NUTRIENT FLUXES FROM ABANDONED MINE SOILS RECLAIMED WITH POULTRY MANURE AND PAPER MILL SLUDGE[1]

Ashlee L. Dere, Richard C. Stehouwer, and Kirsten E. McDonald[2]

Abstract: In the Mid-Atlantic region of the United States, intensive animal production generates manure nutrients in excess of crop needs, increasing the likelihood of transport to water bodies and degradation of ecosystems and water quality. In this same region, 150 years of extensive coal mining has severely degraded land and impaired streams. Excess manure could be utilized in mine reclamation, but the large application rates required for successful revegetation could result in significant nutrient discharge. A preliminary greenhouse study determined that composting or adding organic carbon to poultry layer manure greatly reduced nutrient leaching. Based on these results, a field reclamation study was established on a surface coal mine in Schuylkill County, Pennsylvania in April 2006. Treatments include a lime and fertilizer control, two rates of composted poultry layer manure (78 and 156 Mg ha^{-1} dry weight), and two blends of fresh poultry manure (60 Mg ha^{-1} dry weight) mixed with paper mill sludge (90 and 170 Mg ha^{-1}) to achieve C:N ratios of 20:1 and 30:1. Leachate was collected after every rain event using pan lysimeters located 30 cm below each treatment. Leachate analysis showed a pulse of NO_3^--N from the two rates of poultry manure and paper mill sludge blends (170 and 156 mg N L^{-1}) occurred three months following application. Compost treatments showed no such pulse. Cumulative N losses were greatest in the manure/paper mill sludge blends, but the control retained the least amount of original added N. An initial pulse of phosphate (5.8 mg P L^{-1}) from the control treatment was observed within the first month after application. Subsequently, all treatments show minimal leaching of P (less than 1.0 mg P L^{-1}). This research supports that amending mine soils with either composted poultry layer manure or fresh manure mixed with paper mill sludge are effective strategies to facilitate establishment of sustained vegetative cover on mined lands. Composted poultry manure is superior at controlling N and P loss.

Additional Key Words: Revegetation, C:N ratios, nitrogen, phosphorus, compost

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[2] Ashlee L. Dere, Graduate Research Assistant, Richard C. Stehouwer, Associate Professor, Kirsten E. McDonald, Project Associate, Dept. of Crop and Soil Sciences, The Pennsylvania State University, University Park, PA 16802.

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Introduction

In Pennsylvania alone, there are over 250,000 acres of unreclaimed surface mine lands. The soil at many of these abandoned mine sites supports poor vegetative cover due to acidity, limited water holding capacity, degraded soil physical properties, and low levels of organic matter and nutrients, especially N and P (Bendfeldt et al., 2001). Organic amendments have been shown to improve the fertility of the abandoned mine soil and restore a balance of nutrients if applied in proper ratios (Seaker and Sopper, 1988; Bendfeldt et al., 2001). In Pennsylvania, poultry manure in particular is a problem, as this enterprise is often concentrated on small parcels of land and lacks a land base for the manure it produces (Moore et al., 1995). In combination with other animal production in the region, much land is rendered rich in N and P; the excess often accumulates in the Chesapeake Bay watershed (Chesapeake Bay Program, 2005).

Because problems of both abandoned mineland and excess manure exist in the same region, this manure could be used to ameliorate phytotoxic conditions at these mine sites. However, low organic C levels in mine spoils limits microbial activity at these sites, which severely inhibits the soil regeneration and restoration of nutrient cycling (Ingram et al., 2005; Machulla et al., 2005). To raise the level of C, large applications of manure would be necessary, greatly increasing the risk of nutrient leaching, which could further degrade nearby water bodies. Applications of biosolids at the standard loading rate, for example, supplies ample C and nutrients for successful minespoil revegetation, but is at great risk for excessive nutrient leaching (Stehouwer et al., 2006). One way to overcome this problem is to compost the fresh manure with a high carbon material such as leaf and yard waste. Applying composted poultry manure to minesoil would add necessary C while nutrients such as N and P would be stabilized in the compost pile, therefore minimizing the risk of leaching.

Another option is to mix a high carbon material with fresh poultry manure *in situ*, effectively changing the C:N ratio to help retain nutrients while also adding much needed C to the soil. Studies done by Daniels et al. (2001) and Schmidt et al. (2001) have effectively demonstrated that the use of high C material (sawdust) can improve both agricultural yields and grass biomass, respectively, and reduce nitrogen-leaching loss when co applied to reclaim soil. Paper mill sludge, a waste product of the paper industry, is an ideal candidate due to the high carbon content of the short fibers in the material and the wide availability of the waste product. This material, although variable in composition from one source to another, can not only add C to the soil, but also increase pH, help retain nutrients by adjusting the C:N ratio, and improve vegetative growth (Haering et al., 2000).

