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Research article

Differential release of manure-borne bioactive phosphorus forms to runoff and leachate under simulated rain

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ABSTRACT

Limited information exists on the unhindered release of bioactive phosphorus (P) from a manure layer to model the partitioning and transport of component P forms before they reach an underlying soil. Rain simulations were conducted to quantify effects of intensity (30, 60, and 90 mm h^{-1}) on P release from an application of 60 Mg ha^{-1} of dairy manure. Runoff contained water-extractable- (WEP), exchangeable and enzyme-labile bioactive P (TBIOP), in contrast to the operationally defined "dissolved-reactive P" form. The released P concentrations and flow-weighed mass loads were described by the log-normal probability density function. At a reference condition of 30 mm h^{-1} and maintaining the surface at a 5% incline, runoff was minimal, and WEP accounted for 20.9% of leached total P (TP) concentrations, with an additional 25–30% as exchangeable and enzyme-labile bioactive P over the 1-h simulation. On a 20% incline, increased intensity accelerated occurrence of concentration$_{max}$ and shifted the skewed P concentration distribution more to the left. Differences in trends of WEP, TBIOP, or net enzyme-labile P (PHP_o) cumulative mass released per unit mass of manure between intensities were attributable to the higher frequency of raindrops striking the manure layer, thus increasing detachment and load of colloidal PHP_o of the water phases. Thus, detailed knowledge of manure physical characteristics, bioactive P distribution in relation to rain intensity, and attainment of steady-state of water fluxes were critical factors in improved prediction of partitioning and movement of manure-borne P under rainfall.

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1. Introduction

Animal manure has been recycled through field crop production for the beneficial re-use of the manure-borne nutrients, in addition to the valuable organic carbon. However, manure-amended fields have been associated with nonpoint source pollution of aquatic ecosystems, primarily because of the manure-borne nutrients, sediment, oxygen demanding compounds, and pathogens (Monaghan et al., 2008; Withers and Bailey, 2003). Nutrients, phosphorus in particular, are linked to impairment of water quality by triggering eutrophication of streams, lakes, and estuaries (Carpenter, 2008; Meals and Budd, 1998). There is ample documentation on agricultural P contributing to the P enrichment of surface waters and raising the risk of eutrophication of surface water resources (Lathrop, 2007; Meals and Budd, 1998; Wang et al., 2016). Water extractable P (WEP), or more accurately "dissolved reactive P" (DRP) as commonly measured in manure was suggested to be a good indicator of potential P loss in runoff from manure freshly applied to soils (Kleinman et al., 2007; Miller et al., 2006). According to the proposed analytical procedures, manure DRP was measured after equilibration with distilled water, filtered using a coarse grade filter, such as Whatman No.1 or a finer filter with 0.45 μm openings, leaving behind much colloidal particulates and associated P (Dao et al., 2006; Kleinman et al., 2007). Mobilization and transport of colloids in soil were observed to be plausible avenue for significant transport of sediments and colloid-associated P, reaching a maximum of 80% of P loss to tile drains in Danish soils with well-developed structure (Glæsner et al., 2013; Schelde et al., 2006; Withers et al., 2009).

Numerous simulation models and user-friendly decision-aid tools have been developed for assessing the effectiveness of

Abbreviations: WEP, Water-extractable phosphorus; TBIOP, Total exchangeable and enzyme-labile bioactive P; DRP, Dissolved-reactive P; TP, Total acid-digest P; FWMC, Flow-weighed mean concentration; FWHM, Full width at half-concentration$_{max}$.

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mitigation strategies and BMPs for managing storm runoff and non-point source pollution (Liu et al., 2015; Niazi et al., 2015; Rao et al., 2009). Improvements included descriptors of multiple sources areas and their alterations over time and space. They also included more accurate mechanistic knowledge of the effects of other constituents of the manure matrix on P release (Dao, 2004; Dao et al., 2006; Pouliot et al., 2015; Tian et al., 2016). Indices of susceptibility to losses of P (aka, P index) and model routines to simulate P loss in runoff have been modified to use manure DRP (Butler and Coale, 2005; Jones et al., 1984; Vadas et al., 2007). However, DRP in manure was not always related to runoff P loss. Volf et al. (2007) reported discrepancies between DRP in runoff and WEP in manure, and that field rainfall simulations showed that total P (TP), and DRP concentrations in runoff increased with manure rate for added fresh and residual manure remaining after 1 year after addition. A poor correlation was observed between DRP in runoff and manure WEP (Volf et al., 2007). In most of these studies, the manure was applied on the surface of soils, often incorporated in the soil as a cultural practice to minimize erosional losses and improve manure-borne nutrient mineralization and use by the crop (López-Periago et al., 2000, 2002; Messing et al., 2015; Miller et al., 2006; Volf et al., 2007; Wang et al., 2016; Withers and Bailey, 2003). Sediment and P transfer from soils to runoff water is a complex process. An information deficit exists about the release of manure P to runoff and leached downward from the manure layer free from the confounding effects of the soil surface's properties. This is the case when manure was to be added to the surface of soils under no-till management or under permanent vegetation. This study was conducted to improve our understanding of manure P release to runoff, without the confounding influence of soil properties, given the numerous complex physical and biogeochemical transformations that affect manure and its components in a distinct manure layer and the surface of an underlying soil. The specific objectives of this study were to (a) determine the effects of rain intensity and the degree of the incline of the surface of the manure layer on the release of the partitioning of P forms between runoff and leachate and (b) the P form composition of these waters, and the implication of potential shifts on environmental dispersal of inorganic and enzyme-labile P forms induced by rain intensity.

