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Research article

Assessment of plant availability and environmental risk of biosolids-phosphorus in a U.S. Midwest Corn-Belt Soil

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ABSTRACT

A field experiment was conducted from 2005 to 2008 in Fulton County, Western Illinois with biosolids from conventional wastewater treatment applied as corn fertilizer in a series of P rates (0, 163, 325, 488, 650 kg P ha^{-1}) along with commercial P fertilizer - triple superphosphate P (TSP) as reference to assess biosolids-P plant availability and potential loss to waterbodies through runoff. Air-dried biosolids and TSP were incorporated into surface soil at end of 2005, and corn (*Zea mays)* was planted for three consecutive years (2006–2008). Concentrations of soil extractable P except for Mehlich-3 P were always lower in the biosolids than TSP treatments at the same P rates. The soil potentially available P in water extractable P (WEP) and Olsen P derived from biosolids-P estimated by the exponential depletion model was 2–4% and 15–24% of total P in the applied biosolids, respectively. The residence time of biosolids-induced WEP and Olsen P in Midwest soil under annual corn cropping was 5 and 2 years, respectively. Corn tissue analysis showed lower increase in P concentration by biosolids-P than TSP. The elevation rate of soluble reactive P (SRP) concentration in simulated runoff was less by biosolids than TSP. Based on the data in this study, the plant availability and environmental risk of biosolids-P are lower than those of TSP in the Midwest soil, thus use of biosolids as P nutrient for corn would not cause a major impairment to water sources even P applied through biosolids was not completely used by annual crop.

1. Introduction

Biosolids, the treated sewage sludge of wastewater treatment meeting the land application standards, is a plant nutrient source, including P (Binder et al., 2002; Prescott and Blevins, 2005). The rate of biosolids application to farmland is generally based on N requirement of annual crops (USEPA, 1995). Row crops, for example corn, utilize much less P than N, while P concentrations in biosolids are similar to, or only slightly less than N. Therefore, application of biosolids to meet the crop N requirement can cause the excess P in soil, and this can create a potential for P movement along with runoff to nearby waterbodies. A quick solution for the excessive P-loading issue is shifting from N-based to P-based biosolids land application to reduce P input to soil from biosolids. However, such change can cause the biosolids land application to be impractical, as biosolids application rate in the P-based system can be extremely low. Regulations that restrict organic residues to less than N-based application rates may encourage disposal strategies that are not based on beneficial reuse (Pierzynski and Gehl, 2005; Elliott and O'Connor, 2007), and if biosolids are disposed of in landfill, it can even cause other environmental problems such as greenhouse gas emissions (Brown et al., 2012).

Given the fact P mobility is low in soil, not all the P accumulated in soil by P addition can be transported to a waterbody, and the development of biosolids application addressing the P environmental concern needs to establish plant availability and potential environmental risk of biosolids-P (Elliott and O'Connor, 2007). When P fertilizer is applied to soil, part of its P is fixed in soil through adsorption, precipitation, and crystallization, not available in solution for the transport to waterbodies. McCollum (1991) reported that soil P fixation contributed more than crop removal to the depletion of available P in soil. Dodd and Mallarino (2005) reported that the application of 10 mg P per kg soil is needed to raise the concentration of soil Bray-1 P by 1 mg P kg^{-1} soil under

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cropping in Iowa. The industrial wastewater contains Fe and Al, and in the conventional wastewater treatment, ferric chloride is often added as coagulant to improve biosolids dewatering. Hence, biosolids P can be fixed in soil by amorphous Fe and Al in biosolids in addition to the inherent soil fixation, leading to low potential for the loss of soluble P to waterbodies. The potential P environmental problem in the biosolids farmland application could be over-concerned, and research is clearly needed to generate data on the plant availability and environmental risk of P in biosolids for designing the proper P management for the biosolids land application.

The extractable P in soil is the indicator of P availability for plant P nutrition and P transport to surface runoff (e.g. Torbert et al., 2002; Kumaragamage et al., 2011; Reiter et al., 2013). The soil P extractants are commonly water, Olsen, Bray-1 and Mehlich-3 reagents, which vary in the ability to extract P. The measurement of soluble reactive P in the runoff generated by a rainfall simulator has been widely used as a technique to assess the P environmental risk (Kleinman et al., 2004; Elliott et al., 2005). The objective of the study was therefore to assess the biosolids-P plant availability through monitoring the soil extractable P after biosolids application and environmental risk in terms of loss to waterbodies by measuring P concentrations of the simulated runoff generated from biosolids-amended soil.

