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Soil amendments improve vegetation establishment and evapotranspiration on store and release mine cover systems

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Abstract

Design and construction of mine cover systems in cold regions can often be challenging due to limited availability of appropriate cover materials and harsh climate conditions. Balancing vegetation establishment soil moisture requirements while limiting water ingress into mine rock is one such challenge. Here we examined the effects of surface amendment applications on the establishment of mine cover system vegetation and ecohydrological functions for a low organic content clay-loam soil sourced from an eastern Canadian mine site. Surface amendments manufactured by Profile Products LLC which combines a biotic soil technology, and a flexible erosion resistant growth medium were tested. The amendment's effects on vegetation establishment, infiltration, percolation rates, and evapotranspiration (ET) were assessed. Testing occurred at the Multi-purpose Slope Testing (MOST) Facility at the University of Saskatchewan using four constructed cover systems. Two contained amended covers and two contained unamended control covers, all seeded with herbaceous vegetation local to the southern Ontario, Canada region of interest. Controlled experiments were conducted on the covers over three 4-month long growing seasons. A humid-continental (Dfa/Dfb) climate regime (Koppen-Geiger classification) was simulated, with precipitation inputs of 365 mm per season and growing season average temperatures between 17.5 and 25.9 °C.

Results showed that the amended covers had faster rates of vegetation establishment, higher canopy coverage, and greater total above-ground biomass production. Amended slope vegetation reached more developed growth stages weeks ahead of the control covers, with some species emerging 37 days in advance of those on control covers. Canopy coverage on the amended covers were between 34 – 48% higher during the critical first establishment season. Over three seasons, the control cover's canopy coverage did not attain levels observed on amended covers. Total above-ground biomass production was 2,404 – 2,676 kg/Ha higher on the amended covers. Likely owing to higher vegetation density and surface coverage the amended covers had relatively higher rates of ET: between 21 – 136 mm more per season. Accordingly, 11 – 13 % less percolation into the underlying mine rock was observed. Results suggest that these soil amendments could be a useful way to rapidly stabilize cover systems, improve ET rates, and limit percolation through improved growing conditions on mined land cover systems composed of poor-quality materials.

Keywords: *mine cover systems, surface amendments, land reclamation, vegetation establishment, ecohydrology, net percolation, evapotranspiration*

1 Introduction

Earthen cover systems are often used for the closure of mine waste storage facilities such as tailing storage impoundments, mine rock stockpiles, and spent heap leach pads. These earthen cover systems are designed with specific goals such as dust and erosion control, limiting oxygen and or water ingress to mine rock, and restoration of the disturbed surface to a stable landform suitable for other purposes such as grazing, recreation, or natural habitat (Lamoureux 2012). Mine rock cover systems are designed to limit or eliminate the influx of atmospheric water into mine rock piles in addition to allowing for establishment of sustainable vegetation, and other goals (O'Kane 2012, INAP 2017, Ayres 2013). Store and release (SR) covers limit water ingress into mine rock layers through storage of water in the cover's upper rooting zone, which is subsequently returned to the atmosphere via evapotranspiration (ET) (INAP 2017).

Climate regime, weather patterns, and landform design play an interrelated role in determining the effectiveness of SR covers at limiting net percolation (NP). SR cover systems perform best in climates where ET is higher than precipitation (i.e., arid climates), where the occurrence of precipitation is irregular (i.e., regions without extended rainy seasons), and in regions with consistent high temperatures. Cover system soil properties control a cover's water storage capacity, and combined with antecedent wetness conditions, influences the generation of infiltration-excess overland flow (i.e., precipitation exceeds infiltration capacity) or saturation-excess overland flow. Additionally, design choices such as the inclusion of sloped sections and drainage also impact rates of infiltration, lateral flows, types of surface runoff, and thus NP from SR covers. The interrelated effects of climate, soil properties, weather, and landform design are thoroughly discussed in the International Network for Acid Prevention (INAP) Global Cover System Design Technical Guidance Document (INAP 2017). While not the optimal solution for all regions and mine rock pile types, SR covers can offer advantages in cost savings over other cover system designs (Madalinski 2003, Smith 2013).

There are however challenges related to implementation of SR cover systems in cold regions, such as the cost and difficulty of establishing vegetation, due to often poor-quality local cover soil materials. This, combined with short harsh growing seasons and spring snowmelt volumes, makes cover system erosion a major issue resulting in costly repairs and other negative effects related to mine rock and/or tailings exposure. Furthermore, in climates where precipitation exceeds ET, NP through the cover system into the mine rock layer can be associated with negative downstream effects such as Acid and Metalliferous Drainage (AMD) which can result in long-term closure liability for mine operators to manage. Products that improve cover system geochemical and geotechnical stability through enhanced vegetation growth and increased ET rates are therefore of interest to the mine cover system design community.

This research tests the effectiveness of one such product, the Proganics™ surface amendment system designed by Profile Products LLC (Buffalo Grove, IL, USA). Specifically, we quantify the ecohydrological functions of a set of lab-simulated SR mine cover systems over three successive 4-month long growing seasons. The cover materials used in this research are composed of a clay-loam soil from an eastern Canadian mine site. Four simulated mine cover systems are examined in this research. Two of the covers are amended and two are non-amended controls. Below, we detail the findings of this research as it pertains to cover revegetation rates, long term vegetation responses, and ecohydrological fluxes such as NP and ET. This research is the 3rd phase of testing investigating Profile Products amendment systems at the MOST (Multi-purpose Slope Testing) facility. This phase of research tested the following null hypotheses. 1) The amendments will have no effect on the vegetation health metrics when compared to the non-amended cover systems. 2) The amendments will have no effect on ET rates from the covers when compared to the non-amended cover systems. 3) The amendments will have no effect on NP rates through the cover systems when compared to the non-amended cover systems.

Results showed that the amended covers had faster rates of vegetation establishment, higher canopy coverage, and greater total above-ground biomass production than the non-amended controls. The amended covers had relatively higher rates of ET: between 21 – 136 mm more per season, which we attribute to higher vegetation density. Accordingly, 11 – 13% less percolation into the underlying mine rock was observed. Results suggest that these soil amendments could be a useful tool for rapidly stabilizing mine covers, improving ET rates, and thereby limiting percolation by providing improved growing conditions on mined land cover systems otherwise composed of poor-quality materials.

