

BIORETENTION MEDIA COMPONENT ANALYSIS TO IMPROVE RUNOFF TREATMENT

**Prepared for
Kitsap County**

**Prepared by
Herrera Environmental Consultants, Inc.**



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EXECUTIVE SUMMARY

Bioretention is currently classified in the *Stormwater Management Manual for Western Washington* (SWMMWW) (Ecology 2014) as a basic (solids removal) and enhanced (copper and zinc removal) treatment Best Management Practice (BMP). The guidelines in the SWMMWW for the composition of bioretention media prescribe a mixture of 60 percent sand and 40 percent compost by volume. While bioretention using compost-based media can provide good water quality treatment for some contaminants (e.g., sediment, zinc, hydrocarbons, and likely bacteria), regional and national research indicate nitrogen (N), phosphorus (P), and copper (Cu) may be exported from these systems (Herrera 2014, 2015a, 2015b, 2015c; Mullane et al. 2015).

This project is Phase 1 of a two-part study and implements recommendations and next steps of two previous bioretention media studies: 1) *Analysis of Bioretention Soil Media for Improved Nitrogen, Phosphorus, and Copper Retention* (Herrera 2015c), which examined new bioretention media components; and 2) the *Pacific Northwest Bioretention Performance Synthesis Report* (Herrera 2015a), which summarized knowledge and data gaps examined through several recent regional research projects.

This study (Phase 1) tests previously evaluated and new media components for potential contaminant export and sorption capability, and media blends for hydraulic conductivity. Finally, much of this study focuses on evaluating plant growth in in these high-performance, low-nutrient media blends. The final Phase (Phase 2) of this research beginning in Fall 2017 will move recommendations forward from the previous studies to test additional media blends for flushing and pollutant capture, and evaluate the ability of those media to protect aquatic organisms.

The ultimate goal of Phase 1, Phase 2 and previous studies mentioned above is to develop recommendations for a new statewide, high-performance bioretention soil media (BSM) specification that: 1) reduces contaminant flushing; 2) meets Washington State Department of Ecology's (Ecology) treatment objectives for total suspended solids (TSS), dissolved Cu and Zn, and phosphorus; 3) grows plants; 4) is affordable and available; and 5) minimizes toxicity to aquatic organisms. Project funding was provided through Grants of Regional and Statewide Significance (GRSS) with Washington State Department of Ecology (Ecology). Kitsap County is the grant recipient and Herrera Environmental Consultants (Herrera) is the technical lead.

STUDY DESIGN AND METHODOLOGY

The objectives of the study were to evaluate saturated hydraulic conductivity (Ksat), plant growth characteristics, and ways to optimize plant growth in the low-nutrient environment of high-performance bioretention media designed to reduce contaminant export and improve contaminant capture. There were four primary tasks of the study to realize those objectives:

1. Conduct a rapid survey of potential bioretention media components based on pollutant capture capability, cost, availability, and sustainability. Select individual media components from the survey and project partner input.
2. Conduct Synthetic Precipitation Leaching (SPLP) analysis and sorption testing to determine N, P, and, Cu leaching and sorption potential of selected components. Select the media components that minimize leaching and maximize sorption potential and that are estimated to provide adequate hydraulic conductivity and support plants.
3. Combine selected components into media blends and assess Ksat of those blends. Adjust the blends if necessary to meet an acceptable Ksat range determined by the project team.
4. Conduct plant growth tests with media blends that meet the above objectives.

RESULTS

Survey and Selection of Media Components

A rapid survey of technical bulletins and scientific literature (see reference list at the end of Appendix B) was performed to identify candidate media components for this study. Based on criteria identified in Section 2 (Study Design and Methodology), the following media components from Appendix B were identified for the SPLP extractions described in the next subsection:

Bulk aggregate

- Ecology standard bioretention sand
- Lava sand (scoria earthtone sand)
- Lava sand (scoria surplus sand)
- State sand
- Volcanic sand

Bulk organic

- Compost
- Shredded cedar bark
- Coco coir

Mineral additive

- Activated alumina
- Diatomaceous earth
- Iron aggregate

Organic additive

- High-carbon wood ash (PD 100+ mesh)
- Granular activated carbon 1230AW

Media Component Leaching Tests

SPLP extractions were performed on the 13 prospective media components identified from the survey results. These extractions were subsequently analyzed for total Kjeldahl nitrogen (TKN), nitrate+nitrite (NO₃+NO₂), ortho-phosphorus (ortho-P), and dissolved Cu. Media components selected for sorption tests consisted of:

- Bulk aggregate: Ecology standard sand (for control), volcanic sand, state sand, and scoria surplus sand.
- Bulk organic: coconut coir, compost (for control).
- Mineral additives: activated alumina and iron aggregate.
- Organic additive: granular activated carbon (GAC 1230AW) and high-carbon wood ash.

Table ES-1. SPLP Extraction Results.			
Media Component	Ortho-P (mg/L)	NO₃+NO₂ (mg/L)	Dissolved Cu (µg/L)
Activated alumina (50% 100 micron/50% 14-28 mesh)	0.0000	0.326	0.00
GAC 1230AW	0.0000	0.015	0.00
Iron aggregate	0.0000	0.016	158.00
Volcanic sand	0.0070	0.023	6.60
State sand	0.0070	0.014	6.11
Ecology bioretention standard sand	0.0210	0.000	12.80
Lava sand (scoria surplus sand)	0.0270	0.050	5.58
Lava sand (scoria earthtone sand)	0.1740	0.022	51.80
Coco coir	0.2460	0.029	5.59
High-carbon wood ash PD 100+ mesh	0.4620	0.052	2.33
Diatomaceous earth	0.9000	0.027	9.10
Shredded cedar bark	1.4200	0.032	1.95
Compost	1.5600	0.025	25.10

For more detail on leaching test methods and results see Section 3.2.

Media Component Sorption Tests

Media components that moved forward from the leaching tests were evaluated for their ability to bind contaminants. The sorption analysis was performed for N, P, and Cu on the following media components: state sand, scoria surplus sand, coco coir, high-carbon wood ash, activated alumina, GAC 1230AW, diatomaceous earth, iron aggregate, and shredded cedar bark. See Section 3.3 for sorption test details.

None of the media components showed significant sorption capability for nitrate except for the GAC 1230AW and the iron aggregate at 12 hours.

As anticipated the activated alumina and iron aggregate showed strong sorption capacity for phosphate. The K_d values for the iron aggregate dropped sharply after 6 hours. This can be due to several factors, including dissolution of solid material over time therefore increasing sorbent concentration in solution, changing pH, interference from competing ions or preference for the alumina. However, activated alumina K_d values increased slightly over the 12-hour period indicating that alumina is a reliable phosphate sorbent over typical residence times within bioretention.