A greenhouse experiment was conducted in spring of 2005 to assess nutrient leaching and switchgrass growth in columns of acidic mine spoil amended with several rates of composted manure or fresh manure mixed with varying amounts of paper mill sludge. Increasing amounts of compost or paper mill sludge produced increased switchgrass growth in the mine spoil. While fresh manure alone was able to ameliorate spoil phytotoxicity and produce growth, it also resulted in a large NO_3^- and P leaching losses. By contrast, both composted manure and fresh manure mixed with paper mill sludge greatly decreased nutrient loss compared to the manure alone amendment. The field experiment reported in this paper was conducted to further examine nutrient fate and flux with application under less ideal and less controlled field conditions. Based on our greenhouse experiment which showed that added organic carbon materials (either via composting or *in-situ*) are able to sequester N and P and results of the preliminary study, we predict that 1) using organic amendments will provide superior revegetation while minimizing N and P leaching compared to traditional lime and fertilizer and 2) that compost will be more efficient than fresh manure and paper mill sludge at minimizing N and P loss via leaching.

Materials and Methods

A multi-year field experiment was initiated in the spring of 2006. The field site is an abandoned coal surface mine from the 1950s located in Schuylkill County, Pa (Fig 1.). The soil is classified as an Udorthent strip mine (NRCS). Initial site texture was a very channery sandy loam, with an average soil pH of 5.1(1:1 in water) (Eckert and Sims, 1995). Annual precipitation in the first year at this site was 132 cm (52 inches). Bulk density was estimated at 1.4 g cm^{-3} and initial total soil carbon was measured at 3.1% (Nelson and Sommers, 1996) reflecting the presence of coal fragments in the mine spoil.

Five reclamation treatments were each replicated four times in a randomized complete block design with each plot measuring 6.1 m by 9.1 m. The treatments included the standard reclamation practice control of lime and inorganic fertilizer amendment (112 kg N ha^{-1} as NH_4NO_3; 196 kg P ha^{-1} as triple super phosphate; 186 kg K ha^{-1} as KCl), two rates of composted poultry layer manure, and two blends of fresh poultry layer manure and paper mill sludge (manure+PMS mixes). Table 1 shows treatment quantities and compositions, along with their respective soil additions of N and P. Rates were chosen based on results obtained in the preliminary greenhouse study. The lower rate of compost and the two manure/paper mill sludge blends contain the same quantity of total N (almost all from manure); paper mill sludge was added to fresh manure to adjust the C:N ratio to 20:1 and 30:1. The poultry manure had an initial C:N ratio of 7.3:1 while the paper mill sludge had a C:N ratio of 126:1; C and N were measured using the combustion method on a Fisons NA 1500 Elemental Analyzer (Nelson and Sommers, 1996). Initial pH of the manure and paper mill sludge was 8.3 and 7.3, respectively. The poultry layer manure was composted by mixing with leaves, shredded wood and water and placed in an open windrow. During active composting the windrow was turned every 7 to 14 days depending on temperature. Following active composting the compost was matured for two months in a static pile. The fresh manure and paper mill sludge treatments were hauled to the experiment site and mixed on site to produce the desired C:N ratio blends. All amendments were surface applied and then incorporated into the upper 5 to 8 cm of the soil using the teeth on a front-end loader bucket. Due to the extremely rocky nature of the site, it was not possible to achieve deeper incorporation.

Table 1. Quantity of amendment, N, and P applied to mine soil for each treatment.

Treatment	Amount added to soil	N added to soil	P added to soil
	Mg ha^{-1} dry wt	------------ kg ha^{-1}	------------
Control (Cntrl)	---		
Lime	13.4		
Fertilizer (N,P,K)	0.784	112	196
Compost 1 (Comp1)	78	2117	1052
Compost 2 (Comp2)	156	4234	2104
Manure+PMS 20:1 C:N (Man20:1)	---	2117	1052
Fresh manure	50		
Paper mill sludge	103		
Manure+PMS 30:1 C:N (Man30:1)	---	2117	1052
Fresh manure	50		
Paper mill sludge	184		

Figure 1. Photo of the abandoned mine site in April of 2006 before any amendment application.

