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Reforestation and Water Quality: Optimizing Plant Systems to Minimize Total Dissolved Solid Delivery to Surface Waters

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Project Summary

Total dissolved solids (TDS) coming from surface coal mines are greatly impacting water quality in Appalachia. This study investigated whether vegetation could reduce TDS (specifically calcium, potassium, magnesium, sodium and sulfate ions) in solution draining from the soil into streams. Vegetated and un-vegetated plots were established across eight sites that differed in age, rock material, and plant communities. Ion exchange resins that capture TDS ions in soil solution were used to compare nutrient ion fluxes that contribute to TDS between paired plots. Soil and vegetation properties (used as proxies for evapotranspiration and plant uptake) were characterized at each site and correlated with log ratios of common TDS contributing ions. Strong correlations were found during the peak growing season, suggesting that the presence of vegetation reduced the amount of dissolved ions in soil solution. In addition, soil organic matter was correlated with TDS contributing nutrient ions in all seasons. These finding suggests that productive, growing forests could reduce TDS contributing nutrient ions draining from soils into streams through plant and organic matter retention.

Introduction

One of the major issues in surface coal mine land reclamation is the impact of total dissolved solids (TDS) on water quality. Surface mining practices in the central Appalachian Mountains involves the removal of overburden in order to reach underlying coal seams. After extraction of the coal seam, overburden (i.e., spoil) is replaced to the approximate original contour of the landscape (SMCRA [Sec.515(b)3]), with excess being placed in adjacent valleys or hollows, creating what are known as valley fills (US.EPA., 2011). Exposure and weathering of mine spoil releases ions often in excess of background concentrations, contributing to the increased levels of TDS in streams. This increase in TDS constituent ions causes elevated electrical conductivity (EC) in surface waters, impacting benthic macroinvertebrate communities (Pond et al., 2008; Lindberg et al., 2011; Timpano et al., 2015). The primary TDS constituent ions generated by weathering from central Appalachian mine spoil include Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, SO_4^{2-}, and HCO_3^{-} (Orndorff et al., 2015; Pond et al., 2008; Lindberg et al., 2011; Timpano et al., 2015). Four of these ions are also essential plant macronutrients: Ca^{2+}, K^{+}, Mg^{2+}, and SO_4^{2-}. Most of the current research has focused on how to limit TDS generation by selecting weathered, coarser topsoil substitutes (e.g., sandstone vs. siltstone), and isolating high TDS generating materials by keeping them out of direct contact with drainage waters (Agouridis et al., 2012; Orndorff et al., 2015; Daniels et al., 2013; Daniels et al., 2014). Little has been done to assess the role vegetation plays in reducing TDS loading to surface waters.

The amount of TDS generated is largely dependent on the parent rock material. EC is often used as a proxy for TDS since it is easier to measure and has proven to be strongly correlated with TDS (Daniels et al., 2009; Daniels et al., 2013). In general, weathered mine spoil of the same strata produces less EC than unweathered materials (Agouridis et al., 2012; Daniels et al., 2013). Column leaching experiments have shown that finer textured rock materials, such as shales and mudstones, produce leachates higher in EC compared to sandstones, especially when unweathered (Daniels et al., 2013; Daniels et al., 2014). Research at Bent Mountain, KY, showed EC levels in drainage from mine spoils to be highest in a mixture of shale and sandstone, unweathered sandstone being intermediate, and lowest in weathered sandstone (Agouridis et al., 2012). After 9 years, EC had decreased across all spoil types (Sena et al., 2014). Native hardwood trees were also planted on the sites to test tree growth and survivability. After three years, tree volume and height were highest on weathered sandstone, followed by the shale/sandstone mix, and lowest on unweathered sandstone (Agouridis et al., 2012). By year 9, tree volume was nearly 50 times greater, with 86% survivability, on the weathered sandstone. Though sites were not seeded, volunteer vegetation did provide groundcover. Percent cover and species richness were consistently highest on weathered sandstone (Sena et al., 2014). Thus, productivity and diversity were all highest on the spoil type with the lowest EC.