High-carbon wood ash, GAC, and particularly activated alumina all showed strong sorption capability for dissolved Cu. The activated alumina K_d values dropped sharply after 6 hours. This can be due to several factors, including dissolution of solid material over time therefore increasing sorbent concentration in solution, changing pH, interference from competing ions or preference for high-carbon wood ash that exhibits increasing K_d values from 6 to 12 hours.

See Table ES-2 for sorption test results.

Media Blends and Ksat Tests

Based on the above analyses, best professional judgment, and input from the project advisory group, selected components were combined in blends designed to minimize pollutant flushing, maximize pollutant capture performance, and support plant growth. Composition of each blend is summarized in Table ES-3.

Table ES-2. Average Kd Values for Media Components at 2, 6, and 12 hours.

Average Kd Values for Nitrate-N (mL/g)									
Hours	State Sand	Lava Sand (scoria surplus)	Coco Coir	High-Carbon Wood Ash (PD 100 + mesh)	Activated Alumina (100 micron)	GAC 1230AW	Diatomaceous Earth	Iron Aggregate	Shredded Cedar Bark
2	-0.71	-1.40	3.03	1.54	-4.16	246.27	-0.39	3.81	-1.82
6	-1.17	-1.71	3.18	1.62	-4.36	176.28	-1.08	25.23	-1.49
12	-0.49	-1.29	6.31	2.97	-4.11	304.80	-0.62	226.93	0.24
Average Kd Values for Ortho-Phosphorus (mL/g)									
Hours	State Sand	Lava Sand (scoria surplus)	Coco Coir	High-Carbon Wood Ash (PD 100 + mesh)	Activated Alumina (100 micron)	GAC 1230AW	Diatomaceous Earth	Iron Aggregate	Shredded Cedar Bark
2	0.51	0.99	-13.28	-9.94	1,597.11	189.26	-6.42	1,766.27	-17.97
6	2.06	0.30	-12.72	-6.89	ND	258.89	-6.34	1,754.92	-15.76
12	1.82	-0.74	-12.06	-7.91	1,869.26	294.95	-7.27	545.16	-17.20
Average Kd Values for Total Copper (mL/g)									
Hours	State Sand	Lava Sand (scoria surplus)	Coco Coir	High-Carbon Wood Ash (PD 100 + mesh)	Activated Alumina (100 micron)	GAC 1230AW	Diatomaceous Earth	Iron Aggregate	Shredded Cedar Bark
2	88.59	30.94	65.94	701.58	11,104.89	370.90	171.47	1463.89	365.66
6	137.64	42.73	54.94	799.94	24,694.08	1,091.68	244.28	245.41	329.08
12	190.38	56.14	46.64	1,628.95	4,884.46	1,692.72	317.50	115.63	170.94

Note that the larger the Kd value the greater the affinity and the greater the capacity to sorb the target analyte in solution. Negative numbers in the table indicate release of the analyte from the media component.

ND = 0 or no value for B (final solute concentration) in Kd equation ($K_d = (A-B)*V / ((M_s)*B)$).

Table ES-3. Media Blend Composition and Justification.

No.	Media Blend Abbreviations	Media Blend Treatments ^a	Justification
1	60sand/40comp	60% miles canyon sand/40% compost (control)	Control to compare plant growth with treatments. Note that the 60/40 blend provides optimum plant growth but poor water quality treatment. Therefore, this blend is not viable where the high-performance treatments are applicable and a somewhat misrepresentative control.
2	70vs/20cp/10ash	70% volcanic sand/20% coco coir/ 10% high-carbon wood ash	Top performer from previous media research (Kitsap study).
3	50ss-vs/40cp/10ash	50% state-volcanic sand mix/40% coco coir/10% high-carbon wood ash	Sand: the state (coarse and high Ksat) and volcanic (finer) sands are two of the three clean sands identified; however PSD of these cannot be altered. Therefore the sands were blended (75%ss/25%vs) to attain a desirable coefficient of uniformity, reduce Ksat, and possibly improved TSS capture. OM content: Coir provides high water holding capacity, some nutrient content and potential N capture; therefore, increasing content in the blend may improve plant health.
4	70ss-vs/20cp/10ash	70% state-volcanic sand mix/20% coco coir/10% high-carbon wood ash	Compare lower coir (organic matter content) for plant growth with blended sand.
5	50ls/40cp/10ash	50% lava sand/50% coco coir/ 10% high-carbon wood ash	Sand: lava sand is one of three sands that have low N, P and Cu leaching potential. This is the only sand that the supplier can alter the PSD, therefore, providing greater flexibility to meet hydraulic targets. OM content: Coir provides a high water holding capacity, some nutrient content and potential N capture; therefore, increasing content in the blend may improve plant health.
6	70ls/20cp/10ash	70% lava sand/20% coco coir/ 10% high-carbon wood ash	Compare lower coir (organic matter content) for plant growth with blended sand.
7	70ss-vs/20cp/10ash/ compmulch	70% state-volcanic sand mix/20% coco coir/10% high-carbon wood ash/2-inch compost mulch	This treatment includes lower coir content, and compost mulch to increase nutrients and potentially improve plant growth. The nutrients from the compost mulch may be sorbed by the media below when not taken up by plants.
8	70vs/30comp/p-layer	70% volcanic sand/ 30% compost/polishing drainage layer (medium sand, 5% activated alumina and 5% iron aggregate)	The polishing layer approach is useful for those jurisdictions already deploying compost-based media (Phase 1 communities) and this approach performed well in the Seattle Polishing Layer Study (Herrera, 2016). That study used a 12-inch polishing layer. We used a 2-inch layer for this study.

^a All component mixtures are by volume.

PSD = particle size distribution

Saturated hydraulic conductivity of the blends was evaluated using ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort) to determine optimum moisture content to obtain maximum dry density at 85 percent compaction effort. ASTM D2434 was then used to determine saturated hydraulic conductivity at 85 percent compaction effort (see Figure ES-1 for results). See Section 3.4 for Ksat test details.