Prior to amendment application, all plots were instrumented with 30 cm by 30 cm zero-tension pan lysimeters 30 cm below the surface to allow collection of leachates (Fig. 2). The rocky soil prevented lateral installation of the pan lysimeters below undisturbed soil; therefore, trenches were dug to install lysimeters in the center of each plot. Although this disturbed the soil, this material had already undergone severe disturbance following mining activities, hence our disturbance did not greatly alter the soil profile. Excavated soil material from the upper 10 cm and lower 20 cm was kept separate and replaced in sequence. Drain lines connected to the pans drained leachate to carboys located in dry wells outside the plot area (Fig. 3). Leachates were collected as soon as possible following all precipitation events large enough to generate lysimeter flow over the course of 14 months. Leachate volumes were measured in the field and a 500 ml sample was taken back to the lab for processing and analysis. Concentrations of NO_3^-, NH_4^+, and PO_4^{3-} of filtered leachate samples were determined using flow injection analysis on a Lachat QuickChem FIA+8000 Analyzer (Lachat Instruments, 2003a, 2003b, 2007a). Concentrations of total N and total P were measured using in-line digestion followed by flow injection analysis on a Lachat QuickChem FIA+8000 Analyzer (Lachat Instruments, 2003c, 2007b). Measured pH values of the leachates ranged between 5.9 and 7.4 initially to 5.7 and 8.2 after 14 months. The quantity of N lost in each leaching event was calculated by multiplying labile N (NO_3^- + NH_4^+) concentrations by leachate volume collected in each lysimeter. To determine cumulative N loss we assumed the lysimeter collected leachate from a 30 by 30 cm area and summed these data over the 14-month collection period.

Figure 2. Pan lysimeter installation in the center of a plot. The leveled pan in the foreground drained to a carboy at the bottom of the PVC well in the background. The pan was then covered with the original soil removed from the trench.

Figure 3. Photo of the site taken in August 2006, four months after amendment application. Vegetation is predominantly annual ryegrass. A covered dry well can be seen in the foreground**.**

All plots were initially planted with a combination of 11.2 kg ha^{-1} (10 lbs ac^{-1}) of switchgrass (*Panicum virgatum* L.) and 2.2 kg ha^{-1} (2 lbs ac^{-1}) of annual ryegrass (*Lolium rigidum* Gaud.) immediately following amendment application; the ryegrass was included as a nurse crop to provide some rapid cover prior to switchgrass establishment. Following seeding, one bale of straw mulch was applied to each plot. Vigorous ryegrass growth prevented the establishment of switchgrass in the first year after planting; therefore, plots were reseeded with 22.4 kg ha^{-1} (20 lbs ac^{-1}) of switchgrass seed in spring 2007. To minimize ryegrass competition in the first year, the plots were mowed at approximately 15 cm (6 in) in May and June of 2007. Biomass yield data were obtained by clipping all vegetation present in 1 m^2 quadrats randomly located within each plot in late summer of each year. Harvested plant material was dried and weighed to determine biomass yield.

To test for statistical differences, an analysis of variance was calculated followed by single degree of freedom contrasts between groups of treatments. A significance level of $\alpha = 0.1$ was chosen to protect against a Type II error. All statistical analysis was performed using SAS software (SAS Institute, 2003).

Results and Discussion

Grass Yields

Four months after amendment application, all treatments had good vegetative cover, though annual ryegrass was the dominant species. Although all species present in the 1 m^2 sampling quadrats were collected, there was minimal influence of any weedy species on biomass yield in 2006 and 2007. The only treatment effect on biomass yield in year one was the increase provided by the 30:1 C:N ratio mixture of manure and paper mill sludge (Fig. 4, Table 2). Fourteen months after application all yields were lower than in year one. This reflects the removal of ryegrass and early establishment of switchgrass as well as likely decreased N availability. In year two, the compost treatments and manure plus PMS mixes produced larger biomass yields than the control of lime and fertilizer (Fig. 4, Table 2). In year two the larger rate of compost produced larger yields than the smaller compost application however, there was no difference between the two rates of fresh manure mixed with paper mill sludge (Table 2). These data demonstrate the effectiveness of the organic treatments to improve vegetative growth compared to mine soils reclaimed with customary lime and fertilizer. Because switchgrass is slow to establish and up to 3 years are normally needed to achieve a vigorous stand these data are clearly very preliminary. The experiment will be continued for several more years to determine the long-term effect of these amendments on sustained biomass production.

