USING ORGANIC AMENDMENTS TO RESTORE SOIL PHYSICAL AND CHEMICAL PROPERTIES OF A MINE SITE IN NORTHEASTERN OREGON, USA

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ABSTRACT. *New cost-effective strategies are needed to reclaim soils disturbed from mining activity on National Forests. In addition, disposal of waste wood from local timber harvest operations or biosolids from waste water treatment plants can be expensive. Therefore, using organic byproducts for soil reclamation activities on National Forests may provide an opportunity to increase soil cover and productivity, and decrease restoration costs. To test the effectiveness of these amendments for reclamation, a field study was established using organic amendments applied to gold dredgings capped with 10 cm of loam and with little regenerating vegetation within the Umatilla National Forest in northeastern Oregon. Study plots had biochar (11 Mg/ha), biosolids (17 Mg/ha), or wood chips (22 Mg/ha) applied singly or in combination. Each plot was divided in half. One half of the plot was seeded with native grasses and forb and the other half was planted with a combination of California brome (*Bromus carinatus *Hook & Am.) and Jepson's blue wildrye (*Elymus glaucus *Buckl.). After two growing seasons, there were no significant differences in plant cover between the planted or seeded plots. Biosolids, biosolid + biochar + wood chips, and biosolid + wood chips had greater grass and forb planted cover after two years; seeded plots on the biosolid + biochar + wood chips and biosolid + wood chip treatments had the greatest grass and forb cover. Soil properties were significantly altered by individual treatments; combination treatments improved nutrient availability and soil moisture, resulting in up to twice as much plant cover than in the control plots. Forest managers can produce biochar and wood chips from the abundant forest waste generated during harvest operations, and class "A" biosolids are available in Oregon from local municipalities. Using these three amendments in combination to restore disturbed mine soils can provide an affordable and effective strategy.*

Keywords*. Biochar, Biosolids,* Bromus carinatus*,* Elymus glaucus*, Wood chips.*

Within the last decade, reclamation of abandoned mine land (AML) in the United States has gained government attention and public concern. In the 12 Western states, over 161,000 abandoned mines exist. In 2011, the Office of Accountability estimated the cost of reclaiming abandoned mines on public land in the 12 Western states was in the range of $10-$21 billion dollars. Often, unproductive AMLs are in forested areas, reducing overall forest productivity and timber harvest potential. In the Pacific Northwest, abandoned mine sites are usually located in rural areas with rugged terrain and limited access. Eighty percent of AML on public lands contain physical hazards, but no environmental hazard or contamination (AGI, 2011). Physical hazards include waste rock piles and disturbed landscapes that often lack vegetation and create inhospitable environmental conditions. Combined costs of equipment, transportation, and re-application of needed nutrients rules out many common reclamation strategies. Surface applied amendments, with minimal soil disturbance, are an inexpensive solution to increase soil function and accelerate re-vegetation. Three possible amendments that have shown some success in soil restoration are biochar, municipal biosolids, and wood chips.

Biochar, a solid product from the pyrolysis of biomass, can be used as a soil amendment on agriculture, range, and forest soils (Atkinson et al., 2010; Beesley et al., 2010, 2011; Jeffery et al., 2011; Peltz and Harley, 2016; Page-Dumroese et al., 2017). It may also be suitable for restoring vegetation on pulverized rock piles produced by historic mining activities (Kelly et al., 2014) because it can increase nutrient and water availability by improving the physical, chemical, and biological properties of rocky or coarse-textured growing matrices (Glaser et al., 2002). Proposed uses of biochar applied to the soil are to increase agricultural yield (Sinclair

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et al., 2008; Major et al., 2010), reduce risks at polluted sites (Murano et al., 2009; Fellet et al., 2011), sequester C (Steinbeiss et al., 2009; Galinato et al., 2011), and restore organic matter content in degraded soils or rocky substrates (Stavi, 2012; Anawar et al., 2015).

Biochar has been shown to influence soil chemical and physical properties, resulting in increased available nutrients and plant survival (Lehmann et al., 2003; Tammeorg et al., 2014), water-holding capacity, and decreasing availability of soil contaminants such as heavy metals (Uchimiya et al., 2010; Rodriguez-Vila et al., 2014; Ojeda et al., 2015). It is also known to increase cation exchange capacity (CEC) and retention of cationic nutrients [namely potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and ammonium-N (NH_4^+)] (Liang, 2006; Lehman, 2007), increase total organic carbon (C) (Unger et al., 2011; Tammeorg et al., 2014), and raise soil pH (Chan and Xu 2009). Biochar properties are determined by feedstock and pyrolysis temperatures (Gundale and DeLuca, 2006; Uchimiya et al., 2010), and therefore their effects on soil parameters vary. For example, at the Hope Mine reclamation project in the White River National Forest in Colorado, biochar was applied at varying rates in combination with compost, erosion control webbing, and hydromulching to re-vegetate contaminated mine soil [arsenic (As), cadmium (Cd), lead (Pb), and zinc (Zn)] and prevent erosion on a steep hillside (ACES, 2011). Due to the slope, amendments were not incorporated into the mine overburden. Within the first year, the combined amendments increased soil moisture and native grass growth. The success of the revegetation, however, was not only due to the biochar since compost, applied in quantities of up to 95% of total amendments, provided nutrients and organic matter (USDA Forest Service, 2012). Other recent studies have also found adverse effects of biochar on soil health and plant growth, such as hindering N mineralization and increasing N immobilization (Kookana et al., 2011), absorbing P (Yao et al., 2012), and clogging pore spaces over time, which decreases its surface area and therefore sorption properties (Hammes and Schmidt, 2012).

The vast majority of studies conducted with biochar on mine sites have been for the purpose of remediation by reducing toxic metal uptake and immobilization of contaminants (Fellet et al., 2011, Bakshi et al., 2014, Strawn et al., 2015; Ippolito et al., 2017). Although biochar has been used as a soil amendment on degraded agricultural soils (Atkinson et al., 2010; Lehmann et al., 2012), and recently on rangeland soils (Stavi, 2012), it has not been widely used to alter soil function on degraded mine lands that are not contaminated.