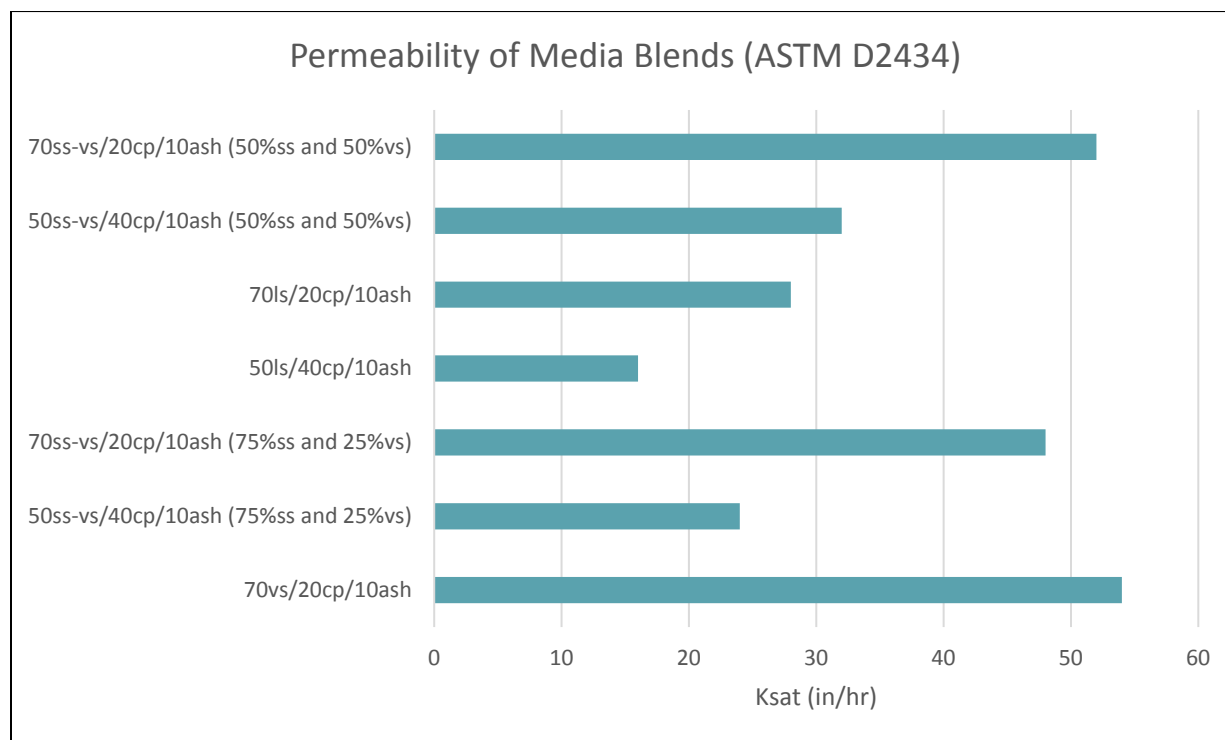


Figure ES-1. Media Blend Saturated Hydraulic Conductivity.

Note that due to budget constraints and the focus on high-performance, non-compost based media, Ksat was not evaluated for the 60sand/40comp and the 70vs/30comp/p-layer blends.

As indicated by the Ksat results, changing the ratio of state (coarser) and volcanic (finer) sands did not substantially influence Ksat. For example, Ksat for the blend with 75 percent state, 25 percent volcanic sand, and 20 percent coir was 122 centimeters per hour (cm/hr) or 48 in/hr and 133 cm/hr (52 in/hr) for the 50/50 percent blend with 20 percent coir. In fact, Ksat was less for the coarser mix, which is likely due to a higher coefficient of uniformity for the 75 percent state/25 percent volcanic sand (see Figure 7 for sand coefficient of uniformity). However, the organic matter (coir) content did significantly influence Ksat. For both, Ksat for the sand blends dropped nearly in half when doubling the coco coir content from 20 to 40 percent. Specifically, 122 cm/hr (48 in/hr) for the 70ss-vs/20cp/10ash with 75 percent state sand and 25 percent volcanic sand and 61 cm/hr (24 in/hr) for the 50ss-vs/40cp/10ash with 75 percent state and 25 percent volcanic sand.

Plant Growth Analysis

Plant selection for the analyses began with selecting common and hearty bioretention plants. A survey was sent to bioretention designers (landscape architects, engineers and installers) in Washington and Oregon. Two species were selected for their good drought tolerance and overall heartiness in a variety of condition: *Deschampsia cespitosa* (tufted hairgrass) and *Juncus patens* (California grey rush). See Appendix E for the plant selection tables.

Plants were placed in 12-gallon buckets with a 45.7-centimeter (cm) (18-inch) layer of media placed on top of a 5-cm (2-inch) drainage layer of coarse sand. The plant study was conducted for 6 months. Plants were watered once at planting with tap water, then once per week starting 1 week after initial watering for 16 weeks with stormwater from the Redmond Operation and Maintenance Facility detention vault. Each planter received approximately 26 liters (5.7 gallons) gallons of stormwater per week at each watering. After approximately 16 weeks, the plants were stressed by reducing the watering regime to once every 3 weeks and reducing the volume to approximately 14.4 liters (3.2 gallons) gallons of water per bucket. Stressing was intended to simulate the dryer conditions of summer, and continued for 8 weeks. See Section 3.5 for plant growth analysis details.

General Growth Observations

Three *J. patens* plants died within the first 2 months of planting. All other *J. patens* planted in the same treatments survived until the end of the trial and, therefore, it is unlikely that the early mortalities were due to inadequacies in the media. Rather, these early deaths may have been due to unhealthy bare roots or to the physical disruption that occurred when pooling water caused the media to float. One other mortality occurred in week 24, well into the dry period (*J. patens* growing in 60sand/40comp). Based on the large size of the other plants in this planter, the *J. patens* in question may have been crowded and/or shaded out.

Plant Stem Comparison

The first measurement of stem height on February 14, 2017, showed that, as expected, the plants in media with compost grew faster than those in media without compost. No significant difference between the height of non-compost plants was seen in any of the three measurements. Observing the trajectory of the plants over time, all three compost treatments continued to grow from the first to the second measurement, while the plants in all non-compost treatments appear to stall in vertical growth after the first measurement. Plants in Treatment 7, which contained only a layer of compost on top, grew as tall as plants in Treatment 1, which had 40 percent compost mixed throughout (Table ES 4).

Stem counts, used to measure horizontal growth, tell a similar story as height measurements. Stem counts for *D. cespitosa* and *J. patens* are shown over time in Figures 10 and 11, respectively. For *D. cespitosa*, plants in compost treatments did have more stalks throughout than those in non-compost treatments, but the difference was not as substantial with horizontal

as with vertical growth. Further, grass stem counts increased throughout the study for all treatments (there was no “stalling” as was seen with vertical growth). However, the opposite was the case for *J. patens*. By the end of the trial, rush plants grown in treatments with compost had significantly more stalks than those grown in non-compost treatments (see Table ES-4). Rushes grown in non-compost treatments also stalled in horizontal growth after the first measurement, and no significant difference was seen between any of the non-compost treatments.