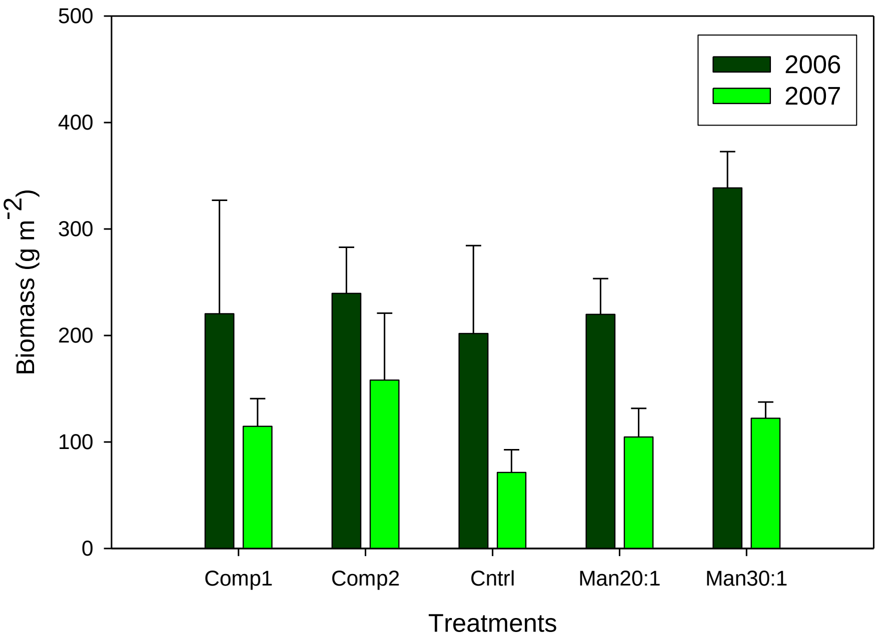

Figure 4. Biomass of plant yield data by treatment in 2006 and 2007 Plant samples were collected from a 1 m^2 quadrat in late summer.

Table 2. Results of single degree of freedom contrasts comparing biomass yields between groups of treatments. Each year of biomass data was calculated separately. Organic refers to the two rates of compost and two rates of fresh manure mixed with paper mill sludge.

Contrast	2006	2007
Organic vs. Control	NS†	*
Compost vs. Manure+PMS	NS	NS
Manure+PMS ratio	*	NS
Compost rate	NS	*

† Not significant
* Significant at $\alpha = 0.1$

Leachate Analysis

The largest concentrations of N and P were leached from the two manure and paper mill sludge blends while compost was extremely effective at minimizing nutrient loss via leaching. Amendment with lime and fertilizer resulted in some nutrient losses immediately following application reflecting the much smaller total nutrient applications in this treatment. In all treatments, leachate NO_3^- concentrations decreased below EPA drinking water standards within six months after application; P concentrations also dropped (< 10 mg L^{-1} total P and < 1 mg L^{-1} PO_4^{3-}). Only N and P nutrient fluxes will be discussed here, as they are the predominant nutrients negatively impacting water bodies in Pennsylvania.

Nitrogen. During the first two months following amendment application, losses of NO_3^- - N were observed only from the larger rate of compost and from the control treatment (Fig. 5). Three months after application, a large pulse of NO_3^- - N was observed in leachates from the two manure+PMS treatments, with maximum concentrations of 170 and 156 mg N L^{-1} in the 20:1 and 30:1 blends, respectively. This pulse subsided after three months and leachate concentrations decreased to below 10 mg N L^{-1} thereafter. One year after application, a small increase in leachate NO_3^- - N concentration was observed only in the 30:1 manure mix, but this pulse remained below the 10 mg N L^{-1} EPA drinking water standard for NO_3^- (U.S. E.P.A., 2008). After the small increase of NO_3^- leaching immediately after application, both rates of composted poultry manure showed essentially no leaching losses of NO_3^- - N throughout the entire length of the experiment.

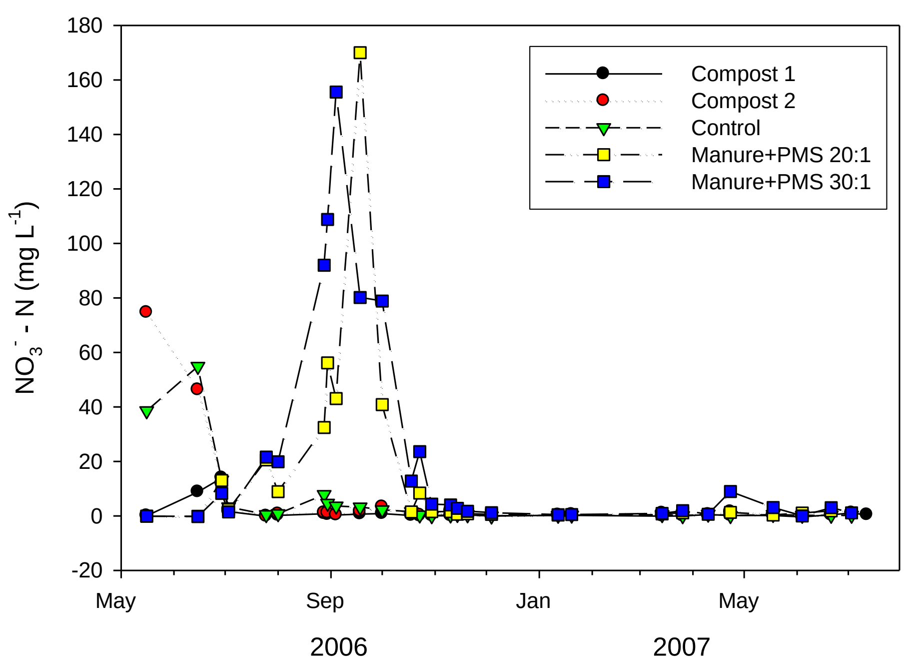

Figure 5. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on leachate concentrations of NO_3^- - N during 14 months following application.

