

Phosphorus Release from a Biosolids-Amended Sandy Spodosol

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Most regulations governing biosolids land application do not consider that phosphorus (P) solubility can vary widely among biosolids. Current regulations typically group all biosolids together in one category or group biosolids together with manures. Research has shown that not all biosolids have the same potential to affect the environment when land applied, but the database is limited. The purpose of this study was to characterize P release from several biosolids produced and/or marketed in Florida. A small soil column dynamic laboratory incubation was conducted to assess P release potential. Eleven biosolids and a mineral fertilizer (triple super phosphate) were individually mixed with a typical low-P sorbing Florida soil (Immokalee fine sand) at 56 and 224 kg P ha⁻¹. Columns were periodically leached over 5.5 mo to attain 60 mL (1/2 pore volume) of drainage in each leaching. Soluble reactive P was determined and summed over the eight leachings to represent total P source release. Cumulative P release (as a percentage of P applied) was greatest from biological P removal (BPR) and BPR-like biosolids and least from heat-dried materials. Phosphorus release from biosolids depends on biosolids treatment type (digestion) and P chemistry, suggesting that biosolids regulations must account for differences in P lability to accurately gauge environmental risk.

THROUGHOUT history, human and animal wastes have been recycled to agricultural land to supply nutrients for crops. However, the development of centralized wastewater treatment systems and an ever-increasing human population has created biosolids disposal challenges. The USA produced an estimated 6.5×10^6 Mg of biosolids in 2000, and approximately 50 to 60% of biosolids were disposed of via land-based recycling (USEPA, 1999). Biosolids are a source of essential plant elements such as nitrogen (N), phosphorus (P), sulfur (S), and micronutrients. Thus, land-based recycling of biosolids to agricultural land can supply farmers with an economic alternative to chemical fertilizers.

In Florida, biosolids are typically applied to sandy soils used to grow Bahiagrass (*Paspalum notatum*) for beef cattle grazing. Tiffany et al. (2001) concluded that biosolids provide sufficient forage nutrients to meet the needs of grazing beef cattle, providing a means for biosolids disposal.

Although land application of biosolids is beneficial, long-term biosolids application can result in accumulation of soil P (O'Connor et al., 2005; Elliott and O'Connor, 2007). Crops typically require lower quantities of P than N. Because of the mismatch between crop fertility requirements and biosolids nutrient contents, when biosolids are applied at an N-based rate to meet crop N requirements, P is typically oversupplied. The excessive P accumulation is not harmful to crops (Peterson et al., 1994) but could lead to severe environmental problems, especially in poor P-sorbing soils. Off-site migration of P to ground and surface waters is a cause for concern because P is generally the limiting nutrient in fresh water ecosystems for accelerated eutrophication (Carpenter et al., 1998). Phosphorus can migrate off-site in dissolved form as biosolids particles or attached to soil particles (Elliott et al., 2005).

Increased concern over P impacts on water quality has led to amplified scrutiny of biosolids land application programs and recommendations that biosolids application be limited to meet crop P needs (P-based). Limiting biosolids land application to P-based rates (typically <2 Mg biosolids ha⁻¹) is impractical and uneconomical to apply. Low application rates mean more land area is required for disposal, increasing disposal costs. Lower biosolids application rates also mean additional N fertilizer is

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Abbreviations: BPR, biological phosphorus removal; GRU, Gainesville Regional Utilities; Lakeland NS, Lakeland North Side; OCUD E, Orange County Utilities Division East; OCUD S, Orange County Utilities Division South; PSI, phosphorus saturation index; PWEP, percent water-extractable phosphorus; PV, pore volume; SRP, soluble reactive phosphorus; TP, total phosphorus; TSP, triple super phosphate; WEP, water-extractable phosphorus.

Table 1. Biosolids digestion and final treatment.

| Material† | Class‡ | Digestion | BPR§ (Y/N) | Final treatment |
|-------------------|--------|-------------------|------------|-------------------------------------|
| Milorganite | A | aerobic | N | thermally dried |
| Broward | B | anaerobic | N | thickened, dewatered |
| GreenEdge | A | anaerobic | N | thermally dried |
| Lakeland NS | A | aerobic | N¶ | thickened, dewatered, ATAD# system |
| OCUD S Cake | B | anaerobic | N | thickened, dewatered, bio-N removal |
| OCUD E Cake | NA | unstabilized | Y | thickened, dewatered |
| OCUD E Dry | NA | unstabilized | Y | thermally dried |
| Disney compost | AA | composted | Y | composted material |
| Boca Raton | B | anaerobic | Y | thickened, dewatered |
| GRU§ | B | aerobic | N¶ | thickened |
| Tallahassee Smith | A | anaerobic/aerobic | N | thickened, dewatered |

† GRU, Gainesville Regional Utilities; Lakeland NS, Lakeland North Side; OCUD E, Orange County Utilities Division East; OCUD S, Orange County Utilities Division South.

‡ USEPA (1995).

§ Biological phosphorus removal.

¶ BPR-like biosolids.

Autothermal thermophilic aerobic digestion.

required, increasing costs to farmers. Ultimately, P-based application rates could threaten land application programs.

Recent research suggests that limiting biosolids application to P-based rates is probably unnecessary for conventionally produced biosolids (Brandt et al., 2004). Biosolids P is not necessarily as labile (defined herein as agronomically or environmentally available P) as P in mineral fertilizers or manures, and lability can be greatly influenced by the wastewater treatment process (Maguire et al., 2001). Treatment processes such as thermal drying can significantly reduce P lability of biosolids compared with conventionally produced cake (Smith et al., 2002). A possible exception may be biological P removal (BPR) biosolids, in which the wastewater treatment process is engineered to promote luxury uptake of P by bacteria. Although the BPR process reduces P concentrations in wastewater effluent, the resulting biosolids have a higher concentration of P than conventionally produced residuals, and labile P in BPR biosolids can be greater than in conventional or heat-dried biosolids (Elliott et al., 2002; Brandt et al., 2004; O'Connor et al., 2004).

