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ANALYSIS OF PHOSPHORUS EXTRACTION FROM SPENT MUSHROOM COMPOST APPLICATION ON RECLAIMED MINE SOILS

SERENA JOY GROFF
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Reviewed and approved* by the following:

Richard Stehouwer
Professor of Soil Science
Thesis Supervisor

Robert D. Shannon
Associate Professor of Agricultural Engineering
Honors Advisor

*Signatures are on file in the Schreyer Honors College

ABSTRACT

Abandoned mined lands are often regarded as infertile zones with limited agricultural potential. However, reclamation with organic materials has been shown to greatly increase biomass crop production on such sites. In Pennsylvania, mushroom industries are looking for an efficient way to handle spent mushroom compost (SMC). Applying SMC to mine soil increases fertility, but also introduces an environmental concern due to high levels of phosphorus (P). Therefore, the fate of P applied from SMC needs to be understood to a greater extent. This laboratory study investigated P loss from surface-applied SMC and its subsequent transport through mine soils. Mine soils amended with manure + paper mill sludge or lime + fertilizer were obtained from a site in Schuylkill County, either with no added SMC or 15 ton/acre repeated applications. A mechanical vacuum extractor was utilized to simulate a 5-year precipitation event so that leachates could be collected after passing through two 5-cm soil layers and P movement could be measured. Colorimetric analysis by an automatic Lachat allowed orthophosphate fractions to be identified, whereas an ICP analysis machine was used to determine total P. By subtracting ortho-P from the total, organic P fractions were obtained. The orthophosphate fraction accounted for about 75% of each leachate. It was found that the spent mushroom compost layer leached approximately 59.7 mg total P/g compost. Repeated applications of SMC increased the amount of P sorption on manure + paper mill sludge reclaimed soils when compared to the reclaimed soils without SMC application. In both treated soils, the amount of P leached below 5-cm was minor in the context of environmental concerns. For all simulations, the subsoil layer effectively immobilized the remaining P. This study shows that P was retained despite previous applications of SMC. Once future studies answer questions about the impacts of other variables on field application of SMC, mushroom industries can begin to efficiently handle their waste product.

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INTRODUCTION

Mine reclamation has been studied extensively, especially the nutrient cycling within acidic and compacted mine soils. Researchers have attempted to find the most practical and environmentally sound combination of soil amendments and reclamation measures applied to mine soils (Haering, 2000). Others have attempted to better understand nutrient fluxes, namely those involving nitrogen, phosphorus and potassium, as well as trace metals (Stehouwer, 2006). Also, more researchers have attempted to gauge soil fertility over longer periods, measuring biomass yields following reclamation (Bendfeldt, 2000). Although Stehouwer et al. (2006) found that phosphorus had low mobility in mine soil, the behavior of phosphorus throughout the soil column is not well understood. With nutrient rich reclamation treatments, it is important to understand the behavior of all nutrients, especially one such as phosphorus, which carries serious environmental implications.

For Americans, coal is one of the main sources of energy, but the acquisition of coal is also a main source of environmental stress, especially in Pennsylvania. In the late 1750s, markets began trading coal in Western Pennsylvania leading it to gradually become a commercial product a few decades later (PDM, 1955). As production increased, economic prosperity rifted throughout many counties across the state. Naturally, periods of growth tend to approach moderation before slowing to a complete halt. For Pennsylvania's coal industry, many mine sites, especially those not regulated under the Surface Mine Reclamation Act, found themselves leaving behind a legacy of mine waste that gradually became a significant part of the ecosystem.

History has shown that humans have powerful means to alter land and extract resources both rapidly and destructively. Though, the reclamation of our disturbances to the land surface and below surface ecosystems is not nearly as rapid. Mining and drilling activities are a threat to the longevity of sustainable air, water and land qualities. Reclaimed sites tend to not be biologically diverse, and may also take decades to reflect any semi-natural appeal (Bice, 2013). Most mining activities compact the soil to the point where seedling mortality hinders effective revegetation. Mining disturbance may also lead to acidic runoff due to oxidation of pyritic materials associated with coal seams and exposed by mining activity. This acidic runoff is commonly referred to as acid mine drainage. Additionally, wildlife habitat loss is common and recreational activities are negatively affected after the land undergoes a transition from what is usually a forested plot to an acidic, rocky segment.

Current widespread solutions to revitalize this land suffer from limited potential, such as the enforced mine-site remediation of providing seventy percent short-grass cover (Bice, 2013). This leaves a significant portion of environmental concerns lingering. Opportunities for more sustainable and effective solutions present themselves on a local level, creating a need for specialization of approaches. By considering surrounding land uses and regional needs, one can repurpose an abandoned mine site in a way that more readily maximizes economic and environmental gains.

The Pennsylvania mushroom industry, based in central and southeastern PA, requires an input of perennial grasses to the substrate on which mushrooms are grown, and also requires marketing and disposal options for their nutrient-rich spent mushroom compost (SMC). Surface application of SMC to abandoned mined land offers an option of revitalizing the infertile land, while also providing a beneficial use for the SMC and facilitating the mushroom industry.

The fate of the nutrients applied by SMC to abandoned mined land needs to be better understood so that potential environmental degradation can be minimized. Though variable, SMC has high phosphorus content relative to other composted materials, both on a wet-basis and dry-basis (Fidanza, 2010). Phosphorus needs for crops are commonly exceeded by nitrogen based compost applications so it is important to understand the movement of phosphorus through the amended soil layers, as well as through the untreated subsurface soil layers of a representative site. The main concern is that excessive phosphorus leaching or runoff loss could contaminate water bodies in surrounding areas.

In the past, researchers Stehouwer and Banfill have examined economic benefits of various soil treatments on the mine soils in Schuylkill County. They paired with the Giorgi mushroom company to reintroduce abandoned mine lands into the economy. Their experiment allowed for the utilization of SMC, which helped to fertilize the land with nutrients, ultimately leading to biomass growth of inputs to mushroom production. In one of their long-term experiments, mine soil was initially reclaimed in 2006 by amendment with lime + fertilizer or with poultry manure + paper mill sludge mixed to achieve a 20:1 C:N ratio and planted with switchgrass. In 2012 they began annual surface application of 15 tons/acre of SMC on half of each plot while the other half received no SMC. As their experimentation had sought out the economic viability and sustainability of the application of spent mushroom substrate to low-fertility mine soils in Central Pennsylvania, this experiment hopes to unveil the environmental limitations that phosphorus loss from soil poses by combining either lime + fertilizer (LF) or manure + paper mill sludge (manure + PMS) amendments with differing application rates of spent mushroom substrate.

Both LF and manure + PMS treatments introduce high pH characteristics to the mine soil they are applied to. When soil pH rises, phosphorus is expected to become more plant available due to the decrease in precipitation reactions with either iron (Fe) or aluminum (Al). Although, an increase in soil pH may also cause phosphorus to react with calcium (Ca), which would again lower P availability to plants (Adams and Odom, 1985). Plant uptake and soil chemistry can highly impact the behavior of P in the soil stratum.

In addition to providing alkalinity to the soil, the initial reclamation treatments also introduce some P of their own. Manure is high in organic phosphorus, and fertilizer is commonly comprised of a combination of nitrogen, phosphorus and potassium. It is reasonable to consider that by combining these reclamation treatments to the soils along with SMC, phosphorus transport or adsorption could change significantly. This research will analyze transport of phosphorus in the two different initial reclamation systems and will compare the effects of surface application of SMC on P transport and adsorption in the amended soil layer (0-5 cm depth) and in the underlying non-amended layer (5 – 10 cm depth).

HYPOTHESES

I hypothesize that in mine soil to which no SMC was added, P loss from the soil layer reclaimed with manure + PMS will be greater than P loss from the lime + fertilizer amended soil due to the higher amount of P introduced in the manure mixture when compared to the fertilizer P. For mine soil amended with SMC, I hypothesize that the phosphorus leached from surface applied SMC will more readily sorb to mine soil amended with the lime + fertilizer because these soils will be more resistant to leaching due to the calcium portion of the lime applied reacting and immobilizing the introduced phosphorus. This would result in higher phosphorus loss from the manure + PMS treated soil after SMC application.

Alternatively, as a null hypothesis, it is possible that no treatment will significantly differ from the others in terms of phosphorus mobility, which could imply that phosphorus behavior in reclaimed mine soils is independent of any prior soil treatment. In this scenario, binding of phosphorus to Al^{3+} and $Fe^{2/3+}$ within the subsurface soil layers present in all treatments would be the primary determinant of the nutrient's behavior. Here, I hypothesize that the subsoil fractions will sorb the majority of the introduced phosphorus due to their acidic nature.