2 Methodology

2.1 Simulated mine cover structure

The research took place indoors at the MOST facility (University of Saskatchewan, SK, Canada) from February 2021 to February 2022. The four simulated cover systems were assigned the following IDs: A40 and A30 for amended covers 1 and 2 respectively, and NA40 and NA30 for the non-amended controls 1 and 2, respectively. NA40 is a paired control for A40, as NA30 is for A30. The covers were built within individual tilting trays, which had inner dimensions of 0.63 m (W) x 1.78 m (L) x 0.45 m (D), a surface area of 1.12 m^2, and allowed for slope angle control. The covers were set at slope angles of 33% (3:1) to represent the sloped edges of real mine rock cover systems. At the base of each cover, 2.5 to 3.8 cm clast size gravel was applied at a 5 cm depth to simulate mine rock and to allow for drainage from the research apparatuses (composition: 88.3% gravel, 11.7% sand). Overtop of the rock layer we applied a cover soil sourced from an eastern Canadian mine site in two lifts. For covers A40 and NA40 each lift depth was 20 cm (total cover depth 40 cm), and for A30 and NA30 each lift was 15 cm (total cover depth 30 cm). Cover depths of 40 cm and 30 cm were selected based on the available capacity of the tilting tray apparatuses, and due to an additional hypothesis related to minimum cover thickness required to maintain vegetation health, the findings of which are not discussed in this paper. After filling, each lift was boot packed to a bulk density of 1.6 g/cm^3 (n = 8, standard deviation (sd) = 0.08 g/cm^3). The clay loam cover soil had the following particle size distribution: sand: 43.1% sd: 7.0%, silt: 25.0% sd: 10.1%, clay: 32.0% sd: 7.9% (n = 25). The surface of all four covers had simulated cat tracking applied, prior to amendment application.

2.2 Amendments and vegetation

This research utilized the Profile Products amendment systems Proganics DUAL, Jumpstart®, and Bioprime®. ProGanics DUAL contains bark and wood fibres that have been phyto-sanitized to eliminate potential weed seeds and pathogens. After phyto-sanitization, a proprietary blend of cross-linked, high-viscosity colloidal polysaccharide biopolymers, biochar, seaweed extract, humic acid, endomycorrhizae, beneficial bacteria (11% total) are then added. The resulting ProGanics DUAL formulation is designed to achieve Bonded Fiber Matrix (BFM) erosion control performance while acting to regenerate denuded soils and promote vegetative establishment. JumpStart is a Fast-Acting bio-stimulant liquid formulation that contains a soil penetration agent (20%), humic acid (1.5%) and over 200 species of beneficial soil bacteria including: *Bacillus licheniformis, Bacillus sonorensis, Bacillus thioparans, Brevibacillus limnophilus, Paenibacillus lentus and Paenibacillus puldeungensis.* BioPrime has a guaranteed nutritive analysis of 18-0-0 (N-P-K), its four active ingredients include slow-release Nitrogen, seaweed extract (1%), humic acid (1%), and endo mycorrhizae

(1%) (*Glomus intradices, Glomus aggregatum and Glomus mosseae).* The amendments, fertilizer, and seed mix, are combined within a hydroseeder, and applied to the surfaces of A40 and A30 to a thickness of 1.5 to 2.5 cm. The hydroseeder mix utilized the following product application rates: Proganics DUAL: 6164.7 kg/Ha; Jumpstart: 23.4 L/Ha; Bioprime: 89.7 kg/Ha; 18-24-12 fertilizer: 112.1 kg/Ha; seed mix: 84.1 kg/Ha. The fertilizer was a generic slow-release nitrogen 18-24-12 (N-P-K) fertilizer. Hydroseeding rates are typically doubled, relative to broadcast techniques, however, to improve comparability between groups, the non-amended covers received the same seed and fertilizer application rate as the amended covers (fertilizer: 112.1 kg/Ha; seed mix: 84.1 kg/Ha). Seed and fertilizer were hand broadcast onto the cat tracked surfaces of the non-amended covers (NA40 and NA30).

The seed mix was a native grass mix representative of local vegetation from our region of interest in southern Ontario, Canada with the following composition (by weight): 22% Slender Wheatgrass (*Elymus trachycaulus*), 15% Canada Wild Rye (*Elymus canadensis*), 14% Fringed Bromegrass (*Bromus ciliatus L*), 11% Big Bluestem (*Andropogon gerardii*), 10% Boreal Creeping Red Fescue (*Festuca rubra*), 10% Nanook Hard Fescue (*Festuca trachyphylla)*, 8% Huia White Clover (*Trifolium repens*), 6% Canada Bluegrass (*Poa compressa*), 4% Fowl Bluegrass (*Poa palustris*). Excluding Big Bluestem, the grasses are cool season species, having the highest growth rates during the cool spring period, followed by a decline in growth rates during summer, and a secondary growth rate peak during fall anthesis. Warm season grasses (i.e., Big Bluestem) see a single peak in growth rates during the warm summer period, declining in fall. Legumes (i.e., Huia White Clover) have a uniform, continuous growth rate through the growing season.

2.3 Simulated climate conditions

We simulated a humid continental DFa/ DFb climate (Koppen-Geiger system) based on historical records from our region of interest, wherein the growing season is typically May 15th to September 15th. For the purposes of this research, we simulated three successive four month long growing seasons representing May to August conditions. We excluded simulation of winter freeze-thaw periods between growing seasons to accelerate potential nutrient depletion effects on the health of the vegetation. Though this experiment took place over a continuous real-world year, we hereafter omit the term *simulated* when referring to the simulated experiment months: May, June, July, and August. We refer to each growing season (GS) by their number (i.e., GS1, GS2, GS3). All liquid precipitation inputs were applied by hand over one-hour intervals using masses of water as determined from the surface area of the covers and the desired mm/ hour event intensity. For each growing season, total precipitation per cover was 364.5 mm (408.8 L). Monthly total precipitation inputs per cover were consistent across each growing season and were as follows, May: 72.1 mm; June: 109.7 mm; July: 93.5 mm; August: 89.2 mm. May to August air temperatures averaged between 17.5 °C to 25.9 °C, with extremes of 10.4 °C (low) and 40.9 °C (high). May to August soil temperatures averaged between 15.6 °C to 24.4 °C with extremes of 12.2 °C (low) and 28.2 °C (high). Daylight was generated with full-spectrum LED grow lights and was applied for 15 hr/ day (May), 16 hr/ day (June), 16 hr/day (July) and 14 hr/day (August). During the experiment, relative humidity levels were between 15 – 20% in GS1, 20 – 24% in GS2, and 14 – 40% in GS3, whereas humidity levels in our region of interest are typically between 69 – 75% during May-August. Average temperatures in the lab during the experiment were between 1.8 – 11 °C higher than averages from our region of interest. These climate conditions may have resulted in slightly higher than expected ET rates from all covers.