A second type of organic amendment available to rehabilitate AMLs are biosolids. These are commonly used for mine land reclamation, especially after the establishment of the Surface Mine Reclamation Act of 1977 (Sopper, 1992; Haering et al., 2000; https://www.osmre.gov/lrg.shtm). Mine soil deficiencies that can be improved by biosolids are low organic matter, CEC, pH, and nutrients (Forsberg and Ledin, 2006; Ojeda et al., 2010). Biosolids contain between 1% and 6% N, depending on the source and processing (Center for Urban Horticulture, 2002). Recent mine land reclamation research with biosolids and sewage sludge show they can be used as a manufactured topsoil (Brown et al., 2003) or incorporated into unproductive soils to increase vegetation growth.

Wood chips are another frequently used surface-applied amendment on mine sites. Wood chips add few soil nutrients, but they promote biological activity during decomposition, thereby having the potential to increase soil organic matter content and increasing soil water holding capacity by changing soil structure (Edwards et al., 1992; Walsh and Redente, 2011). Organic C can also change water retention because it forms polysaccharides that bind soil particles together, causing aggregation and allowing infiltration. Wood chips also reduce surface evapotranspiration. In a reclamation project on mine land in North Idaho, Walsh and Redente (2011) found wood chips increase organic matter, ammonium-N and nitrate-N after 4 years. Wood chips on the soil surface also block direct sunlight, keeping the soil cool and reducing evaporation (Schoenholtz et al., 1992).

The United States Department of Agriculture, Forest Service (USFS), in cooperation with the City of Bend, Oregon, initiated a mine tailing reclamation project in the Umatilla National Forest in northeastern Oregon to determine the benefits of surface applied organic amendments, and to determine if AML reclamation would be a beneficial utilization option for biosolids, wood chips, or biochar. For this study, the USFS worked with Biochar Solutions Inc. (Anderson et al., 2013) to produce biochar near forest sites where biomass waste has either become a fire hazard or is left over from logging activity (USDA Forest Service, 2012; Page-Dumroese et al., 2017). To help restore AML productivity, we conducted a field study using surface applied organic amendments. Surface applications are likely to be used more often on abandoned hardrock mine tailings since mixing the organics into the rocks is not feasible. In addition, AMLs on National Forests are generally remote; making it difficult and costly to move in large equipment to mix amendments into soil caps, if present. Other concerns are that mixing tailing piles can expose more contaminants or pollutants and hazardous elements to air and water and disrupt plant and soil structure, leading to increased erosion and loss of nutrients. Thus, to develop effective and economical reclamation strategies for forest soils, research into surface applied amendments on AML soils in field settings (application rates, and overall effectiveness to develop ground cover) is necessary.

Our objectives were: 1) to determine if surface applied soil amendments affect soil water holding capacity, plant available nutrients, pH, CEC, and C; and 2) to determine if surface applied soil amendments affect seeded or planted grasses or forb survival and areal extent of ground cover.

Methods and Materials

Experimental Site and Soil Characteristics

The study site is in the Granite mining district of Grant County, Oregon and is part of the larger "Oregon Gold District," which produced gold throughout the 19th and 20th centuries. Clear Creek is a dredged creek located approximately 3 miles west/southwest of Granite, Oregon

(44.780541-118.459623; fig. 1). The site is a flattened tailings pile left over from dredging activities dating as far back as 1862, lining the north side of Clear Creek (EOMA, 1999). The tailings pile was capped in the 1970's with roughly 10 cm of loam. Between 2001 and 2007, the Umatilla National Forest planted ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and seeded with native grasses and forbs. These re-vegetation attempts had limited success, resulting in <10% ground cover of grasses and forbs and less than 1% survival based on personal observation.

The site is in located in Climate Division 8 (NOAA) with an average annual precipitation of 62.8 cm per year. According to the Palmer Drought Severity Index (PDSI) the site is in a region of moderate drought (NIDIS) and in a region of severe to extreme drought during 6 months of the year (July-Oct.) (https://www.drought.gov/drought/dews/pacific-northwest). Since the soil cap was applied in the 1970's, the surface loam material has become embedded with rocks from the subsurface. Rock fragment content of the soil ranges from 28% to 52%, increasing from the surface down to 20 cm (table 1.). Before applying the amendments, soil samples were collected and physicochemical properties determined (table 1). Analysis methods are described under Laboratory Methods.

Experimental Design

In October 2014, experimental plots were constructed in a completely randomized design. The plots were 3 × 3 m in size, with three replicates of each single amendment and combinations, plus an untreated control in each replicate (8 treatments × 3 replicates = 24 plots). Biochar, biosolids, wood chips and their 2- and 3-way combinations were surface applied. Application rates were as follows: biochar-11 Mg/ha, biosolids- 17 Mg/ha and woodchips- 22 Mg/ha.

Table 1. Initial characterization of the fine-fraction and rock content of the topsoil cap (n=6).

Property	Amount
Rock fragment content	28-52%
Sand	47 ± 5%
Silt	35 ± 3%
Clay	18 ± 2%
Textural class (USDA)	Loam
Total soil bulk density	1.8 Mg/m^3
pH	5.5 ± 0.4
Total carbon (C)	3.8 ± 0.4%
Total nitrogen (N)	<0.01%

The application rates were chosen in an attempt to standardize the amount of C applied. Amendments were applied as close to this rate of C as possible. C:N ratio of these biosolids was 5.9. Table 2 provides a summary of the chemical and physical properties of the Class A biosolids (BioVir Laboratories, Benicia, Calif.), wood chips, and biochar, as applied.

Biosolids were obtained from the Bend Water Reclamation facility in Bend, Oregon. Biosolids were anaerobically digested and dewatered using a belt filter press prior to drying on 12 acres of asphalt drying beds. Because our study plots were near two fish-bearing streams, we applied Class A biosolids (pathogen-free). Biochar was made from mill and forest residues, which contained little bark or foliage. Biochar Solutions, Inc. (Carbondale, Colo.) used a two-stage reactor and carbonized the feedstock in a controlled aerobic environment with limited oxygen and temperatures between 700°C and 750°C for less than 1 min before it passed into the second reactor and held there for 10 to 15 min at temperatures between 400°C and 550°C (See Anderson et al., 2013 for details on the biochar). Final C:N ratio of the biochar was 342. Wood chips were created from ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* var. glauca Beissn. Franco) at a local sawmill and had a C:N ratio of 392. All

Figure 1. Map of the Clear Creek reclamation project in northeastern Oregon.

