P leaching risks of BPR biosolids and biosolids with BPR like characteristics (BPR-like biosolids) were similar to TSP fertilizer. Milorganite leached (released) the least amount of P at both P-based and N-based application rates. Less than 20% of the total-P applied leached for N-based Milorganite treatments (Fig. ES-1), suggesting that most Milorganite-P is ultimately insoluble and will not leach. The laboratory incubation study confirmed that PWEP and PSI values are useful qualitative gauges of the P leaching potential of biosolids; P leaching risks increased considerably for biosolids possessing PWEP values $\geq$ 14% and PSI values $\geq$ 2.0. Chinault (2007) and Chinault and O'Connor (2008) provide detailed summaries of the laboratory incubation study.

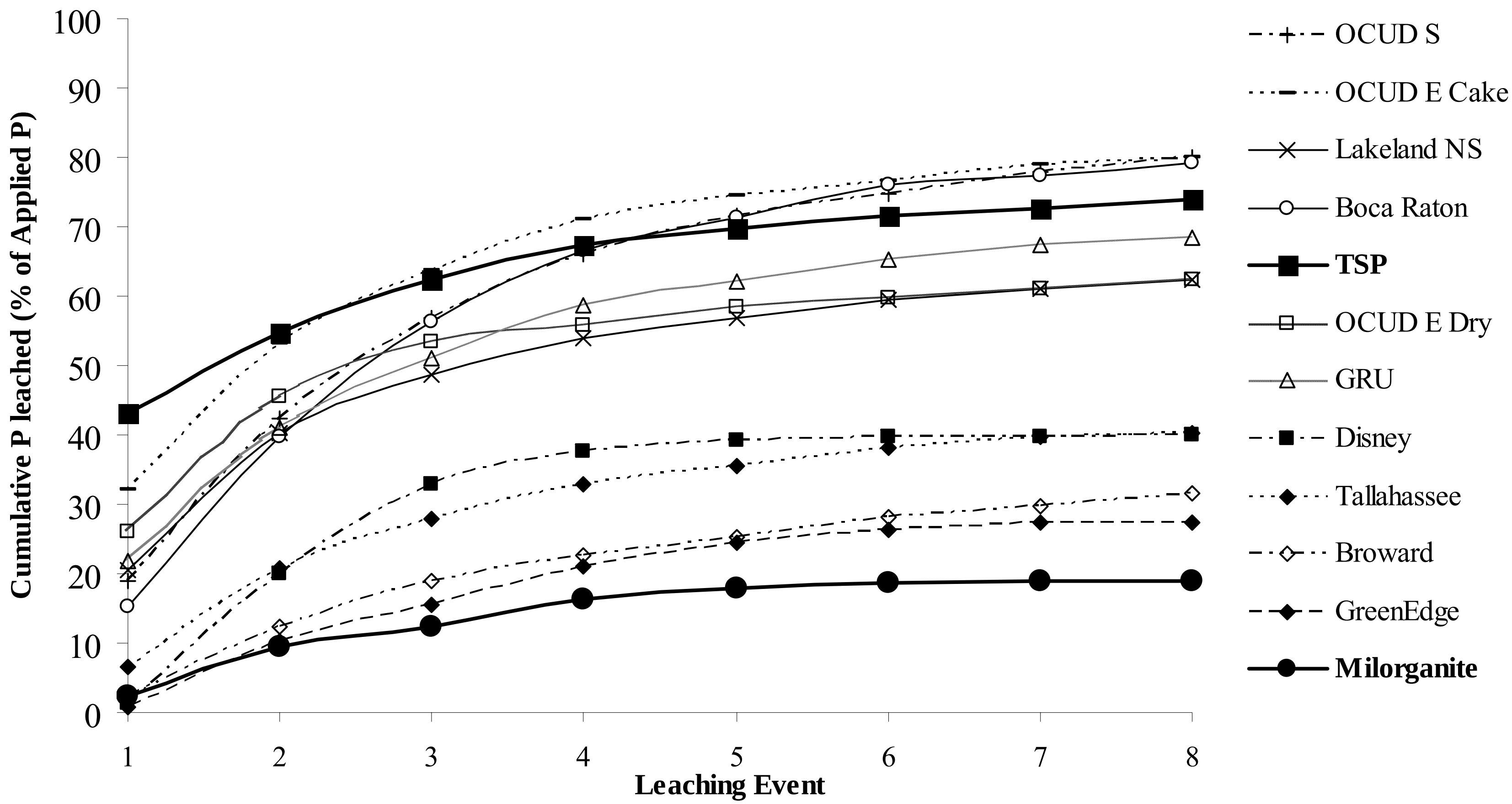

Figure ES-1. Cumulative P released (% of applied P) per leaching event for N-based (224 kg P ha^{-1}) treatments of the dynamic laboratory incubation study.