Analysis of NH_4^+- N showed concentrations in leachates from the two manure+PMS mixes were initially much greater than either that from the compost or control treatments (Fig. 6). A relatively small pulse of NH_4^+- N was observed in leachates from the manure mix treatments corresponding to the large NO_3^- - N pulse four months after amendment application. After five months, virtually no N was lost in the form of NH_4^+- N from any treatment.

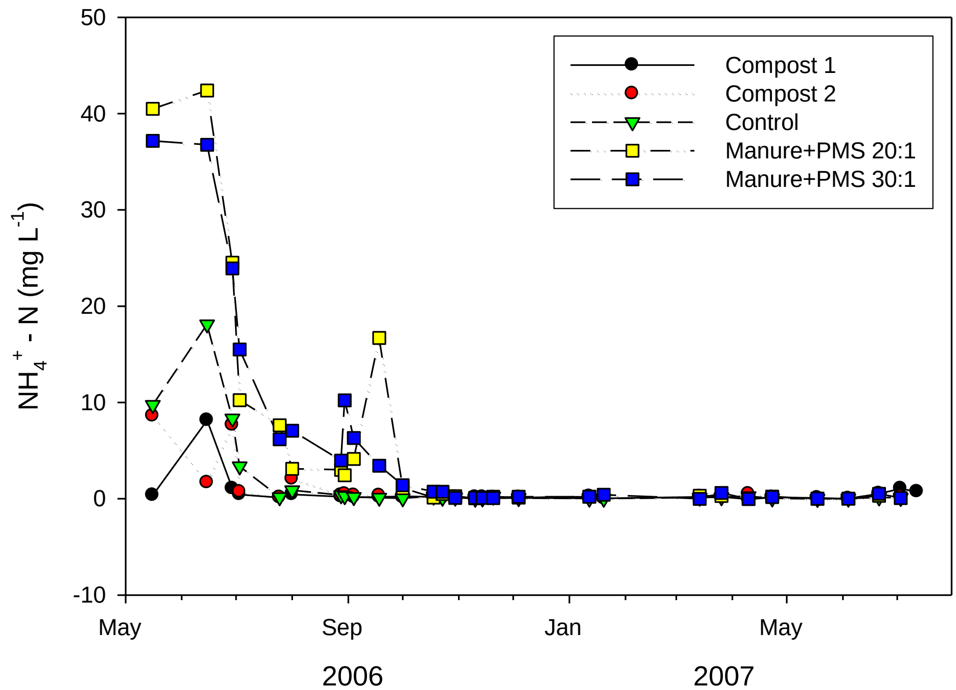

Figure 6. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on leachate concentrations of NH_4^+- N during 14 months following application.

Total N concentrations in leachate samples showed initially high values in the two manure and paper mill sludge treatments and the high rate of compost (Fig. 7). Concentrations dropped quickly in the 30:1 manure/paper mill sludge mix and the compost, but increased in the 20:1 manure mix. The control and lower rate of compost also increased shortly after amendment application, but total N concentrations for these two treatments quickly diminished. As was observed with leachate NO_3^- - N (Fig. 5), total N increased slightly one year after application in only the 30:1 manure mix; this was not seen with any other treatment. The large pulse of total N observed four months after amendment application in the 20:1 and 30:1 manure+PMS mixes (188 mg N L^{-1} and 169 mg N L^{-1} maximum concentrations, respectively) was very similar to maximum concentrations seen in the NO_3^- - N peak, suggesting leachate coming through the lysimeters at this period was largely in the form of inorganic N (Fig. 5, 7). Conversely, the 20:1 manure treatment showed a large concentration of total N immediately following application , but there was minimal NO_3^- - N and a concentration of approximately 40 mg L-1 in the form of NH_4^+- N, implying this pulse of N was largely organic N (Fig. 6, 7).