Table 2. Average physical and chemical properties of applied biochar, biosolids, and wood chips.

Applied Material	Total N (%)	Total C (%)	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)	P (mg/kg)	pH	EC (µS/cm)	Particle Size Range (mm)
Biosolid	56	38	9500	1450	2900	30,250	7.1	160	1-2
Biochar	0.26	89	6700	990	3900	490	7.2	103	0.5-5
Wood chips	0.12	47	1590	240	770	0.47	na[a]	na	1-25

[a] na indicates these properties were not analyzed.

amendments were evenly applied to the soil surface. Combination treatments had biochar applied first, then wood chips, then biosolids.

Immediately after applying the organic amendments to each plot, a native grass and forb seed mixture was applied to half of the plot and lightly raked into the soil and amendments, if present (table 3). This seed mix contains local, native species and is commonly used by the USFS on restoration sites in this area. The other half of each plot was planted in April 2015 with greenhouse-grown seedlings of California brome (*Bromus carinatus* Hook. & Arn.) and Jepson's blue wildrye (*Elymus glaucus* Buckl). Twenty-five seedlings of each species were planted. Seedlings were grown from seed collected near the study plots and grown at the Rocky Mountain Research Station, Moscow, Idaho. Seedlings were grown in RootMaker containers [model RM105T, 105 cavities/tray; cavities were 2.0 × 2.5 × 5 cm (25 mL volume)] with 710 cavities/m^2 (Steuwe and Sons, Inc., Tangent, Ore.). Seedlings were grown for 6 weeks and refrigerated until the snow left the field site.

Soil Sampling

Post-treatment soil samples were collected in May 2016, 19 months after amendment application, from the 0 to 3 cm and 3 to 12 cm depths. The soil surface was brushed free of amendments in order to sample only the mineral soil. Samples were placed in zip-type plastic bags, placed in a cooler to minimize biological nutrient cycling, and transported to the lab where they were kept refrigerated until processing. Bulk density was measured using excavation and polyurethane foam method on site (Page-Dumroese et al., 1999). Excavated soil was weighed for total soil mass then sieved through a 2-mm sieve. The foam cores were removed, transported to the lab, and volume determined by water displacement.

Resin Capsules and Soil Moisture Measurements

In fall 2015, Unibest resin capsules (Unibest International LLC, Walla Walla, Wash.) were installed in each plot at 10 cm. Capsules remained *in situ* for a 6-month period. These capsules absorb bioavailable cations and anions from soil solution and concentrations reflect plant available nutrients (Schoenau and Huang, 1991, Qian et al., 1992, Drohan et al., 2005). The resin capsules were returned to Unibest to obtain total N, Ca, Mg, K, phosphorus (P), and sulfur (S) concentrations reported as mg/L.

Soil moisture was logged at 2-h intervals in one plot of every treatment from plot install through September of the following year with Onset Hobo loggers and 5 cm soil moisture sensors (Onset Computer Corp., Bourne, Mass.).

Laboratory Methods

The collected soil samples were kept cold until reaching the lab, at which time ammonium-N and nitrate-N extractions (Keeney and Nelson, 1982) were performed (within 24 h). Extracts were frozen until analysis by flow injection (FIA2500, FIAlab Instrument, Bellevue, Wash.). To measure potentially mineralizable N (PMN), an anaerobic digestion of soil samples was conducted with field-wet soil (Powers, 1980) and analyzed by FIA2500 flow injection analyzer. Soil moisture content of the field-wet samples was measured on a mass basis by oven drying the subsamples at 105°C for 24 h. The remaining samples were allowed to air dry at room temperature (~20°C). Pre- and post-treatment soil pH and electrical conductivity (EC) was determined on a 2:1 water:soil slurry (Orion Star A215, Research, Inc., Boston, Mass.). Total C and N were measured by dry combustion at 950°C on a CN analyzer (Leco TruSpec, St. Joseph, Mich.). Soil texture was determined by the hydrometer method. Cation exchange capacity (CEC) was measured only on soil from the single amendment plots using the ammonium acetate method (Miller and Sumner, 1996). Extracts were analyzed for ammonium-N with an NH_3 gas-sensing ion selective probe (Banwart et al., 1972, Mulvaney, 1996). Accuracy and quality control for all samples were checked using standards and reference soil.

Soil Water Retention

Initial soil moisture content was measured by oven-dry method using subsamples of 10 to 15 g. Field capacity and permanent wilting point were measured as water retention by pressure plate extraction (Klute, 1986). Water retention at 0.3 and 1.5 MPa was determined for each pressure and this was used to calculate plant available water (PAW).

Table 3. Species and percentages in the seed mix sown in each treatment.

Common Name	Scientific Name	Relative Percentage
Western yarrow	*Achillea millefolium* L.	1.2%
Mountain brome	*Bromus marginatus* Nees es Steud.	35%
Bottlebrush squirreltail	*Elymus elymoide*s (Raf.) Swezey	9.4%
Jepson's blue wildrye	*Elymus glaucus* Buckley	25.9%
Idaho fescue	*Festuca idahoensis* Elmer	4.7%
Prairie junegrass	*Koeleria macrantha* (Ledeb.) Schult.	7.1%
Sandberg's bluegrass	*Poa secunda* J. Presl	4.7%
Bluebunch wheatgrass	*Pseudoroegneria spicata* (Pursh) A. Love	11.8%

PLANT COVER AND SURVIVAL

In May 2016, survival of all planted grasses was determined. In addition, a 0.33-m plot frame was placed on the soil surface and a digital photo taken in each half of each plot. Cover was determined from the digital photo by using the Cover Monitoring Assistant (Steinfeld et al., 2011), which randomly assigns analysis points within the defined photo area. Proportion of the following cover classes was assessed: bare soil, biochar, biosolids, wood chip, grass, forb, coarse wood, litter, rock, and undetermined.