Greenhouse Studies

A prolonged (16-month) greenhouse study was conducted to determine the agronomic effectiveness (phytoavailability) and environmental lability of biosolids-P. Short-term biosolids-P phytoavailability and environmental lability was determined in an initial 4-month characterization (Chinault, 2007), while the entire 16-month characterization represented long-term biosolids-P phytoavailability and environmental lability (Miller, 2008). The environmental lability characterization for the greenhouse study quantified P leaching from a vegetated, sandy Florida soil (Immokalee fine sand). The short-term and long-term environmental lability characterizations show minimal P leaching risk for Milorganite; in fact, P leaching from Milorganite treatments was not significantly different from control treatments. Leaching of P was minimal for all P-sources at the P-based application rate. At the N-based rate, P leaching varied with P-source: TSP fertilizer > BPR-biosolids and BPR-like biosolids >> conventional biosolids.

Phosphorus uptake data from the greenhouse studies were used to determine the phytoavailability of biosolids-P compared to TSP fertilizer-P. The relative P phytoavailability (RPP) determinations suggest that the short-term phytoavailability of conventional biosolids-P is about 25-50% that of TSP-P (Milorganite-P was about 25-30% as phytoavailable as TSP-P). The BPR and BPR-like biosolids-P were about equally as phytoavailable as TSP-P (Table ES-3). The long-term RPP determinations suggest that conventional biosolids-P are ultimately about 50-70% as phytoavailable as TSP-P and that Milorganite is ultimately about 50% as phytoavailable. Milorganite applications rates about twice that of TSP are needed to supply plant available-P in quantities equal to TSP fertilizer.

Table ES-3. Various estimates of biosolids relative P phytoavailability (RPP) determined after 4 harvests (short-term) and 12 harvests[Ŧ] (long-term).

	Short-term Estimates			Long-term Estimates		
P Source	Point RPP (%)	Slope-Ratio RPP (%)	RPP Category[†]	Point RPP (%)	Slope-Ratio RPP (%)	RPP Category[†]
TSP	100	100	High	100	100	High
Milorganite	31	26	Mod.	52	46	Mod.
Greenedge	49	47	Mod.	71	68	Mod.
Disney	62	56	Mod.	83	79	High
GRU	92	93	High	96	98	High
Boca Raton	92	91	High	115	116	High
Lakeland NS	96	93	High	109	100	High
OCUD S	110	110	High	130	131	High

Ŧ RPP estimates for 56 kg P ha^{-1} rate amended columns were determined after 11 harvests
† RPP category as suggested by O'Connor et al. (2004)

Measures of P that are used to determine the phytoavailability of fertilizer-P (neutral ammonium citrate extraction) are not useful for biosolids (Elliott et al., 2005), and currently, no *a priori* measure of biosolids-P exists to quantitatively distinguish P phytoavailability differences among biosolids. Several measures of biosolids-P were correlated to cumulative P uptake in the prolonged greenhouse study to identify the best measure of biosolids-P phytoavailability. Biosolids PSI values multiplied by the total-P load (termed the labile P load) were strongly correlated ($r^2 = 0.85$) to cumulative P uptake, suggesting that biosolids PSI values are a useful *a priori* tool for estimating biosolids-P phytoavailability. The usefulness of biosolids PSI values was further validated by showing that biosolids PSI values were well correlated ($r^2 = 0.70$) to biosolids RPP values determined in related short-term and long-term studies utilizing a wide range of biosolids (Fig. ES-2). Biosolids PSI values are not useful for distinguishing P phytoavailability differences in soils that are not responsive to P additions (soils already high in soil test P or soils with appreciable capacity to fix P), or in Ca-dominated (lime-stabilized) biosolids.