Total P (TP) concentration of biosolids is generally a poor indicator of P lability and phytoavailability. Only a small fraction of P from most conventionally produced biosolids is soluble, making most biosolids less likely to negatively affect the environment compared with soluble P sources (e.g., mineral fertilizer and manures). The water-extractable P (WEP) content of biosolids has been highly correlated to P lability (Brandt et al., 2004). For typical (conventionally produced) biosolids, percent water-extractable P (PWEP = WEP/TP × 100) is <5% (Brandt et al., 2004). Biosolids produced using iron (Fe) and aluminum (Al) salts in the process stream can have less P lability and small PWEP values (<0.5%) (Corey, 1992; Brandt et al., 2004). Biological P removal biosolids typically have greater soluble P concentrations and greater PWEP (≥14%) than conventionally produced biosolids (Brandt et al., 2004).

The P saturation index (PSI) has also been correlated to environmental P leaching risk (Elliott et al., 2002). The PSI is calculated as the molar ratio of oxalate-extractable P to Fe and

Al ($[P_{ox}]/[Al_{ox} + Fe_{ox}]$). When biosolids have PSI values <1.1, little P leaching is expected to occur, even in sandy, low P-sorbing soils (Elliott et al., 2002). Both PWEP and PSI can serve as a priori estimates of biosolids-P lability, and both measures can better estimate how P in biosolids will affect the environment when land applied than biosolids-TP or measures of soil test P that are common in Florida (Maguire et al., 2001; Elliott et al., 2002; Brandt et al., 2004, O'Connor et al., 2004).

The purpose of our experiment was to examine the leaching characteristics of biosolids produced and marketed in Florida applied to a typical Florida sand with minimal P retention capacity.

Materials and Methods

Biosolids Chemical and Physical Analysis

Each P source was analyzed for TP following the digestion method outlined by Andersen (1976). Biosolids were dried and ground before analysis. Biosolids samples (0.2 g) were ashed and treated with 6 mol L⁻¹ HCl. Phosphorus in the digests was determined colorimetrically (Murphy and Riley, 1962). Biosolids total N and total carbon (C) was determined by combustion at 1010°C using a Carlo Erba analyzer (NA-1500 CNS; Carlo Erba, Milan, Italy). Organic matter was determined using the loss on ignition method (Sparks, 1996). Percent solids and pH (1:10 solid to solution) were determined using standard methods (Sparks, 1996). Total Fe, Al, and Ca concentrations were measured on the TP extracts via inductively coupled plasma-atomic emissions spectrophotometry (PerkinElmer Plasma 3200; PerkinElmer, Wellesley, MA).

Water-extractable P (WEP) was determined using a 1:200 biosolids (dry weight equivalent) to distilled, deionized water (Sharpley and Moyer, 2000). The biosolids/water mixture was shaken on an orbital shaker for 1 h. After centrifugation, the supernatant was vacuum filtered through a 0.45-µm filter. The solution was analyzed for P colorimetrically (Murphy and Riley, 1962). Percent WEP (PWEP) was calculated by dividing WEP by TP and multiplying by 100.

Oxalate-extractable P, Fe, and Al concentrations were determined by shaking 0.5 (dry weight equivalent) of biosolids with 30 mL of 0.175 mol L⁻¹ ammonium oxalate and 0.1 mol L⁻¹ oxalic acid for 4 h in a sealed box to avoid exposure to light (Loeppert and Inskeep, 1997). After centrifugation, samples were vacuum filtered through a Whatman #42 filter. The supernatant was analyzed for P, Fe, and Al via ICP. Moles of oxalate-extractable P, Fe, and Al were used to calculate PSI, an indication of labile P in residuals [$PSI = \text{moles P}/(\text{moles Fe} + \text{mole Al})$] (Elliott et al., 2002).

Laboratory Incubation

We used 11 biosolids (Table 1) and one mineral fertilizer (triple super phosphate [TSP]) as P sources in a dynamic labora-

tory incubation lasting 5.5 mo. Each P source was applied in triplicate to a P-deficient Spodosol from Florida. The P sources were applied at two rates, equivalent to P-based and N-based rates (56 and 224 kg P ha⁻¹). A control (no added P) was used for comparison. Phosphorus release was quantified as soluble reactive P (SRP) (determined colorimetrically) measured in column leachates.

Amendments were mixed with 400-g samples of Immokalee A horizon soil (Immokalee fine sand, sandy, siliceous, hyperthermic Arenic Alaquods; TP: 15.5 g kg⁻¹, WEP: 1.1 mg kg⁻¹, relative P adsorption: 2.0%) and enough water (40 mL) to reach the water-holding capacity of the soil. The biosolids-amended soils were incubated for 2 wk in zip-lock plastic bags. The bags of soil were mixed and opened daily during the initial incubation to avoid anaerobic conditions. Ammonium nitrate was added to all soil columns at a rate of 75 kg N ha⁻¹.

Incubation columns were constructed of 17 × 5 cm sections of polyvinyl chloride tubing with screening in the bottom to prevent soil loss. After the initial 2-wk bag incubation, 400 g of biosolids-amended soils were packed into the incubation columns to a depth of 13 cm at a bulk density of 1.51 g cm⁻³. Seventy-five columns were used (12 materials × 2 rates × 3 reps + 3 controls = 75). The columns were positioned vertically in wooden racks for leaching events.