STATISTICAL ANALYSIS

Results from all soil and plant measurements were analyzed using SAS (SAS Institute, Cary, N.C.). The data was first analyzed by univariate tests to choose appropriate transformations if necessary to normalize the distributions. A pooled generalized linear mixed model using log, beta, and Poisson transformations, in accordance with data distributions, was used for analysis of variance tests between treatments (Stroup, 2015). P-values less than 0.05 were considered significant.

RESULTS

All soil amendments provided additional C to the soil surface. Nitrogen in the biosolids was much higher than in the biochar or wood chips, but all three amendments had higher total N and other nutrients than the native soil (tables 1 and 2). In addition, both the biochar and biosolid amendments had a higher pH than the mineral soil.

SOIL PROPERTIES

Nineteen months after applying soil amendments significant differences in pH, EC, CEC, and total C were observed between treatments, primarily in the surface soil (0-3 cm; table 4). Both biosolids and biochar significantly increased soil pH as compared to the 2- and 3-way amendment combination treatments. All amendments containing biosolids had significantly increased EC, but the other soil amendments did not affect it. Biosolids increased total C concentration of the surface soil more than the biochar and wood chip amendments. All of the single amendment treatments increased CEC of the surface soil, but only biosolids treatment produced a statistically significant increase.

In the subsurface (3-12 cm depth) the amendments did not alter soil properties as much as they did in the surface (table 4). However, the trends in pH, EC, and CEC in the subsurface soils were similar to the surface soils. Thus, it appears that after 19 months, soil amendments are slowly moving into the subsurface, but subsurface total C concentrations were similar for all treatments.

NUTRIENT AVAILABILITY

The highest N concentrations occurred in the soils amended with biosolids (table 5). Ammonium-N and nitrate-N concentrations were combined to determine the total, plant available, inorganic nitrogen content for each treatment (fig. 2). The subsurface (3-12 cm depth) had less total N than the surface (0-3 cm depth). Subsurface N was relatively unaffected by the soil amendments after 19 months. As expected, biosolids had the greatest impact on inorganic-N content while wood chips generally had significantly less N (fig. 2). Biosolids + wood chips had less inorganic-N than biosolids alone and at both soil depths, wood chips and biochar + wood chip had lower inorganic-N concentrations than the control plots.

Table 4. Mean (standard deviation) soil pH, electrical conductivity, total carbon, and cation exchange capacity of the surface (0-3 cm) and subsurface (3-12 cm) soil 19 months after soil amendment application.

Treatment	Soil Depth (cm)	pH[a]	Electrical Conductivity (ds/cm)	Total Carbon (%)	Cation Exchange Capacity (cmolc/kg)
Control	0-3	5.6 (0.2) abcd	40.5 (2.4) a	3.6 (0.2) a	22.2 (1.7) a
	3-12	5.7 (0.2) ABC	32.3 (4.3) ACD	3.8 (0.2) A	20.9 (0.9) A
Biosolids	0-3	5.9 (0.1) a	254.5 (64.8) c	5.6 (0.6) bc	27.1 (2.2) b
	3-12	5.3 (0.1) ACD	120.8 (23.0) B	3.7 (0.2) A	24.4 (1.3) AB
Biochar	0-3	6.0 (0.1) a	40.8 (6.7) a	4.3 (0.3) ad	24.8 (1.2) ab
	3-12	5.8 (0.2) B	27.0 (1.6) AD	3.8 (0.2) A	25.95 (2.8) B
Wood chips	0-3	5.9 (0.1) ab	38.5 (6.9) a	4.3 (0.2) abd	23.8 (1.6) ab
	3-12	5.8 (0.1) AB	25.2 (2.5) A	3.7 (0.2) A	27.9 (1.0) B
Biosolids + Wood chips	0-3	5.6 (0.1) bcd	133.8 (14.3) bc	5.6 (0.2) c	
	3-12	5.1 (0.1) CD	75.0 (15.8) BC	3.6 (0.6) A	
Biosolid + Biochar	0-3	5.6 (0.1) bcd	188.1 (23.7) bc	5.5 (0.2) bc	
	3-12	5.0 (0.1) D	143.2 (11.1) B	3.9 (0.02) A	
Biochar + Wood chips	0-3	5.4 (0.1) dc	32.5 (3.9) a	4.7(0.23) bcd	
	3-12	5.2 (0.1) CD	23.8 (0.8) A	3.7 (0.2) A	
Biosolids + Biochar + Wood chips	0-3	5.3 (0.2) d	127.7 (43.3) b	5.4 (0.6) bc	
	3-12	5.1 (0.1) CD	69.3 (15.9) DB	3.7 (0.2) A	

[a] Lower case letters indicate significant differences among soil amendments at the 0-3 cm depth ($p \leq 0.5$) using Tukey's multiple comparison test. Capital letters indicate significant differences among soil amendments at the 3-12 cm depth ($p \leq 0.5$) using Tukey's multiple comparison test.

Table 5. Mean (standard deviation) total nitrogen, ammonium-N, nitrate-N, and potentially mineralizable nitrogen (PMN) in the surface (0-3 cm) and subsurface (3-12 cm) soil 19 months after amendment application.