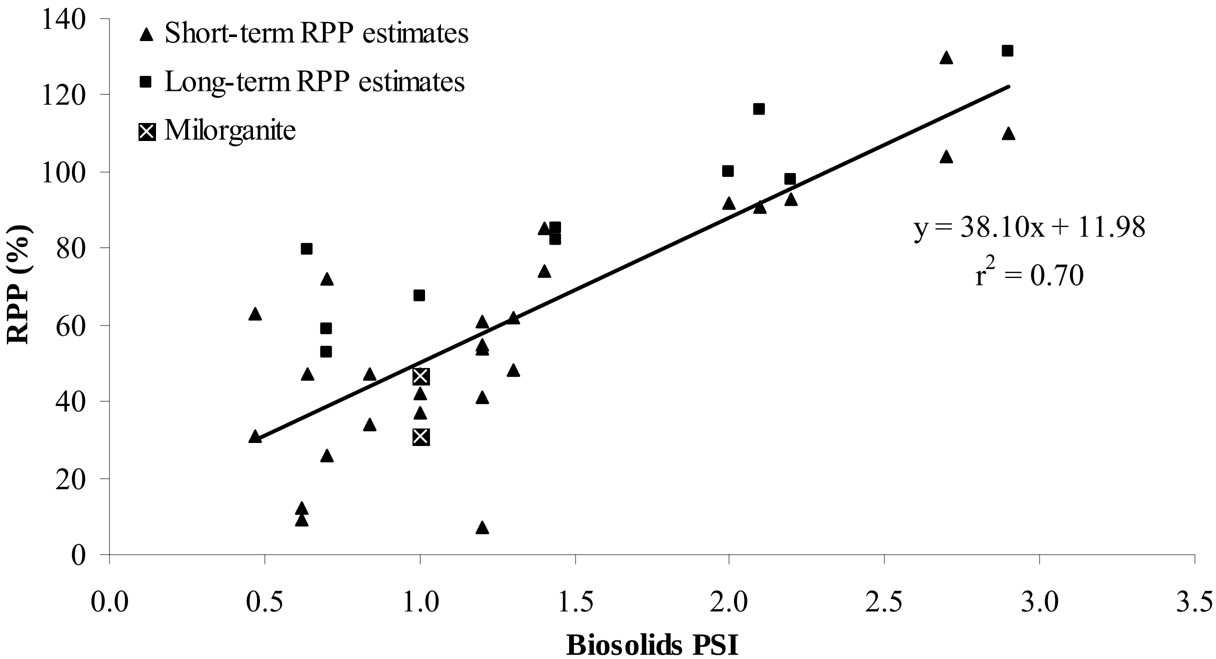

Figure ES-2. Long-term (Oladeji, 2006; Miller, 2008) and short-term estimates (O'Connor et al., 2004; Chinault, 2007) of biosolids relative P phytoavailability (RPP) values as a function of biosolids phosphorus saturation index (PSI) values. The linear regression equation and r^2 value include data for all biosolids utilized in the long-term and short-term studies; data for Milorganite treatments are specifically identified.

Phosphorus leaching and plant uptake in the prolonged greenhouse study were combined in a measure termed "overall P lability" to indicate the fraction of biosolids-P that is ultimately biologically and environmentally available (labile). The overall P lability of Milorganite was significantly less than TSP, and BPR and BPR-like biosolids. Data suggest that conventional biosolids-P (including Milorganite) is ultimately about 40-55% as labile as TSP-P, whereas BPR and BPR-like biosolids are about 90-115% as labile as TSP. A very strong relationship ($r^2 = 0.90$) existed between the labile P load (biosolids PSI*total-P load) and biosolids overall P lability (Fig. ES-3), suggesting that biosolids PSI is useful for quantitatively distinguishing ultimate P lability differences among biosolids. A complete summary of the prolonged (16-month) greenhouse study is found in Miller (2008) (attached).