Studies conducted on forest ecosystems recovering from disturbance have demonstrated the significant role of plants in regulating the balance and loss of nutrients (e.g., Ca^{2+}, K^{+}, and Mg^{2+}) (Vitousek and Reiners, 1975). This is particularly true in early successional ecosystems compared with mature ecosystems, where nutrient retention generally scales with net primary productivity. Woody species have been shown to account for over 60% of the nutrient accumulation in above ground biomass four years after forest disturbance

(Hendrickson, 1988). Crow et al. (1991) demonstrated that woody and woodland herbaceous species together accounted for more than 70% of the nutrients captured by vegetation, while early successional graminoids (e.g., grasses, sedges, and rushes) accounted for only a small percentage of the nutrient accumulation. Mou et al. (1993) also showed recovering tree species to accumulate higher amounts of nutrients than herbaceous species six years after forest disturbance. Other studies continue to show that understory vegetation accounts for a small percentage of the total nutrient mass (Zhang et al., 2009; Turner et al., 1976). In a natural secondary forest, grasses accounted for 13% of the total nutrients accumulated (Zhang et al., 2009). Similarly, in a maturing red alder stand, understory vegetation (predominantly ferns) contribution was greater (25% of the total nutrient mass), but still notably lower than what woody species account for in nutrient mass (Turner et al., 1976).

Vegetation may reduce the potential for TDS export via two mechanisms: evapotranspiration and plant uptake. Evapotranspiration decreases water and drainage in the rooting zone, and plant uptake of nutrients may reduce concentrations of TDS-contributing nutrient ions in soil solution. Vegetation also plays an important role in the water budget of an ecosystem through transpiration and evaporation of intercepted water from canopy surfaces. It has been shown that with the removal of forest cover, reduced evapotranspiration increases the amount of water discharged to streams (Brown et al., 2005). Sena et al. (2014) have also shown decreased water discharge volumes between the dormant and growing seasons from a surface mine in eastern Kentucky, demonstrating that transpirational demands from an aggrading forest can reduce waters draining from a reclaimed mine land. The study concluded that evapotranspiration from trees exerted a greater influence over the quality of discharged water than spoil type. It is hypothesized that aggrading forests can reduce TDS loss from the rooting zone both by decreasing the quantity of water leaving the rooting zone through increased evapotranspiration, and decreasing the concentration of TDS-contributing nutrient ions in percolating waters through plant uptake. The outcomes to this research are especially pertinent to mine land reclamation as TDS loading to surface waters is a major water quality concern.

The primary objectives for this study are to:

1) quantify the effect of vegetation on reducing soil solution fluxes of common TDS-contributing nutrient ions in reclaimed mine lands,
2) assess vegetation and soil properties to determine their effects on loading of TDS-contributing nutrient ions, and
3) recommend reclamation strategies that optimize vegetation communities for reducing TDS-contributing nutrient ion loading from reclaimed mined lands.

Materials and Methods

Detailed methods can be found in the completed thesis of Amy C. Gondran (2016) at the following website, or by contacting Brian Strahm (brian.strahm@vt.edu).
http://vtechworks.lib.vt.edu/handle/10919/5534

Site Description and Preparation

Study sites are located in southwest Virginia at the Powell River Project in Wise County (37°00'17"N 82°42'26"W). Eight sites were selected across a range of post-reclamation ages (1-8 years). Due to logistical constraints of vegetation removal, sites greater than eight years post-reclamation were not included. In addition, it has been suggested that as reclamation age approaches 10 years, EC values diminish (Sena et al., 2013; Daniels et al., 2014; Orndorff et al., 2015). Where possible, multiple sites within a particular age were selected to represent various spoil materials and extents of weathering, thus providing gradients in both productivity and potential TDS generation.

At each site, vegetated and un-vegetated paired plots were established to evaluate the effect of vegetation on common TDS-contributing nutrient ion fluxes (Figure 1). Plot sizes were variable (12 to 45 m^2) based upon the dominant vegetation height. Plot perimeters extended from the center a minimum of one meter if the dominant vegetation was less than one meter tall. Otherwise, plot perimeters extended from the center a distance equal to the height of the dominant vegetation.