METHODS AND MATERIALS

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SITE DESCRIPTION

The experimental soils were collected from an abandoned mine site, referred to as the "Barry Site," located in Schuylkill County, Pennsylvania. This site was also previously used for the Stehouwer Giorgi Mushroom remediation study done in years prior. Before remediation, the soils were classified as Udorthent strip mine with a channery sand loam and a low pH between 4.5 and 5.1 (NRCS, 2015). Reclamation efforts on the site included a combined treatment of lime + fertilizer (LF) and 20:1 C:N mixture of manure + paper mill sludge (MPS), among three other treatments that weren't studied here. Each of these treatments had the additional amendment of SMC applied on a regular basis, at rates of 0 Tons/Acre, 15 Tons/Acre, or 30 Tons/Acre (Stehouwer, 2015).

Surface soil samples (0- to 5-cm depth) of interest for this study were collected from multiple locations within the "Barry Site" (Figure 1) corresponding to the soil amendments, so that homogeneity in the soil samples was ensured. Subsurface soil samples (5- to 10-cm depth) were also collected to serve as the third layer of the experimental design.

All of the collected samples were transported to and stored in a Penn State greenhouse to dry out for a few days. After the soils dried sufficiently, rock fragments and gravel constituents greater than 2-cm were sieved out.

Manure to Mineland Project: Barry's Site
Field Experiment Plot Plan

North

Access Road

	110			**120**			**130**			**140**			**150**		10' offset														
	M20			**LF**			**M30**			**C1**			**C2**			**310**			**320**			**330**			**340**			**350**	
111	112	113	121	122	123	131	132	133	141	142	143	151	152	153		**C1**			**C2**			**M20**			**LF**			**M30**	
2	0	1	0	2	1	2	0	1	1	0	2	0	1	2	311	312	313	321	322	323	331	332	333	341	342	343	351	352	353
	210			**220**			**230**			**240**			**250**		1	2	0	1	0	2	2	0	1	2	0	1	2	1	0
	LF			**M20**			**M30**			**C2**			**C1**			**410**			**420**			**430**			**440**			**450**	
211	212	213	221	222	223	231	232	233	241	242	243	251	252	253		**C1**			**M30**			**M20**			**C2**			**LF**	
0	2	1	1	0	2	2	0	1	1	0	2	1	2	0	411	412	413	421	422	423	431	432	433	441	442	443	451	452	453
											10' offset				0	1	2	1	0	2	2	1	0	1	0	2	1	0	2

South

Plot label key

Lines 1 & 2: Main plot number and main plot treatment applied April 2006.
Lines 3 & 4: Sub-plot number and sub-plot SMS level applied April 28, 2011.
0 = 0 T/A, 1 = 15 T/A, 2 = 30 T/A (1=138 lb/sub-plot, 2=276 lb/sub-plot)

Main plot dimensions: 20 x 30 feet
Sub-plot dimensions: 6'8" x 30 feet

Figure 1. Map of the reclaimed mine soil plots in Schuylkill County, referred to as the "Barry" site, with corresponding soil treatments (M20, M30, LF, C1, C2) and spent mushroom application levels (0,1,2).

The spent mushroom compost was kept consistent with the soils from the "Barry" site. During Stehouwer and Banfill's research, the SMC was tested over the course of 3-4 years. The values in Table 1 are the averaged results in regard to pH, percent phosphorus, percent organic matter and carbon to nitrogen ratio observed in the SMC used for this study.

Table 1. Compost test results obtained from Penn State's Ag Analytics Soil Lab regarding SMS (n=5) from the "Barry" site, also used in this experiment.

	pH	Phosphorus (%)	Organic Matter (%)	C:N
SMS	7.05	0.45	45.57	13.3:1

EXPERIMENTAL SETUP

To test the hypotheses, it is necessary to identify the phosphorus leaching from each of the soil layers to fully understand the movement and behavior of the macronutrient. In order to do this, a typical rainstorm event was replicated in a laboratory setting. The EPA's synthetic precipitation leaching procedure method 1312 was used to create the synthetic rainwater for the experiment. A mixture of 60/40 H_2SO_4/HNO_3 by weight was added to de-ionized water until a pH of 4.6 ($^+$/- 0.05) was reached, matching the current rainfall acidity east of the Mississippi River. The soil particle sizes were sieved to a size less than 2-mm to better fit in the syringes and to focus on studying the dependent variable of phosphorus movement in response to the independent variable of treated soil influences, rather than interactions with rock fragments.

Sieved soil samples were also sent to Pennsylvania State University's Agricultural Analytical Soil Lab to be tested for pH, nutrient concentrations, acidity, and cation exchange capabilities to compare the influences specific differences in the soils could have on the behavior of phosphorus, especially the initial soil pH. Table 2 shows the results of the lab's analysis.

Table 2. Soil test results obtained from Penn State's Ag Analytics Soil Lab regarding the different independent variables, either manure + paper mill sludge (MPS) or lime + fertilizer (LF) treated soils, with and without spent mushroom compost application, as well as the subsoil layer. Note that these were obtained immediately after collecting soils from the sample site, prior to introducing the phosphorus-rich leachate from the experimental SMS layer.

Soil Sample	pH	Phosphorus (mg/kg soil)	Acidity	CEC
MPS w/o SMS	7.66	424	0	16.0
MPS w/ SMS	7.63	460	0	17.3
LF w/o SMS	6.96	67	0	10.0
LF w/ SMS	7.38	338	0	17.4
Subsoil	5.60	12	5.1	8.6

Notice the soil phosphorus in the manure + PMS soil, without SMC applied, had a level of 424 mg P/kg soil compared to the LF soil, without SMC applied, having a level of 67 mg P/kg soil. The first hypothesis is based upon the fact that the manure + PMS amendment is introducing between six to seven times more P into the soil than the LF treatment. This makes it reasonable to assume more P would be lost from the manure + PMS treatment.

Syringes, 60-mL in volume, were connected with tubing as a way to construct segmented columns with controlled leaching rates in the Centurion Model 24 mechanical vacuum extractor. This allowed leachates to be collected, analyzed, and also applied to the following experimental soil layers. The vacuum extractor was set at a rate of 0.37 cm/hr to coincide with the representation of a typical 2-5 year storm in the Schuylkill County region of Pennsylvania, with 3.0 to 3.5 inches of rainfall per 24 hours (USDA, 1986).

For the first experiment, comparing the reclamation treatments of phosphorus loss from lime + fertilizer to manure + paper mill sludge, both without SMC applied, two constructed columns were used, each with two syringes, superimposed in the vacuum extractor. Each bottom syringe was used to collect leachate from the syringe above it. The first syringe contained approximately 12-14g of the treated soil. The following top syringe contained 17g of the subsoil.

For the second experiment, comparing lime + fertilizer with SMC applied to manure + paper mill sludge with SMC applied, three constructed columns were used, each with two syringes, superimposed in the vacuum extractor. Each bottom syringe was used to collect leachate from the syringe above it. The first syringe contained 3.6 g of sieved and moistened spent mushroom compost with 40-mL of rainfall-simulated reagent added on top. The second top syringe contained approximately 12-14g of the treated soil. The third top syringe contained 17g of the subsoil.

Three replications of each soil column were included to ensure a higher level of accuracy within the results. After each run, the leachate was promptly recovered and 5-mL was removed, filtered, and set in the freezer to prevent further microbial transformations before later analysis to identify separate forms of phosphorus. The remaining leachate solution was then manually added to the following soil column. See Figure 2 for clarification.