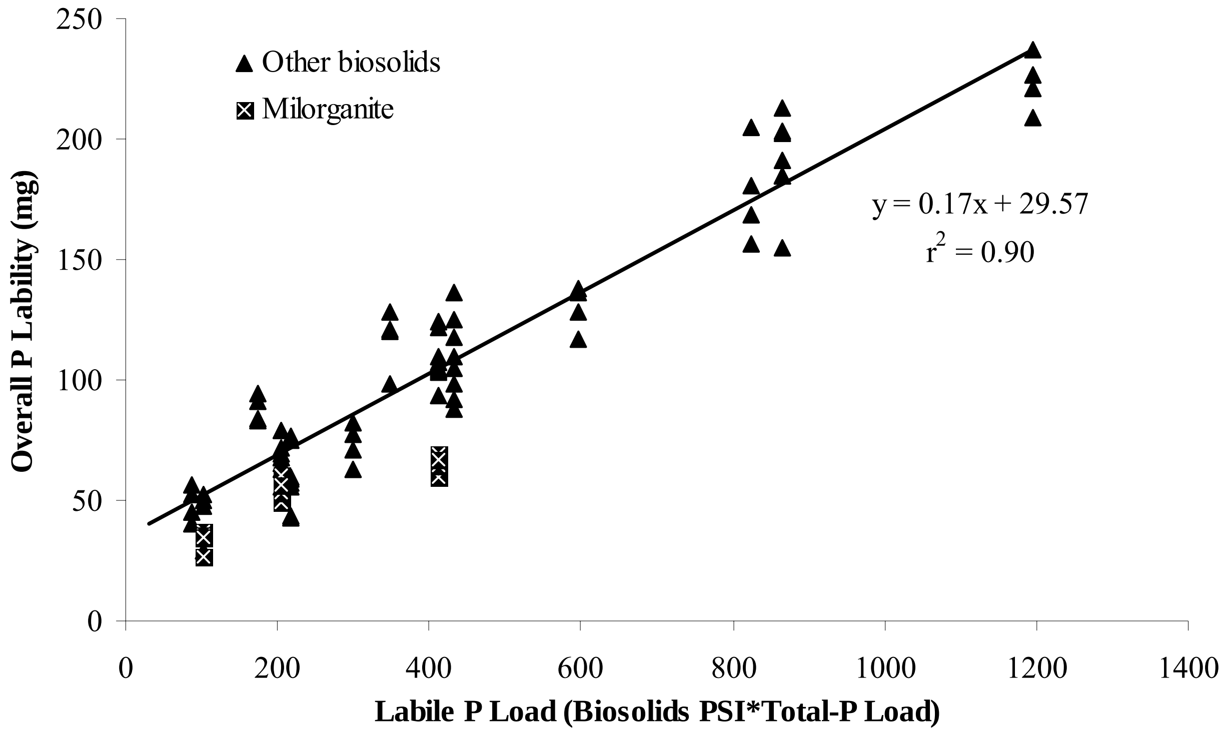

Figure ES-3. Overall P lability (P leaching and plant uptake) plotted as a function of the labile P load. The linear regression equation and r^2 value apply to data for all 7 biosolids (each applied at 3 rates) utilized in the prolonged greenhouse study; data for Milorganite treatments are specifically identified.

Rainfall Simulations

Rainfall simulations were conducted to determine the effect of P-source application method (surface applied or incorporated into the soil) on P loss risks from a sandy, Florida soil (Immokalee fine sand) with minimal capacity to retain P. Total P (TP) loss, total dissolved P (TDP) loss, and soluble reactive P (SRP) loss were quantified in runoff and leachate. Data suggested that P-source solubility controls runoff and leachate P losses from sandy soils with low P retention capacity, and that P-source application method has little effect on P loss risks in such soils. Milorganite-P losses in runoff and leachate were significantly less than in TSP fertilizer and BRP-like biosolids treatments for the surface applied and incorporated application methods. Moreover, soluble reactive P (SRP) losses from Milorganite and control treatments were not statistically different for both application methods. Biosolids PWEP values multiplied by the total P load (termed the environmentally effective P load) were very strongly ($r^2 = 0.94$) correlated to the mass of total dissolved P (TDP) in runoff and leachate, suggesting that biosolids PWEP values are a useful *a priori* measure of the environmental P risk of biosolids applied to sandy, low P retention capacity soils. Agyin-Birikorang and O'Connor (2008) and Alleoni et al. (2008) provide detailed summaries of the rainfall simulation studies on the FL sand.

Another rainfall simulation study was conducted on a vegetated Wisconsin soil (Blount silt loam) that is more representative of soils nationally where Milorganite may be applied. The rainfall study quantified runoff and leachate P loss from surface-applied Milorganite and TSP fertilizer treatments. Milorganite treatments resulted in minimal P loss increase compared to an unamended soil (control treatments), whereas P loss from TSP treatments was ≥10 fold greater than P loss from unamended soil. The growth of P-starved algae is well correlated with P extracted from sediment laden runoff using iron-impregnated strips (ISP) (Sharpley, 1993). Bioavailable P (BAP) was estimated using ISP, and no significant differences in BAP loss existed between the Milorganite-amended and the unamended soil (Fig. ES-4), which suggests applying Milorganite to soils with appreciable P retention capacity does not increase P loss risks compared to a soil receiving no P-source additions. Details are provided in an attached summary.