Every 2 wk, sufficient tap water was applied to the columns to result in 60 mL (1/2 pore volume [PV]) of drainage. We adjusted the pH of the water from 8.0 to 5.0 to better simulate the pH of rainfall in south Florida (Elliott et al., 2002). Laboratory tap water was analyzed before the experiment for SRP to confirm low P concentration (below detection limit, 0.001 ppm). For the first two leaching events, P analysis of the leachates included total P (TP), total dissolved P, and SRP; pH and EC were also determined. Total P in leachate was determined by digestion of unfiltered leachate with potassium persulfate and 5.5 mol L⁻¹ H₂SO₄ (USEPA, 1993). Total dissolved P was determined via the same method on filtered leachate samples. Soluble reactive P was determined on vacuum-filtered, 0.45-μm, undigested leachate. Phosphorus concentrations (all forms) were determined colorimetrically (Murphy and Riley, 1962). Organic P was estimated by subtracting SRP from TDP. Results from the first two leaching events revealed that the SRP represented the majority (>80%) of the total P leached from the amended soils and that organic P was minimal (<10% of TP). Only SRP was measured in the remaining leaching events and was assumed to represent released P. Leachate pH and EC was measured directly on unfiltered/undigested leachate.

Statistical Analysis

Cumulative P leached from the laboratory incubation was subjected to a time-series analysis using the PROC TSCSREG procedure of the SAS software (SAS Institute, 2002). Data were tested

Table 2. Selected general chemical and physical properties of source materials.†

| P Source | C | N | C/N ratio | Solids | LOI | pH | EC | Fe | Al | Ca |
|-------------------------|-----------------------|----|-----------|--------|-----|-----|-------------------------|-----------------------|-----|-----|
| | —g kg ⁻¹ — | | | —%— | | | S m ⁻¹ | —g kg ⁻¹ — | | |
| Milorganite | 360 | 60 | 6.0 | 95 | 72 | 6.3 | 0.29 × 10 ⁻⁴ | 40 | 2.7 | 15 |
| Broward County | 390 | 53 | 7.3 | 13 | 74 | 7.9 | 0.36 × 10 ⁻⁴ | 16 | 6.6 | 39 |
| GreenEdge | 350 | 50 | 7.0 | 93 | 71 | 6.9 | 0.26 × 10 ⁻⁴ | 15 | 8.4 | 25 |
| Lakeland NS | 380 | 59 | 6.4 | 3 | 75 | 8.5 | 0.66 × 10 ⁻⁴ | 4.5 | 11 | 22 |
| Orange County South | 380 | 60 | 6.3 | 11 | 76 | 7.8 | 0.28 × 10 ⁻⁴ | 5.4 | 5.6 | 24 |
| Orange County East Cake | 430 | 70 | 6.2 | 16 | 84 | 5.9 | 0.27 × 10 ⁻⁴ | 2.2 | 7.7 | 17 |
| Orange County East Dry | 430 | 70 | 6.2 | 95 | 84 | 5.9 | 0.11 × 10 ⁻⁴ | 1.9 | 7.5 | 17 |
| Disney compost | 410 | 28 | 15 | 66 | 77 | 5.7 | 0.52 × 10 ⁻⁴ | 38 | 10 | 16 |
| Tallahassee Smith | 430 | 65 | 6.6 | 98 | 20 | 5.9 | 0.17 × 10 ⁻⁴ | 8 | 13 | 26 |
| Boca Raton | 370 | 62 | 6.0 | 13 | 76 | 7.5 | 0.34 × 10 ⁻⁴ | 12 | 6.4 | 25 |
| GRU | 400 | 64 | 6.2 | 5 | 80 | 6.4 | 0.11 × 10 ⁻⁴ | 7.7 | 5.5 | 14 |
| TSP | ND | ND | ND | 92 | 21 | 5.9 | ND | 16 | 10 | 140 |

† EC, electrical conductivity; GRU, Gainesville Regional Utilities; Lakeland NS, Lakeland north side; LOI, loss on ignition; TSP, triple super phosphate.

for normality using PROC UNIVARIATE and were normalized with a square transformation based on the Box-Cox test (Box and Cox, 1964). Treatment effects were evaluated using the general linear model (PROC GLM) of the SAS software version 9 (SAS Institute, 2002) along with Tukey's mean separation. Treatment differences were tested at a significant (α) level of 0.05. Analysis of variance was evaluated using the general linear model (PROC GLM) of the SAS software version 9 (SAS Institute, 2002). The logarithmic relationship between cumulative P released as a function of applied P was determined using a logarithmic regression (PROC LOG) of the SAS software version 9 (SAS Institute, 2002).

Results and Discussion

General Biosolids Characteristics

Total N concentrations ranged from 28 to 70 g kg⁻¹ (2.8–7%), and biosolids C/N ratios were generally low (6–15) (Table 2). The total N and C/N ratios were typical of conventionally produced biosolids in the USA (USEPA, 1995). Biosolids pH values varied with source and product form (Table 2). Cakes were circum-neutral to alkaline, and thermally dried products were slightly acidic.

Total P concentrations of biosolids (Table 3) ranged from 15 to 31 g kg⁻¹ (1.5–3.1%), typical of TP concentrations of conventionally produced biosolids nationwide (~20–40 g kg⁻¹) (USEPA, 1995). The difference in TP values resulted from the differences in wastewater characteristics and treatment practices (Brandt et al., 2004). Biological P removal or BPR-like biosolids typically had greater quantities (TP content of Gainesville Regional Utilities [GRU] = 31 g P kg⁻¹) of TP than biosolids, which were heat dried and high in Fe and Al (TP content of Milorganite = 21 g kg⁻¹).