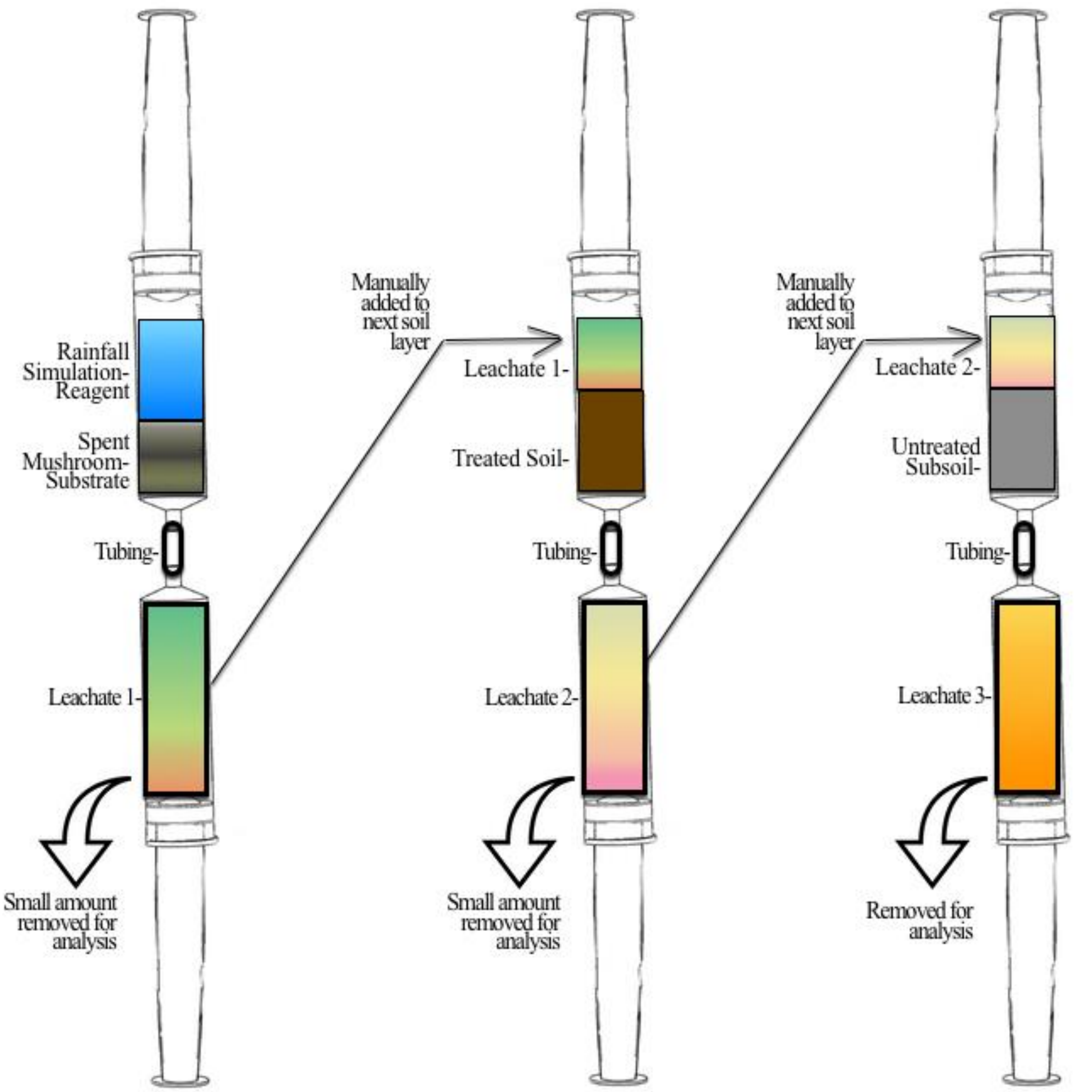

Figure 2. Segmented soil column schematic in mechanical vacuum extractor. Soil treatments, including manure + paper mill sludge and lime + fertilizer, were compared for P loss and P retention. For experiment one, the soils columns without SMC applied have the first pair of superimposed syringes omitted.

PHOSPHORUS ANALYSIS

After removing frozen samples and allowing them to reach room temperature, each leachate from the spent mushroom compost and the treated soils were diluted on a 1:1 basis with DI water, allowing for a greater volume of solutions to be available for analysis. Prior to analysis, standards were carefully prepared for the creation of a calibration curve to identify phosphorus concentrations in each sample. The standard solution contained a mixture of primary standard grade anhydrous potassium phosphate monobasic (KH_2PO_4), dried for one hour at 105 degrees centigrade, and DI water, so that concentrations of 0.00 to 2.500 mg P/L were represented (Diamond, 1995).

The first analysis utilized an automatic Lachat colorimetric spectrometer to obtain the orthophosphate fraction of each solution. According to the QuikChem Method 10-115-01-1-T, in each sample, the orthophosphate ion (PO_4^{3-}) reacts with ammonium molybdate and antimony potassium tartrate under acidic conditions to form a complex. The complex is reduced with ascorbic acid to form a blue complex which allows light, proportional to the orthophosphate present in the sample, to be absorbed (Diamond, 1995). As necessary, reagents were carefully prepared to allow for complete functioning of the Lachat machine.

The next technique used the same samples, which were instead analyzed by an inductively coupled plasma atomic emission spectrometer (ICP). The ICP works by exciting atoms to emit radiation at wavelengths characteristic of the element of interest. The intensity of the radiation emission allowed the concentration of phosphorus to be quantified for this experiment (Govere, 2015). The ICP readings indicated total dissolved phosphorus, allowing subtraction of the orthophosphate fractions, determined with the Lachat, to identify the organic phosphorus portion. For the samples that were diluted, the obtained concentration values were doubled to represent the true phosphorus concentration.

To best reflect the interactions between phosphorus and the soil layers, concentration values (mg P/L) were converted to a weight basis (mg P/g soil) by multiplying the average P concentrations of different replications by their corresponding leachate volumes and dividing that by the soil layer weight. By separately weighing out soils, the columns better simulated field interactions because they incorporated the bulk densities of the separate soils, as well as the estimated depths of layers that the phosphorus would travel through. This was done after solving for total P present or transferred within each layer. To understand the interaction between the leached P and subsequent soil layers, the difference between the P introduced from the previous soil layer and the P lost from the soil layer in question was computed, resulting in an estimation of the P sorption capacity.

STATISTICAL ANALYSIS

Due to the nature of data received from this study, normal distribution was assumed for analysis of the phosphorus concentrations for each of the soil layers. To test for significance in differences between soil treatments, data was analyzed for compared variance across phosphorus release in treatments without SMC application, and for phosphorus absorption in treatments with SMS application.

The ANOVA function in SAS was used to determine effects of P loss due to reclamation of the soils, the presence of SMC, and the interaction between the reclamation and the SMC, when present. By analyzing the data through accounting for each variable, significant relationships among variables and between variables could be identified.

The level necessary for satisfaction of statistical significance was set at the traditional value of $\alpha=0.05$. Tabled numbers and graphical depictions for standard deviations (n=3) were calculated in a Microsoft Excel spreadsheet and are shown in the figures and tables seen in the results section.

RESULTS

Phosphorus concentrations in the amended soil layer differed across treatments in both the SMC applied and SMC independent leachates. The following figures and tables provide an overview of the resulting data from the phosphorus analysis, taking into account inorganic and organic fractions of P observed in the soil layers corresponding to each soil treatment.