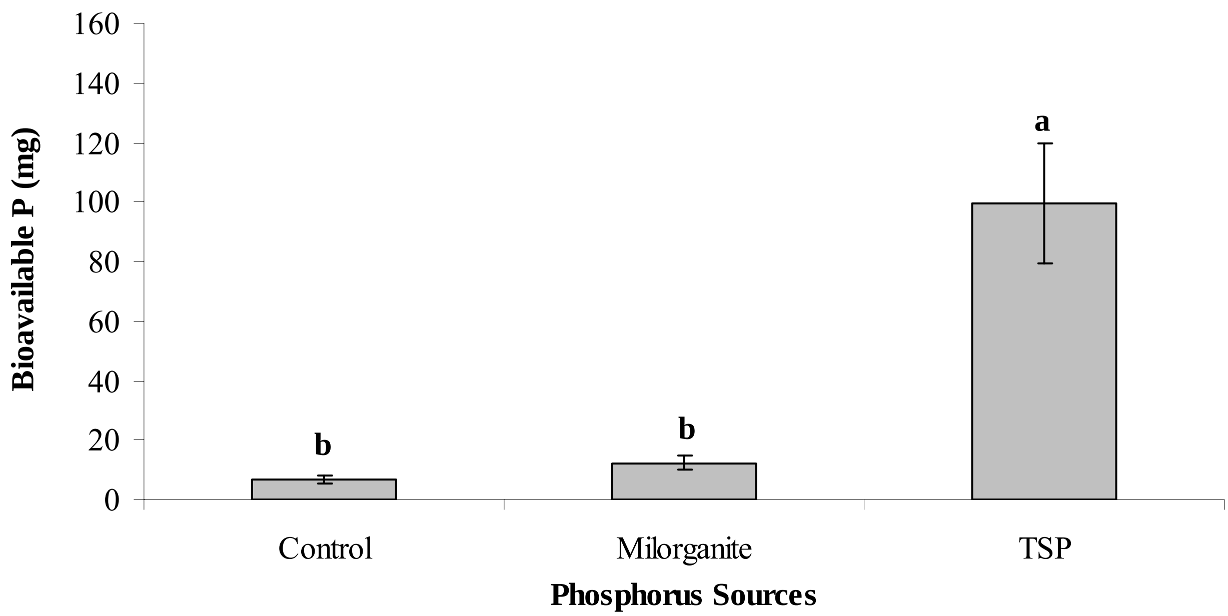

Figure ES-4. Effects of P-source surface application on cumulative runoff and leaching bioavailable P (BAP) loss for 3 rainfall events conducted on a grassed Blount soil. Treatments having the same letter are not significantly different.

Phosphorus Retention Study

Anecdotal evidence from an unpublished study by Cisar and Snyder (2006) suggested that Milorganite could have some capacity to retain soluble P; leachate P concentrations were lower in TSP + Milorganite treatment than a TSP only treatment, even though the same quantity of TSP was used in both treatments. A study, utilizing multiple isotherm experiments, was conducted to investigate the potential of Miloganite to retain soluble P (P sorption) without releasing the retained-P back into solution (P desorption). Phosphorus sorption by Milorganite was linear within an initial solution P concentration range of 0-2000 mg P kg^{-1}, suggesting that

Milorganite has appreciable P retention capacity and the P sorption maxima of Milorganite exceeds 1800 mg P kg^{-1}. A P desorption experiment showed that only ~20% of the P initially retained by Milorganite desorbed, suggesting that P retention by Milorganite is not readily reversible. Milorganite's capacity to retain P was not appreciably affected by varying solution pH values from about 5 to 7 (a pH range common to most soils of agricultural importance). The P sorption study suggests that Milorganite may actually increase the P retention capacity of soils with low native P sorption capacity, while simultaneously supplying enough plant available P to support crops. Details are provided in an attached summary.