Table ES-4. Final Height and Stem Count for <i>D. cespitosa</i> and <i>J. patens</i>.					
No.	Treatment	Stem Height (cm)		Stem Count	
		<i>D. cespitosa</i>	<i>J. patens</i>	<i>D. cespitosa</i>	<i>J. patens</i>
1	60sand/40comp	99.8 ± 1.8	51.3 ± 1.1	59 ± 1	149 ± 33
2	70vs/20cp/10ash	36.0 ± 10.6	21.0 ± 3.5	26 ± 6	24 ± 8
3	50ss-vs/40cp/10ash	45.3 ± 8.1	21.0 ± 0.0	42 ± 4	12 ± 0
4	70ss-vs/20cp/10ash	44.3 ± 20.9	21.0 ± 0.7	28 ± 1	19 ± 6
5	50ls/40cp/10ash	46.0 ± 3.5	18.8 ± 0.4	27 ± 5	9 ± 10
6	70ls/20cp/10ash	44.3 ± 5.3	22.3 ± 0.4	31 ± 12	21 ± 0
7	70ss-vs/20cp/10ash/compmulch	99.3 ± 20.9	45.5 ± 0.7	54 ± 34	130 ± 75
8	70vs/30comp/p-layer	90.3 ± 2.5	47.5 ± 0.7	65 ± 28	191 ± 42

Analysis of Nitrogen and Phosphorus Content

There is a clear divide between treatments with compost (1, 7, and 8) and treatments without, which is supported by the Tukey’s multiple comparison test for both the grass and rush species (see Tables ES 5 and ES 6). Plants grown in Treatments 1 (60sand/40comp) and 8 (70vs/30comp/p-layer) had significantly higher total N concentration in their tissue than plants grown in the remaining treatments.

Again the presence or absence of compost made the largest difference for P concentrations in the plant tissue. For the grass tissue, Treatments 1 (60sand/40comp) and 8 (70vs/30comp/p-layer) were statistically higher than all the non-compost treatments. The P concentration of grass in Treatment 7 (70ss-vs/20cp/10ash/compmulch) was variable, such that Treatment 7 was statistically similar to all treatments, both those with and without compost. All non-compost treatments had statistically similar P concentrations, and for rush tissue Treatment 7 (70ss-vs/20cp/10ash/compmulch) performed similarly to Treatments 1, 8, 4, and 6. See Tables ES-5 and ES-6 for summaries of tissue analyses.

Table ES-5. Tissue Analysis of Grass (<i>D. cespitosa</i>) Grown in Different Soil Mixtures.					
No.	Treatment	Total N (percent)		Total P (percent)	
1	60sand/40comp	A	0.98 ± 0.06	AB	0.38 ± 0.08
2	70vs/20cp/10ash	B	0.50 ± 0.04	C	0.23 ± 0.00
3	50ss-vs/40cp/10ash	B	0.57 ± 0.12	BC	0.25 ± 0.04
4	70ss-vs/20cp/10ash	B	0.61 ± 0.22	C	0.21 ± 0.02
5	50ls/40cp/10ash	B	0.57 ± 0.08	C	0.23 ± 0.02
6	70ls/20cp/10ash	B	0.48 ± 0.04	C	0.18 ± 0.05
7	70ss-vs/20cp/10ash/compmulch	B	0.59 ± 0.07	ABC	0.25 ± 0.03
8	70vs/30comp/p-layer	AB	0.74 ± 0.08	A	0.38 ± 0.06

Mean, standard deviation, and Tukey HSD statistical groups are shown for total N (percent) and total P (percent). If two treatments share a letter, they are NOT statistically different.

Table ES-6. Tissue Analysis of Rushes (<i>J. patens</i>) Grown in Different Soil Mixtures.					
No.	Treatment	Total N (percent)		Total P (percent)	
1	60sand/40comp	A	1.54 ± 0.16	A	0.41 ± 0.07
2	70vs/20cp/10ash	C	0.81 ± 0.03	C	0.20 ± 0.02
3	50ss-vs/40cp/10ash	C	0.71 ± 0.01	C	0.19 ± 0.00
4	70ss-vs/20cp/10ash	C	0.76 ± 0.02	BC	0.23 ± 0.02
5	50ls/40cp/10ash	–	–	–	–
6	70ls/20cp/10ash	C	0.75 ± 0.16	BC	0.24 ± 0.02
7	70ss-vs/20cp/10ash/compmulch	B	1.15 ± 0.07	AB	0.31 ± 0.02
8	70vs/30comp/p-layer	A	1.47 ± 0.07	A	0.36 ± 0.03

Mean, standard deviation, and Tukey HSD statistical groups are shown for total N (percent) and total P (percent). If two treatments share a letter, they are NOT statistically different.

Plant Biomass

After 6 months plants were removed from the buckets, roots carefully separated from the media and washed. The whole plant was placed on a grid to visually compare growth and then the stems and roots separated and placed in paper bags for drying. Stems and roots were placed in a drying oven at 105 degrees C (°C) for 18 hours and then weighed.

The plant biomass analyses for stems and roots shows a clear division between compost-based media (including compost mulch media) and non-compost media. All compost-based media performed statistically the same for stem and root biomass development and all non-compost media the same as well. The difference in biomass production between the compost and non-compost media was significant. For example, mean total biomass for Treatment 8 (70vs/30comp/p-layer) was 58.41 grams and 3.93 grams for Treatment 2 (70vs/20cp/10ash). Just considering mean values, Treatment 8 with 30 percent compost produced the most biomass of any treatment including Treatment 1 with 40 percent compost.

Of interest is that Treatment 7 (70ss-vs/20cp/10ash/compmulch) performed statistically similarly to the other compost-based media with either 30 or 40 percent compost mixed throughout the media column. While this media strategy performs very well for plant growth, the water quality performance is not known.

CONCLUSIONS AND RECOMMENDATIONS

Media Components

1. Three sands (one medium to fine and one with coarser particle size distribution and one with a porous structure) have now been identified that leach minimal contaminants. Two have been tested multiple times with good SPLP extraction results for each analysis. The porous scoria sand particle size distribution can be altered by the supplier. These three sands should move forward and provide the mineral aggregate component for Phase 2 media blends.
2. Activated alumina and iron aggregate continue to exhibit strong sorption capability for ortho-P in sorption tests. Activated alumina, iron aggregate, and high-carbon wood ash show strong sorption capability for total Cu. All these materials also exhibited low leaching potential in previous studies. The activated alumina and high-carbon wood ash demonstrated low leaching potential in these tests; however, the iron aggregate leached high concentrations of dissolved Cu in this analysis. Given previous tests, the dissolved Cu results may be unusual for this material and further testing is warranted. These three materials should move forward to Phase 2 media blends as organic additives (high-carbon wood ash) or polishing layer components (alumina and iron).