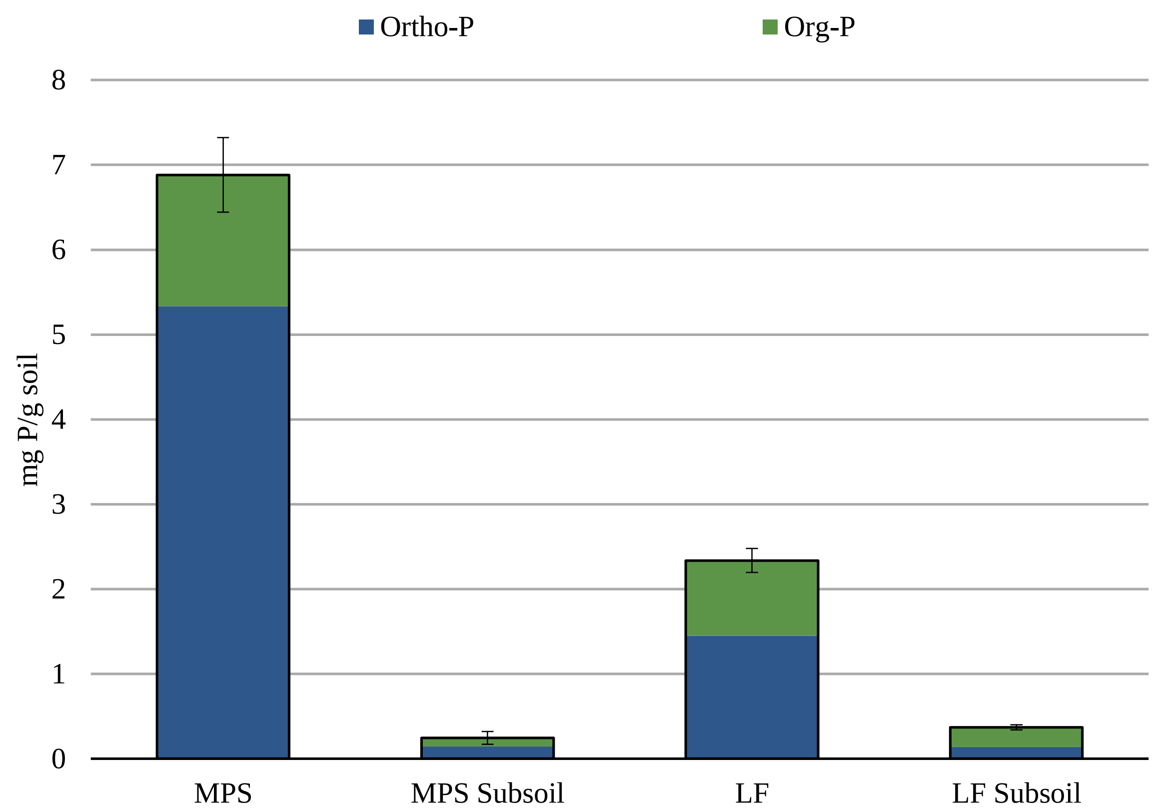

Figure 3. Inorganic and organic P leached from mine soils reclaimed with manure + paper mill sludge and lime + fertilizer, on a by weight basis, as well as their corresponding subsoil layers. Standard deviation (n=3) values calculated from total P also shown.

Figure 3 shows that soil with manure + paper mill sludge releases a higher concentration of P per weight of soil than does the soils treated with lime + fertilizer when no SMC was applied. Note that the P loss in the manure + PMS is almost three times the amount that was lost from the LF treated soil. The subsurface soil layers released low amounts of phosphorus, both under 0.5 mg P/g soil.

Table 3. Probability values associated with inorganic, organic and total P leached from mine soils reclaimed with manure + paper mill sludge and lime + fertilizer without spent mushroom compost applied.

	Total P	Ortho-P	Org-P
MPS v. LF without SMC	0.0392	0.0269	0.6243

Table 3 shows that the manure + PMS reclamation versus LF reclamation had a statistically significant impact on total P and inorganic P loss in the absence of SMC application.

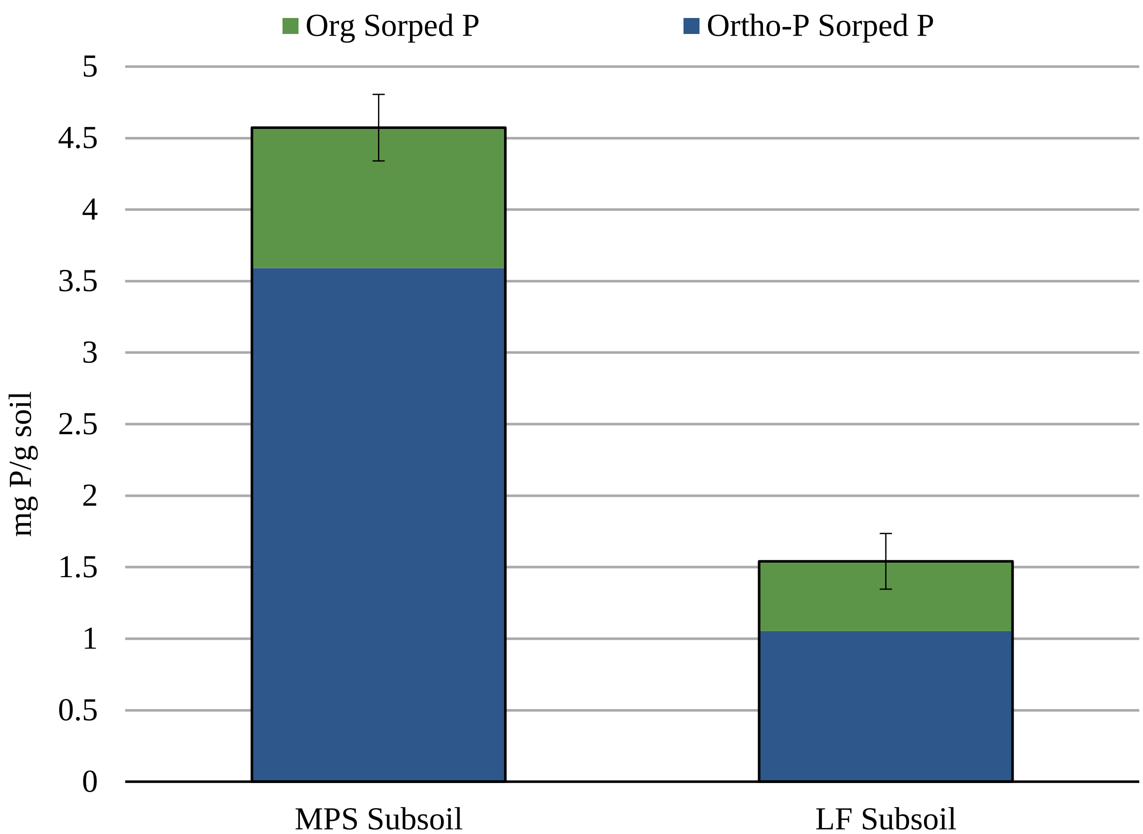

Figure 4. Inorganic and organic P absorption, on a by weight basis, observed in subsurface soils pertaining to the leached P from manure + paper mill sludge and lime + fertilizer treated soils. Standard deviation (n=3) values calculated from total P also shown.

Figure 4 shows the amount of introduced P that the subsurface soil captured. In this figure, it initially looks as though the manure + PMS subsurface soil layer was more effective at capturing the introduced P from the previous layer. Keep in mind that the P loss was much lower in the LF treated soil, so the introduced P to the LF subsurface soil layer was also much lower.

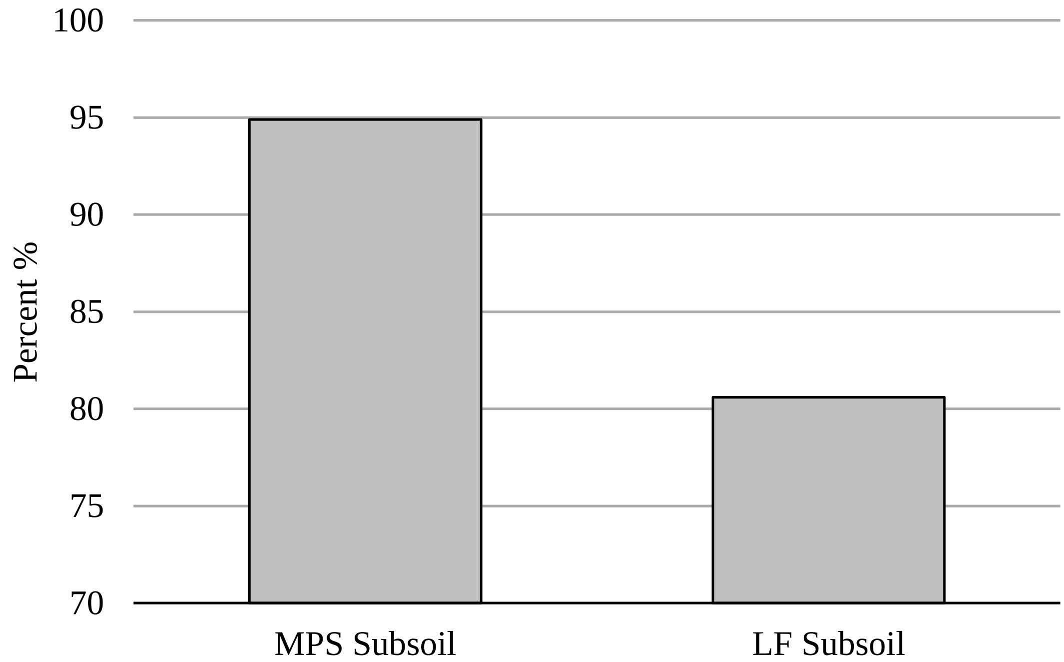

Figure 5. Percent of Total P leached that was absorbed by the subsurface soil following manure + paper mill sludge or lime + fertilizer reclamation.

Figure 5 shows the percent capture of total P for the subsurface soil layers following manure + paper mill sludge and lime + fertilizer without SMC applied. The percentage of P sorbed by each subsurface soil layer shows that significant portions of P were captured by the acidic subsoil layers in both treatments. Again, take into regard that 0.5 mg P/g soil would constitute approximately 30 percent of the LF subsoil capture, and almost 12 percent of the manure + PMS subsoil. This small-scale difference could also present a noticeable graphical depiction, which is less significant than it initially appears to be.

