Discovery, The Student Journal of Dale Bumpers College of Agricultural, Food and Life Sciences

Volume 15 Article 12

Fall 2014

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Recommended Citation

Rossetti, Maria S.; Ownby, Nicole K.; Scott, Erin; and Haggard, Brian E. (2014) "The potential release of phosphorus in floodplains," *Discovery, The Student Journal of Dale Bumpers College of Agricultural, Food and Life Sciences*. University of Arkansas System Division of Agriculture. 15:68-75.
Available at: https://scholarworks.uark.edu/discoverymag/vol15/iss1/12

The potential release of phosphorus in floodplains

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ABSTRACT

In the Illinois River Watershed, there has been growing concern over elevated phosphorus concentrations in the water column. This study evaluated how much phosphorus is contributed from floodplain soils into surface waters, examining the relationship between the flux of phosphorus released and the amount of phosphorus stored in the soil. This was investigated by artificially inundating soil cores from four sites and determining the soluble reactive phosphorus concentrations of the overlying water and the levels of Water and Mehlich-3 extractable phosphorus in the soil. The flux of phosphorus to the overlying water ranged from 0.43 to 6.61 mg m^{-2} hr^{-1} within the short-term (16.5-hr incubation) and 0.06 to 1.26 mg m^{-2} hr^{-1} over the long term (282.5-hr incubation). Phosphorus flux to the overlying water was significantly correlated with the amount of phosphorus stored in the soil. This study showed that riparian soils with elevated phosphorus content have the potential to release phosphorus when flooded.

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‡ Brian E. Haggard is a professor in the Department of Biological and Agricultural Engineering and the director of the Arkansas Water Resources Center.

MEET THE STUDENT-AUTHORS

I am from Fayetteville, Arkansas and I graduated from Fayetteville High School in 2013. I began my studies in the fall of 2013, and I am majoring in Chemical Engineering and minoring in Sustainability and Math. I am also a Julian and Nana Stewart Honors College Fellow. This project was result of the 6th annual Honors Research Symposium, which is part of the Freshman Engineering Program. The symposium allows freshman students to learn about different kinds of research in the field of engineering and gives freshman research experience. As a result of this research project, I've learned more about the environmental research opportunities in the field of engineering and I am particularly interested in issues with water quality and I hope to be able to conduct more research about these topics during the remainder of the my time as an undergraduate. After I complete my undergraduate studies, I plan on attending graduate school and becoming a professor. I would like to thank Brian Haggard and Erin Scott for their guidance during this project, without them it would not have been possible.

Maria Rossetti

I am from St. Louis, Missouri, where I graduated from Lafayette High School in May, 2013. I just completed my first year at the University of Arkansas, where I recently declared my major as biomedical engineering. These past two semesters have allowed to me gain experience in the research field of biological and agricultural engineering throughout the process of writing the following paper and the field work required to do so with my research partner and departmental mentor. This coming fall I plan to perform undergraduate biomedical engineering research under the supervision of a biomedical engineering professor at the university, specifically with a focus on tissue engineering either with muscle cells or in dealing with traumatic brain injury. After graduation, I plan to attend graduate school in St. Louis, most likely at St. Louis University, for biomedical engineering and ultimately develop a career in an industry setting to further my knowledge and understanding of the field of biomedical engineering.

Nicole Ownby

INTRODUCTION

Over the last half century, there has been growing concern over elevated phosphorus concentrations and its effect on the quality of surface waters. In Northwest Arkansas, this issue has garnered more attention in the past twenty years due to litigation revolving around phosphorus concentrations in the Illinois River Watershed. In 2005, the state of Oklahoma sued 13 poultry companies in the state of Arkansas over water quality in the Illinois River and its other scenic rivers. This lawsuit was based on the premise that phosphorus (P) in poultry litter contributed to water quality problems in the Illinois River Watershed. Each year an estimated 312,978 metric tons of chicken manure and bedding (i.e., poultry litter) is produced in this area (Flynn, 2009). The poultry litter produced is frequently used as fertilizer on pastures and when applied to meet nitrogen (N) needs of the forage, it often results in the buildup of P in soils (Eghball and Power, 1999).