2. Materials and methods

2.1. Simulations of P release from high-solid content reconstituted dairy manure

A controlled-intermittent rainfall simulator was used to induce the release of bioactive forms of P from reconstituted dairy manure that was used in a previous study of the release of fecal microorganisms described in Blaustein et al. (2015). High-solid content dairy manure was prepared from excreta obtained from Holstein cattle of the USDA-ARS Dairy Research Facility, in Beltsville, MD. Fresh feces and urine were collected from 2 to 5 year-old dairy cattle that were fed a corn silage-based diet before the day of collection. The manure was obtained by mixing feces and urine at a 6:1 ratio (vol/vol), and then combined with saw dust, a commonly used bedding material in the animal stalls. A high-solid manure (approximately 30% dry matter by weight) was generated, representing a thickened mix likely found in wastewater storage structures on dairy farms in the USA mid-Atlantic States region. Composite samples were collected on the day of each simulation to obtain an average physical, chemical, and microbial composition of the manure prior to rainfall initiation (Table 1).

Table 1
Selected chemical properties of the reconstituted high-dry matter dairy manure used.

Element		
Organic N	($g\ kg^{-1}$)	3.25[c] (±0.08)
Acid-digest P[a]	($g\ kg^{-1}$)	6.9 (±0.09)
Potassium[b]	($g\ kg^{-1}$)	5.0 (±0.05)
Calcium[b]	($g\ kg^{-1}$)	28.6 (±0.17)
Magnesium[b]	($g\ kg^{-1}$)	3.1 (±0.04)
Iron[b]	($mg\ kg^{-1}$)	606 (±16)
Copper[b]	($mg\ kg^{-1}$)	80 (±4)

[a] Persulfate digestion (Nelson, 1987).
[b] X-ray fluorescence spectroscopy (Dao and Zhang, 2007).
[c] Mean (±SD) of five replicates.

2.2. Rainfall simulator and leaching-runoff boxes

The rainfall simulator was built according to a design of Meyer and Harmon (1979). In brief, different rainfall intensities were achieved by controlling the length of pauses between nozzle oscillation sweeps. The simulator design allowed for raindrop impact energies to be about 275 kJ ha^{-1} mm^{-1}, which has been reported to approximate that of natural rainfall greater than 25 mm h^{-1} (Meyer and Harmon, 1979). For each simulation, the high-solid content dairy manure mix was spread on a fine mesh screen of triplicated leaching-runoff boxes (0.70 × 0.70 m), at the rate of 2.94 kg box^{-1}, or the equivalent of 60 Mg ha^{-1} (wet weight basis). Details of the box design are found in Blaustein et al. (2015). In brief, the boxes consisted of three superimposed compartments – a top support frame, a middle frame covered with a fine mesh nylon screen (P/N U-CMN-185, Component Supply Co., Fort Meade, FL 33841), and a lower compartment with a plywood base lined with a polyethylene sheet to pool and route the leachate to a collection trough. The boxes were placed on an incline to maintain the manure layer at a slope of either 5 or 20% under the rainfall simulator. Constant rainfall intensities of either 30, 60, and 90 mm h^{-1} were maintained for 1-h long simulations. These intensities were chosen because of their linearity and correspondence to precipitation intensities in the mid-Atlantic region, where the one-year recurrence of rainfall for a 10 min duration is 87 mm h^{-1} and that for a 60 min duration is 31 mm h^{-1}, according to the USDC-NOAA point precipitation frequency estimates (U.S. Department of Commerce, 2004).

During each simulation, runoff and leachate samples were collected in 100-mL plastic bottles at 0, 1, 2, 4, 7, 10, 15, 20, 30, 40, 50, and 60 min following initiation of runoff or leaching. Artificial rainwater was prepared to represent natural rainfall for the Maryland, Pennsylvania, and Delaware region (Dao et al., 2008; Green et al., 2007). The artificial rainwater contained Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, NO_3^-, Cl^-, and SO_4^{2-} at 0.08, 0.03, 0.02, 0.12, 0.34, 1.36, 0.26, and 1.9 mg L^{-1}, respectively. The rainwater solution was mixed in 1800-L polyethylene holding tanks; the final pH of the rainwater solution was adjusted to 4.5.

2.3. Bioactive P fractions

Bioactive P fractions in samples of manure, leachate, and runoff were determined according to an incubation-extraction enzymatic assay developed by Dao (2003, 2004). Fractions of bioactive P forms included 1) water-extractable P (WEP), 2) total ligand (EDTA)-exchangeable inorganic phosphate-P (TEP_i), and 3) an all-inclusive total bioactive P (TBIOP) fraction that was concurrently extracted by 5 mmol L^{-1} EDTA and added fungal phosphohydrolase enzymes. In addition, the EDTA-exchangeable inorganic phosphate-P (EEP_i) fraction was calculated as the difference between TEP_i and WEP, and the PHP_o fraction as the difference between TBIOP and TEP_i.