Total metal (Fe, Al, and Ca) concentrations (Table 2) were representative of biosolids produced nationally and reflected the individual biosolids treatment processes. Total Fe ranged from 1.9 to 40 g kg⁻¹ (0.19–4.0%), Al ranged from 2.7 to 13 g kg⁻¹ (0.27–1.3%), and Ca ranged from 14 to 39 g kg⁻¹ (1.4–3.9%). The greater a residual's Fe and Al content, the better the material is able to retain P, leading to lower phytoavailability and lower leaching risks (O'Connor et al., 2004; Elliott et al., 2002). Milorganite (40 g kg⁻¹ Fe, 2.7 g kg⁻¹ Al)

Table 3. Selected phosphorus characteristics of source materials.†

| P source | Total P —g kg ⁻¹ — | WEP % | PWEP % | Oxalate extractable | | | PSI |
|--------------------------|----------------------------------|----------|-----------|---------------------|-----|-----|------|
| | | | | P | Al | Fe | |
| Milorganite | 21 | 0.12 | 0.58 | 16 | 1.2 | 25 | 0.55 |
| Broward County | 20 | 1.3 | 6.7 | 18 | 6.0 | 5.0 | 2.0 |
| GreenEdge | 17 | 0.19 | 1.1 | 13 | 5 | 13 | 1.0 |
| Lakeland NS‡ | 29 | 14 | 47 | 22 | 3.2 | 8.3 | 2.0 |
| Orange County South | 23 | 4.8 | 21 | 23 | 5.0 | 4.4 | 2.9 |
| Orange County East Cake‡ | 20 | 8.0 | 41 | 17 | 1.3 | 3.1 | 4.1 |
| Orange County East Dry‡ | 23 | 2.7 | 11 | 22 | 4.5 | 1.1 | 3.8 |
| Disney compost‡ | 15 | 1.2 | 8.4 | 11 | 7 | 20 | 0.43 |
| Tallahassee Smith | 21 | 1.4 | 6.1 | 19 | 6.5 | 5.2 | 1.8 |
| Boca Raton‡ | 26 | 3.9 | 15 | 33 | 14 | 7.3 | 2.1 |
| GRU | 31 | 7.9 | 26 | 21 | 6.4 | 3.7 | 2.1 |
| TSP | 190 | 170 | 85 | 186 | 11 | 6.8 | NA |

† GRU, Gainesville Regional Utilities; PSI, phosphorus saturation index; PWEP, percent water-extractable phosphorus; TSP, triple super phosphate; WEP, water-extractable phosphorus.

‡ Biological phosphorus removal (BPR) or BPR-like biosolids.

contained relatively high amounts of Fe and Al and resulted in especially small P release.

Water-extractable P (WEP) values ranged from 0.12 to 14 g kg⁻¹ (Table 3). Water-extractable P was used to calculate percent water-extractable P (PWEP = WEP/TP × 100). Two of the non-BPR biosolids analyzed (Milorganite and GreenEdge) had PWEP values <5%, which is typical of non-BPR biosolids produced in the USA (Brandt et al., 2004). The remaining conventionally digested biosolids (Broward and Tallahassee Smith) had PWEP values of 6.7 and 6.1%, respectively. Biological P removal biosolids (Boca Raton, Orange County Utilities Division East [OCUD E] cake and dry) had PWEP values ≥11%. Brandt et al. (2004) determined the average PWEP for various BPR biosolids sampled nationwide to be ≥14%. Disney is a BPR product; however, the PWEP (8.4%) was below average for a BPR residual. The Disney material is a composted mixture of biosolids, food, and yard waste. Brandt et al. (2004) reported that composting an anaerobically digested cake decreased WEP by 10-fold. The yard waste could have decreased PWEP; the Disney compost was sieved to pass through a 2-mm sieve before analysis, but small

pieces of wood were obvious. The yard waste composted with the Disney biosolids decreases the mass of biosolids per kilogram of land-applied finished product (composted biosolids + yard waste, even after sieving), thus reducing labile P.

Percent water-extractable P values were high for Lakeland North Side (Lakeland NS) (47%) and GRU (26%) biosolids. These materials are not produced via BPR processes, but personal communication with plant operators suggests that P removal is likely occurring in both systems. Plant capacity at the Lakeland NS and GRU plants was underutilized; therefore, P removal efficiency was increased. The resulting TP and PWEP values were similar to BPR biosolids. We have categorized these materials as “BPR-like.”

Oxalate-extractable Fe, Al, and P concentrations (Table 3) were used to calculate PSI values for the materials. Biosolids-PSI can be used as an a priori gauge of the lability of P in many biosolids in sandy soils (Elliott et al., 2002). Biosolids-PSI relates the moles of oxalate-extractable P to the moles of extractable Fe and Al (PSI = moles P/[moles Fe + moles Al]).

Biosolids with high concentrations of Fe and Al tend to have less labile P. Biosolids-PSI has no meaning for biosolids whose P chemistry is controlled by Ca (lime-stabilized materials). Elliott et al. (2002) suggested a critical PSI value of 1.1 for non-lime stabilized materials. That is, if the PSI of a biosolids exceeds the critical value, appreciable P leaching may occur from amended, sandy soils with limited P retention capacity. Biosolids with PSI values ≤1.1 resulted in minimal P leaching in the Elliott et al. (2002) study. Most of the biosolids analyzed herein were BPR or BPR-like materials, and the PSI values exceeded the critical value proposed by Elliott et al. (2002). Therefore, we expected significant P release when the biosolids were amended to the Immokalee soil, which retains P poorly.

Phosphorus Release

Soil columns were leached a total of eight times (~4 total PV) over 5.5 mo. The first seven leaching events were conducted bi-weekly to attain ~60 mL (1/2 PV) of drainage in each event. Significant P release (leaching) ceased after five leachings (2.5 mo). A time-series analysis (SAS Institute, 2002) showed no difference

in cumulative P released for leachings 5 through 7 (data not presented). We waited 2 months to conduct the final leaching to allow for additional P dissolution and distribution through the individual columns of soil and to confirm P release from all materials was maximized. Indeed, P loss from all materials during leaching 8 was minimal (<1 mg). Data from the final leaching were added to the original time-series analysis. There was no change in cumulative P released between leachings 5 through 8 (data not presented). Three months passed between leachings 5 and 8. Because cumulative P release did not change over the 3-mo time frame, we assumed that P release from the materials had ceased, and the experiment was terminated. To calculate P released as a percentage of applied P (Table 4), the mean