2.4 Instrumentation, data collection, vegetation assessments

2.4.1 Climate and hydrological data

A Lufft WS600-UMB (Fellbach, Germany) weather station measured indoor climate conditions. In this phase of testing, we were interested in potential differences in net percolation (NP) responses between the amended and non-amended covers and as such all covers used runoff control barriers which had closed ends at the toe end of the covers to prevent surface runoff. Liquid percolation through each cover system was collected via ports at the toe-end base of each tilting tray and was assessed after and immediately preceding each precipitation event. Precipitation input masses (convertible to mm inputs) were recorded for each event. Soil volumetric water contents (VWC) (in m^3 water/m^3 soil) were measured at four locations per cover and logged on 15-min intervals for the duration of this experiment using METER (Pullman WA, USA) 5TM soil moisture and temperature probes. Each cover had two lines of 5TM probes, with two probes per line, and a line each in the upslope and downslope regions. Each line was located 0.36 m away from the up and down slope container edges with the individual probes located at the following depths: 0.20 m and 0.35 m from the container base (A40 and NA40), and 0.15 m and 0.25 m from the container base (A30 and NA30).

Evapotranspiration (ET) is the sum of water transpired from within vegetation and the evaporation of free water from the surface upon which vegetation grows. ET rates from the cover systems were calculated with a water balance equation (Equation 1) utilizing the following collected data: percolation discharge (Qb), precipitation (P), and change in storage (δS).

$$ET = P - Qb - \delta S \qquad (1)$$

where:

ET	=	evapotranspiration for a discrete period (in mm)
P	=	precipitation input for a discrete period (in mm)
Qb	=	percolation discharge for a discrete period (in mm)
δS	=	change in storage for a discrete period (in mm)

Water storage is an estimation of the volume of water contained within the cover system at a given time. To determine storage (S) data for the cover systems we calculated S for each probe from VWC data and the thickness of discrete sections of the soil profile centred around each probe. We then add the S values for each probe in a given sensor line (upslope and downslope regions), then average the S values for the two sensors lines to get an S value for the entire cover at a given point in time. Change in storage over a given period (δS) is calculated from two S values at discrete time slices.

2.4.2 Vegetation development and coverage metrics

Vegetation establishment assessments were made from daily and weekly photographs and in-lab observations. Fractional green canopy coverage (FGCC) was assessed from collected bi-weekly plan view photographs analysed via the Canopeo software (Patrignani 2015). Bi-weekly vegetation density counts were collected from each cover at non-repeating, randomly selected locations using a 40 cm^2 sampling hoop and by counting individual plants present in that hoop. Those counts were discontinued after week 24 in mid-June, GS2, at which point vegetation density was high enough on the amended covers that discerning individual plants was no longer feasible. Vegetation heights were collected from 20 randomly selected individuals per cover at bi-weekly intervals. Total above-ground biomass (TAB) production was assessed at the end of the third growing season wherein all vegetation on all covers was trimmed off, dried, and weighed.

Any abscission of vegetation off the covers over the course of the experiment was collected, dried, and weighed and included in the final TAB tallies.

2.4.3 Statistical analyses

We applied two tailed t-tests to the vegetation health metric data: plant density counts, height measurements, and FGCC at significance levels of $\alpha = 0.05$ to determine if these data were statistically different between cover pairs A40 – NA40, and A30 – NA30, and to assess if the applied amendments impacted those metrics. Pearson correlation coefficient analyses were carried out for each cover utilizing all three seasons' data and comparing FGCC (%) against ET rates (mm) to assess if vegetation coverage was correlated with ET rates. ET was summed for each period over which FGCC data was collected resulting in $n = 27$ ordered pairs per cover. Additionally, t-scores and p-values were calculated for each correlation coefficient (r) at significance levels of $\alpha = 0.05$ to determine if the correlation relationships were statistically significant.

3 Results

3.1 Vegetation health data

3.1.1 Vegetation emergence and initial establishment

For the amended covers, emergence of clover and grasses occurred six and seven days, respectively, after application of the amendments, seed, and fertilizer. For NA40 a single grass seedling emerged eight days after seeding, and for NA30 grass seedling emergence occurred nine days after seeding. Emergence on the non-amended covers occurred only in cracks formed along the cat track lines, whereas vegetation emerged with more even distribution on the amended covers. Clover emergence did not occur on NA40 and NA30 until 37 days after seeding (mid-June GS1). For all covers, emergence was initially concentrated in the downslope regions. During the first individual plant density count, occurring 11 days after seeding, there were 36 (A40) and 58 (A30) individual seedlings present in the sampling hoop. Conversely, there were 5 (NA40) and 0 (NA30) individual plants counted for the non-amended covers at that location. By the end of May GS1 (week 4), FGCC was at 12.8 % for A40 and 17.9% for A30 while only at 0.4% on NA40 and 0.3% on NA30. At that time the seedlings on the amended covers had average heights of 18.4 cm, sd: 7.2 cm (A40) and 18.0 cm, sd: 8.0 cm (A30) (n = 20/ cover); and were at the two and three leaf developmental stages. Whereas seedlings on NA40 and NA30 were present only in surface cracks and had average heights of 9.0 cm, sd: 4.9 cm (NA40) and 7.8 cm, sd: 2.9 cm (NA30) (n = 20/ cover); and were at the one and two leaf developmental stages. Vegetation emerged faster, reached further developmental stages more rapidly, and had greater surface coverage on the amended covers.

3.1.2 Vegetation density counts

Vegetation density counts occurred bi-weekly during experiment weeks 2 to 24 at non-repeating randomly selected locations. For all assessed weeks A40 and A30 had higher counts than their non-amended controls (Table 1). A40 had between 27 – 77 more individual plants per sampling square relative to NA40, depending on week of sampling. A30 had between 35 – 99 more individual plants per sampling square relative to NA30, depending on week of sampling. The amended cover's density data were significantly different from their non-amended controls with p-values of $1.2e^{-6}$ (A40 vs NA40), and $1.3e^{-9}$ (A30 vs NA30) ($\alpha = 0.05$). We attribute the higher vegetation density on A40 and A30 to the effects of the amendments, all other things being equal.