Media Blends

1. Saturated hydraulic conductivity is a balance between particle size and particle size distribution (coefficient of uniformity), compaction, and other factors. The sand blends developed for this study were not strongly influenced by more or less coarse material in the blend. Instead, Coefficient of Uniformity appeared to offset the potential to increase Ksat with the addition of coarser aggregate. However, organic matter (coco coir) in these blends did strongly influence Ksat. At the same time, additional organic matter did not make a significant difference for plant health and vigor. Accordingly, a maximum of 20 to 30 percent organic matter is recommended for blends in Phase 2.
2. Cementing or caking was observed in one of the polishing layer treatments indicating that 5 percent iron content was too high (see Section 3.5.4 for more detail). Accordingly, polishing layer treatments should contain no more than 2 percent iron by volume and trials with only activated alumina should be evaluated.

Plants

1. Plants survived in all treatments. But the subjective question remains whether plants grown in the non-compost treatments are “good enough” for a functioning bioretention system. More specifically, is a plant that is aesthetically pleasing and survives through mild stress good enough for a bioretention system whether or not the plant grows to its full potential? While this question will remain as plant studies progress, one treatment shows promise to support healthy plant growth nearly equal to compost-based media. The 70 percent volcanic sand/20 percent coco coir/10 percent high-carbon wood ash with a compost mulch performed statistically similarly to the media with 30 to 40 percent compost. This high-performance media, without the compost mulch, performed very well for low leaching potential and very good pollutant capture in a previous media study (Herrera 2015c). However, the contaminant flushing or capture performance of this approach has not been tested. Accordingly, the high-performance media blends including clean sands, coir, and ash as well as these blends with a compost mulch should move ahead to Phase 2 for more flushing and contaminant capture analyses.

Summary Recommendations and Phase 2

Many of the media components evaluated in previous studies tested well in this study. Accordingly, confidence in these media components for minimal leaching potential and binding target contaminants has increased. An exception to this was the iron aggregate for leaching dissolved Cu. Discussions with the material supplier to confirm feedstocks and processing as well further testing is necessary to rely on iron aggregate for polishing layer applications.

All the non-compost media supported plants. The ability of compost-based media to support superior plant growth was not in question, but rather the ability of high-performance, low-nutrient media to support adequate plant growth. The question of what is adequate will vary across users and settings. The timeframe for the plant study was short and the plant palette limited to two plant species. Additionally, the treatments were purposely limited to media alone rather than including and organic mulch (e.g. arborist wood chips) typical to actual installations. The exception to this was the use of a compost mulch on the 70 percent volcanic sand/20 percent coco coir/10 percent high-carbon wood ash.

Given the results of this and previous studies, next steps for Phase 2 should include:

- Final leaching and sorption analysis of media components,
- The Ksat for all media blends test well above the 30.5 cm/hr (12 in/hr) maximum Ksat recommended by Ecology. While the 30.5 cm/hr will remain for design purposes, decisions must be made by Ecology and the advisory group concerning the appropriate actual Ksat target range for the blending, flushing and dosing of media blends in Phase 2.

- Include orifice and/or other hydraulic controls to attain more reliable Ksat ranges in Phase 2 column tests and full-scale pilots.
- Continue to test the polishing layer approach using reduced iron aggregate volumes and activated alumina alone.
- Flush and dose media blends that have demonstrated superior pollutant capture combined with elements that potentially improve plant health. For example, the 70 percent volcanic sand/20 percent coco coir/10 percent high-carbon wood ash with a compost mulch (which performed statistically similarly to the media with 30 to 40 percent compost) should be evaluated for water quality treatment. However, other components that may support improved plant health such as wood chips or slow release nutrients should also be included in the experimental blends and assessed for treatment performance.

1. INTRODUCTION

The current Washington State, Phase I municipal National Pollutant Discharge Elimination System (NPDES) stormwater permit (effective January 1, 2017) requires the use of low impact development (LID) practices as the first option for managing stormwater where feasible. Bioretention is the most widely applicable and flexible Best Management Practice (BMP) in the suite of LID practices. Typically, they are shallow landscaped depressions with a designed soil mix and plants adapted to the local climate and soil moisture conditions. Sized to receive stormwater from a small contributing area, these systems are designed to more closely mimic natural forested conditions where healthy soil structure and vegetation promote the infiltration, storage, filtration, and slow release of stormwater flows. When used in a typical LID application, bioretention areas are designed as small-scale, dispersed systems that are integrated into the site as a landscape amenity (see Figure 2). Bioretention systems may include underdrains, when design specifically for water quality treatment or in areas with soils that are less suitable for infiltration. In these cases, a portion of the treated runoff is discharged back into the stormwater conveyance system rather than infiltrated.



Figure 2. Typical Bioretention Swales (from City of Seattle and Kitsap County).

Bioretention is currently classified in the *Stormwater Management Manual for Western Washington* (SWMMWW) (Ecology 2014) as a basic (solids removal) and enhanced (copper and zinc removal) treatment BMP. The guidelines in the SWMMWW for the composition of bioretention media prescribe a by-volume mixture of 60 percent sand and 40 percent compost. While bioretention using compost-based media can provide good water quality treatment for some contaminants (e.g., sediment, zinc, hydrocarbons, and likely bacteria), regional and national research indicate nitrogen (N), phosphorus (P), and copper (Cu) may be exported from these systems (Herrera 2014, 2015a, 2015b, 2015c, Mullane et al. 2015). Export of N, P, and Cu is of particular concern for bioretention installations with under-drains that discharge to receiving waters. Export of these pollutants is also a concern for bioretention installations with or without

underdrains when located over shallow groundwater or in proximity to phosphorus and nitrogen sensitive receiving waters.

This project is Phase 1 of a two-part Study and implements recommendations and next steps of two previous bioretention media studies: 1) *Analysis of Bioretention Soil Media for Improved Nitrogen, Phosphorus, and Copper Retention* (Herrera 2015c), examined new bioretention media components; and 2) the *Pacific Northwest Bioretention Performance Synthesis Report* (Herrera 2015a), summarized knowledge and data gaps evaluated through several recent regional research projects.