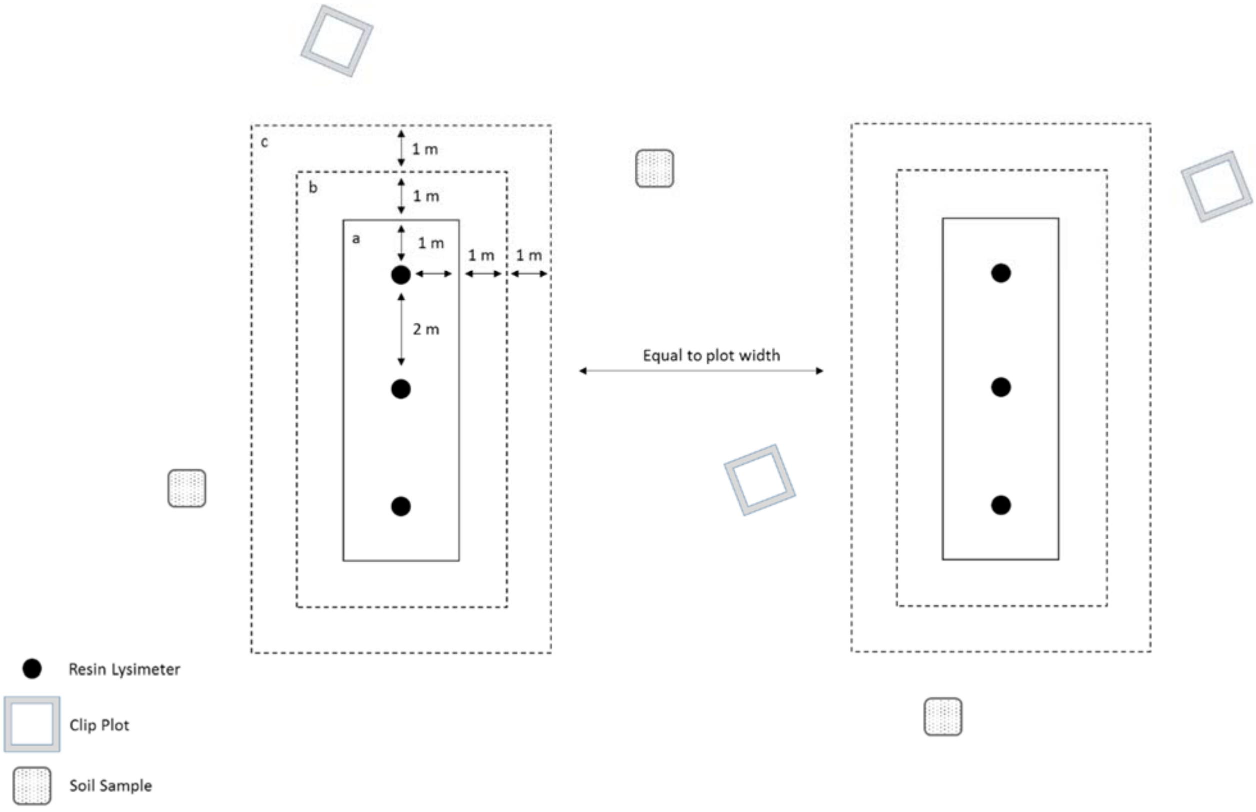

Figure 1. Plot layout, and soil and vegetation sampling. Plots were established on the backslope of the hills, parallel to the slope, and set apart at a minimum distance equal to the plot width**.** (a) is an example of a plot if dominant vegetation is less than 1 m in height, (b) if dominant vegetation is 2 m, and (c) if dominant vegetation is 3 m. Vegetation clip plots and soil samples were randomly selected near, but outside plot boundaries.