Treatment	Depth (cm)	Total Nitrogen (%)[a]	Ammonium-N (mg/kg)	Nitrate-N (mg/kg)	Potentially Mineralizable Nitrogen (mg/kg)
Control	0-3	0.03 (0.02) a	7.9 (1.8) bc	5.6 (0.7) bc	40.5 (2.4) ac
	3-12	0.04 (0.03) A	0.7 (0.1) B	2.9 (0.3) DC	24.9 (6.2) A
Biosolids	0-3	0.31 (0.07) b	56.2 (25.4) a	62.0 (28.0) a	156.0 (49.5) b
	3-12	0.04 (0.02) A	33.3 (16.2) A	17.1 (4.9) AB	17.4 (1.6) AB
Biochar	0-3	0.02 (0.02) a	3.9 (0.5) bc	6.2 (1.1) bc	37.1 (3.5) a
	3-12	0.03 (0.02) A	1.0 (0.1) B	3.1 (0.7) DC	19.2 (0.4) AB
Wood chips	0-3	0.01 (0.01) a	1.2 (0.4) c	1.3 (0.5) c	51.7 (2.4) ac
	3-12	0.02 (0.02) A	0.6 (0.1) B	0.8 (0.2) D	19.3 (0.3) AB
Biosolids + Wood chips	0-3	0.28 (0.03) b	34.4 (10.7) ab	20.3 (5.4) bc	139.0 (12.0) b
	3-12	0.08 (0.08) A	5.6 (8.1) B	12.1(3.7) ABC	19.5 (4.2) AB
Biosolids + Biochar	0-3	0.27 (0.01) b	11.4 (3.0) bc	39.2 (8.2) ab	119.0 (45.6) b
	3-12	0.02 (0.01) A	31.9 (2.1) A	19.5 (6.2) A	8.6 (1.9) B
Biochar + Wood chips	0-3	0.03 (0.01) a	1.04 (0.3) c	2.1 (0.1) c	59.3 (8.4) ac
	3-12	0.03 (0.02) A	0.7 (0.1) B	1.1 (0.2) D	21.4 (1.9) AB
Biosolids + Biochar + Wood chips	0-3	0.19 (0.07) ab	6.37 (2.1) bc	23.0 (8.1) bc	97.7 (28.7) bc
	3-12	0.02 (0.01) A	1.6 (0.2) B	9.3 (1.7) BCD	5.1 (2.5) B

[a] Lower case letters indicate significant differences among soil amendments at the 0-3 cm depth (p≤0.5) using Tukey's multiple comparison test. Capital letters indicate significant differences among soil amendments at the 3-12 cm depth (p≤0.5) using Tukey's multiple comparison test.

Similar to the other measures of N, PMN was highest in the biosolids amended soil. In the biochar and woodchips treatments, along with their combinations, PMN was not statistically different from the control (table 5). However the 3-way combination and biosolids + biochar amendments resulted in a significant decrease in PMN in the subsurface soil.

Resin Capsules

Nutrient data from the *in-situ* ion resin capsules were used to indicate nutrient release into the soil solution within a six month time period (Qian, 1992). Similar to plant roots, concentrations of ions on the resin capsules are dependent on diffusion rates for nutrient capture, and diffusion rates increase with soil moisture (Blank et al., 2007). The highest nutrient concentrations of N, P, K, Ca, and Mg were found in the biosolid plots (table 6), while nutrient recovery on the resin capsules in the biochar and woodchip amended plots were low. The ion resin capsule results have high standard deviations, which reflects the inherent variability present in field settings, and has been documented in previous studies using resin capsules (Gundale and DeLuca, 2006).

Plant Available Water and Soil Moisture

Soil amendment was a significant factor in both the surface and subsurface soils for plant available water (PAW; the difference between field capacity and permanent wilting point) (table 7). Plant available water was significantly greater in the biosolids amended soil in the surface 0-3 cm (table 7). The lowest PAW occurred in the biochar + wood chips plots. In the subsurface soil, the control, single, and

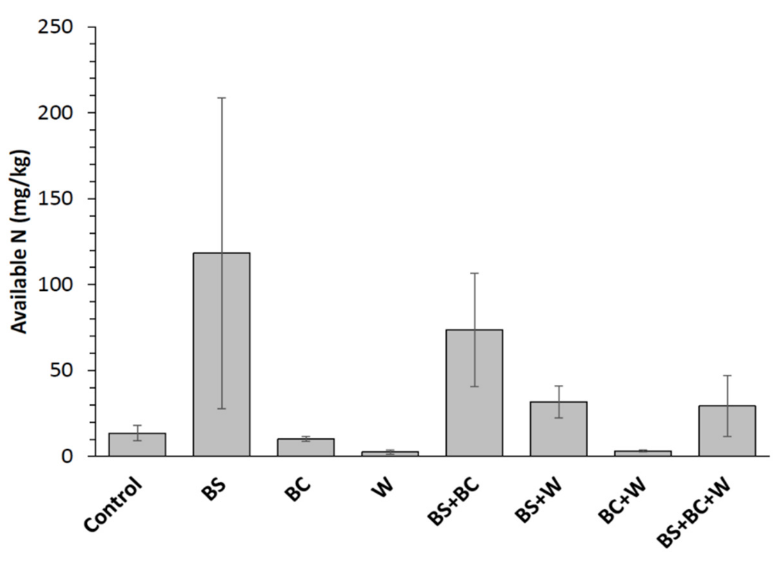

Figure 2. Extractable inorganic nitrogen concentration in the surface (0-3 cm) soil. Error bars indicate standard deviations. Soil amendment treatments are BS- Biosolid, BC-Biochar, W-wood chips and their 2- and 3-way combinations.

Table 6. Mean nutrient recovery (standard deviation) from resin capsules placed in the soils at 10 cm from date to date, n=3.

Treatment	Total Nitrogen (mg/kg/month)[a]	Calcium (mg/kg/month)	Potassium (mg/kg/month)	Magnesium (mg/kg/month)	Phosphorus (mg/kg/month)	Sulphur (mg/kg/month)
Control	0.12 (0.06) b	5.60 (2.13) b	0.84 (0.30) a	2.73 (1.06) c	0.31 (0.05) b	0.67 (0.55) b
Biosolid	19.02 (8.54) a	30.82 (16.39) a	2.58 (2.63) a	12.88 (4.59) a	9.83 (2.62) ab	6.73 (3.66) a
Biochar	0.75 (1.0) b	4.91 (3.22) b	1.83 (2.53) a	2.53 (1.87) c	0.30 (0.31) b	0.68 (0.61) b
Wood chips	0.14 (0.02) b	4.73 (1.19) b	1.07 (0.53) a	2.26 (0.69) c	0.15 (0.15) b	1.19 (0.85) b
Biosolids + biochar	15.95 (6.15) a	18.09 (7.26) b	3.24 (1.11) a	9.17 (2.17) ab	12.03 (4.06) a	1.78 (1.02) b
Biosolids + wood chips	12.52 (2.79) a	15.09 (2.24) b	2.29 (0.55) a	8.01 (1.56) b	4.92 (5.37) ab	2.13 (0.53) b
Biochar + wood chips	0.14 (0.03) b	4.46 (1.56) b	0.86 (0.24) a	2.14 (0.80) c	0.30 (0.22) b	0.33 (0.09) b
Biosolids + biochar + wood chips	15.01 (4.00) a	17.3 (7.44) b	1.82 (1.28) a	9.56 (4.42) ab	8.05 (12.07) ab	3.10 (2.13) b

[a] For each element, different letters indicate significant differences among soil amendments (p≤0.5) using Tukey's multiple comparison test.