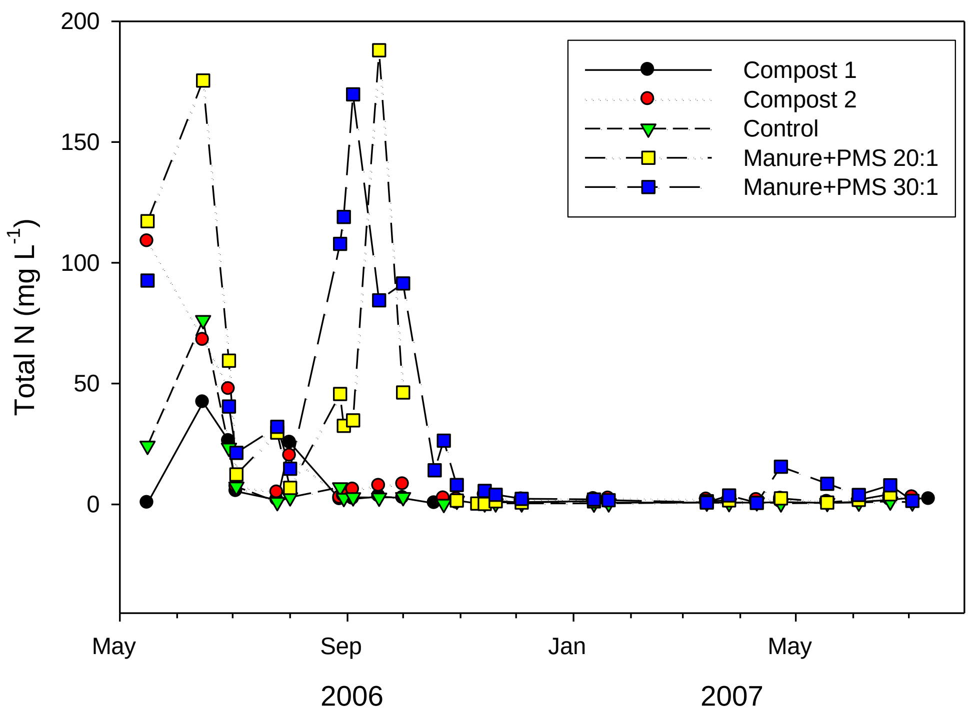

Figure 7. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on leachate concentrations of total N during 14 months following application.

Cumulative labile N losses (NO_3^- + NH_4^+) over the fourteen months of leachate collection showed large differences between the compost treatments and the manure mixed with paper mill sludge (Table 3). Although the cumulative labile N leached from the two manure+PMS mixes was associated with a high degree of variability, they leached more N during the first 14 months of the experiment than the other treatments (Fig. 8). Comparison of the quantities of N lost by leaching with the initial quantities of N added with each treatment showed that the control treatment retained the least amount of original N (80%) (Table 1). Both rates of compost retained 99% of added N, while the two 20:1 and 30:1 manure and paper mill sludge blends retained 94% and 89% of added N, respectively (Table 1). These results suggest the organic treatments are superior at retaining N compared to the inorganic control even though the fresh manure paper mill sludge treatments have lost more cumulative labile N.

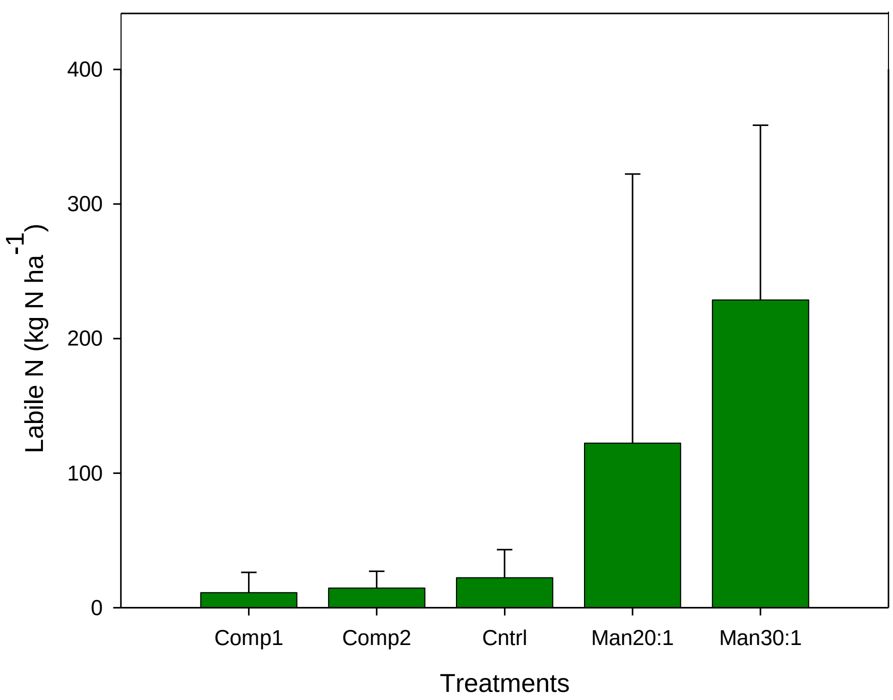

Figure 8. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on cumulative labile N (NO_3^- + NH_4^+) in kg N ha^{-1} lost via leaching during 14 months of monitoring.

Table 3. Results of single degree of freedom contrasts comparing cumulative labile N and P loss between groups of treatments. Organic refers to the two rates of compost and two rates of fresh manure mixed with paper mill sludge.