Each set of paired plots were laid on the backslope of a hill, running parallel with the slope, and separated by a minimum distance equal to the plot width. In order to establish un-vegetated plots, vegetation was removed manually (pulling, clipping, and sawing as required) and with herbicide (BrushMaster® active ingredient: Glyphosate; Roundup® active ingredients: 2,4-D, 2,4-DP, and Dicamba). Regrowth was treated with herbicide and manual removal as needed, typically twice for each sampling period. Decomposition of roots releasing nutrient ions after herbicide application is likely minimal as previous research has indicated that less than three percent of dry matter for Ca^{2+}, K^{+}, Mg^{2+}, and sulfur accumulates in roots of grasses, herbaceous, and woody species (Mou et al., 1993; Peri et al., 2008; Zhang et al., 2009; Peri and Lasagno, 2010;).

TDS Sampling and Extraction

Sampling for common TDS-contributing nutrient ions (i.e., Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, SO_4^{2-}) took place in two month increments seasonally through 2015 and 2016. Ion exchange resins (Amberlite® IRA-400 Cl^{-} and Amberlite® IR-120 H^{+}) encapsulated in a screened PVC lysimeter were used to absorb cations and anions contributing to TDS in soil solution under locally saturated conditions (i.e., zero tension). Three resin lysimeters were placed in each vegetated and un-vegetated plot, linearly in plot centers, spaced 2 meters (Figure 1). Vegetation was removed from un-vegetated plots five weeks prior to resin lysimeter deployment. Sampling periods took place July 6, 2015 to September 8, 2015 (peak growing season), October 9, 2015 to December 10, 2015 (fall), and January 14, 2016 to March 15, 2016 (winter). A fourth sampling period was planned for mid-April to mid-June, but a wildlife disturbance prematurely ended the study.

Vegetation Characterization

Vegetation was classified into three categories: herbaceous, trees [>2.5 cm at diameter at breast height (DBH)], or other woody vegetation (OW) (<2.5 cm at DBH). Each category was characterized by measuring biomass, basal area, and leaf area index (LAI).

Soil Characterization

Three soil samples per 0-10 cm and 10-20 cm depth were taken at each site. Soil samples were randomly located outside of plot boundaries to minimize the effect of soil disturbance on TDS fluxes (Figure 1). Soils were air-dried and mineral soil separated from course fragments with a 2mm sieve. Mineral soil samples were analyzed for pH, particle size, and organic matter. Samples were sent to the Virginia Tech Soil Testing Lab for pH analysis using 1:1 (vol/vol) water to soil ratio (Kalra et al., 1995).

Results

During the peak growing season (sample period July to September), LAI and live herbaceous biomass tended to increase with post-reclamation age (Table 1). LAI ranged from 0.5 to 4.9, generally increasing with age with the exception of the one-year-old site (Table 1). Average live herbaceous biomass ranged from 15 g to 83 g. The one-year-old site

(site 1) is comparatively higher in live herbaceous (46 g) when compared to sites 3 years (sites 3a and 3b) and 6 years (sites 6a and 6b) old (Table 1). This may be because site 1 had been recently hydroseeded and fertilized. Biomass and stem density of trees, and volume and stem density of OW, tended to be more variable than live herbaceous biomass, reflecting the different productivity gradients of each site. Only three sites supported trees (6a, 6b, and 8b), but OW vegetation was present on most sites. Tree stem density and biomass were highest on 8b (0.12 kg m^{-2} and 3.9 kg m^{-2}, respectively). Site 6a was slightly lower in stem density than 6b, but higher in biomass (Table 1). While 8a lacked trees, it was higher in OW stem density and volume than 8b (Table 1). OW volume and stem density increased across sites by age.

Soil properties of the study sites are shown in Table 2. On average, sandy loam was the dominant soil textural class across all sites. The pH ranged from 6.3 to 8.1 at 0-10 cm depth and 6.0 to 8.3 at 10-20 cm depth. EC of the combined coarse fragments ranged from 0.316 mmhos cm^{-1} to 0.871 mmhos cm^{-1}. Most sites had an EC value less than 0.600 mmhos cm^{-1}, but the two sites with the highest ECs (3a and 6a; $p<0.005$) exceeded 0.800 mmhos cm^{-1}. Percent organic matter ranged from 4.4 to 9.8% at 0-10 cm depth and 3.0 to 6.2% at 10-20 cm depth, generally increasing with age.