3.1.3 Vegetation height assessments

3.1.3.1 A40 vs NA40 height data

During GS1 and GS2 all grasses growing on the cover systems were eligible for height measurement, while during GS3, only newly growing grasses were measured (Table 1). Across all growing seasons the average heights of grasses were greater on A40 than on NA40. In GS1, A40 average grass heights were between 2.4 – 13.4 cm taller than those in NA40. During GS2, A40 average grass heights were between 3.0 – 15.8 cm taller than those of NA40. Differences between the average grass heights of A40 and NA40 were largest during GS3 with A40 average heights being 12.0 – 19.2 cm taller than those in NA40. While there was notable overlap in the height ranges between A40 and NA40, A40's vegetation was consistently taller than NA40's, during GS3; the upper bounds of the grass heights in NA40 were consistently lower than the average heights of A40 grasses (Figure 1).

Over GS1 A40's grass heights were significantly different than NA40's for the first five assessments ($p<0.05$, $n = 20$ ordered pairs per sampling event,). We attribute this rapid development and the enhanced heights of A40's vegetation to the effects of the amendments. Thereafter, NA40 vegetation heights became similar to A40's, and height data sets were not significantly different through the rest of GS1's remaining three assessment events. In GS2, 6 of 9 assessment events had statistically similar grass heights between A40 and NA40, and 3 of 9 had significantly different grass heights ($p<0.05$). During GS3 when we began measuring only new growth again, all nine assessment events saw significantly different grass heights between A40 and NA40 ($p<0.05$).

3.1.3.2 A30 vs NA30 height data

Height differences between A30 and NA30 weren't as notable as in the 40 cm covers and during some periods the non-amended cover had taller grasses likely due to colonization of A30 by clover, which outcompeted grasses and stunted their growth. Conversely the clover in NA30 only colonized the lower 1/3 of the cover, leaving the grasses in the upper 2/3 to grow without competition thereby allowing for taller grasses. Generally, A30 had taller grasses than NA30 during weeks (W) 1 to 10 and marginally taller grasses during GS3 (W38 to W54), but NA30 had taller grasses during GS2. During GS1, until W12, A30 average grass heights were 1.2 to 16.5 cm taller than those of NA30. From GS1 W14 to GS2 W36, NA30 average grass heights were 1.1 to 11.6 cm taller than those of A30. Finally, during GS3 from W38-W54, A30 grass heights were only marginally taller than those of NA30 at 1.0 to 6.5 cm taller (Figure 1, Table 1).

For the first 4 of 8 assessment events in GS1 A30's initial vegetation heights data were significantly different from NA30's ($p<0.05$). We again attribute these initially enhanced height differences to the effects of the amendments. However, a side effect of the amendments improved growing conditions, and the use of clover in the seed mix was that clover quickly became the dominant vegetation on A30. As noted above it outcompeted the grasses in A30 beginning around week 6 after which grass heights remained stunted on A30. These effects were apparent in the height data's statistical intercomparisons: beginning at GS1 assessment event 5 and continuing to the start of GS3, grass heights were not significantly different between A30 and NA30 ($p > 0.05$). In GS3 only 3 of 9 assessment events saw statistically different heights between A30 and NA30. We attribute the lack of statistical difference in grass heights to the dominating effect of clover colonization in A30.

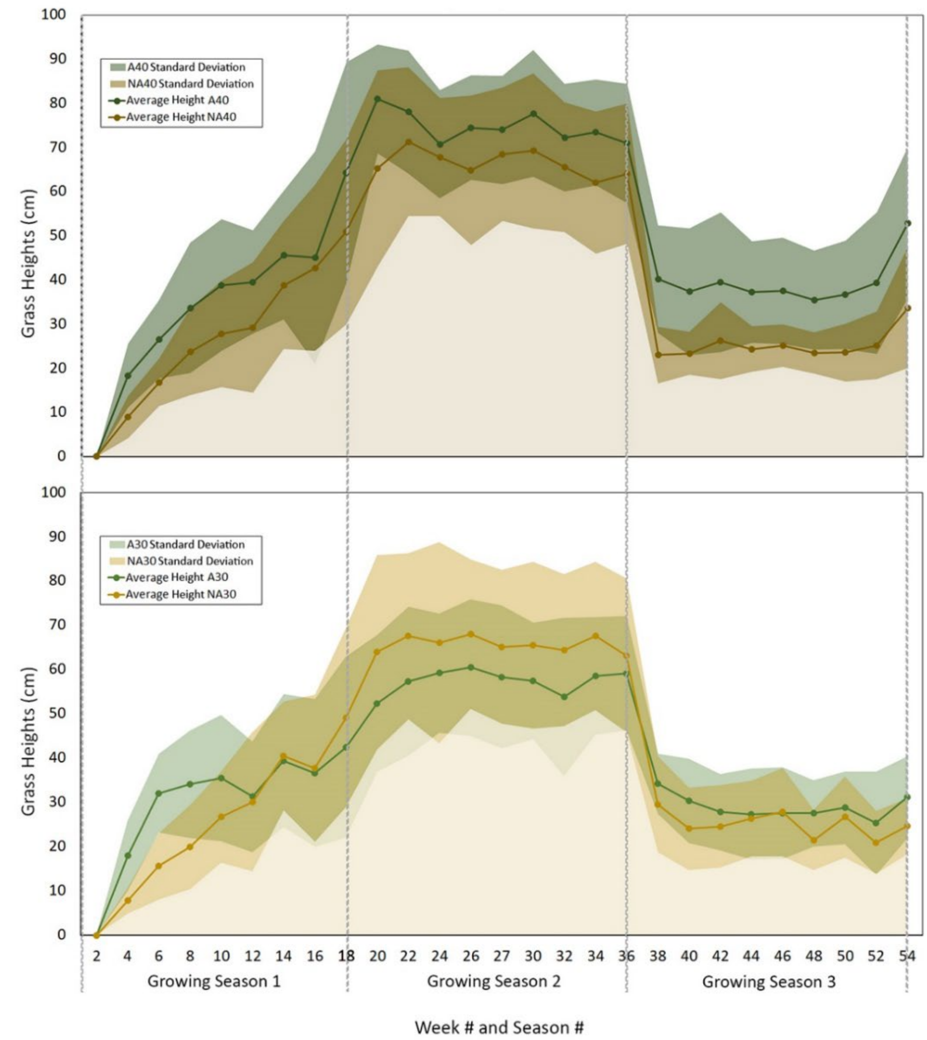

Figure 1 Average grass heights from the test covers over the three growing seasons. During GS1 and GS2 all grasses were eligible for measurement whereas in GS3 only new grasses were measured. The dotted lines are the average grass heights from n = 20 randomly selected grasses/ cover. The shaded bars represent standard deviation ranges for the data collected during each evaluation.