The first study (Herrera 2015c), conducted in partnership with Kitsap County in 2014 through 2015, focused on the selection, pollutant export, and pollutant capture characteristics of new BSM components and media blends for high performance water quality treatment. The study indicated that some of the new media blends significantly reduce the export of N, P, and Cu compared to the currently prescribed compost-based media. However, the study was limited in scope and did not include: chemical (with the exception of leaching tests) or physical characterization of the media components; hydraulic analysis; plant growth tests using plants typical to western Washington bioretention systems; selection of appropriate metrics to describe the media components and blends in a specification; and toxicity testing to evaluate how well these new blends protect targeted aquatic organisms from acute and sub-lethal toxicity.

This study (Phase 1) tests previously evaluated and new media components for potential contaminant export and sorption capability, and media blends for hydraulic conductivity. Finally, much of this study focuses on evaluating plant growth in in these high-performance, low-nutrient media blends. The final Phase (Phase 2) of this research will move recommendations forward from the previous studies to test additional media blends for flushing and pollutant capture, and evaluate the ability of those media to protect aquatic organisms.

The ultimate goal of Phase 1, Phase 2 and previous studies mentioned above is to develop recommendations for a new statewide, high-performance bioretention soil media (BSM) specification that: 1) reduces contaminant flushing; 2) meets Washington State Department of Ecology's (Ecology) treatment objectives for total suspended solids (TSS), dissolved Cu and Zn, and phosphorus; 3) grows plants; 4) is affordable and available; and 5) minimizes toxicity to aquatic organisms.

This project was funded by Grants of Regional and Statewide Significance (GRSS) through Washington State Department of Ecology (Ecology). Kitsap County is the grant recipient and Herrera Environmental Consultants (Herrera) is the technical lead. An Advisory Group was convened at the beginning of the study to provide a broad perspective and context to the study approach and findings. That group includes:

- Kitsap County
- Ecology
- City of Redmond
- City of Seattle

- City of Tacoma
- City of Portland, OR
- Thurston County
- King County
- Washington State University
Department of Crop and Soil
Sciences
- University of Washington
- Shannon and Wilson

2. STUDY DESIGN AND METHODOLOGY

The approach for this study is part of a larger body of work that includes previous studies mentioned above and the Phase 2 studies commencing in fall 2017. Overall, the complete set of studies are designed to optimize bioretention media to meet Ecology water quality treatment goals outlined in the introduction. This study focuses on evaluating media component leaching and sorption potential as well as permeability and plant growth characteristics of media blends. There are four primary tasks of the study:

1. Conduct a rapid survey of potential bioretention media components based on pollutant capture capability, cost, availability, and sustainability. Select individual media components from the survey and project partner input.
2. Conduct Synthetic Precipitation Leaching analysis and sorption testing to determine N, P, and Cu leaching and sorption potential of selected components. Select the media components that minimize leaching and maximize sorption potential and that are estimated to provide adequate hydraulic conductivity and support plant growth.
3. Combine selected components into media blends and assess the saturated hydraulic conductivity (Ksat) of those blends. Adjust the blends if necessary to meet an acceptable Ksat range determined by project team.
4. Conduct plant growth tests with media blends that meet the above objectives.

For a more detailed description of the study design and Method Quality Objectives, see the Quality Assurance Project Plan (QAPP) in Appendix A.

2.1. RAPID SURVEY OF MEDIA COMPONENTS

The BSM components from the previous media research (Herrera 2015c) that exhibited the best TSS, metals, and nutrient removal were selected for additional media testing. New media components were selected for treatment effectiveness of target stormwater pollutants using a rapid survey of the scientific literature and project partner input.

The media components are organized into a matrix by three categories: bulk aggregate (e.g., sands); bulk organic (e.g., compost) that comprise the majority of the media blends; and mineral and organic amendments that provide specific pollutant capture and/or hydraulic characteristics, and comprise less of the overall volume. A complete list of media components considered for media blends are included in Appendix B.

With input from the project Advisory Group, a subset of media components were prioritized for further analyses in this study using the following criteria:

- Treatment performance: including potential for both leaching and estimates of pollutant capture capability from the literature.
- Sustainability: including availability, transportation requirements, manufacturing and/or extraction processes.
- Cost: media components with lower unit costs were prioritized in the selection process. Cost was considered along with the above criteria to attain the best balance of cost to optimum performance. See Appendix B for estimated component cost per cubic yard.

2.2. MEDIA COMPONENT LEACHING TESTS

The leaching potential for N, P, and Cu for selected media components was assessed using Synthetic Precipitation Leaching Protocol (SPLP) (EPA Method 1312). The analysis was performed at Analytical Resources Inc. (ARI), an Ecology certified laboratory. Parameters analyzed for the SPLP extraction are contaminants found in sand and compost from previous studies (Herrera 2014a, 2015) and consisted of: total Kjeldahl nitrogen (TKN), nitrate+nitrite as N (NO_3+NO_2), ortho-P, and dissolved Cu using two procedures:

- Metals: weak acid ($\text{H}_2\text{SO}_4/\text{HNO}_3$) extraction using a pH recommended for western United States.
- Nutrients: deionized water extraction.

A 0.7-micron filter was used in the SPLP extraction procedure for copper to isolate the dissolved fraction.

Media components were selected from the SPLP analysis using the following criteria:

- Extraction concentrations: dissolved Cu $\leq 5 \mu\text{g/L}$; $\text{NO}_3+\text{NO}_2 \leq 0.1 \text{ mg/L}$; and ortho-P $\leq 0.1 \text{ mg/L}$.
- If none of the components initially selected meet these criteria, additional components were considered for SPLP analysis.
- If none of the components initially or subsequently selected meet these criteria, then components with the lowest concentrations were selected and proprietary and non-proprietary components were considered for use as a polishing layer to reduce effluent concentrations from the media blends comprised of the components with the lowest SPLP concentrations.

See Section 3.2 for leaching test results.

2.3. MEDIA COMPONENT SORPTION TESTS

Media components meeting the SPLP extraction criteria in Section 2.2 were selected for sorption tests. Equilibrium batch studies to assess total Cu, nitrate as N, and ortho-P sorption capability were conducted on each component. The batch studies focused on kinetic processes to determine the time required to reach sorption equilibrium using a sorption fluid.

Dissolved organic carbon (DOC) is a strong sorbent and was added to the sorption solution (Table 7) to simulate this component of actual stormwater and assess DOC interference.