CONCLUSIONS

Environmental P management tools, such as the P-index, often do not acknowledge or account for P risk differences that exist among P-sources. Laboratory characterizations showed that biosolids tend be uniformly about 2-3% total P, but P solubility differs greatly among biosolids; Milorganite and some other conventional biosolids contain elevated quantities of Fe and Al that reduce P solubility. Ultimate P leaching risks are considerably less for conventional biosolids compared to BPR and BPR-like biosolids, and inorganic fertilizer. Rainfall simulation studies confirmed that conventional biosolids pose a reduced environmental P hazard; P losses in runoff and leachate: conventional biosolids << BPR and BPR-like biosolids < TSP. A prolonged greenhouse study validated short-term P lability differences, and indicated that the ultimate lability of conventional biosolids-P is about 40-55% that of TSP fertilizer. Regulatory distinctions for conventional biosolids such as Milorganite are justified, and P-indices should account for the reduced environmental risk of such materials by incorporating P-source coefficients that account for P lability differences. Biosolids PSI and PWEP values could be utilized as tools to distinguish P risk differences among biosolids.

Land application programs should also account for the differences in agronomic effectiveness (P phytoavailability) that exist among biosolids. Milorganite and other conventional biosolids are about 25-50% as agronomically effective as TSP fertilizer in the first cropping season and ultimately about 50-75% as agronomically effective as TSP fertilizer. If state P-indices mandate P-based application rates, conventional biosolids should be applied at rates ~2 times greater than fertilizer P recommendations to account for the reduced phytoavailability of conventional biosolids-P.

Literature Cited

Alleoni, L.R.F., S.R. Brinton, and G.A. O'Connor. 2008. Runoff and leachate losses of phosphorus in a sandy Spodosol amended with biosolids. J. Environ. Qual. 37:259-265.

Agyin-Birikorang, S., and G.A. O'Connor. 2008. Evaluating phosphorus loss from a Florida spodosol as affected by P-source application. J. Environ. Qual. 37:1180-1189.

Brandt, R.C., H.A. Elliott, and G.A. O'Connor. 2004. Water-extractable phosphorus in biosolids: implications for land-based recycling. Water Environ. Res. 76:121-129.

Chinault, S.L. 2007. The agronomic and environmental characterization of phosphorus in biosolids produced and/or marketed in Florida. Master's thesis presented to the University of Florida Graduate School, Gainesville, FL.

Chinault, S.L., and G.A. O'Connor. 2008. Phosphorus release from a biosolids-amended sandy Spodosol. J. Environ. Qual. 37:937-943.

Cisar, J.L. and G.H. Snyder. 2006. Effect of Milorganite inclusion in root zone media on grow-in of cv. Tifdwarf Bermudagrass in South Florida. Final Report to Milorganite, Inc.

Elliott, H.A., G.A. O'Connor, and S. Brinton. 2002. Phosphorus leaching of biosolids-amended sandy soils. J. Environ. Qual. 31:681-689.

Elliott, H.A., J.M. Potter, J.H. Kang, R.C. Brandt, and G.A. O'Connor. 2005. Neutral ammonium citrate extraction of biosolids phosphorus. . Commun. Soil Sci. Plt. Anal. 36:2447-2459.

Miller, M. 2008. Characterizing the long-term lability of biosolids-phosphorus. Master's thesis presented to the University of Florida Graduate School, Gainesville, FL.

O'Connor, G.A., D. Sarkar, S.R. Brinton, H.A. Elliott, and F.G. Martin. 2004. Phytoavailability of biosolids phosphorus. J. Environ. Qual. 33:703-712.

Oladeji, O.O. 2006. Management of phosphorus sources and water treatment residuals (WTR) for environmental and agronomic benefits. Dissertation presented to the University of Florida Graduate School, Gainesville, FL.

Sharpley, A.N. 1993. An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron oxide-impregnated paper. J. Environ. Qual. 22:597–601.

LITERATURE PRODUCED FROM THE MILORGANITE®, INC. FUNDED PROJECT

Agyin-Birikorang, S., and G.A. O'Connor. 2008. Evaluating phosphorus loss from a Florida spodosol as affected by P-source application. J. Environ. Qual. 37:1180-1189.

Alleoni, L.R.F., S.R. Brinton, and G.A. O'Connor. 2008. Runoff and leachate losses of phosphorus in a sandy Spodosol amended with biosolids. J. Environ. Qual. 37:259-265.

Chinault, S.L. 2007. The agronomic and environmental characterization of phosphorus in biosolids produced and/or marketed in Florida. Master's thesis presented to the University of Florida Graduate School, Gainesville, FL.

Chinault, S.L., and G.A. O'Connor. 2008. Phosphorus release from a biosolids-amended sandy Spodosol. J. Environ. Qual. 37:937-943.

Miller, M. 2008. Characterizing the long-term lability of biosolids-phosphorus. Master's thesis presented to the University of Florida Graduate School, Gainesville, FL.