3.1.4 Fractional green canopy coverage

Across all three growing seasons FGCC was higher on the amended covers than on the non-amended covers. At no point during the experiment did the FGCC on the non-amended covers surpass those on the amended covers. Generally, the amended covers had rapid increases in FGCC to peaks around 82% at the end of GS1. Thereafter, during GS2 and GS3 A40 and A30 had some fluctuations in FGCC but maintained average FGCCs of 78% (A40) and 84% (A30) and ended the trial at FGCC peaks of 91% (A40) and 94% (A30) (Table 1, Figure 2). Conversely, in GS1, the non-amended covers saw more gradually rises in coverage to lower peaks of 48% (NA40) and 34% (NA30) by the end of that season. Both covers then experienced FGCC declines until the midpoint of GS2 with coverage lows of 8% (NA40) and 23% (NA40). Subsequently, FGCC on the non-amended covers increased to trial peaks of 64% (NA40) and 77% (NA30) at the end of GS3.

During GS1 A40's FGCC peak was 34% greater than NA40's and A30's was 48% greater than NA30's. In GS2 A40 and A30's FGCC peaks were 48% greater that NA40 and NA30's. In GS3 A40 and A30's peak FGCC were 27% and 17% greater than NA40 and NA30's, respectively. During all growing seasons A40 and A30's FGCC were statistically significantly higher than NA40 and NA30's ($p<0.05$, n = 9 ordered pairs per GS). We attribute enhanced coverage on A40 and A30 to the effects of the amendments, all other things being equal.

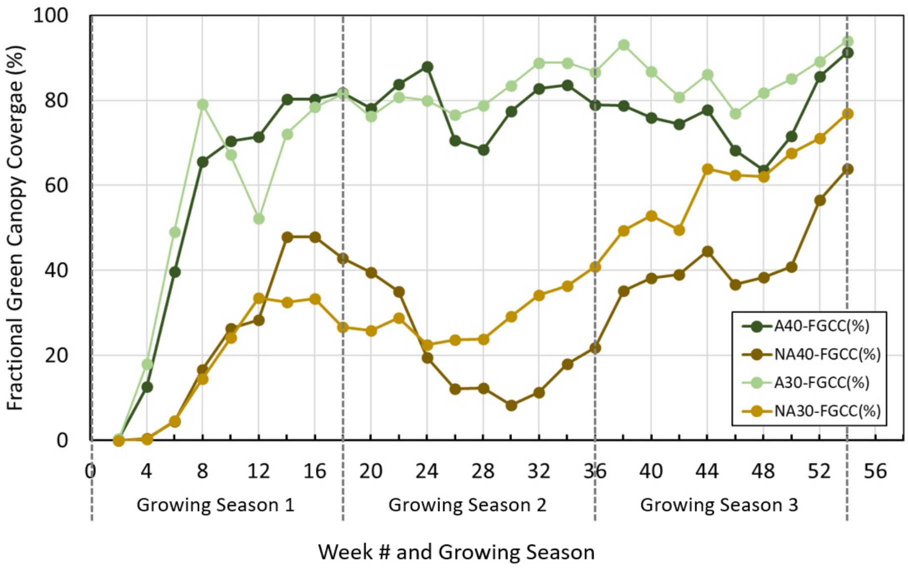

Figure 2 Fractional green canopy coverage (FGCC) data for all three growing seasons in %. A40 and A30 are the amended covers. NA40 and NA30 are the non-amended covers.

3.1.5 Total above-ground biomass production

Total dry above-ground biomass production, measured at the end of GS3 is detailed here as the actual mass collected from each slope and scaled to kg/ m^2, and kg/ Ha. A40 produced 0.99 kg of biomass, equivalent to 0.89 kg/m^2 and 8869 kg/Ha. A30 produced 0.81 kg of biomass, equivalent to 0.73 kg/m^2 or 7257 kg/Ha. NA40 produced 0.69 kg of biomass, equivalent to 0.62 kg/m^2 or 6193 kg/Ha. NA30 produced 0.54 kg of biomass which is an equivalent to 0.49 kg/m^2 or 4856 kg/Ha. The amended covers produced 30.2% (A40) and 33.1% (A30) more biomass than their non-amended controls NA40 and NA30, respectively.

3.2 Evapotranspiration data

A40 and A30 had higher total ET and greater ET as a percentage of precipitation than NA40 and NA30 for all three growing seasons (Table 2). In GS1 and GS2, the 30 cm amended cover A30 also had higher ET than NA40 (40cm cover depth). Over GS1, ET was 48.7 mm and 111.0 mm greater from A40 and A30 than NA40 and NA30, respectively. Over GS2, ET was 135.6 mm and 99.6 mm greater from A40 and A30 than NA40 and NA30, respectively. Over GS3, ET was 52.6 mm and 21.2 mm greater from A40 and A30 than NA40 and NA30, respectively.

Table 1 Total ET and ET as a percent of precipitation inputs for the growing season (GS)

	GS1		GS2		GS3	
Slope	**ET (mm)**	**ET as % of P**	**ET (mm)**	**ET as % of P**	**ET (mm)**	**ET as % of P**
A40	359.5	98.9	459.8	126	403.8	110.7
NA40	310.8	85.5	324.2	88.9	351.2	96.3
A30	327.2	90	363	99.5	297.3	81.5
NA30	216.2	59.5	263.5	72.2	276.2	75.7

3.3 Percolation data

During GS1 as vegetation established, percolation rates were similar between the paired amended and non-amended covers (i.e., A40 – NA40; A30 – NA30), but were different between covers of differing depths (i.e., 40 cm vs 30 cm depths). A40 and NA40 had GS1 total percolation rates of 34.3% – 32.7% of precipitation inputs, respectively; while for A30 and NA30 total percolation rates were 42.3% – 45.8% of precipitation, respectively (Figure 3). On a month-by-month basis during GS1, percolation rates were initially higher in the amended covers. In May percolation rates were 48.1% (A40) and 58.8% (A30) of precipitation, relative to their non-amended controls at 22.8% (NA40) and 34.6% (NA30). But, as vegetation developed more rapidly on A40 and A30 during GS1, and ET rates were higher, percolation rates declined substantially from the amended covers by August. GS1 August percolation rates were at 19.9% (A40) and 29.6% (A30) for the amended covers and at 36.2% (NA40) and 43.2% (NA30) on the non-amended covers.

During GS2 the percolation rates between amended and non-amended continued to be different. However, differences between depth pairs A40 – A30 and NA40 – NA30 were less distinct. GS2 total percolation for A40 and A30 was 23.4% and 29.3% of precipitation, respectively, whereas NA40 and NA30 had percolation rates of 44.5% and 49.6%, respectively.