Table 4. Cumulative P released (% of applied P) for each leaching event (P-rate = 224 kg P ha⁻¹).

| P source | Leaching event | | | | | | | |
|-------------|----------------|--------|---------|---------|---------|---------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Milorganite | 2.33fg† | 9.51d | 12.4e | 16.4f | 18.0g | 18.7f | 19.0f | 19.0f |
| GreenEdge | 0.907g | 10.3d | 15.6e | 21.0ef | 24.4fg | 26.3ef | 27.3ef | 27.4ef |
| Disney | 1.74fg | 26.3c | 44.9c | 46.8cd | 47.7de | 51.9cd | 52.1cd | 52.3cd |
| Tallahassee | 6.52f | 20.7c | 28.0d | 32.8de | 35.6ef | 38.2de | 39.8de | 40.3de |
| Broward | 2.25fg | 12.5d | 18.9de | 22.7ef | 25.3fg | 28.2ef | 29.8ef | 31.5ef |
| GRU‡ | 21.8cd | 41.0b | 51.0bc | 58.6abc | 62.1abc | 65.3abc | 67.3ab | 68.5ab |
| OCUD E Dry | 26.1c | 45.4b | 53.5abc | 55.6bc | 58.4bcd | 59.7bc | 61.0bc | 62.4bc |
| TSP | 43.3a | 54.8a | 62.4a | 67.4ab | 69.7abc | 71.5ab | 72.7ab | 74.0ab |
| Boca Raton | 15.3e | 39.87b | 56.3ab | 66.6ab | 71.3ab | 76.1a | 77.2a | 79.3a |
| Lakeland NS | 20.6d | 40.2b | 48.7bc | 53.9bc | 56.8cd | 59.5cb | 61.1bc | 62.4bc |
| OCUD E Cake | 32.2b | 53.2a | 63.8a | 71.1a | 74.6a | 76.6a | 78.8a | 80.0a |
| OCUD S | 18.8de | 42.3b | 56.9ab | 66.1ab | 71.5ab | 74.6a | 78.0a | 80.0a |

† Means within the same leaching event with the same letter are not different (Tukey $p \leq 0.05$).

‡ GRU, Gainesville Regional Utilities; TSP, triple super phosphate; OCUD S, Orange County Utilities Division South; OCUD E, Orange County Utilities Division East.

mass of P released from the control treatment was subtracted from the masses of P released for all other treatments, and the difference was divided by the appropriate mass of P originally applied at each rate. The cumulative P release from the control columns was 0.004 ± 0.006 mg P.

We can roughly convert total PVs leached to residence time in a field setting. One PV of leachate represents ~ 5.64 cm drainage. Cumulative leaching (~ 480 mL) represented 22.6 cm of drainage. Yearly rainfall in south Florida averages ~ 140 cm yr^{-1} (Obeysekera et al., 2004), and evapotranspiration is $\sim 70\%$ of rainfall (Nachabe et al., 2005). Subtracting evapotranspiration from rainfall ($140 - 100$ cm yr^{-1}) yields 40 cm yr^{-1} drainage. Assuming 40 cm drainage yr^{-1} , we can calculate the number of PVs leached per year ($40 \text{ cm } \text{yr}^{-1} / 5.64 \text{ cm PV}^{-1} = 7.09 \text{ PV } \text{yr}^{-1}$). Thus, the four PVs of drainage effected up to about 7 mo of field conditions. Results were expected to represent realistic conditions for Florida.

Analysis of variance showed significant effects of P-source, P-rate, and P-source by P-rate interaction. Means separation using Tukey ($p \leq 0.05$) showed that cumulative P release (percentage of P applied) was greatest from BPR and BPR-like materials (Lakeland NS, GRU, Boca Raton, and OCUD E cake) (Table 4) and equaled TSP at the 56 (data not shown) and 224 kg P ha^{-1} application rates (Table 4). The OCUD E dry material was produced by thermally drying the OCUD E cake material. The OCUD E cake is undigested biosolids and is not lawfully land applied but was included for scientific interest. Heat drying the OCUD E cake created a class A material that may be land applied. Heat drying typically decreases labile P (Smith et al., 2002), and, indeed, P release from the OCUD E dry biosolids was less than P release (as a percentage of P applied) from the OCUD E cake biosolids at both application rates. However, P release (as a percentage of P applied) from the OCUD E dry biosolids was equal to TSP at the 56 kg P ha^{-1} application rate, indicating that the residual still had a high quantity of labile P.

Cumulative masses of P released expressed as a percentage of P applied from the Orange County Utilities Division South (OCUD S) material and TSP were the same at the 56 kg P ha^{-1} application rate (data not shown). At the 224 kg P ha^{-1} application rate, the cumulative mass of P released (percent of applied P) from the OCUD S material was greater than TSP. The OCUD S material is a conventionally produced biosolids; however, the PWEP (21%) and the PSI (2.9) values of the OCUD S material are high and are similar to BPR biosolids, which accounts for the high quantity of P leached. Given the treatment process of the OCUD S biosolids (anaerobically digested), we would not have expected PWEP and PSI values to be so high. However, because the total Fe + Al concentrations of the OCUD S material are low (11 g kg^{-1}), the resulting PSI value is high, and quantities of P released (percentage of P applied) were equal to or greater than that released by TSP. Biosolids-TP is not a good indicator of P lability. However, PWEP can be used to gauge the environmental impact a