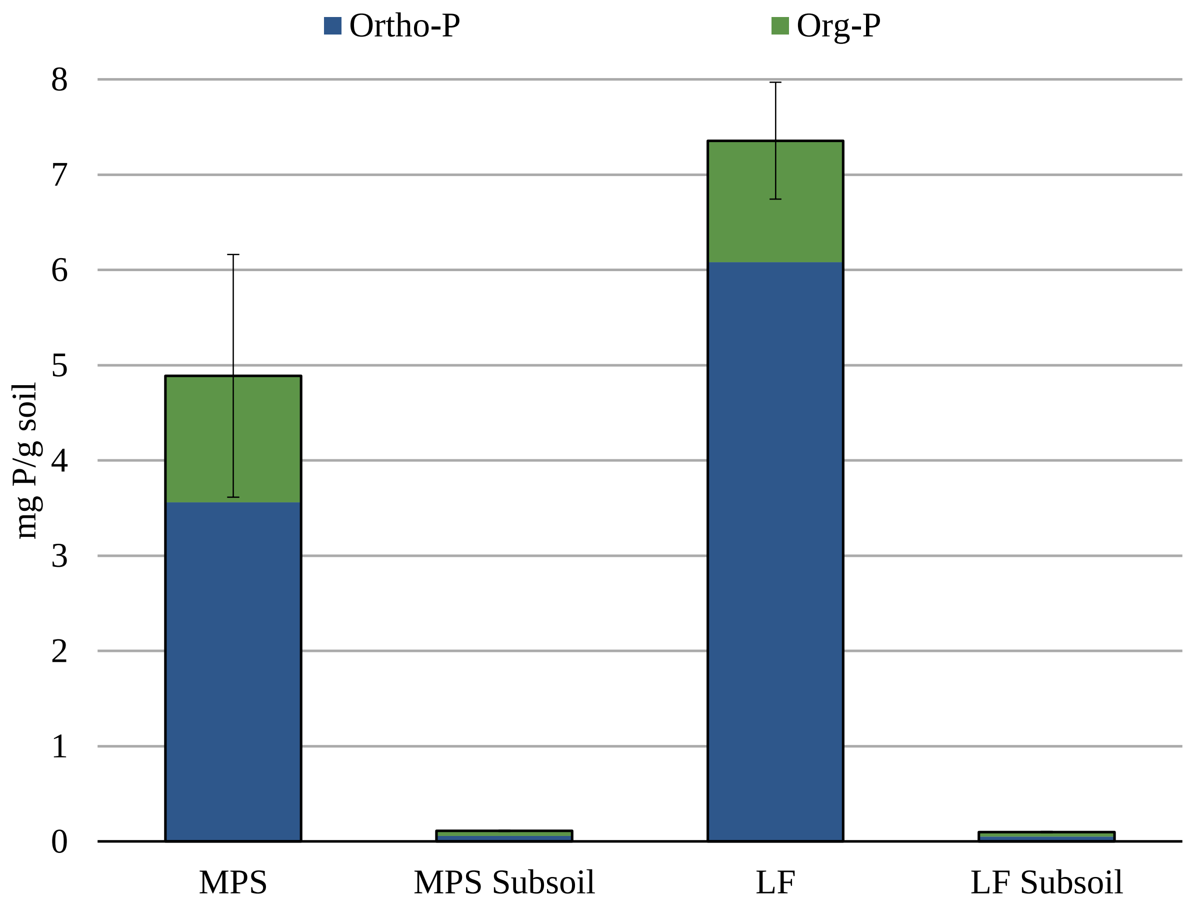

Figure 6. Inorganic and organic P leached from mine soils reclaimed with manure + paper mill sludge and lime + fertilizer, with SMS applied, on a by weight basis, as well as their corresponding subsoil layers. Standard deviation (n=3) values calculated from total P also shown.

Figure 6 shows that with SMC application, soil with manure + paper mill sludge releases a slightly lower concentration of P per weight of soil than does the soil treated with lime + fertilizer. Subsurface soils released very small amounts of P.

Although not graphically depicted here, SMC applied resulted in a total 58 mg P leached/g compost, with inorganic P accounting for 52.6 mg and organic P accounting for 5.3 mg. The variability in the SMC was especially high, leading to a standard deviation (n=3) of 19.6 mg P/g compost.

Table 4. Probability values associated with inorganic, organic and total P leached from mine soils reclaimed with manure + paper mill sludge and lime + fertilizer with spent mushroom compost applied.

	Total P	Ortho-P	Org-P
MPS v. LF with SMC	0.0415	0.7080	0.0003
SMC v. no SMC applied	<0.0001	0.0003	<0.0001
Impact of SMC + reclamation	0.0166	0.9425	0.0002

Table 4 shows the manure + PMS reclamation versus LF reclamation had a statistically significant impact on total P and organic P loss with SMC application. The application of SMC had a statistically significant impact on P loss throughout the soil layers. Finally, the impact of SMC paired with the reclamation treatment had a statistically significant effect on the total P loss and the organic P loss.

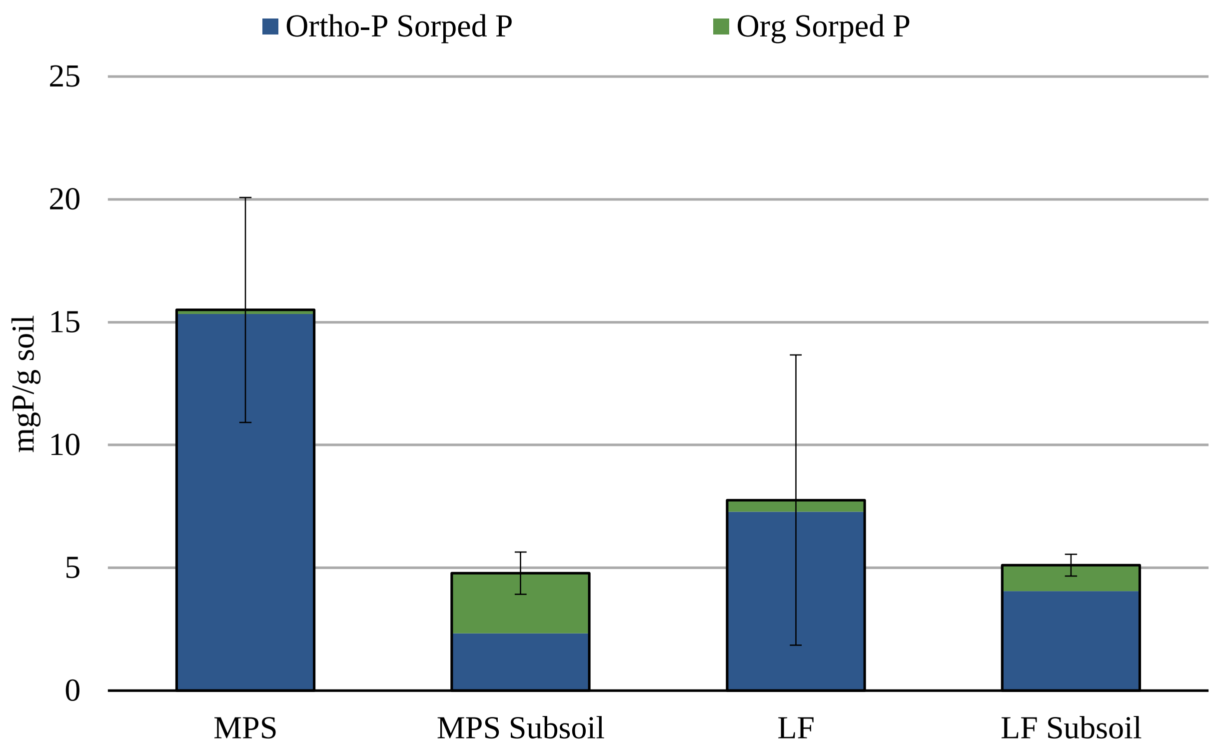

Figure 7. Inorganic and organic P absorption, on a by weight basis, observed in mine soils reclaimed with manure + paper mill sludge and lime + fertilizer, as well as their corresponding subsurface soils. This P absorption is in relation to the leached P from SMC application or, in the case of the subsurface layers, the reclaimed soils listed. Standard deviation (n=3) values calculated from total P also shown.

Figure 7 shows the amount of introduced P that was retained in each of the soil layers following SMC application. The manure + PMS treated soil retained almost double the introduced P than did the LF treated soil. Both subsoil layers retained comparable amounts of P.