During GS3 the amended covers continued to have lower percolation rates than their non-amended controls, but now as vegetation had begun to establish at greater rates on the non-amended covers, the percolation difference between thicker and thinner covers had declined, although the 30 cm covers still had greater percolation than the 40 cm covers. GS3 total percolation as a percent of precipitation was 26.1% (A40), 31.7% (A30), 41.1% (NA40), and 47.7% (NA30).

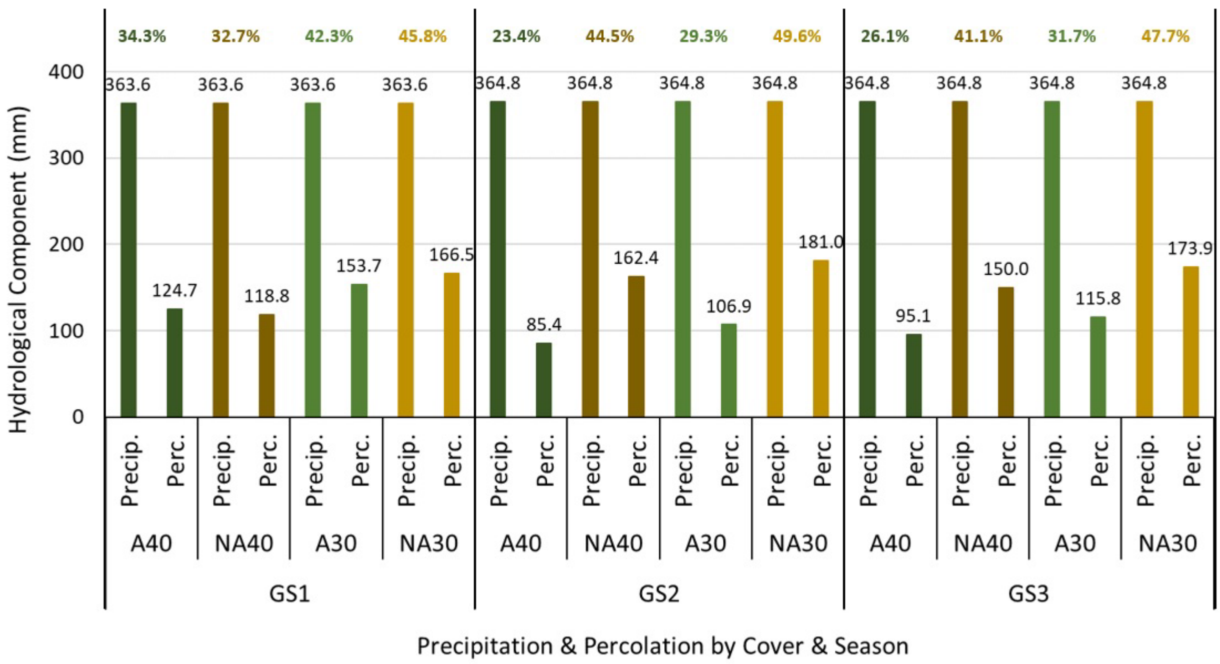

Figure 3 Precipitation and percolation data (in mm) collected from the four cover systems during all three growing seasons (GS1-3). Percentages listed above the bar chart data show percolation as a percent of precipitation inputs for the individual covers.

3.4 Correlation analyses

Correlation analyses were carried out assessing the relationship between FGCC (%) and ET (mm) for all three seasons. Correlation r-values, a measure of the strength of the relationship, and p values, a measure of statistical significance of the relationship between FGCC and ET, are shown in Table 3. There was weak, but statistically significant positive correlation between FGCC and ET for covers A40, A30 and NA30.

Table 2 Results of correlation analysis between FGCC (%) and ET (mm) for all four covers using all three seasons' data. A positive relationship between the variables is indicated by r-values>0. The significance level of the test was $\alpha = 0.05$, with p-values<0.05 implying a statistically significant relationship

Correlation Analysis FGCC (%) vs ET (mm)				
Cover	**r-value**	**Strength of relationship**	**p-value**	**Statistically significant relationship (yes/no)**
A40	0.40	weak	0.037	yes
NA40	0.11	very weak	0.578	no
A30	0.41	weak	0.036	yes
NA30	0.47	weak	0.013	yes

4 Discussion

4.1 Effects of the amendments on vegetation health metrics

The term amendment is broad and can indicate additions as simple as wood products (residues, dust, chips), animal manures, and soil additions or replacement; to intermediate products like compost or sewage slurries, biochars, pH buffering agents, and organic or inorganic fertilizers; to specifically engineering products like those tested in our research involving complex mixtures of woody materials, beneficial organic compounds, soil microbial community inoculations, and other soil nutrient sources. Other studies and reviews have assessed the effects of various types of amendments on contaminated soils, spent mine rock piles, and mine site soils, and have shown that some types of amendments are useful reclamation tools (Schoenholtz 1992, Sheoran 2010, Carvhalo 2013, Bacchetta 2015, Luna 2017, Hamza 2020, Simiele 2020, Hagner 2021). While the amendments tested in our study are materially, chemically, and biologically unique (in their proprietary formulation) relative to the amendments tested in the aforementioned studies, our findings shared similarities with previous research. Mainly that soil amendments, depending on type, can improve vegetation health outcomes on poor quality or contaminated soils.

During reclamation a number of soil factors can affect vegetation health, such as soil pH, soil fertility, rock content, soil texture, soil aggregation, soil moisture level, bulk density, compatibility, presence of toxic concentrations of heavy metals or other molecules toxic to vegetation, available rooting depth, slope stability, soil microbial and bacterial community (or lack thereof), and mycorrhizal fungi (Sheoran 2010, Carvhalo 2013, Luna 2017). Soil amendments are applied to mine rock piles, mine covers, or other industrial remediation sites to improve one or many of these factors in order to enhance vegetation health outcomes. Gypsum neutralized Bauxaline combined with various carbon-based amendments were shown to increase soil pH, electrical conductivity (EC) and reduce redox potential while also improving plant growth on a mine-contaminated soil (Simiele 2020). Biochar and a composted sewage sludge were applied to iron mine covers and tailings and were shown to markedly improve plant growth relative to controls resulting in 71-250% higher plant biomass generation (Hagner 2021). The use of compost and organic fertilizer amendments were also shown to improve germination rates and, hypogeal and epigeal growth for vegetation intended for phytoremediation on a SR mine cover in a semi-arid region (Hamza 2020).