Table 7. Sorption Fluid Composition (20 L).	
Standards	Concentration
Dissolved organic carbon (Suwannee River natural organic material)	4,000 µg/L
Phosphorus	100 µg/L
Nitrate (potassium nitrate)	1,000 µg/L
Copper (cupric sulfate pentahydrate)	100 µg/L
Buffer (sodium bicarbonate)	0.185 mg/L
Interference ions (sodium chloride)	1.0 mg/L

A distribution coefficient, which describes the affinity of the media components for target analytes, was developed from the sorption analysis. The coefficient is calculated as follows:

$$K_d = (A-B) \cdot V / ((M_s) \cdot B)$$

Where:

K_d = distribution coefficient (mL/g)

A = initial concentration of the solute defined as the mean concentration of the blanks (µg/mL)

B = final concentration of the solute after 2, 6, and 12 hours in contact with the media (µg/mL)

V = Volume of the solution used (mL)

M_s = mass of soil expressed on an oven-dried basis (g)

See Section 3.3 for sorption analysis results.

2.4. COMBINE MEDIA COMPONENTS AND CONDUCT SATURATED HYDRAULIC CONDUCTIVITY TESTS

Media components meeting criteria identified in Section 2.2 and that have the highest sorption capability were combined into media blends to test K_{sat} . The minimum target for K_{sat} was 10 cm/hr or 4 in/hr (10 cm/hr x the maximum correction factor for BSM of 0.25 = 2.5 cm/hr

[1 in/hr] or Ecology's recommended minimum Ksat for custom BSM). The maximum range will be determined from the tests. The primary considerations for selecting mineral and organic matter component were gradation and availability. Coefficient of Uniformity, Guidelines for Filter Media in Biofiltration Systems (FAWB 2009), and best professional judgment were also used to estimate proper gradation of components. See Section 3.4 for selected media blends.

To test blend Ksat, ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort) was used to determine optimum moisture content to obtain maximum dry density at 85 percent compaction effort. ASTM D2434 was then used to determine Ksat at 85 percent compaction effort.

2.5. PLANT GROWTH ANALYSIS

Media components meeting criteria in Sections 2.2, 2.3, and 2.4 were combined into media blends to conduct plant growth tests. Media and plants were placed in 45.42-liter (12-gallon) buckets and grown in the Center for Urban Horticulture greenhouse under controlled conditions for the duration of the study. Each treatment was replicated three times, and treatments were arranged in a random block design (See Appendix D for media treatment organization).

A 45.7-cm (18-inch) layer of media was placed on top of a 5-cm (2-inch) drainage layer of coarse sand in each bucket leaving approximately 2.5 cm (1 inch) of freeboard for ponding of influent water. *Deschampsia cespitosa* (tufted hairgrass) and *Juncus patens* (California grey rush), two species typically used in bioretention systems in western Washington, were selected for the experiment (see Appendix E for plant selection). Plants were bare root stock delivered from Four Corners Nursey in Bellingham, Washington in bundles of 50. Bare root plants were used to minimize contamination of the treatment media by planting soil. The roots were loosened and straightened to prevent roots from growing in a circular, constrained pattern. Each plant was photographed prior to planting in front of a gridded backdrop. Initial photographs provide a point of reference to compare with subsequent photos for determining plant health and vigor at the end of the project. Buckets were filled with media and four plants were planted in each bucket (two *D. cespitosa* and two *J. patens*). The greenhouse photo period was set at 12 hours from 7 a.m. to 7 p.m., and the temperature range was set at 68 to 72 degrees Fahrenheit. High-pressure sodium (400 watt) lights were used for the light source.

The plant study was conducted for 6 months. Plants were watered once at planting with tap water, then once per week for 16 weeks starting 1 week after initial watering with stormwater from the City of Redmond Maintenance and Operations Facility detention vault. Each planter received approximately 26 liters (5.7 gallons) gallons of stormwater per week at each watering. This period simulated the wetter conditions of winter. After approximately 16 weeks, plants were stressed by reducing the watering regime to once every 3 weeks and reducing the water volume to approximately 14.4 liters (3.2 gallons) gallons per container. Stressing was intended to simulate the dryer conditions of summer, and continued for 8 weeks.

Stormwater for plant watering was collected at City of Redmond's Maintenance and Operations Facility (18080 Northeast 76th Street Redmond, Washington 98052) and delivered weekly in a 747-liter HDPE tank by Herrera. Stormwater from the tank was pumped into LDPE plastic carboys for watering the plants. Samples were collected from the stormwater used to water the plants prior to each watering and delivered for analysis to ARI. The samples for water quality analysis were collected by taking a grab sample from the top, middle and bottom of the delivery tank, composited into one 20-liter (4.40-gallon) LDPE sample bottle, and stored at 3°C until delivery to the lab. Each sample was analyzed for pH, total P, ortho-P, NO₃+NO₂, and TKN.

Plant analysis, to assess the comparative health of plants in the various treatments, consisted of measurements for stem height and count, tissue total nitrogen, tissue total phosphorus, and total biomass. Procedural details for these analyses are described below.

Starting approximately 2 months after planting, pictures were taken once per month of all replicates for each treatment to compare growth. Pictures were taken from above and to the side of the plants. Pictures from the side were taken with a grid background. See Appendix F for time series photographs. Additionally, measurements of the longest live stalks were recorded and the number of live stalks counted for one rep in each treatment at approximately 2 months after planting, at the end of the wet watering period, and at the end of the drier watering period.

On May 2, 2017, after 5 weeks of "dry period" watering schedule, small cuttings were taken of each plant for tissue total N and total P analysis. The tallest stalks were not cut so that height measurements could still be taken in subsequent weeks. Tissue from the two *D. cespitosa* in each bucket were homogenized, as was that from the two *J. patens* in each bucket. Cuttings were weighed, rinsed with DI water to prevent contamination from soil, and then dried in a drying oven at 60°C for 48 hours. Dried cuttings were weighed again and then shipped to Kansas State University Soil Testing Lab for analysis. Ground tissue was subjected to a salicylic-sulfuric acid digest and then analyzed simultaneously for total N and total P using a Technicon AAI auto analyzer with the colorimetric Industrial Method 334-74W/B.

At the end of the study (June 12, 2017) all plants (roots and stems) were harvested. The roots were rinsed, the roots and stems divided and placed in paper bags, dried at 105°C for 18 hours, and then weighed to determine dry biomass. Additionally, pictures taken of the plant roots and stems on the grid used at planting to assess growth.