Table 7. Plant available water (standard deviation) at each soil depth for all treatments.

Treatment	0-3 cm depth	3-12 cm depth
Control	14.0 (1.4) a[a]	13.2 (0.9) a
Biosolids	16.9 (1.9) b	13.2 (0.3) a
Biochar	15.1 (1.0) ab	13.5 (1.7) a
Wood chips	15.4 (0.1) ab	12.7 (0.9) a
Biosolid + biochar	15.4 (1.1) ab	10.4 (2.1) b
Biosolid + wood chips	15.2 (1.5) ab	10.8 (0.3) b
Biochar + wood chips	13.7 (0.8) a	10.6 (0.6) b
Biosolids + biochar + wood chips	15.9 (1.8) ab	13.6 (1.7) a

[a] Within each soil depth, letters with different letters are significantly different among soil amendments (p≤0.5) using Tukey's multiple comparison test

biosolids + biochar + wood chips amendments had significantly higher PAW than the paired amendment treatments. Average yearly soil moisture measure in situ also indicates that soil under biosolids had more moisture throughout the year (fig. 3). All the other amendments and control plots had lower soil moisture levels. Monthly averages of soil moisture indicate that the control plot had the lowest soil moisture in August whereas the biochar and wood chip plots had the lowest soil moisture in November (fig. 4). The biosolid plots maintained more soil moisture as compared to the other single amendment plots beginning in June and continuing through the rest of the year.

Plot Cover and Plant Survival

The soil amendments were evenly applied on the plots and resulted in 100% ground coverage at year 1. After 2 years, bare ground ranged from 0% (biochar + biosolids + wood chip) to 69% (control). There was less ground cover when biochar and biosolids were applied singly, (bare, 23% and 17%, respectively). Vegetative debris (litter) was slightly greater in the planted side of the plots than in the seeded side (data not shown).

Many of the planted seedlings had been pulled from the ground due to ungulate browsing, which accounted for approximately 30% mortality. In both planted and seeded plots, cover by grasses and forbs was lowest in the control plots (table 8). On the planted side of the plots, forbs were beginning to grow within the planted seedlings, comprising at least ½ of the plant cover on all plots except the control and biosolids + biochar + wood chip. Since one forb species was included in the seed mix, it was expected it to be more prevalent on the seeded rather than on the planted side. In fact, forb presence on the seeded site was equal to or more than the grass cover for all treatments except the single applications of biosolids and biochar indicating that some seed likely was in the seed bank or was blown in since the forbs noted in many plots was not western yarrow. For planted seedlings, survival of California brome was significantly higher in the control, biochar, wood chip and combined biochar + wood chip plots. Jepson's blue wildrye seedlings had significantly higher survival in the biochar and biochar + wood chip plots.

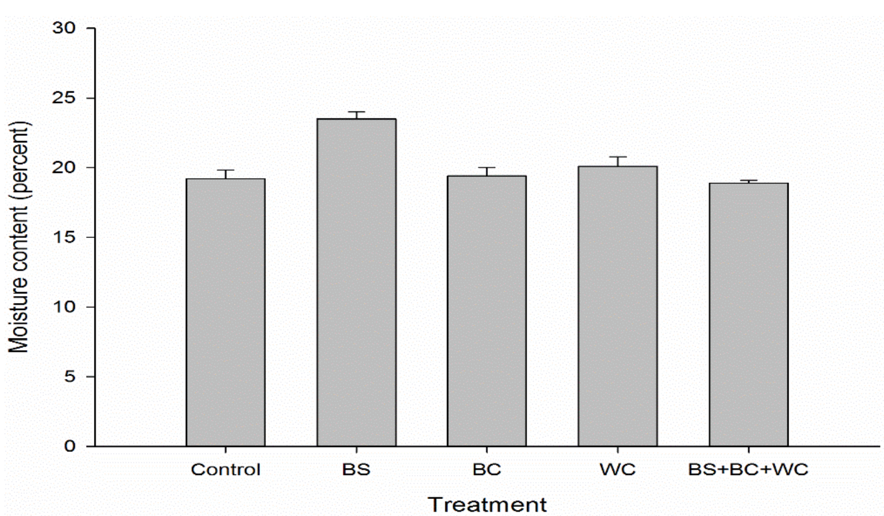

Figure 3. Average annual soil moisture in each soil single soil amendment and three amendment combination. Error bars represent the standard deviation. Soil amendment treatments are BS-Biosolid, BC-Biochar, W-wood chips and the three-way combinations.

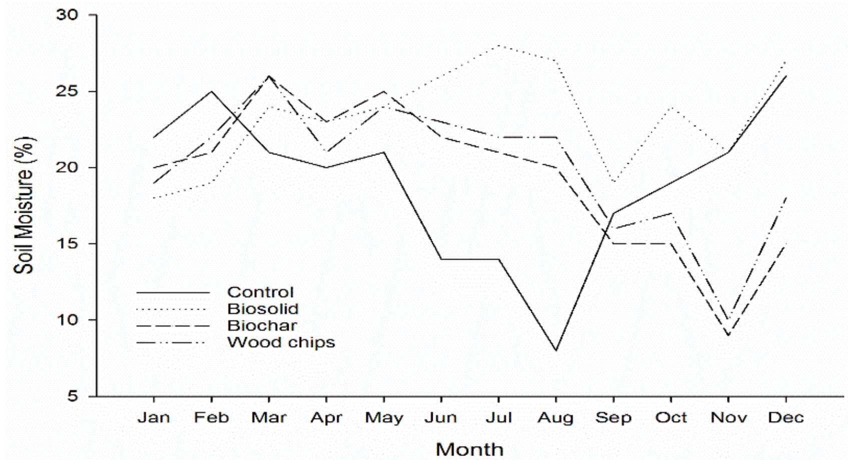

Figure 4. Monthly soil moisture (percent) in the control and single amendment plots.