Table 5. Probability values associated with the total, inorganic and organic P adsorbed in mine soils reclaimed with manure + paper mill sludge and lime + fertilizer with spent mushroom compost applied.

	Total P	Ortho-P	Org-P
MPS v. LF following SMC	0.1474	0.1329	0.3274
Subsurface layers of reclaimed mine soils following SMC	0.0250	0.0190	0.7830

Table 5 shows that the subsurface soil layers for the reclaimed mine soils had a statistically significant amount of total P and inorganic P adsorbed.

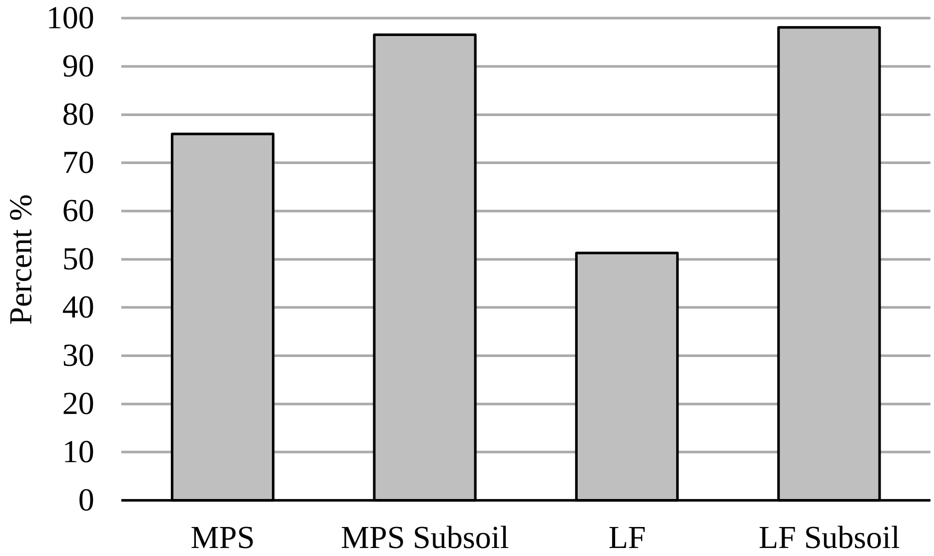

Figure 8. Percent of Total P leached that was absorbed by the soil layers following SMC application and either manure + paper mill sludge or lime + fertilizer reclamation.

Figure 8 shows the percent capture of total P for the soil layers following SMC application to manure + paper mill sludge and lime + fertilizer treated soils. The manure + PMS treated soil and the LF treated soil received comparable amounts of P from the SMC application, though the manure + PMS amendment behaved in a way that captured more P than the LF amendment. In both cases, the subsurface soil layers captured nearly 100 percent of the P they received.

Table 6. Probability values associated with the percent P adsorbed in mine soils reclaimed with manure + paper mill sludge and lime + fertilizer with spent mushroom compost applied.

	Percent
MPS v. LF following SMC	0.0532
Subsurface layers of reclaimed mine soils with SMC applied	0.0960

Table 6 shows that manure + paper mill sludge reclamation versus lime + fertilizer reclamation had a statistically significant impact on the percent of P adsorbed following SMC application.

It was found that the spent mushroom compost layer leached an approximate total 58 mg P/g compost. For treated soils without SMC application, higher total phosphorus leaching was found in the manure + paper mill sludge soil, at a value of 6.9 mg P/g soil. The leachate for the soil layer amended with lime + fertilizer, without SMS applied, had a total phosphorus value of 2.3 mg P/g soil.

In contrast, the leachates which resulted from the soils receiving SMC application had larger average total phosphorus levels in the lime + fertilizer treated soils, at 7.4 mg P/g soil. The soil amended with manure + paper mill sludge had a total phosphorus leachate level of 4.9 mg P/g soil.

In all simulations, the subsoil layer effectively immobilized the majority of the phosphorus leaching from the previous soil layers, with itself leaching insignificant phosphorus concentrations, ranging 9 μg P/g soil to 37 μg P/g soil.

DISCUSSION

This study aimed to observe the behavior of phosphorus when spent mushroom compost was applied to remediated mine soil. By understanding nutrient behaviors with these combined treatments on mine soil, this study, paired with previous studies and future studies, will lead to an opportunity for the mushroom industry in Pennsylvania to benefit from the revival of abandoned mine plots in their surrounding regions. All of the soil treatments in question have been continually remediated for at least eight years, and a history of spent mushroom compost applications has been shown in previous experiments to result in phosphorus accumulation in the soil (Banfill, 2013). Table 2 shows that SMC applications on the two soil treatments studied in this experiment increased the soil test P. This increase could lead to future environmental concern, as uncontrolled P introduction to an ecosystem could upset interactions between species already in place. Understanding what happens to P after it has been introduced is a key goal toward implementing bio-economical market opportunities, such as the case of the mushroom industry's production inputs and outputs.

It was found that phosphorus leaching in amended mine soils behaves differently between lime + fertilizer treatments and manure + paper mill sludge treatments. Furthermore, SMC application has an impact on the transport of P through the mine soil. Specifically, it was hypothesized that the manure + paper mill sludge treatment would release more phosphorus regardless of SMC application. Although this was true for the soils without SMC, this was not the case for mine soil treatments with SMC application. Given this result alone, the null hypothesis that neither treatment would impact the behavior of phosphorus can be rejected.

As shown in Figure 3, in the absence of SMC application, the manure + paper mill sludge treated soils leached a higher amount of phosphorus per gram of soil than the soils treated with lime + fertilizer. Therefore the null hypothesis for the first experiment, that neither treatment would significantly impact P behavior, can be rejected. The results from the soil test in Table 2 are a strong indication as to why the manure + paper mill sludge soil leached more phosphorus than the soils treated with lime + fertilizer. Due to the higher amount of initial P, certain manure amendments may be more at risk for P transport than P introduced with a fertilizer mixture.

The manure + paper mill sludge treated soils lost less phosphorus per gram of soil than the soils treated with lime + fertilizer when SMC was applied. Figure 7 shows that the organic phosphorus from SMC was not absorbed into either of the treated soils and remained constant as a form of P loss. Due to organic P's behavior, it is important to note that the inorganic fractions of P travelling through these layers were not consistent. Overall, it can be concluded that lime + fertilizer soils do a worse job at retaining introduced phosphorus and organic P readily moves through the initial soil layers. For reclamation projects, these are important factors to consider when applying P and choosing reclamation treatments for mine soils that hope to retain P for plant available purposes.

The large variability seen in the sample set with SMC, depicted in Figure 7, resulted in no statistical significance between lime + fertilizer and manure + paper mill sludge soils in regard to P retention. By increasing the number of samples, a significant relationship is likely to surface. Figure 7 depicts an evident difference in the mean values of P absorption when comparing manure + paper mill sludge treated soils with the lime + fertilizer treated soils. The P movement throughout the constructed laboratory soil columns reflects differences in P behavior between the soil treatments. Future studying can unveil statistical difference with decreased variability. Furthermore, the percent absorption of P between the reclamation treatments is statistically significant. Figure 8 implies that manure + paper mill sludge does a better job at capturing repeated applications of P. Seeking out the reason why this occurs would also be a fruitful place to focus future studying.

The results suggest high amounts of labile orthophosphate, readily available for plant uptake, are held in the amended soil layer. The slow movement downward of this form of phosphorus implies that the soils in question would be conducive toward biomass growth, as long as other nutrients, both macro-nutrients and micro-nutrients, are also understood and accounted for in relation to the biomass growth desired. The slow movement downward in the soil profile would also allow this phosphorus to be accessible by deeper roots, and would be less at risk for drying out close to the surface. This finding is beneficial to the overall reclamation of the site for any reclamation approach, as it would allow for vegetation beyond grass cover.

Possible sources of error could upset the data acquired and analyzed in this experiment. Failure to account for a factor, such as microbial transformation of phosphorus forms in the soils on the field, or while in storage prior to laboratory testing, could affect the leaching behavior. Environmental factors such as temperature of introduced synthetic rainfall, as well as dispersion could impact soil interactions. Additionally, calibration curves for the Lachat and ICP laboratory instruments were not perfect, thus upsetting the acquisition of exact phosphorus levels, though the curves were deemed acceptable to analyze with. Finally, physical alterations may have taken place during the time frame between the end of mechanical vacuum extractions and the collection and storage of leachate samples.