Table 1. Vegetation characteristics of study sites. Includes peak live herbaceous (mean and standard errors),

Age Post-Reclamation	Herbaceous	Trees		Other Woody		LAI
	Live (g)	Stems (m^2)	Biomass (kg/m^2)	Stems (m^2)	Volume (cm^3/m^2)	
1	46 ± 14	0	0	0	0	1.7
3*a*	15 ± 3	0	0	0	0	0.5
3*b*	22 ± 3	0	0	0.1	3.56	0.5
6*a*	24 ± 14	0.03	1.7	0.2	444	2.3
6*b*	18 ± 11	0.04	0.9	0.2	79.5	1.4
8*a*	58 ± 4	0	0	0.5	2350	2.1
8*b*	83 ± 28	0.12	3.9	0.3	1730	4.9
8*c*	78 ± 24	0	0	0.2	987	2.8

Table 2. Means and standard errors for soil properties of each site. Includes percent sand, percent clay, percent organic matter, pH, EC of coarse fragments, and hydraulic conductivity (*K*).

Age Post-Reclamation	% Sand		% Clay		pH		% Organic Matter		EC (mmhos/cm)	*K* (cm/hr)
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-20 cm	
1	58 ± 2	61 ± 10	12 ± 1	11 ± 3	6.3 ± 0.3	6.0 ± 0.5	4.4 ± 0.1	3.5 ± 0.5	0.316 ± 0.08	0.1 ± 0.1
3*a*	55 ± 2	60 ± 1	17 ± 1	16 ± 1	7.5 ± 0.2	7.5 ± 0.2	6.2 ± 0.5	4.3 ± 0.7	0.833 ± 0.03	0.4 ± 0.1
3*b*	62 ± 2	67 ± 2	13 ± 1	13 ± 1	7.7 ± 0.1	7.5 ± 0.3	3.8 ± 0.0	3.0 ± 0.2	0.474 ± 0.03	2.7 ± 0.6
6*a*	68 ± 1	67 ± 0	9 ± 1	10 ± 0	6.4 ± 0.0	6.7 ± 0.5	7.2 ± 0.8	5.0 ± 0.3	0.871 ± 0.05	0.6 ± 0.1
6*b*	64 ± 0	67 ± 2	10 ± 1	11 ± 1	7.8 ± 0.3	8.1 ± 0.2	4.3 ± 1.2	3.4 ± 0.5	0.640 ± 0.01	0.4 ± 0.0
8*a*	55 ± 2	54 ± 1	16 ± 1	19 ± 2	8.1 ± 0.1	8.3 ± 0.0	5.7 ± 0.2	3.9 ± 0.4	0.504 ± 0.01	0.5 ± 0.1
8*b*	61 ± 1	61 ± 2	11 ± 1	14 ± 1	6.6 ± 0.2	7.1 ± 0.2	7.9 ± 0.2	6.2 ± 0.3	0.464 ± 0.01	0.8 ± 0.2
8*c*	61 ± 2	64 ± 2	12 ± 1	13 ± 2	6.8 ± 0.2	7.2 ± 0.2	9.8 ± 0.8	6.1 ± 0.6	0.527 ± 0.06	0.9 ± 0.3

A correlation analysis was performed including and excluding sites 3a and 6a (EC > 0.800 mmhos cm^{-1}) to determine the effect high EC materials may have on vegetative influences on solute fluxes (Figure 2). Positive trends between TDS variables and site characteristics were expected. Figure 2a shows correlations for the peak growing season with all sites included. Most correlations were less than 0.40, with the exception of percent organic matter, age, and live herbaceous vegetation. When sites 3a and 6a with the highest EC values were excluded, correlations become stronger and more positive (Figure 2b). This suggests that initially selecting lower EC materials is necessary before a vegetative effect can be determined. Otherwise, mine spoil or topsoil substitute with EC greater than 0.800 mmhos cm^{-1} may generate TDS nutrient ions in amounts greater than the capacity for vegetation to mitigate.