Contrast	Cumulative labile N loss	Cumulative labile P loss
Organic vs. Control	NS†	NS
Compost vs. Manure+PMS	*	NS
Manure+PMS ratio	NS	NS
Compost rate	NS	NS

† Not significant
* Significant at $\alpha = 0.1$

Phosphorus. Immediately following application, elevated total P concentrations were seen in the leachates from the manure blends and from the control; a maximum concentration of 75 mg P L^{-1}

was observed one month after application (Fig. 9). Concentrations of total P in all treatments drop to less than 10 mg P L^{-1} within two months. The PO_4^{3-}– P fraction of the total P showed a similar pattern, with the highest concentration loss reaching 5.8 mg P L^{-1} in the control treatment within the first month after amendment application (Fig. 10). Again, PO_4^{3-} – P concentrations dropped considerably after two months, but the higher rate of compost application continued to leach slightly more than all other treatments.

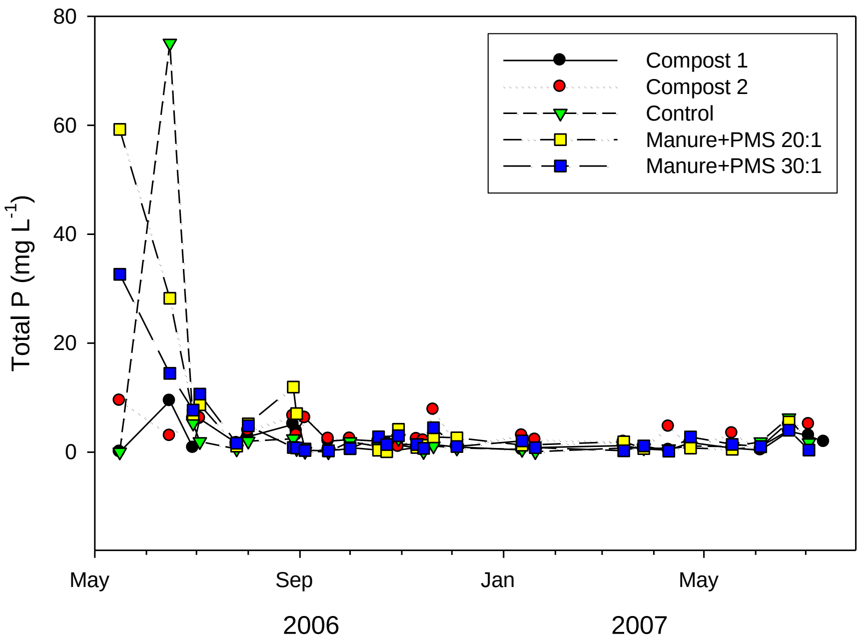

Figure 9. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on leachate concentrations of total P during 14 months following application.

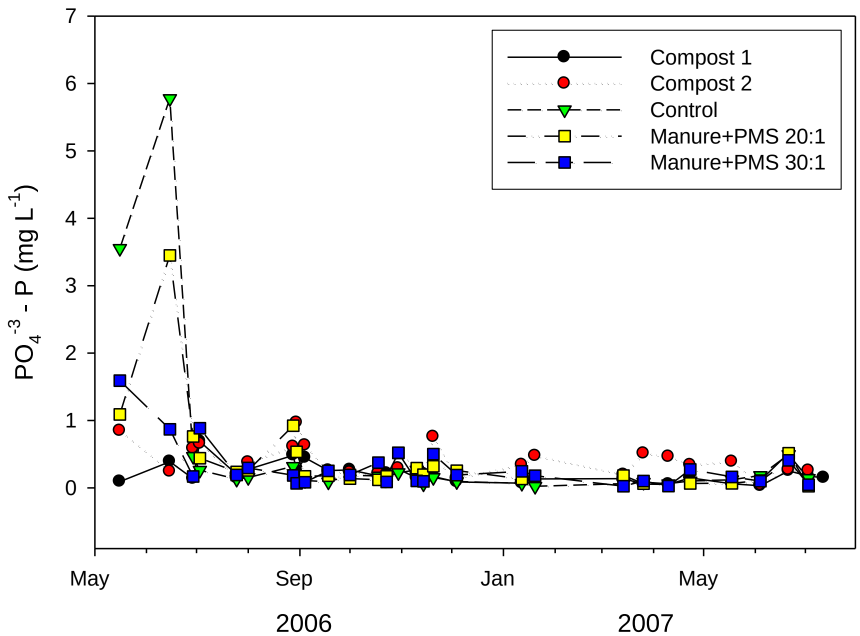

Figure 10. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on leachate concentrations of PO_4^{3-} – P during 14 months following application.