2. Materials and methods

2.1. Study site

The study was conducted during 2006–2008 at a site located at Fulton County, western Illinois. The site has a continental climate with annual mean air temperature of 10.4 °C and annual precipitation of 1013 mm. The soil in the experimental plot was predominantly Clarksdale series (Fine smectitic, mesic Udollic Endoaqualf) with a small portion of Sable series (Fine-silty, mixed, superactive, mesic Typic Endoaquoll). Before the study, the field was cropped with corn from 2003 to 2005 without P fertilization. At the establishment of treatment, soil extractable P values were 13.9 mg kg^{-1} (Bray-1 P), 23.2 mg kg^{-1} (Olsen P), and 26.0 mg kg^{-1} (Mehlich-3 P). The surface soil had the following properties: pH 6.3, organic C 16.5 g kg^{-1}, total P 451 mg kg^{-1}, and silty clay loam texture (sand 123 g kg^{-1}, silt 617 g kg^{-1}, and clay 260 g kg^{-1}).

2.2. Treatment design

The experimental design was a randomized complete block with four replications. The treatments included four biosolids rates, four triple superphosphate (TSP) rates, and a control. Both biosolids and TSP treatments had a same series of P rates as 163, 325, 488 and 650 kg P ha^{-1}. No P was applied in the control. Both P sources were applied only once in November 2005 for the use of corn for three croppings (2006–2008). Large plots were used in this study with treatment plot size of 0.1 ha (27 × 37 m).

2.3. Experimental operation

The biosolids were prepared through treating sewage sludge generated from the treatment of combined domestic and industrial wastewater and storm water. The waste activated sludge and primary sludge were anaerobically digested at 35 °C for at least 15 days to meet the criteria for biosolids suitable for farmland application (USEPA, 1995). Then, the biosolids were held in a lagoon for at least 1.5 years for further stabilization. After that, biosolids in the lagoon were placed on paved beds and air-dried, aided by mechanic agitation to approximately 60–70% total solids content. Of the total P in biosolids used in this study, there are 8.5% as organic form and 91.5% as inorganic one, including 2.2% as KCl–P, 58.2% as Fe/Al-bound P, and 31.1% Ca-bound P. The other analysis of the biosolids is presented in Table 1.

The biosolids were applied using a manure spreader, and were incorporated into the plow layer by discing. Corn was planted in 2006, 2007, and 2008 and managed conventionally without irrigation. A blanket dose of 320 kg N ha^{-1} as urea, and 110 kg K ha^{-1} as muriate of potassium, which could support the historically highest corn grain yield in the region, was broadcast each year at each planting. Corn was harvested for measuring the grain yield and stover dry matter.

2.4. Sampling and analysis

Soil samples (0–15 cm) were collected from each plot before the application of treatments in 2005, before each year's planting, and after each year's crop harvest in 2006–2008. Soil samples at 15–30 cm depth were also collected at the beginning and end of the experiment. The soil samples were air-dried and ground to pass a 2-mm sieve. Samples of corn grain and stover were collected at harvest. The plant samples were oven-dried and ground to pass a 1-mm sieve for the analysis.

Soil samples were analyzed for water extractable P (WEP) (Self-Davis et al., 2000), Olsen extractable P (Olsen et al., 1954), Bray-1 extractable P (Bray and Kurtz, 1945), and Mehlich-3 extractable P (Mehlich, 1984). The corn earleaf, stover, and grain were analyzed for total P (USEPA, 1979).

2.5. Runoff simulation

The runoff simulation was conducted using the soil samples collected at 1.5 and 2.5 years after TSP and biosolids application. At each runoff simulation, 10-kg soil was placed in a metal tray (100 cm long × 15 cm wide × 5 cm deep) with the cheesecloth on the bottom. Then, reverse osmosis water was added gradually until the tray started draining water from the bottom. The tray was covered with plastic sheet, and left to stand for approximately 24 h. Trays were placed at a slope of 3% under a simulated rainfall. A set of nine prepared trays was randomly placed on the rack under the rain simulator. A metal funnel was attached to the down-slope end of the tray, and the hose from the funnel was inserted into a collection bottle to collect runoff. The intensity of rainfall was simulated at 75 mm h^{-1}. The runoff was collected for 30 min after its commencement. After the rainfall simulation, the tray was

Table 1
Analysis of air-dried biosolids used in the study.

Analyte	Result (g kg^{-1})[a]
Volatile solids	394 ± 3
Organic N	14.4 ± 0.7
NO_3^-–N	4.25 ± 0.24
NH_4^+–N	0.014 ± 0.01
Total Fe	30.9 ± 2.0
Oxalate extractable Fe	23.5 ± 0.1
Total Al	13.4 ± 1.1
Oxalate extractable Al	5.61 ± 0.01
Total Ca	51.9 ± 1.1
Total Mg	16.0 ± 0.5
Total P	29.1 ± 0.4
Extractable P	
Water	1.03 ± 0.01
Olsen	2.77 ± 0.08
Bray-1	14.5 ± 0.2
Mehlich-3	21.3 ± 0.5

[a] Mean ± SE, on a dry weight basis.