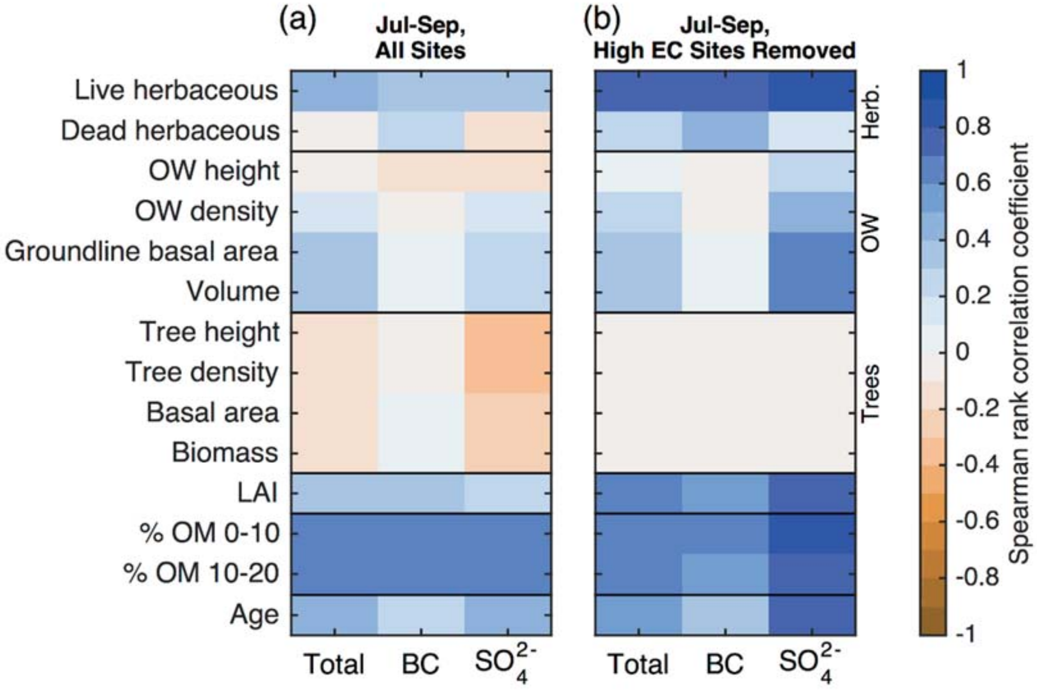

Figure 2. Spearman rank correlation coefficients where intensity of blue indicates the scale (or magnitude) of positive correlations and intensity of tan indicates the scale of negative correlations. Correlations are between ΔTDS, ΔBC, and ΔSO_4^{2-} and parameters for herbaceous vegetation, OW, Trees, and integrative characterizations (LAI and % Organic Matter) (a) shows correlations for all sites during peak growing season. (b) excludes sites 3a and 6a based on high EC.

Vegetated plots often yielded higher values for TDS nutrient ions than un-vegetated plots, contrary to the hypothesis. Despite this, the data shows positive Spearman correlations between calculated ratios (R_{Total}, R_{BC}, and R_{SO4-2}) and vegetative characteristics. The strongest of these correlations were between R_{SO4-2} and live herbaceous vegetation (ρ = 0.89), LAI (ρ = 0.77), percent organic matter (0-10 cm ρ = 0.83; 10-20 cm ρ = 0.77), and OW volume (ρ = 0.60). Tree characteristics (ρ = -0.07), groundline basal area (ρ = 0.09), and volume (ρ = 0.09) were not correlated with R_{BC}, while live herbaceous (ρ = 0.71), percent organic matter (0-10 cm ρ = 0.60; 10-20 cm ρ = 0.54), and LAI (ρ = 0.54) were the most positively correlated characteristics with R_{BC}. Live herbaceous vegetation was most positively correlated in the peak growing season compared to the fall and winter dormant periods (Figure 3). During the fall sampling season (Figure 3b), all OW and tree characteristics exhibited moderate correlations (ρ = 0.44 to > 0.70), suggesting that even during dormant periods woody vegetation had an apparent influence on the flux of common TDS nutrient ions. During this period, OW volume had its strongest correlation with R_{BC} ($\rho = 0.71$), and trees were moderately correlated with R_{Total} ($\rho = 0.44$). Correlations during the winter sampling season (Figure 3c) for trees were weakly negative ($\rho \leq -0.3$), while OW density ($\rho = 0.67$), groundline basal area ($\rho = 0.77$), and volume ($\rho = 0.77$) increased over the fall period with $R_{SO4\text{-}2}$.