While a vital nutrient for plants and aquatic organisms, P can result in water quality problems when applied or available in excess of plant needs. Phosphorus inputs are a potential cause of eutrophication, which is the process in which a body of water becomes enriched with nutrients that stimulates the growth of aquatic plant life. Elevated concentrations of P can cause an increase in algal blooms which can lead to large diurnal swings in oxygen, possible fish kills from lack of dissolved oxygen in water, taste and odor issues in drinking water, and even algal toxins (Daniel et al., 1998).

Phosphorus can come from many different sources including point and non-point sources. Point sources are identifiable, confined sources from which a pollutant is discharged or emitted; examples include wastewater treatment plants, storm conveyance outlets, and even large confined agricultural operations. Non-point sources are diffused in nature and transported into bodies of water from the landscape during excess rainfall when all the water does not infiltrate the soil and instead runs off (i.e. a rainfall-runoff event).

Phosphorus in poultry litter has been applied to the landscape for many decades in the Illinois River Watershed, as well as other watersheds across the U.S. This P is stored in the soil and it is transported downhill toward the streams and rivers with each runoff event. Furthermore, P can be stored in riparian areas and floodplains, and there is a potential for the riparian soils to release P into surface waters during runoff events or inundation. Several researchers have shown the potential for P in soils to be released (via surface runoff and even subsurface flow) at levels that have the potential to cause eutrophication (Fuchs et al., 2009; Pote et al., 1999). Extensive research has been done regarding how point and non-point sources affect P concentrations in surface water. For instance, research has been conducted on how the application of poultry litter—which can contain elevated amounts of P relative to N—increases P concentrations in runoff water and contributes to non-point source pollution (Haggard et al., 2005). In addition, other studies have shown that effluent discharges from wastewater treatment plants can increase P concentrations in streams and rivers for several kilometers downstream (Haggard, 2010; Scott et al., 2011).

It is important to understand all the potential sources of P in a watershed to better understand how to improve watershed management and water quality. The historic application of P to the soils and introduction to streams from wastewater treatment plants and agriculture represents a legacy source in the riparian floodplains and within the stream channel (Jarvie et al., 2013). In order to better understand all sources of P and provide more information on how P might be released from these soils when inundated during rainfall-runoff events, we evaluated how P is released to the overlying water from soils during inundation and related the amount of P stored in riparian soils to P flux into the overlying water.

MATERIALS AND METHODS

In order to determine the amount of P released from inundated riparian soils, four sites were chosen at the Water Research and Education Center at the Arkansas Agricultural Research and Extension Center, Fayetteville, Ark., that have varying levels of soil P based on historic records (Fig. 1). Then three Plexiglas cores (~6 cm inside diameter) were pushed into the ground at each site and removed with an intact soil core. The cores were transported back to campus and allowed to equilibrate to room temperature (~20 °C). After temperature equilibration, the bottoms of the cores were sealed with a stopper and weatherproof tape and then wrapped in aluminum foil to limit light in order to prevent algal growth in the overlying water during incubation. The cores were flooded with 0.75 L of tap water and monitored approximately daily to maintain a constant volume of overlying water during the incubation period.

Approximately three times a week, water samples were taken from each core. The water samples (~20 mL) were pulled from the overlying water, then filtered through a syringe filter (0.45-μm pore size) and acidified to $\mathrm{pH} < 2$ using concentrated HCl. The samples were analyzed for soluble reactive phosphorus (SRP) using the ascorbic acid method (APHA, 2012). After two weeks, each core was drained and the top 5 cm of the soil was removed and analyzed for water extractable P (WEP) and Mehlich-3 extractable P (M3P), which are two different fractions of P stored in soils. The WEP represents the P that is easily released to the water, and it is measured using a 1:10 soil (dry weight)-to-water extraction ratio and the sample is filtered through a 0.45-

Fig. 1. Locations of sites where soil samples were collected from the Watershed Research and Education Center (WREC, black boundary) at the Arkansas Agricultural Research and Extension Center (AAREC), Fayetteville, Arkansas. The provided values are the experimentally determined average Mehlich-3 phosphorus values.

µm pore size filter with a vacuum and analyzed using Inductively Coupled Plasma Optical Emissions Spectrometry (ICP OES); WEP is reported as mg kg^{-1} dry soil. The M3P represents the P that is available to support plant growth and it is a typical agronomic soil test in Arkansas; it is also measured using a 1:10 extraction ratio and ICP OES (Pierzynski, 2000).