To address these sources of error, as well as introduce additional experimentation, this study could be redone with the inclusion of more treated soils from the Barry site, such as the 30:1 carbon to nitrogen ratio of manure + paper mill sludge soils, or the soils amended with compost. With time allowance, more replications of the experiment could broaden the data, leading to more statistically conclusive results. Future experimentation could allow for analysis of other nutrients, such as nitrogen and potassium, as well as trace metals.

The result of this study also leads to more research questions to be sought after. Why did the capacity to adsorb phosphorus in manure + paper mill sludge treated soils increase with repeated applications of spent mushroom compost? At what point would the subsurface soil layers be less able to capture phosphorus introduced in leachate from the previous soil layer? What difference in phosphorus mobility would arise between applications of fresh spent mushroom compost versus aged spent mushroom compost? How could incorporation of spent mushroom compost into the soil layers impact leachate concentrations of phosphorus? What are the implications of larger rainfall events on nutrient mobility? Among others, all of these questions are important in answering before widespread application and implementation of nutrient-rich remediation techniques take place.

Management of environmental resources requires a full understanding of the interactions between the various biotic and abiotic features of a given area. Land, air and water stewardship requires an array of experts to aspire toward ecologically sound economic decisions. The legacy of abandoned mine soils is not unique to Pennsylvania, but each mine plot needs an individual approach to reclamation, usually derived from a general framework.

The purpose of this laboratory study was to provide a fuller understanding of the introduction of phosphorus-rich soil amendments onto abandoned mine plots. This experiment promotes the waste valorization, or “the process of converting waste materials into more useful products” (Arancon, 2013) of spent mushroom compost for mushroom industries in Pennsylvania or other states.

Key findings in this study include the fact that phosphorus was retained despite previous applications of spent mushroom compost. This is evident by the fact that an average of about 58 mg P/g compost was introduced into the soil layers, and 50-80 percent was captured by the treated soils that had undergone previous SMC applications. Therefore, there is a direct effect of the reclamation on the behavior of phosphorus on mine soils. Specifically, the manure + paper mill sludge treatment, when paired with spent mushroom compost, allowed for a high capacity of phosphorus capture. By understanding the soil mechanics of pairing remediation techniques, science can be applied to assist with the alleviation of soil degradation within mine legacies across Pennsylvania and in other parts of the world.

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APPENDIX A. RAW DATA FROM LACHAT ANALYSIS

Table 7. Raw data retrieved from Lachat analysis of samples.

Sample ID	Cup No.	orthophosphate (mg/L)
CalStd A1	S1	2.50
CalStd B1	S2	1.00
CalStd C1	S3	0.500
CalStd D1	S4	0.250
CalStd E1	S5	0.100
CalStd F1	S6	0.0250
CalStd G1	S7	0.00
B1	S2	0.924
E1	S5	0.114
BLANK	1	0.0552
MPS0 1	2	0.992
MPS0 2	3	1.13
MPS0 3	4	1.08
MPS0 Subsoil 1	5	0.0857
MPS0 Subsoil 2	6	0.161
MPS0 Subsoil 3	7	0.128
MPS1 SMS 1	8	3.55
MPS1 SMS 2	9	2.73
MPS1 SMS 3	10	1.85
BLANK	11	0.0462
MPS1 1	12	0.441
MPS1 2	13	0.765
MPS1 3	14	0.836
MPS1 Subsoil 1	15	0.0444
MPS1 Subsoil 2	16	0.0441
MPS1 Subsoil 3	17	0.0585
B1	S2	0.931
E1	S5	0.116
LF0 1	18	0.363

LF0 2	19	0.319
LF0 3	20	0.335
LF0 Subsoil 1	21	0.102
LF0 Subsoil 2	22	0.140
LF1 SMS 1	23	2.96
LF1 SMS 2	24	1.18
LF1 SMS 3	25	1.94
BLANK	26	0.0534
LF1 1	27	1.25
LF1 2	28	1.09
LF1 3	29	1.35
LF1 Subsoil 1	30	0.0431
LF1 Subsoil 2	31	0.0434
B21	S2	0.924
E31	S5	0.117

APPENDIX B. RAW DATA FROM ICP ANALYSIS

Table 8. Raw data retrieved from ICP analysis of samples.

Sample ID	Analyte Name	Wavelength	Conc (Samp)	Corr Coef	Samp Units	Int (Corr)1
Calib Blank 1	P 214.914	214.914			mg/L	221.4130505
CalStd 0.025	P 214.914	214.914			mg/L	6.995412993
CalStd 0.1	P 214.914	214.914			mg/L	68.71963307
CalStd 0.25	P 214.914	214.914			mg/L	210.0209888
CalStd 0.5	P 214.914	214.914			mg/L	420.2743348
CalStd 1.0	P 214.914	214.914			mg/L	843.4686567
CalStd 2.5	P 214.914	214.914			mg/L	2193.252934
CalstdB 1.0	P 214.914	214.914	0.9580666601	0.9998903317	mg/L	827.7046368
CalstdE 0.1	P 214.914	214.914	0.08360483192	0.9998903317	mg/L	58.36206052
Blank 1	P 214.914	214.914	0.01043749063	0.9998903317	mg/L	-6.009818311
MPS0 1	P 214.914	214.914	1.27927828	0.9998903317	mg/L	1110.303336
MPS0 2	P 214.914	214.914	1.449763218	0.9998903317	mg/L	1260.294241
MPS0 3	P 214.914	214.914	1.400721454	0.9998903317	mg/L	1217.147799
MPS0 Subsoil 1	P 214.914	214.914	0.1405054422	0.9998903317	mg/L	108.4226357
MPS0 Subsoil 2	P 214.914	214.914	0.2679926396	0.9998903317	mg/L	220.5845686
MPS0 Subsoil 3	P 214.914	214.914	0.2244226168	0.9998903317	mg/L	182.252108
MPS1 SMS 1	P 214.914	214.914	3.742904221	0.9998903317	mg/L	3277.776252
MPS1 SMS 2	P 214.914	214.914	2.936549947	0.9998903317	mg/L	2568.354005
MPS1 SMS 3	P 214.914	214.914	2.090923172	0.9998903317	mg/L	1824.380214
Blank 2	P 214.914	214.914	-0.007811475523	0.9998903317	mg/L	-22.06507216
MPS1 1	P 214.914	214.914	0.657660702	0.9998903317	mg/L	563.4105461
MPS1 2	P 214.914	214.914	1.032728578	0.9998903317	mg/L	893.3914286
MPS1 3	P 214.914	214.914	1.114317834	0.9998903317	mg/L	965.1728226
MPS1 Subsoil 1	P 214.914	214.914	0.1041257803	0.9998903317	mg/L	76.41618113
MPS1 Subsoil 2	P 214.914	214.914	0.09365495146	0.9998903317	mg/L	67.20405295
MPS1 Subsoil 3	P 214.914	214.914	0.09242246146	0.9998903317	mg/L	66.11972085
LF0 1	P 214.914	214.914	0.5759076682	0.9998903317	mg/L	491.4850628
CalStd 1.0	P 214.914	214.914	0.9733290617	0.9998903317	mg/L	841.1323417
Calstd 0.1	P 214.914	214.914	0.0676951471	0.9998903317	mg/L	44.36488248
LF0 2	P 214.914	214.914	0.5104778697	0.9998903317	mg/L	433.920595
LF0 3	P 214.914	214.914	0.5520518019	0.9998903317	mg/L	470.4969155
LF0 Subsoil 1	P 214.914	214.914	0.298885096	0.9998903317	mg/L	247.7634359
LF0 Subsoil 2	P 214.914	214.914	0.3369474314	0.9998903317	mg/L	281.2502894
LF1 SMS 1	P 214.914	214.914	3.283290396	0.9998903317	mg/L	2873.412708
LF1 SMS 2	P 214.914	214.914	1.416177593	0.9998903317	mg/L	1230.745952
LF1 SMS 3	P 214.914	214.914	2.178361586	0.9998903317	mg/L	1901.307637
Blank 3	P 214.914	214.914	-0.02356282607	0.9998903317	mg/L	-35.92294934
LF1 1	P 214.914	214.914	1.501832591	0.9998903317	mg/L	1306.104343
LF1 2	P 214.914	214.914	1.357346823	0.9998903317	mg/L	1178.987242
LF1 3	P 214.914	214.914	1.604790171	0.9998903317	mg/L	1396.68537
LF1 Subsoil 1	P 214.914	214.914	0.08563986528	0.9998903317	mg/L	60.15246207