During the peak growing season, percent organic matter exhibited moderate to strong correlations with R_{Total}, R_{BC} and $R_{SO4\text{-}2}$, with ρ values of 0.66, 0.60, and 0.83 for 0-10 cm, respectively, and 0.60, 0.54, 0.77 for 10-20 cm, respectively. Correlations with R_{Total}, R_{BC} and $R_{SO4\text{-}2}$ strengthen during the fall. For 0-10 cm depth, ρ values were 0.71, 0.77, and 0.90, respectively, and 0.66, 0.71, 0.84 for 10-20 cm depth, respectively. In winter, correlations weakened, but overall remained positive for R_{Total}, R_{BC} and $R_{SO4\text{-}2}$ (0-10 cm $\rho = 0.37$, 0.43, and 0.71, respectively; 10-20 cm $\rho = 0.26$, 0.31, and 0.60, respectively).

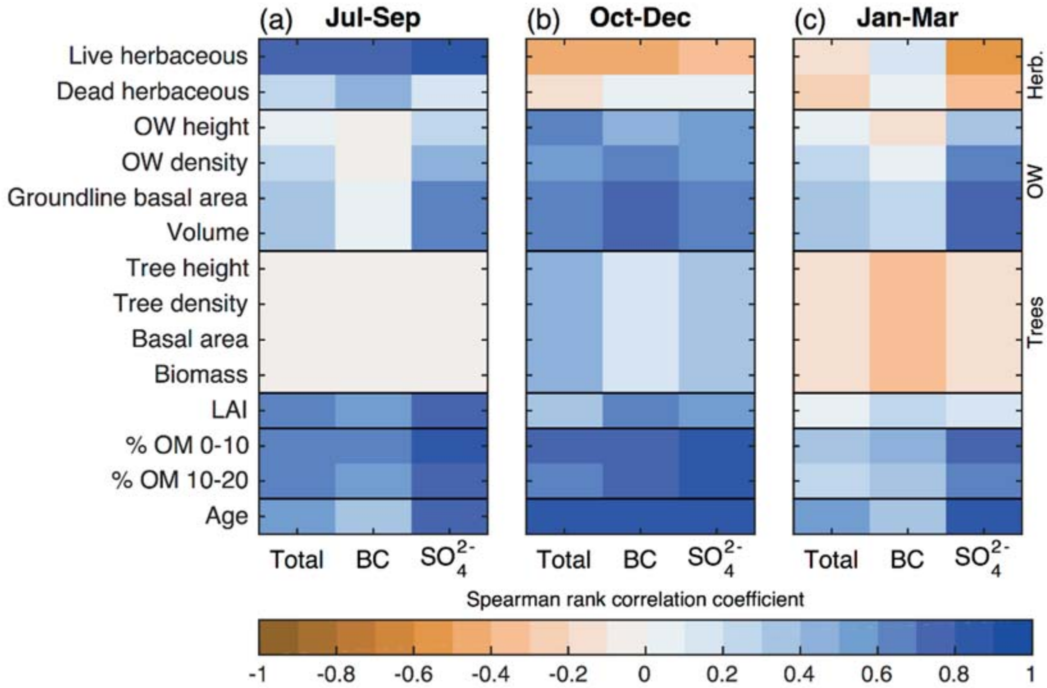

Figure 3. Spearman rank correlation coefficients where intensity of blue indicates the scale (or magnitude) of positive correlations and intensity of tan indicates the scale of negative correlations. Correlations are between ΔTDS, ΔBC, and ΔSO_4^{2-} and parameters for herbaceous vegetation, OW, Trees, and integrative characterizations (LAI and % Organic Matter) (a) shows the peak growing season, (b)