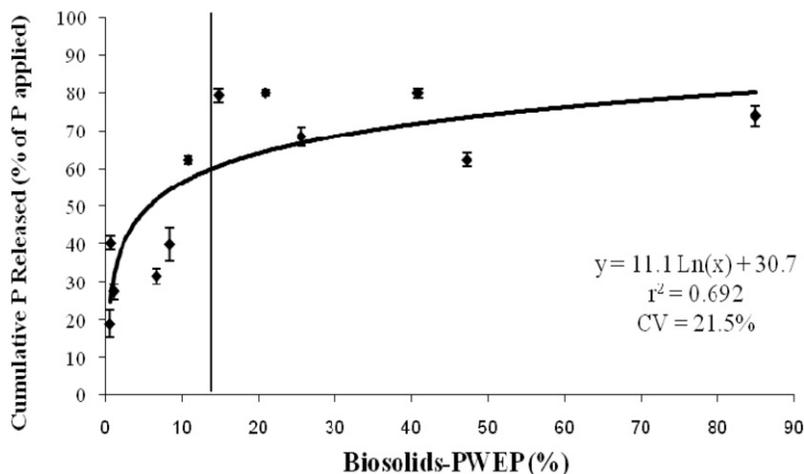


Fig. 1. Dynamic laboratory incubation. Cumulative P released (% of applied P) as a function of biosolids-percent water-extractable P (PWEP). P-rate: 224 kg P ha^{-1} . Error bars represent 1 SE. Vertical line at biosolids-PWEP = 14% indicates when increased negative environmental impact may occur.

residual will have once land-applied (Elliott and O'Connor, 2007). Logarithmic relationships existed between cumulative P released (% of applied P) and biosolids-PWEP at the 56 and 224 kg P ha^{-1} rates. The mathematical relationship for the 224 kg P ha^{-1} rate is shown in Fig. 1 (data for 56 kg P ha^{-1} rate are similar; not shown). The correlations were similar for the 56 kg P ha^{-1} rate ($r^2 = 0.62$; CV = 21.5%) and the 224 kg P ha^{-1} application rate ($r^2 = 0.69$; CV = 18.5%). The correlation between cumulative P released (% of applied P) and biosolids-PWEP was not strong enough to indicate that PWEP can be used to predict the precise quantity of P leaching that will occur when biosolids are land applied. However, Brandt et al. (2004) demonstrated that PWEP is a superior measure of the environmentally relevant portion of P in biosolids and manures than biosolids-TP or soil test P. Biosolids-PWEP can be used a priori to gauge the potential of a residual to negatively affect the environment. The data suggest that biosolids with PWEP values $\geq 14\%$ (vertical line in Fig. 1) should be assumed to have a larger negative environmental impact than biosolids with PWEP values $< 14\%$. Recall that Brandt et al. (2004) reported the average PWEP for BPR biosolids produced nationwide to be $\geq 14\%$. Elliott et al. (2006) used source WEP to improve P source coefficient assignments (phosphorus source coefficient = $0.102 \times \text{WEP}^{0.99}$) for state P-indices, and runoff dissolved P was well correlated ($r^2 = 0.80$) with source-WEP.

Figure 2 shows P released (% of applied P) as a function of PSI values of the biosolids applied at the 224 kg P ha^{-1} rate (data for the 56 kg P ha^{-1} rate are similar; not shown). Elliott et al. (2002) demonstrated that for biosolids with PSI values ≤ 1.1 , no appreciable leaching occurred from another sample of the Immokalee soil amended with biosolids. Several materials used in this study had PSI values above the suggested critical point of 1.1, which portends significant P losses measured from the BPR and BPR-like materials. Data from the current study indicate that a critical PSI value of ~ 2.0 better separates biosolids where leaching was greatest. However, the Elliott et al. (2002) study differed from the current study in two ways: (i) the Elliott et al. (2002) study used much larger

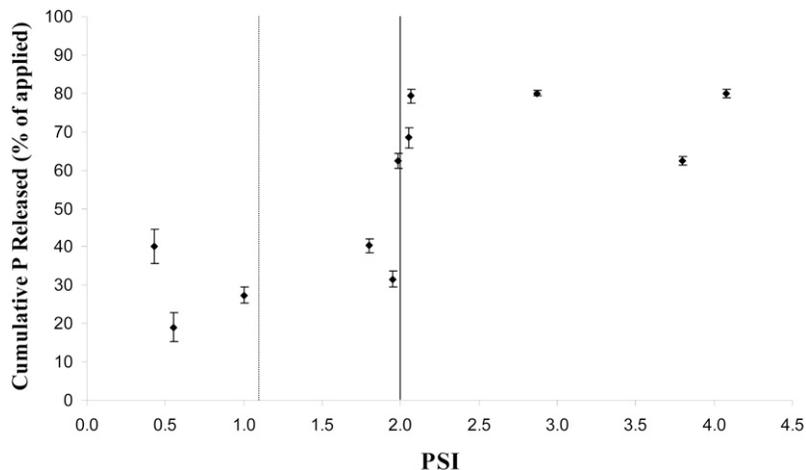


Fig. 2. Dynamic laboratory incubation. Cumulative P released as a function of phosphorus saturation index (PSI) showing a change point at PSI 2.0. P-rate: 224 kg P ha⁻¹. Dashed vertical line at 1.1 PSI represents change point proposed by Elliott et al. (2002). Solid vertical line at 2.0 PSI represents increased critical PSI value suggested by data in the current study.

soil columns, where one quarter of a pore volume was 500 mL and 4 monthly leachings were necessary to reach 1 pore volume of drainage; and (ii) Bahiagrass was grown in the Elliott et al. (2002) soil columns, reducing the quantity of P available for leaching. Data published separately (O'Connor et al., 2004) showed that Bahiagrass took up 29 to 57% of applied P at the 56 kg P ha⁻¹ application rate. In the dynamic laboratory incubation, ~4 pore volumes of drainage were collected versus 1 pore volume of leachate collected in the Elliott et al. (2002) study. The small columns in the current study included no plants and were flushed with more pore volumes of water than the large glasshouse columns, which encourages P release and movement downward (and out) of the small columns. Given the differences in experimental design between the current study and the Elliott et al. (2002) study, raising

the critical value from 1.1 to ~2 is probably not justified. Although there is no clear mathematical relationship between cumulative P release and PSI, P release clearly increases when PSI >2.0 (Fig. 2). Indeed, a Cate-Nelson approximation (not shown) demonstrated that a step change occurs at PSI 2.0. Phosphorus release appears maximized at ~80% of applied P for biosolids with PSI values >2.0