Discussion

Soil Properties

Mining causes significant land disturbances which often results in areas with little or no vegetation, erosion, or invasion by undesirable weeds for a long period of time (Peltz and Harley, 2016). Using local organic material as amendments can be cost-effective, can mitigate other environmental impacts, such as forest residue slash pile burning and facilitate suitable disposal of biosolids from waste water treatment facilities. These organic materials can be particularly effective on sites with low available water (Fellet et al., 2011). In addition, we expect that over time these amendments will add a significant amount of C to the surface mineral soil.

Often soil acidity is the largest problem to remediate at AML, and several studies have shown soil pH generally increases after biochar amendment (Fellet et al., 2011; Hardie et al., 2014). However, Mukherjee et al. (2014) conducted a two-year study with 0.5% biochar by weight as a soil amendment and observed no significant increase in soil pH. In addition, Kelly et al. (2014) conducted a 65-day column study on hardrock mine tailings with biochar application rates of 10%, 20%, and 30% biochar by weight; the maximum change in pH was observed in the 30% application rate, but was only a 0.3 pH unit increase. The pH of the biosolids was 6.4 while the biochar was 7.2, while the control soil pH was only 5.5, thus the amendment caused a slight increase in pH by the end of the second growing season. However, when biosolids were combined with wood chips, soil pH went down. This is likely from soluble organic chemicals in the wood which leaches into the soil and buffered the pH change (Larney et al., 2008). Over time, exchangeable acidity and buffering capacities of soils is expected to cause the pH of amended soils to return to its original value. Nutrient uptake by plant roots also contributes to pH buffering because as the roots absorb cation nutrients, they release protons to maintain electrical neutrality, thereby decreasing the surrounding soil pH (Hedley et al., 1982; Marschner, 1995).

Electrical conductivity is one indicator of changes in soil physical and chemical properties such as salinity, CEC, pore space, and soil moisture content. In our amended plots, EC was affected by both biosolids and biochar amendments. Agricultural land application of biosolids has increased in the last several decades (Goldstein and Steuteville, 1996), but it is rarely used to amend forest soils or mine sites. After two years on the soil surface, the biosolid amendment plots had the highest EC as compared to the other treatments. This was likely caused by the addition of soluble salts in the biosolids amendments. Sidhu et al. (2016) found similar increases in EC from applying biosolids to copper mine tailings at application rates of 2.5%, 5%, 10%, and 20% of the dry weight, where maximum EC occurred in the 20% amendment rate. In contrast, biochar plots had the lowest EC values, which may be a result of adsorption of soluble salts on the charged surface. Contrary to this study, Fellet et al. (2011; 2014) noted that biochar increased EC in proportion to increasing application rates of 1%, 5%, and 10% by dry weight in the laboratory. It has been noted that biochar can also have a neutral effect on EC in field studies (Mukherjee et al., 2014).

Table 8. Overall average grass and forb cover (standard deviation) in planted and seeded plots and two year survival of California brome and Jepson's blue wildrye in each treatment.

Treatment	Cover (%)		Survival (%)	
	Planted	Seeded	California Brome	Jepson's Blue Wildrye
Control	8 (1) c	9 (2) b	28 (4) a	18 (7) ab
Biosolid	29 (3) a	17 (2) ab	13 (4) ab	17 (6) ab
Biochar	14 (2) b	12 (3) ab	24 (4) a	24 (4) a
Wood chips	10 (1) b	17 (2) ab	26 (5) a	18 (7) ab
Biosolid + wood chips	21 (2) ab	28 (2) a	12 (2) ab	18 (1) ab
Biosolid + biochar	10 (2) b	18 (3) ab	7 (5) c	12 (3) b
Biochar + wood chips	9 (2) b	13 (3) ab	26 (2) a	24 (4) a
Biosolid + biochar + wood chip	31 (2) a	27 (2) a	14 (3) ab	12 (2) b

[a] Within each column, letters with different letters are significantly different among soil amendments ($p \leq 0.5$) using Tukey's multiple comparison test.

An important soil property for reclamation of disturbed soils is C content. Since amendments in this study were only applied once, treatments that sustained elevated C over time would be beneficial for improving soil properties, which would subsequently improve water holding capacity and plant cover. After 2 years, all treatments containing biosolids had similar total C amounts, but all amended plots had higher C as compared to the control, indicating that all of the soil amendments would be useful for increasing soil C.

Biosolid materials are small and can be readily decomposed because of their large available surface area, whereas the woodchips and biochar are more durable and have larger particle sizes. Biosolids have a C:N ratio of approximately 14-40 (depending on the source material; Wu et al., 2000), which is much lower than the wood chips (392) or biochar (342; Anderson et al., 2013). The biosolids contained 55,000 mg/kg N, which continued to provide N, as indicated with the ion resin capsules, through the second growing season. In fact, compared to the initial total N values (0.01%), all post-amendment N concentrations were higher (table 6).

Nutrient Availability

Biosolids significantly increased plant available N and P. The biosolids applied were 5.5% N by weight. At the biosolids amendment application rate of 17 Mg/ha, 920 kg of total N were applied per ha or 0.9 kg-N/plot. Ninety-seven percent of the total N was organic-N, requiring mineralization for plant use, and three percent, equaling 11.22 kg N, was plant available at the time of application (table 5). California brome and Jepson's blue wildrye have fertilization requirements of 34 to 55 kg of N/ha and 22 to 33 kg of N/ha, respectively, when planted on infertile soils (USDA, 2012; USDA-NRCS, 2013). The immediately available-N portion of the biosolids at the time of application met nearly all N requirements for growth. During the growing season, as plants uptake nutrients for new growth, soil N decreases (Schroth and Sinclair, 2003). The loss of total-N and available-N may be attributed to the large amount of plant cover (uptake), as well as possible nitrate-N leaching or N use by soil organisms.