The Proganics amendment system is designed to improve multiple of the above factors such as soil fertility, available N, surface soil moisture levels, to resist erosion and surface compaction, to improve slope surface stability, provide ideal sites for seedling germination, as well as provide an inoculation of beneficial soil bacteria. As with previous research (Carvhalo 2013, Bacchetta 2015, Luna 2017, Hamza 2020, Hagner 2021) we found the addition of amendments aimed at improving vegetation health controlling soil factors resulted in improved vegetation health outcomes. Specifically, we found that in comparison to their non-amended counterparts, our amended covers had more rapid vegetation emergence, their seedlings reached further developmental stages more rapidly, they reached statistically significant higher levels of surface coverage (FGCC) more rapidly, vegetation density counts were significantly higher ($p<0.05$), and they and produced more total above-ground biomass (TAB) (also seen in Hagner 2021). Even with a thinner soil profile, implying less available water and nutrients, A30 generated more TAB than NA40. Overall, we attribute these improved vegetation metrics on covers A40 and A30 to the effects of the applied amendments, all other factors being equal between the paired groups. We therefore reject null hypotheses #1.

4.2 Effects of the amendment on cover hydrodynamics

Limiting water movement into the mine rock layer, one of the design goals for SR covers (Lamoureux 2012, Clark 2016, Luna 2017), is achieved by utilizing vegetated soil layers with large enough storage capacity to retain water until it can be removed through ET (Madalinski 2003, Christenen and O'Kane 2005, O'Kane and Ayres 2012, Ayres and O'Kane 2013). Establishment of sustainable vegetation is well understood to contribute to restoration and modification of the hydrodynamics of mine covers and other reclamation sites (Clark 2016) and as vegetation communities mature, evapotranspiration has been shown to increase resulting in declining discharge rates (Sena 2014) and limiting percolation (Lamoureux 2012). While research has investigated and described the effects of vegetation cover on surface runoff and erosion (see the introduction of Clark 2012), and many studies have shown the positive effects of surface amendments on vegetation health outcomes (see our discussion in 4.1), limited research has attempted to connect the effects of soil amendments on subsequent ET and NP rates. However, a great deal of research has investigated the connection and strong relationship between ET and leaf area index (LAI), a metric for the projected area of leaves over a unit of land (Mingyue 2022, Good 2014, Schlesinger and Jasechko 2014, Liu 2016). A 14-year long dataset showed that greening or browning of vegetation in China led to increased or decreased annual ET, respectively (Liu 2016, Mingyue 2022). An alternative metric for assessing vegetation coverage is FGCC, which has been statistically correlated with LAI (Patrignani 2015).

ET rates are controlled by climatic factors, soil property factors, and the types of vegetation functional groups carrying out transpiration. Transpiration is in turn controlled by the vegetation's physiological and morphological traits such as leaf anatomy and area (LAI), water use efficiency (T/ET), rooting depth, plant available water and so on (Lamoureux 2012, Mingyue 2022). Generalizing, increases in vegetation coverage (LAI, FGCC) and the number of mature transpiring leaves typically results in increases in ET (Zhao 2022, Lamoureux 2012, Mingyue 2022).

Of the three vegetation functional groups commonly applied on covers and in reclamation projects (trees, shrubs, and grasses) grasses have the shallowest rooting depths (between 0.5 ± 0.1 m for tundra to 2.6 ± 0.2m in temperate grasslands), and their root density is highest in the upper 0.3 m of the soil (Canadel 1996, Jackson 1996 Lamoureux 2012), allowing grasses quick access to infiltrating water. We grew eight grass species and one legume species and utilized FGCC as one of our main metrics for assessing their rates of establishment and coverage extent. We attribute partially the statistically significant improvements made to FGCC and vegetation density by amendments with increased ET and subsequently decreased rates of NP. Our research showed that the applied amendments resulted in significantly greater canopy coverage (FGCC) ($p<0.05$) and individual plant densities. We found that there was a weak, but positive, statistically significant ($p<0.05$) correlation between FGCC and ET for A40 and A30, and we point also to previous studies which have indicated the strong correlation between increased vegetation coverage (LAI) and ET (Mingyue 2022, Good 2014, Schlesinger and Jasechko 2014, Liu 2016). Our observations show that ET was higher on the amended covers than the non-amended covers for all three growing seasons with ET rates from the amended covers being 21.2 mm to 135.6 mm greater per season.

Global average ET rates for grasslands were estimated at 311 ± 193 mm/ year (Zhang et al 2010, Lamoureux 2012) and for Canadian grasslands were 275 mm/year ± 42 (sd) (Liu 2003, Lamoureux 2012). For our region of interest, ET rates can be between 450 – 550 mm/yr (Liu 2003). Our observed ET rates were in excess of these global and Canadian rates for grasslands, but not for our region of interest. We note a few important considerations related to our ET findings. The modelled ET rates from Liu 2003 are for multiple vegetation coverage types, whereas we are using only grasses. Further, our system did not allow for surface discharge as we were forcing percolation in order to assess specifically if the amendment impacted NP rates, and as a result more water than would realistically occur was forced to infiltrate into the simulated covers. This likely had nock on effects to other water balance components (NP, ET). Additionally, the lab simulated climate was slightly hotter, had wider diurnal temperature fluctuations, and had lower humidity levels than are seen in our region of interest, all which will have impacted observed ET rates.

SR cover systems are most effective at preventing water ingress (NP) into mine rock when ET is in excess of precipitation inputs (Smith 2013, INAP 2017) and the amended covers in this study had ET either in excess of P (A40 ET was 98.9 – 126% of P) or close to P (A30 ET was 90 – 99% of P), whereas the non-amended cover's ET performance was worse with worse: NA40 ET being 85 – 96% of P, and NA30 ET being 60 – 76% of P.

Given the increased rates of ET on the amend ed covers, NP was accordingly lower. When considering total NP for all three growing seasons, the amended covers had 11 – 13% less percolation than the non-amended covers. At the season scale NP in GS1 was similar between the paired covers with differences in NP of only 1.6% to 3.5%. These similarities were due to the fact that vegetation was establishing, and rooting depths and density were likely at their lowest for the trial. However, by GS2 when differences in FGCC and ET between the amended and non-amended covers were highest, differences in percolation were also their greatest for the whole trial (20.3% to 21.1% less NP from amended covers relative to the non-amended covers). Then finally in GS3, FGCC increased on the non-amended covers, as had ET rates; differences in NP between the paired covers therefore decreased to 15.1% to 15.9% less relative NP from the amended covers.

While these findings are compelling, we cannot fully reject null hypothesis #2 and #3, acknowledging that while these results may indicate the amendment had some effect on ET and thus NP through their statistically significant improvements to FGCC and vegetation density, future research should include a greater number of simulated covers replicated to further prove out these initially promising findings.