One objective of the study was to quantify water-soluble P (mass of P released) from various biosolids representing a range of chemical characteristics. Biosolids with smaller quantities of water-soluble P are less likely to negatively affect the environment. The quantity of water-soluble P is governed by several factors, including biosolids treatment processes (especially heat drying [Smith et al., 2002; Maguire et al., 2001]), and biosolids chemical composition (especially the quantity of Fe and Al in the material). Residuals high in total Fe and Al retain P and result in less P release (Brandt et al., 2004; Elliott et al., 2002). Thus, we expected

significantly more P release from BPR biosolids low in total Fe and Al than thermally dried residuals high in total Fe and Al.

Kinetics of P Release

The second major objective of this dynamic laboratory study was to examine the kinetics of P release. Figure 3 shows cumulative P leached as a percentage of P applied per leaching event for the 224 kg P ha⁻¹ rate (data for the 56 kg P ha⁻¹ rate are similar; not shown). Materials with high PWEP values (OCUD E cake, Lakeland NS, GRU, OCUD S) released large quantities of P quickly (within the first three leachings). In contrast to the fast rate of P release from the biosolids with high PWEP values, the thermally dried biosolids (Milorganite, GreenEdge, and Tallahassee) and the conventionally produced Broward cake released <7% of applied P during the first leaching event.

Conclusions

As opposed to biosolids-total P, biosolids-PWEP is an excellent indicator of how biosolids-P affects the environment when land applied to sandy, low-P-sorbing soils. Biosolids with high PWEP values, including BPR and BPR-like materials, yielded the greatest cumulative P leached. Biosolids with PWEP values ≥14% should be assumed to have a larger potential negative environmental impact than biosolids with PWEP values <14%. Biosolids-PSI values can also be used to gauge the environmental impact of

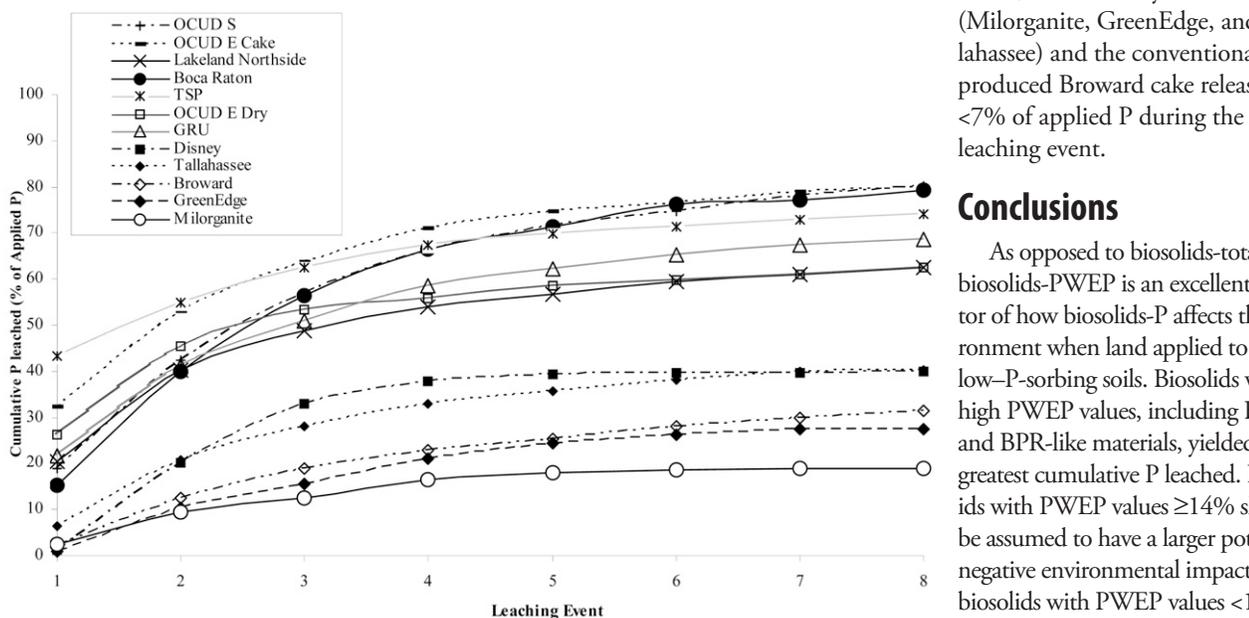


Fig. 3. Dynamic laboratory incubation. Cumulative P released (% of applied P) per leaching event. P-rate: 224 kg P ha⁻¹.

biosolids land applied to sandy soils with minimal P-sorbing capacity. Although exceptions exist, much research has shown that BPR and BPR-like materials have a greater risk of P loss compared with conventionally produced and pelletized biosolids.

Thermally dried and conventionally produced residuals have a slower rate of P release than BPR and BPR-like products. Knowledge of the kinetics of P release is important to understanding the effects a residual will have on the environment. A slower rate of P release is desirable because the opportunity for plant uptake is increased and there is less P in the soil solution at any given moment. The less P in the soil solution at any given time means less P is available for leaching through and out of the soil profile, risking impairment of water bodies.

This study demonstrates that land application of biosolids should not be regulated by assuming all biosolids have equal amounts of labile P. Measurements such as PWEP and PSI should be considered in developing biosolids land application regulations and guidelines. Assuming all biosolids to have equal amounts of labile P and requiring P-based application rates without considering a residual's individual environmental hazard could unfairly burden municipalities facing disposal problems or unfairly advantage wastewater treatment plants producing BPR products. Decreasing the land application rates of biosolids could greatly increase the cost of disposal for municipalities. Blanket regulation of biosolids land application is also unwise given the benefits biosolids can have to soil and crops when land applied. Biosolids land application can decrease chemical fertilizer inputs. Chemical fertilizers, designed to be water-soluble and to provide instant plant nutrition, are a greater environmental hazard than conventionally produced or thermally dried residuals. Although BPR and BPR-like biosolids treatment processes are environmentally beneficial to reduce P in wastewater effluent, the materials likely pose a greater environmental hazard due to more P and greater P lability when land applied.