The mass of P released to the overlying water in each core was determined by multiplying the SRP concentration by the volume of overlying water in each core (0.75 L). The mass of P (mg) released to the overlying water was compared against time (h) using simple linear regressions, and the slope (mg h^{-1}) was divided by the surface area of the soil in the cores to give the flux or rate of release per unit area (mg m^{-2} h^{-1}). The data from the 282.5-h inundation period was analyzed using linear regression to estimate "long-term flux"; whereas the slope between two points (i.e., 16.5-h incubation) was used to estimate the "short-term flux". The individual flux rates were used in an analysis of variance with means separated using least significant difference (ANOVA LSD) to determine differences between sites. The soil data, i.e. M3P and WEP content, was compared to the flux data using linear regression. In addition, the M3P and WEP content was compared across the sites using ANOVA LSD. All statistical comparisons were made using $\alpha = 0.05$ to determine significant differences between means.

RESULTS AND DISCUSSION

The linear regression for the long-term SRP flux was significant ($P < 0.05$) in almost all cases, except for one or more replicates at sites 2, 3, and 4. The mean flux rates for each site ranged from 0.06 mg m^{-2} h^{-1} at site 3 to 1.26 mg m^{-2} h^{-1} at site 1. Sites 1 and 2 (on average 1.26 and 0.83 mg m^{-2} h^{-1}, respectively) had significantly greater P flux than the other two sites at the Watershed Research and Education Center ($P = 0.0042$; Table 1), and these sites also had the highest soil P content.

However, it was observed that the mass of SRP released to the overlying water was not necessarily linear across the long-term inundation, thus indicating that this model was not always the best fit for our data (Fig. 2). The mass of SRP in the overlying water increased faster in the beginning and then tended to reach a plateau over time. For this reason, the data was analyzed using a power function to reflect how the amount of SRP released by the soil reaches a plateau concentration that is at equilibrium with the overlying water column by the end of the two-week period (Fig. 2).

Table 1. Mean soluble reactive phosphorus (SRP) flux, standard deviation, and homogenous groups (based on LSD groupings) over the long-term incubation (282.5 h).

Site†	Mean Flux (mg m^{-2} h^{-1})	Standard Deviation (mg m^{-2} h^{-1})	LSD Groupings‡
1	1.26	0.03	A
2	0.83	0.60	A
3	0.06	0.09	B
4	0.13	0.12	B

† See Fig. 1 for site information.

‡ Least significant difference (LSD) groupings with the same letter aren't statistically different (P = 0.0042).

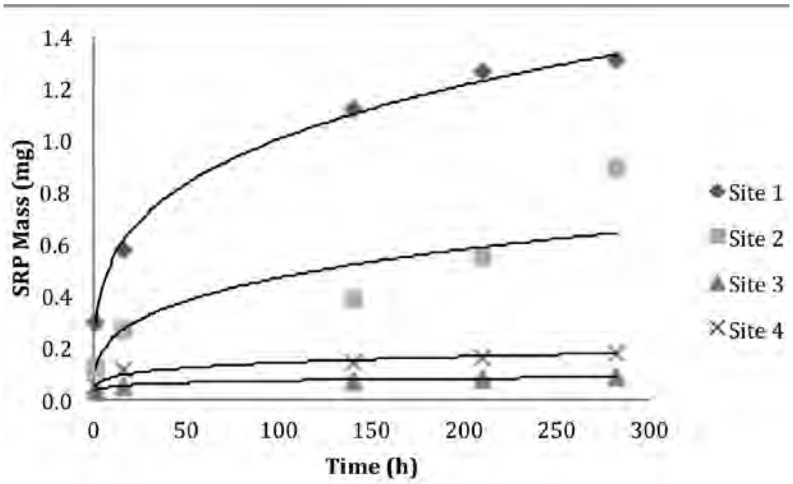

Fig. 2. Mass of soluble reactive phosphorus (SRP) released from the soil to the overlying water over the long-term incubation (282.5 h), fit to a power function. (n = 4).

Floodwaters typically do not inundate riparian soils for more than a few days, especially at the Watershed Research and Education Center where the soil cores were collected. As a result it was decided that since overlying waters remain for only a few days, the flux should be calculated based on our first two samples taken over the first 16.5 hours of inundation. This short-term flux (based on a 16.5-h inundation) represents maximum potential release, which could possibly occur during short-term inundation of riparian soils. This is consistent with a study by Aldous et al. (2005) where net SRP flux was greater after 1 day compared to 4 days.