The original biosolids contain 3.03% total P by weight. Unlike N, which is mobile in soils, P is less available, remaining in the soil through a wet season (Stevenson, 1986). In previous biosolid application studies, available P remained in the surface soil (0-10 cm; Maguire et al., 2000; Shober et al., 2003; Sidhu et al., 2016). In addition, Maguire et al. (2000) found at 11 different test sites of varying application rates, iron and aluminum-bound P was the dominant form of P below 10 cm, which caused decreased plant available-P. Shober et al. (2003) found no increase in available P below 10 cm after up to 18 years of annual biosolid application (53.71 Mg/ha). In the present study, the ion resin capsules were located at a depth of 10 cm, meaning that all increases seen in biosolid treatments represented the soil at that depth, thus suggesting vertical movement of available-P at this study site, which could be attributed to the skeletal nature of the soil.

The lack of significant effects of biochar on nutrient enhancement is consistent with other biochar field studies. Kelly et al. (2014) found no increase in P for biochar at any application rate. However, we show that in combination plots of biochar with biosolids, nutrients were released and we had higher concentrations of all measured nutrients (N, P, K, Ca, and Mg) than biochar alone (table 6). The rate of application of biosolids was the same in the single and mixed treatments, so the rate of nutrient release from biosolid alone and biochar + biosolids should be similar. Although available nutrient concentrations were higher in the biochar + biosolid treatment than in biochar alone, they were still lower than biosolids alone. This could be indicative of adsorption of nutrients from solution to biochar surfaces, which are then available to plants through diffusion.

Available Water and Soil Moisture

In the surface 0-3 cm soil, all amendments raised the level of PAW as compared to the control. Soil amendments may have differing effects on PAW, depending on soil and site conditions (Struebel et al., 2011). For example, Hardie et al. (2014) incorporated 47 Mg/ha of biochar in a field study, and reported no significant effects on soil water retention. However Mukherjee et al. (2014) found that in a 1-year field study on a silt loam amended at a rate of 7.5 Mg/ha oak wood biochar, PAW increased by 63%. Any increases in PAW on AMLs sites will likely help improve revegetation since many of these sites have skeletal soils or pulverized rock. In an agricultural study in southern Finland, biochar increased available soil water by 11% (Karhu et al., 2011). In our plots we saw an increase of PAW in the surface 0-3 cm of 8% to 12%, depending on the amendment. Only the biosolid plots had significantly higher PAW as compared to the other amended plots and the control. In addition, we detected a significant decrease in PAW deeper in the soil profile. This decline in available water deeper in the profile may be attributed to water being absorbed by the amendments higher in the profile.

All soil amendments were very dry when applied to the plots, but with spring moisture they gained and retained more moisture throughout the growing season as compared to the control (fig. 4). The biochar did not exhibit hydrophobicity as noted by Page-Dumroese et al. (2015) likely because of the range of particle sizes. We expected that wood chips would act as a barrier to evaporation in this dry environment and the monthly data shows a similar soil moisture trend as compared to the biochar amended plots. As with the yearly average data (fig. 3), biosolids retained more soil moisture than the other plots. Biosolids have been shown to increase water retention properties, particularly on coarse-textured soils (Gardner et al., 2010) Soil water storage is often limiting for native vegetation and crops in the Inland Northwest (Novak et al., 2012; Page-Dumroese et al., 2017) and biochar has been noted as one method to improve soil physical conditions and water retention (Glaser et al., 2002). Biochar has been shown to modify soil pore size distribution and may provide a long-term benefit on degraded soils (Novak et al., 2012). We noted in our fall sampling that plants in the all amended plots remained green into September indicating that water was still available on these plots after the control plot vegetation had dried.

Planted Seedling Survival and Soil Cover

Soil amendments increased soil cover and seedling production. Since PAW was increased by soil amendment, this may be a likely reason for more cover. Schoenholtz et al. (1992) measured PAW and tree growth after wood chip application on mine soils and found that they were directly related to better survival and growth because of increased water. In the current study, grass plugs planted on biochar or biochar + wood chips amendments had the greatest survival. However, survival of planted grasses was low overall and may be attributed to the small size of the plugs at outplanting (a 25-mL root plug) and elk and deer easily pulling up the grass. However, the small root plug was used because soil depth was limited and made planting relatively easy in this rocky soil. Soil pH was altered by soil amendments, but there was not clear trend in relation to overall soil cover or planted seedling success. The rates of the amendments both singly and in combination were effective in covering the study areas. The larger size of the wood chips and the biochar led to more spotty application and more exposed mineral soil than the finer amendments, which were distributed more evenly. While the seeded side of the plots had slightly more mean plant cover, the planted side had more organic input in the form of dead plant material. For the development of soils, the continued addition of organic material should be a consideration when choosing plantings over seeding for revegetating AML. Biochar applications can have a high level of heterogeneity which subsequently affect both soil properties and seedling response (Olmo et al., 2016). Our plots were relatively small and all soil amendments were applied in homogeneous layers. However, as this work moves from plot to larger-scale restoration activities, the heterogeneity of application should be assessed.

Conclusions

This study reports on the 2-year results of surface application of organic soil amendments to non-vegetated dredged tailings with a loam soil cap on the Umatilla National Forest. Soil amendments were easy to apply, but when adding combinations of amendments it would be better to mix them together prior to application to reduce wind erosion of small biochar particles. Similarly, on areas with adequate soil depth and without rocky subsoil, amendments could be mixed into the surface horizons. We used Class A biosolids for this study because of the proximity to water, however in areas without nearby water, Class B biosolids could be used.

All soil amendments increased total ground cover and plant cover in both the planted and seeded sides of the plots. Many forbs and native grasses were becoming established within the planted seedlings plots and, after two years, the seeded side of the plot was also gaining more cover. Biochar and biochar + wood chips and the control plots had more California brome and Jepson's wildrye survival than the other plots, some of this was likely due to greater PAW, but in the control plots we are unsure why survival was greater than some of the soil amendment plots. We speculate that wood chips or other amendments may have been mixed into the planting hole preventing proper root-soil contact. This may be one reason, but there could be other amendment-related mortality that we did not account for in our study. Increased overall plant cover in all of the amended plots confirm that single or multiple amendments will help restore soil function on AMLs with a soil cap. Other research should evaluate the success of organic amendments on un-capped dredge material.

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