Our study was meant to mimic realistic biosolids land application conditions in FL: The amount of water applied represented realistic Florida rainfall conditions, we used a typical FL sand, and we amended the soil at realistic application rates with materials produced and marketed in FL. The soil used had minimal P-sorbing capacity, and no plants were grown to uptake applied P. Another purpose of the study was to examine the P leaching risks of BPR biosolids because most previous biosolids research has not focused on the uniqueness of BPR materials. We wished to show that, in general, most biosolids (with the exception of BPR biosolids) do not pose a significant P leaching risk, even in a soil with little P-sorption capacity. If typical (non-BPR) biosolids are applied at N-based rates to soils with even moderate P-sorbing capacity (most soils in the USA), little P leaching would be expected to occur. Our study was designed to specifically replicate conditions in Florida, but the results are generally applicable wherever biosolids are land applied.

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References

- Andersen, J.M. 1976. An ignition method for determination of total phosphorus in lake sediments. *Water Res.* 10:329–331.
- 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.
- Box, G.E.P., and D.R. Cox. 1964. An analysis of transformations. *J. R. Stat. Soc. Ser. B* 26:211–243.
- Carpenter, N.F., Sr., D.L. Caraco, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Non-point pollution of surface water with phosphorus and nitrogen. *Ecol. Appl.* 8:559–568.
- Corey, R.B. 1992. Phosphorus regulations: Impact of sludge regulations. *Crop Soils* 20:5–10.
- Elliott, H.A., R.C. Brandt, P.J.A. Kleinman, A.N. Sharpley, and D.B. Beegle. 2006. Estimating source coefficients for phosphorus site indices. *J. Environ. Qual.* 35:2195–2201.
- Elliott, H.A., R.C. Brandt, and G.A. O'Connor. 2005. Runoff phosphorus losses from surface-applied biosolids. *J. Environ. Qual.* 34:1632–1639.
- Elliott, H.A., and G.A. O'Connor. 2007. Phosphorus management for sustainable biosolids recycling in the United States. *Soil Biol. Biochem.* 39:1318–1327.
- Elliott, H.A., G.A. O'Connor, and S. Brinton. 2002. Phosphorus leaching of biosolids-amended sandy soils. *J. Environ. Qual.* 31:681–689.
- Loeppert, R.H., and W.P. Inskeep. 1997. Iron. p. 640–650. *In* Sparks et al. (ed.) *Methods of soil analysis. Part 3: Chemical Methods.* SSSA, Madison, WI.
- Maguire, R.O., J.T. Sims, S.K. Dentel, F.J. Coale, and J.T. Mah. 2001. Relationship between biosolids treatment process and soil phosphorus availability. *J. Environ. Qual.* 30:1023–1033.
- Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural water. *Anal. Chim. Acta* 27:31–36.
- Nachabe, M., N. Shah, M. Ross, and J. Vomacka. 2005. Evapotranspiration of two vegetation covers in a shallow water table environment. *Soil Sci. Soc. Am. J.* 69:492–499.
- Obeyseker, J., J. Browder, L. Hornung, and M.A. Harwell. 2004. The natural south Florida system I: Climate, geology, and hydrology. *Urban Ecosystems.* 3:223–244.
- O'Connor, G.A., S. Brinton, and M.L. Silveira. 2005. Evaluation and selection of soil amendments for field testing to reduce P losses. *Proc. Soil Crop Sci. Soc. Fla.* 64:22–34.
- 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.
- Peterson, A.E., P.E. Speth, R.B. Corey, T.W. Wright, and P.L. Schlecht. 1994. Effect of twelve years of liquid sludge application on soil phosphorus level. p. 237–247. *In* C.E. Clapp (ed.) *Sewage sludge: Land utilization and the environment.* SSSA, Madison, WI.
- SAS Institute. 2002. SAS online doc. Version 9. SAS Inst., Cary, NC.
- Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. *J. Environ. Qual.* 29:1462–1469.
- Smith, S.R., D.M. Beller-Travers, R. Morris, and J.N.B. Bell. 2002. Fertilizer value of enhanced-treated and conventional biosolids products. Paper 10. *In* Proc. CIWEM Conf.-Biosolids: The Risks and Benefits, an Update on the Latest Res., London. 9 Jan. 2002. Chartered Inst. Water and Environ. Mgmt., London.
- Sparks, D.L. 1996. *Methods of soil analysis. Part 3.* SSSA Book Ser. 5. SSSA, Madison, WI.
- Tiffany, M.E., L.R. McDowell, G.A. O'Connor, H. Nguyen, F.G. Martin, N.S. Wilkinson, and N.A. Katzowitz. 2001. Effects of residual and reapplied biosolids on forage and soil concentrations over a grazing season in north Florida: I. Macronutrients, crude protein, and in vitro digestibility. *Commun. Soil Sci. Plant Anal.* 32:2189–2209.
- USEPA. 1993. *Methods for determination of inorganic substances in environmental samples.* Revision 2.0 365.1. USEPA, Washington, DC.
- USEPA. 1995. *Process design manual: Land application of sewage sludge and domestic septage.* EPA/625/R-95/001, Office of Research and Development, Cincinnati, OH.
- USEPA. 1999. *Biosolids generation, use and disposal in the United States.* Available at <http://www.epa.gov/epaoswer/non-hw/compost/biosolid.pdf> (verified 10 Jan. 2008). USEPA, Washington, DC.