The initial change in SRP concentration (from 1-h to 16.5-h) was used to approximate how much P would be released during inundation for a short duration, showing that short-term flux varied from an average of 0.43 to 6.61 mg m^{-2} h^{-1} across the four sites (Table 2). The short-term P fluxes in this study were greater than the rates reported for a study of sediments of river impoundments, where P flux from aerobic cores ranged from 0.02 to 0.15 mg m^{-2} h^{-1} (Haggard and Soerens, 2006; Haggard et al. 2012). Differences in dynamics between floodplain soils and reservoir sediments likely led to the large differences in flux rates measured in this study. Studies of P flux from lake-bottom sediments generally find that data are linear over a 10-14 d incubation, while the P concentrations through time did not follow a linear trend in the current study. Additionally, the soils used in the current study (up to 297 mg M3P kg soil^{-1}) may have had far more stored P than lake-bottom sediments.

The short-term flux rates were an order of magnitude greater than that observed over the long-term inundation, showing that the amount of SRP released from the soil to the overlying water was much greater in the beginning and then only smaller incremental increases occurred with time. During several days of soil inundation, P release to the water column may reach an equilibrium concentration, where P is neither released nor retained by sediments (Lottig and Stanley, 2007) or soils (Taylor and Kunishi, 1971). Whenever sediments and soils are incubated with overlying water under aerobic conditions, then the phosphate is released to a plateau concentration, representing an equilibrium between the solid and aqueous phases.

The sites had M3P contents ranging from 41 mg kg^{-1} at site 3 to 297 mg kg^{-1} at site 1, and WEP contents ranging from 9.0 mg kg^{-1} at site 3 to 61.0 mg kg^{-1} at site 1. The sites had significantly different M3P contents (P = 0.0001); site 1 had the greatest mean M3P content (297 mg kg^{-1}), and site 3

Table 2. Mean soluble reactive phosphorus (SRP) flux, standard deviation, and homogenous groups (based on LSD groupings) over the short-term incubation (16.5 h).

Site†	Mean Mass at 1 h (mg)	Mean Mass at 16.5 h (mg)	Mean Flux (mg m^{-2} h^{-1})	Standard Deviation (mg m^{-2} h^{-1})	LSD groupings‡
1	0.294	0.581	6.61	2.29	A
2	0.121	0.269	3.40	1.39	B
3	0.034	0.053	0.43	0.68	B
4	0.048	0.114	1.52	1.92	B

† See Fig. 1 for site information.

‡ Least significant difference (LSD) groupings with the same letter aren't statistically different ($P = 0.0094$).

Table 3. Mean Mehlich-3 phosphorus (M3P) and water extractable phosphorus (WEP) in soils, standard deviation and homogenous groups (based on LSD groupings).

Site†	Mean M3P (mg kg^{-1})	Standard Deviation (mg kg^{-1})	LSD Groupings	Mean WEP (mg kg^{-1})	Standard Deviation (mg kg^{-1})	LSD Groupings‡
1	297	35	A	61	5	A
2	225	28	B	34	3	B
3	41	28	D	9	8	C
4	96	24	C	25	7	B

† See Fig. 1 for site information.

‡ Least significant difference (LSD) groupings for each soil-test P type with the same letter aren't statistically different ($P < 0.001$).

had the lowest M3P content (41 mg kg^{-1}) (Table 3). Also, the WEP contents across the sites showed significant differences ($P = 0.0002$); WEP content was greatest at site 1 (61 mg kg^{-1}), slightly lower at sites 2 and 4 (34 and 25 mg kg^{-1}, respectively), and lowest at site 3 (9 mg kg^{-1}). Differences in soil-test P between sites complemented those differences observed in mean SRP flux rates across these sites. The mean flux rate at site 1 was significantly greater relative to sites 2, 3, and 4 ($P = 0.0094$; Table 2). The flux rate at site 1 was 6.60 mg m^{-2} h^{-1}; whereas the lowest flux was 0.43 mg m^{-2} h^{-1} at site 3, which reflects the pattern seen in the soil-P content data.