Reclamation Strategies

The goal of this study was to investigate whether vegetation could mitigate TDS-contributing nutrient ion loading from reclaimed mine lands, and provide strategies for reclamation practitioners to utilize. Our findings suggest that both herbaceous and woody vegetation can reduce TDS nutrient ions leaching from the rooting zone when topsoil substitutes are low in soluble salts. Interception from woody vegetation and ion retention by organic matter may provide year round control. Three strategies are proposed to optimize vegetative control of TDS fluxes to surface waters draining from reclaimed surface coal mine lands:

1) Use spoil materials low in soluble salts. High EC materials may generate TDS nutrient ions in amounts greater than what vegetation is able to mitigate.
2) Establish non-competitive herbaceous vegetation in early reclamation stages to reduce TDS nutrient ion fluxes and build soil organic matter.
3) Establish woody species for year round control of TDS nutrient ion loading

The benefits of low EC are twofold. Vegetative productivity is higher on materials low in soluble salts, and low EC materials tend to yield drainage waters lower in specific conductance. Establishing tree compatible herbaceous ground cover increases evapotranspiration and plant uptake during the growing season, and builds organic matter via senescence and decomposition, which exerts an influence during the non-growing season. Tree compatible ground covers will also aid in seedling survival of woody species, whether they are established by planting or natural recruitment. As reclaimed forests aggrade, woody species will have greater influence on TDS nutrient ion fluxes through evapotranspiration and plant uptake during the growing season, and through interception in the dormant season. Together, these three strategies may help reclamation practitioners decrease the amount of TDS nutrient ions reaching surface waters, thereby mitigating water quality impacts.

Conclusions

One of the major issues in surface coal mine land reclamation is the impact of TDS on water quality. To address this water quality concern, we assessed whether vegetation could reduce TDS loading, specifically nutrient ions Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, and SO_4^{2-}, likely through increased evapotranspiration and plant uptake. Paired vegetated and un-vegetated plots were established, and vegetation properties (i.e., LAI, tree biomass, OW volume, etc.) measured as proxies for evapotranspiration and plant uptake. Results were not definite in this study. Vegetated plot often produced higher TDS-contributing nutrient ions than un-vegetated plots, which suggests that vegetation did not have a significant influence on reducing TDS nutrient ions in soil solution. However, Spearman correlations with vegetation characteristics, age, and org matter followed expected patterns that TDS nutrient ions were reduced in soil solution within the rooting zone of more vegetated system, which warranted exploration. Interception by woody vegetation and litter may also influence TDS nutrient ion loading during the dormant season. Soil organic matter may also to be important for the retention of TDS nutrient ions during the dormant season.

These finding suggest that aggrading forests and good vegetative cover may reduce TDS nutrient ion loading by decreasing the quantity of water leaving the rooting zone through increased evapotranspiration, and decreasing TDS nutrient ions in percolating waters through plant uptake in the growing season. However, this study could not unquestionably show this effect. An increased sample size and including sites between the ages of 6 and 12 years of age may be need to detect a vegetation effect. Based on implications from this study, it is recommended that reclamation practitioners 1) choose topsoil substitutes low in soluble salts, 2) establish non-competitive herbaceous vegetation in early reclamation stages to reduce TDS nutrient ion fluxes and build soil organic matter, and 3) establish woody species for year round control of TDS nutrient ion loading once EC levels are below 0.800 mmhos cm^{-1}. These three strategies combined may help reclamation practitioners decrease the amount of TDS nutrient ions reaching surface waters, thereby mitigating water quality impacts.

Reference

Gondran A.C. 2016. Vegetative Potential to Reduce Total Dissolved Solids Generated from Reclaimed Mine Lands in Central Appalachia. M.S. Thesis.