LF1 Subsoil 2	P 214.914	214.914	0.09017003533	0.9998903317	mg/L	64.13805937
LF1 Subsoil 3	P 214.914	214.914	0.07949948517	0.9998903317	mg/L	54.75021843
CalstdB 1.0	P 214.914	214.914	0.9553759536	0.9998903317	mg/L	825.3373808
CalstdE 0.1	P 214.914	214.914	0.07695165735	0.9998903317	mg/L	52.50866556

APPENDIX C. P LOSS IN SPENT MUSHROOM COMPOST

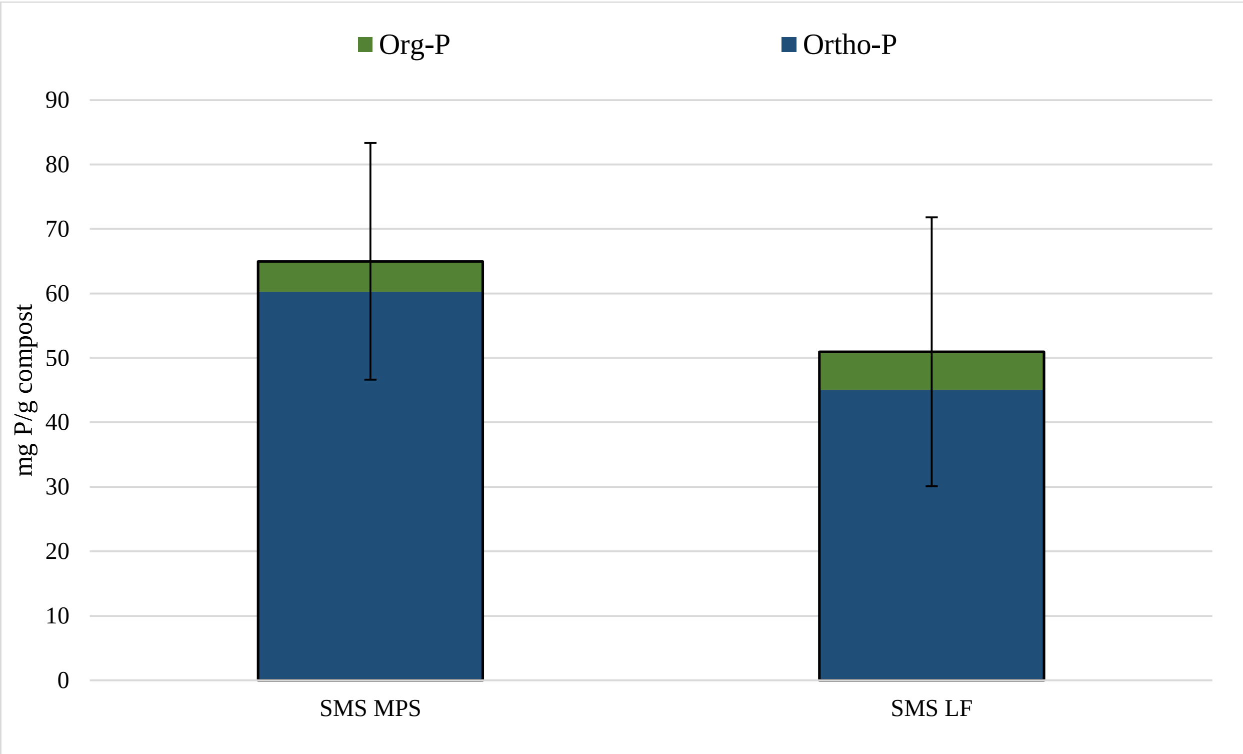

Figure 9. Observed variability in inorganic and organic P leached from spent mushroom compost, on a by weight basis, applied onto manure + paper mill sludge or lime + fertilizer reclaimed mine soils. Standard deviation (n=3) values calculated from total P also shown.

Although there was no difference in the preparation between the spent mushroom substrate applied to the manure + paper mill sludge and the lime + fertilizer treated soils, a slight difference was observed between the total amounts of P introduced to the soil layers in this experiment. Considering the final conclusive results that manure + paper mill sludge treated soils retained more phosphorus while lime + fertilizer soils lost more phosphorus, this should not be considered a significant source of error in the experimental conclusions. If anything, more consistent spent mushroom substrate phosphorus levels may have led to more significance for the statistical analysis of this study.

APPENDIX D. SUMMARY TABLES OF DATA PRESENTED

Table 9 shows the summary of the values found in Figures 3, 4 and 5 for the soil treatments without SMC application.

Table 9. Summary of total, inorganic and organic P fractions from soil layers without SMC application, as well as the observed percentage of P sorption in subsequent layers. Standard deviation values are also listed.

Soil Layer	Total P	Ortho-P	Org-P	Standard Deviation	Total P Sorbed
		mg P leached/g soil			%
MPS	6.9	5.3	1.5	0.4	--
MPS Subsoil	0.2	0.1	0.1	0.1	94.9
LF	2.3	1.5	0.9	0.1	--
LF Subsoil	0.4	0.1	0.2	0.0	80.6

Table 10 shows the summary of the values found in Figures 6, 7 and 8 for the soil treatments with SMC application.

Table 10. Summary of total, inorganic and organic P fractions from soil layers with SMC application, as well as the observed percentage of P sorption in subsequent layers. Standard deviation values are also listed.

Soil Layer	Total P	Ortho-P	Org-P	Standard Deviation	Total P Sorbed
		mg P leached/g layer			%
SMC	58	52.6	5.3	19.6	--
MPS	4.9	3.6	1.3	1.3	76.0
MPS Subsoil	0.1	0.1	0.1	0.01	96.6
LF	7.4	6.1	1.3	0.6	51.3
LF Subsoil	0.1	0.1	0.0	0.01	98.1

ACADEMIC VITA

SERENA GROFF
SerenaG519@gmail.com
2625 Chestnut Avenue, Ardmore PA, 19003-2015

EDUCATION

The Pennsylvania State University — University Park, PA
College of Agricultural Sciences, Schreyer Honors College — *Aug. 2011 to May 2015*
Bachelor of Science, Environmental Resource Management
Minors in Environmental and Renewable Resource Economics, Watersheds and Water Resources

RESEARCH EXPERIENCE

Eissenstat Root Ecology Lab — University Park, PA
College of Agricultural Sciences, Department of Ecosystem Science Management — *Fall 2012*

Aquaponics Experiment — University Park, PA
College of Agricultural Sciences, Department of Horticultural Science — *Spring 2013*

Undergraduate Teaching Assistant of Soils Chemistry — University Park, PA
College of Agricultural Sciences, Department of Ecosystem Science Management — *Spring 2013*

Swim Lab on Environmental Sociology — University Park, PA
College of Liberal Arts, Department of Psychology — *Summer 2013*

WORK EXPERIENCE

The Pennsylvania State University — University Park, PA
Office of Residence Life, Resident Assistant — *Jun. 2013 to ongoing*

The Pennsylvania State University — University Park, PA
Eberly College of Science, Chemistry Grader and Proctor — *Aug. 2013 to ongoing*

The Pennsylvania State University — University Park, PA
Student Support Services Program, Tutor — *Jan. 2014 to ongoing*

ACTIVITIES

Students Taking Action To Encourage Recycling — Club
President, former Vice President — *2012-2014*

Business and Society House — Special Living Option
Volunteer Chair — *2012-2013*

Council of LionHearts — Roundtable
Delegate — *Aug. 2012 to ongoing*

Pollock Student Green Team — Residence Life
Student Leader — *Aug. 2014 to ongoing*

HONORS AND AWARDS

Clyde & Mildred Sidler Scholarship (2011-2013)
Sustainable Student Featured Weekly Leader (2012)
Jeffrey S. Blanton Endowment in Environmental Resource Management (2012-2013)
Edward W. Blosinski Scholarship in the College of Agricultural Sciences (2012-2013)
Oswald Scholarship (2012-2013)
Ilene Glenn Scholarship in Environmental Resources (2013-2014)
Gerald and Leoda Gummo Excellence Fund in Agriculture (2013-2014)
Gamma Sigma Delta Honors Society Member (2014-2015)
Keystone Chapter of the Soil and Water Conservation Society Senior Scholarship (2014)
Settlemyer Fund for International Studies (2014)
William D. And Clara Calhoun Phillips Scholarship (2014-2015)
Robert and Catherine Shannon Scholarship in Environmental Resource Management (2014-2015)
Schreyer Honors Thesis Research Grant (2014-2015)
Ready to Succeed PHEAA Scholarship (2015)
Student Marshal at Commencement (2015)