The M3P and WEP contents were compared to the short-term flux data using linear regression, showing that (1) soil M3P content was positively related to short-term SRP flux ($r^2 = 0.76$, $P < 0.0001$), and (2) WEP content was also significantly related to short-term flux ($r^2 = 0.75$, $P < 0.0001$) (Fig. 3). Other studies have shown that P concentrations in runoff waters (from rainfall simulation studies) are positively correlated to WEP and M3P content of soils (Pote et al., 1999), especially with the amount of P near the soil surface (0-5 cm) (Torbert et al., 2002). This suggests that as the amount of P stored in the riparian soils (e.g., WEP and M3P) increases, so does the potential for SRP to be released to the overlying water during runoff events and especially when inundated during flooding.

In conclusion, the data analyses show that P was released to the overlying water when soils were inundated to simulate flooding. There was variability in the amount of P released due to the amount of P stored in the soil (e.g., WEP and M3P) at the different sites at the Watershed Research and Education Center. There was a significant positive relationship between the amount of P released into the overlying water in each core and the amount of P (M3P and WEP) measured in the upper 5 cm of the soil in each core. Hence, there was a significant increase in SRP flux with increase in soil P measured as either M3P or WEP. Riparian soils, which have stored large amounts of P from upstream sources or direct application, have the potential to be a P source when inundated during flood events. In addition, comparing the long-term versus short-term SRP flux demonstrates that the rate with which P is released from the soil tends to increase rapidly in the beginning and then level off over time.

ACKNOWLEDGMENTS

The College of Engineering Freshman Engineering Program Honors Symposium, University of Arkansas System Division of Agriculture and the U.S. Geological Survey Water Resources Research Institutes Program through the Arkansas Water Resources Center (AWRC) provided funding for this project. The water samples were analyzed by Brina Smith in the AWRC Water Quality Research Support Lab, and the soil samples were analyzed at the Agricultural Diagnostic Lab within the Division of Agriculture. We also thank Vaughn Skinner and Dirk Philipp for providing historic soil-test P data from the Watershed Research and Education Center.

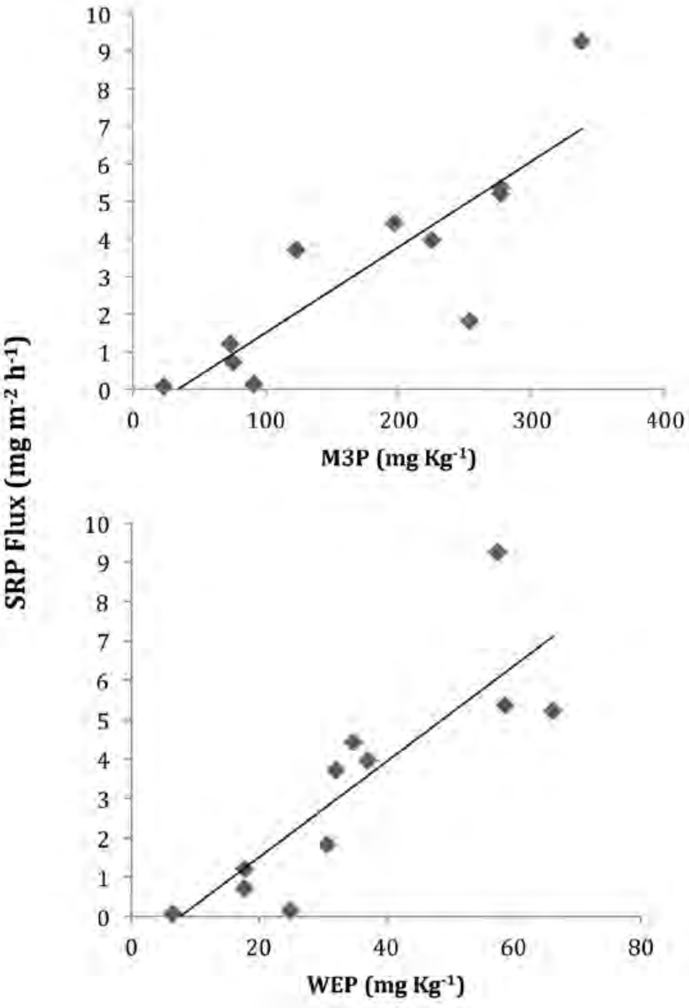

Fig. 3. Soil Mehlich-3 phosphorus (M3P) and water extractable phosphorus (WEP) content compared to short-term (16.5 h) soluble reactive phosphorus (SRP) flux to the overlying water column during inundation for each replicate.

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