Table 3 **Summary of vegetation health metric data. Vegetation Density counts from non-repeating random locations. Heights collected from n = 20 randomly selected individual grasses/ cover/ sampling event. Growing seasons (GS) 1 and 2 heights collected from all available grasses, while in GS3 only newly growing grasses were selected. Fractional green canopy coverage (FGCC) data is in percent green surface coverage. Avg: average, sd: standard deviation.**

Growing Season	Sim. Month	Week #	Veg. Density Counts A40	Veg. Density Counts NA40	Veg. Density Counts A30	Veg. Density Counts NA30	Heights Data A40 Avg (cm)	Heights Data A40 sd (cm)	Heights Data NA40 Avg (cm)	Heights Data NA40 sd (cm)	Heights Data A30 Avg (cm)	Heights Data A30 sd (cm)	Heights Data NA30 Avg (cm)	Heights Data NA30 sd (cm)	FGCC (%) A40	FGCC (%) NA40	FGCC (%) A30	FGCC (%) NA30
1	May	2	36	5	58	0	-	-	-	-	-	-	-	-	0.3	0.0	0.3	0.0
		4	71	41	103	4	18.4	7.2	9.0	4.9	18.0	8.0	7.8	2.9	12.6	0.4	17.9	0.3
	June	6	53	22	67	6	26.5	8.9	16.8	5.4	32.1	8.9	15.6	7.5	39.7	4.4	49.1	4.7
		8	72	41	102	27	33.7	14.7	23.8	9.8	34.2	12.2	20.0	9.5	65.6	16.6	79.0	14.4
	July	10	78	1	81	7	38.9	14.9	27.8	12.1	35.5	14.2	26.7	10.2	70.4	26.3	67.2	24.2
		12	73	23	66	11	39.6	11.7	29.2	14.8	31.3	12.5	30.2	15.7	71.4	28.3	52.1	33.6
	August	14	95	34	70	22	45.6	14.6	38.9	14.4	39.5	15.0	40.5	12.3	80.2	47.8	72.1	32.6
		16	84	29	76	5	45.1	24.0	42.7	18.8	36.7	16.7	37.8	16.6	80.3	47.9	78.4	33.3
		18	63	1	67	6	64.3	25.0	50.9	21.0	42.5	20.4	49.2	20.2	81.8	42.8	81.5	26.7
2	May	20	58	22	54	17	81.0	12.3	65.3	22.2	52.4	15.4	64.0	21.9	78.0	39.6	76.2	25.7
		22	53	18	79	8	78.0	13.9	71.3	16.8	57.4	16.8	67.6	18.8	83.7	35.1	80.8	28.8
	June	24	39	12	55	20	70.8	12.2	67.8	13.4	59.2	13.5	66.1	22.7	88.0	19.4	80.0	22.5
		26	-	-	-	-	74.5	11.9	64.9	16.9	60.5	15.4	68.1	16.9	70.6	12.2	76.5	23.7
	July	27	-	-	-	-	74.0	12.2	68.5	15.1	58.4	16.1	65.2	17.3	68.4	12.3	78.7	23.9
		30	-	-	-	-	77.7	14.3	69.3	17.6	57.4	13.1	65.5	18.8	77.4	8.3	83.4	29.2
	August	32	-	-	-	-	72.2	12.2	65.6	14.7	53.8	17.9	64.4	17.1	82.7	11.3	88.8	34.1
		34	-	-	-	-	73.4	12.0	62.1	16.0	58.6	13.2	67.6	16.7	83.6	18.0	88.9	36.3
		36	-	-	-	-	70.9	13.5	64.1	15.9	59.2	12.9	63.2	17.3	79.0	21.8	86.7	40.9
3	May	38	-	-	-	-	40.2	12.2	23.0	6.4	34.3	6.8	29.6	10.8	78.8	35.2	93.2	49.4
		40	-	-	-	-	37.4	14.4	23.4	4.9	30.4	9.5	24.1	9.3	76.0	38.2	86.7	52.9
	June	42	-	-	-	-	39.5	15.8	26.3	8.7	27.8	8.6	24.6	9.3	74.4	39.1	80.8	49.5
		44	-	-	-	-	37.3	11.5	24.4	5.2	27.4	10.3	26.4	8.5	77.7	44.6	86.1	63.9
	July	46	-	-	-	-	37.6	12.1	25.1	4.8	27.6	10.4	27.8	10.0	68.2	36.7	77.0	62.4
		48	-	-	-	-	35.5	11.2	23.5	4.7	27.6	7.5	21.5	6.8	63.6	38.4	81.7	62.0
	August	50	-	-	-	-	36.7	12.2	23.6	6.5	28.8	8.2	26.7	9.2	71.6	40.8	85.1	67.6
		52	-	-	-	-	39.3	16.0	25.2	7.7	25.3	11.6	21.0	7.1	85.7	56.6	89.2	71.0
		54	-	-	-	-	52.9	17.0	33.7	13.6	31.2	9.3	24.7	6.3	91.2	63.9	94.0	77.0

5 Conclusion

Results showed that the amended cover systems had increased rates of vegetation establishment, higher canopy coverage, and greater total above-ground biomass production. Amended slope vegetation reached more developed growth stages weeks ahead of the control covers, with some species emerging 37 days in advance of those on control covers. Canopy coverage on the amended covers were 34 – 48% higher during the critical first establishment season. Over three seasons, control slope canopy cover did not attain levels observed on amended covers. Total above-ground biomass production was 2,404 – 2,676 kg/Ha higher on the amended covers. Owing in part to higher vegetation density and coverage the amended covers had relatively higher rates of ET: between 21 – 136 mm more / season. Accordingly, 11 – 13 % less percolation into the underlying mine rock was observed.

These findings suggest that the tested soil amendment system, Proganics DUAL, could be a useful way to rapidly stabilize cover systems, improve ET rates, and lower percolation through improved growing conditions on mined land SR covers composed of poor-quality materials. Increasing rates of ET from SR covers is a critical component of limiting water percolation into underlying mine rock storage piles. The findings of this study do not suggest that SR covers be designed at the depths tested herein and we direct readers to the INAP Global Cover System Design Technical Guidance Document (INAP 2017) for information on cover depth requirements. We reiterate that SR covers are most effective in regions where ET is greater than precipitation. Cover designers must incorporate knowledge and effects of expected climate regimes, weather patterns, soil properties, and landform design controls on SR covers to maximize the 'storage' and 'water release' functions of those covers. SR covers have specific applications and should be utilized only in areas where best suited.

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