Cumulative labile P, which includes only inorganic PO_4^{3-} – P, shows no significant difference among treatments, along with high variability of measured PO_4^{3-} – P (Table 3, Fig. 11). These results demonstrate that all treatments are equally effective at minimizing P loss via leachate over time, even though the control treatment initially lost more P than the other treatments. All treatments have retained approximately 99% of original P added with the amendments (Table 1).

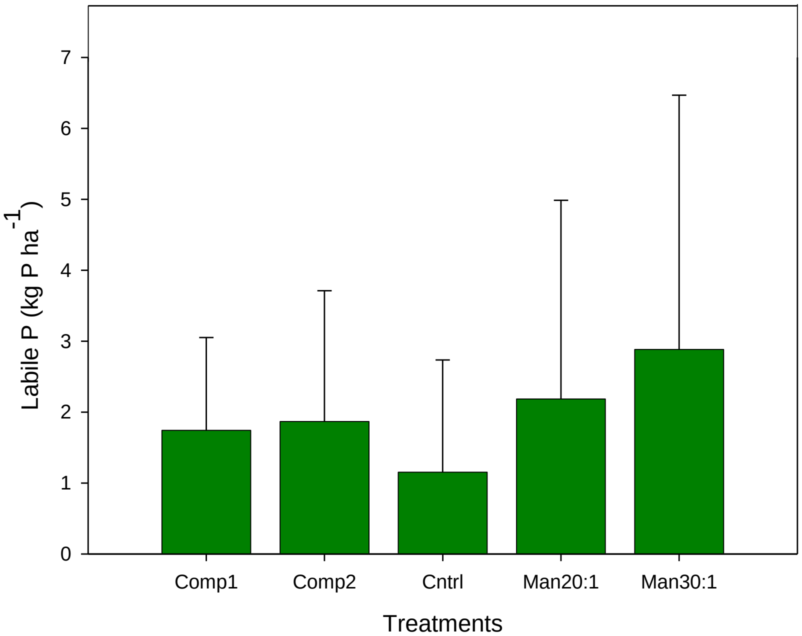

Figure 11. Effect of compost, manure+PMS, and limestone and fertilizer (control) amendment of mine soil on cumulative labile P (PO_4^{3-}) lost by leaching during 14 months following application.

Conclusions

Both composting poultry layer manure and mixing fresh manure with paper mill sludge are effective ways of preparing these materials for use in revegetating abandoned strip mines. Composting the manure appears to maintain the benefits of successful revegetation while essentially eliminating the risk of N and P leaching, providing an excellent revegetation method. Manure+PMS treatments are very effective at limiting P loss, although less effective at limiting N leaching loss. Better vegetative growth was seen with both of the organic treatments than with the inorganic control of lime and fertilizer. The control lost less cumulative labile N over the course of the experiment than the manure+PMS mixes, however it was less effective at retaining the N added. Should this inorganic N continue to leach, there will be no N to sustain vegetation, rendering the reclamation unsuccessful in the long term.

There appears to be some risk of leaching from direct application of manure and paper mill sludge mixes, however, this method would still be an improvement over current reclamation methods when considering N leaching losses. Currently, another prevalent reclamation method is the application of biosolids to abandoned mineland. When applied at the suggested loading rate, cumulative N loss via leachate has been reported at 2327 kg N ha^{-1} over a two-year period, with only 44% retention of original N added (Stehouwer et al., 2006). Furthermore, the greenhouse study performed prior to this field experiment demonstrated that a straight manure application on minespoil without adding a C material leached almost 7 times more N over a six month period than a manure+PMS treatment with a 25:1 C:N ratio. The field data presented in this paper suggests an approximate N loss of 120 to 230 kg N ha^{-1} over fourteen months (Fig. 8). Not only are these quantities much smaller than those shown in a similar biosolids application study, but these data show better N retention rates as well, indicating the system is potentially more sustainable.

Additionally, there may be soil restoration benefits obtained by co-application of manure and a high C material. When fresh manure and a high C substrate are co-applied to the mine spoil, the flush of microbial activity that would have occurred in the compost windrow now occurs in the mine spoil. With this *in-situ*, "composting" the large increase in microbial activity could enhance mine spoil restoration and soil development by accelerating soil structural formation and stability and increasing nutrient and water availability.

Ongoing research will continue monitoring this field site to help determine if the benefits of adding manure and paper mill sludge to mine soil are sufficient to outweigh the potential negative environmental impacts of N leaching loss. These results suggest the amount of manure applied to the soil could be considerably reduced yet still achieve revegetation success for strip mine soils while minimizing N loss due to leaching. Compost has proven to be extremely effective at limiting N and P loss while supporting vegetation, even when applied at large rates. However, composting adds significantly to the overall cost of utilizing manures for mine reclamation due to the extra material handling, processing, and transportation required. Because the economics of mine reclamation favor an *in situ* reclamation approach, co application of manure with a high C material should be further investigated.

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