Data was plotted in box plots to visually inspect for normality. Additionally, Shapiro Wilks Normality Test and Q-Q plots were developed to determine if parametric or non-parametric statistics should be run to evaluate differences in means. Those tests were inconclusive; however, given the small dataset, non-parametric analyses were selected. Accordingly, a Kruskal-Wallis rank sum test (Helsel and Hirsch 2002) was then run to determine if any of the means were significantly different and a Tukey's multiple comparison test run to determine which specific means were significantly different. See Figures 14 through 19 for means comparison tests; means with different letters are statistically different ($\alpha = 0.05$). S

3. RESULTS

This section presents results from the four primary tasks performed for this study. Results are organized to include separate sections for each of the following study tasks:

- Survey and selection of potential media components
- Media component leaching tests
- Media component sorption tests
- Media blends and saturated hydraulic conductivity tests
- Plant growth analysis

Summary tables and statistics are used in this section. More detailed information and complete data sets are provided in the following supporting appendices and referred to in those sections where applicable:

- Appendix A Quality Assurance Project Plan
- Appendix B Media Component Matrix
- Appendix C Sorption K_d Value Table
- Appendix D Plant Study Treatment Placement
- Appendix E Plant Selection Tables
- Appendix F Plant Image Time Series
- Appendix G Plant Biomass Data and Summary Statistics

3.1. SURVEY AND SELECTION OF MEDIA COMPONENTS

A rapid survey of technical bulletins and scientific literature (see reference list at the end of Appendix B) was performed to identify candidate media components for this study in each of the following categories: bulk aggregates (e.g., sands) and bulk organic materials (e.g., compost) that comprise the majority of the media blends; and mineral and organic additives that provide specific pollutant capture and/or hydraulic characteristics, and comprise less of the overall volume. Candidate media components identified through this and previous surveys are shown in Appendix B.

Based on criteria identified in the Study Design and Methodology section, the following media components from Appendix B were identified for the SPLP extractions described in the next subsection.

Bulk Aggregate

- Ecology bioretention standard sand
- Lava sand (scoria earthtone sand)
- Lava sand (scoria surplus sand)
- State sand
- Volcanic sand

Selection Criteria

Used in 60%sand/40%compost media for control and polishing layer treatments.

Potential high water holding capacity. Locally available. Other studies suggest this sand may improve plant growth.

Potential high water holding capacity. Locally available. Other studies suggest this sand may improve plant growth.

Low leaching potential in previous studies. Coarser PSD and higher Ksat than volcanic sand.

Low leaching potential in previous studies. Very good performance from previous studies in media blends.

Bulk Organic

- Compost
- Coco coir
- Shredded cedar bark

Selection Criteria

Used in 60%sand/40%compost media for control and polishing layer treatment.

Low leaching potential in previous studies. High water holding capacity.

Locally available. Possible high water holding capacity.

Mineral Additive

- Activated alumina
- Diatomaceous earth
- Iron aggregate

Selection Criteria

Low leaching potential in previous studies. Strong P and Cu sorption.

Low leaching potential in previous studies. High water holding capacity. Improved plant growth in other studies.

Low leaching potential in previous studies. Strong P sorption.

Organic Additive

- High-carbon wood ash (PD 100+ mesh)
- Granular Activated Carbon 1230AW

Selection Criteria

Low leaching potential in previous studies. High water holding capacity. Metals sorption.

Low leaching potential in previous studies. High water holding capacity. Metals sorption.

Samples of the selected media components were subsequently collected from suppliers by Herrera staff. Where possible, these samples were collected from multiple locations in material stockpiles and composited for analysis.

3.2. MEDIA COMPONENT LEACHING TESTS

SPLP extractions were performed on the 13 media components identified from the survey results described in the previous subsection. These extractions were analyzed for TKN, NO₃+NO₂, ortho-P, and dissolved Cu. The SPLP extraction results are provided in Tables 8 through 10, organized by contaminant and ranked from lowest to highest concentration. Note that except for compost (1.5 mg/L), shredded bark (0.9 mg/L), and coir (0.9 mg/L), TKN concentrations were all at or below reporting limits (0.5 mg/L); accordingly, no table is provided for those results. (For all reporting limits, see the QAPP in Appendix A). All values are from single extractions (no replication); therefore, no statistical tests were performed for SPLP results.

Table 8. SPLP Extraction Results for Ortho Phosphorus.			
Media Component	Sample Treatment Type	Units	Value
Activated alumina (50% 100 micron/50% 14-28 mesh)	mineral additive	mg/L	0.0000
GAC 1230AW	organic additive	mg/L	0.0000
Iron aggregate	mineral additive	mg/L	0.0000
Volcanic sand	mineral bulk	mg/L	0.0070
State sand	mineral bulk	mg/L	0.0070
Ecology bioretention standard sand	mineral bulk	mg/L	0.0210
Lava sand (scoria surplus sand)	mineral bulk	mg/L	0.0270
Lava sand (scoria earthtone sand)	mineral bulk	mg/L	0.1740
coco coir	organic bulk	mg/L	0.2460
High-carbon wood ash PD 100+ mesh	organic additive	mg/L	0.4620
Diatomaceous earth	mineral additive	mg/L	0.9000
Shredded cedar bark	organic bulk	mg/L	1.4200
Compost	organic bulk	mg/L	1.5600

mg/L: milligrams per liter

Components are arranged from lowest to highest concentration.

Table 9. SPLP Extraction Results for Nitrate+Nitrite.

Media Component	Sample Treatment Type	Units	Value
Ecology bioretention standard sand	mineral bulk	mg/L	0.000
State sand	mineral bulk	mg/L	0.014
GAC 1230AW	organic additive	mg/L	0.015
Iron aggregate	mineral additive	mg/L	0.016
Lava sand (scoria earthtone sand)	mineral bulk	mg/L	0.022
Volcanic sand	mineral bulk	mg/L	0.023
Compost	organic bulk	mg/L	0.025
Diatomaceous earth	mineral additive	mg/L	0.027
Coco coir	organic bulk	mg/L	0.029
Shredded cedar bark	organic bulk	mg/L	0.032
Lava sand (scoria surplus sand)	mineral bulk	mg/L	0.050
High-carbon wood ash PD 100+ mesh	organic additive	mg/L	0.052
Activated alumina (50% 100 micron/50% 14-28 mesh)	mineral additive	mg/L	0.326

mg/L: milligrams per liter

Components are arranged from lowest to highest concentration.

Table 10. SPLP Extraction Results for Dissolved Copper.

Media Component	Sample Treatment Type	Units	Value
Activated alumina (50% 100 micron/50% 14-28 mesh)	mineral additive	µg/L	0.00
GAC 1230AW	organic additive	µg/L	0.00
Shredded cedar bark	organic bulk	µg/L	1.95
High-carbon wood ash PD 100+ mesh	organic additive	µg/L	2.33
Lava sand (scoria surplus sand)	mineral bulk	µg/L	5.58
Coco coir	organic bulk	µg/L	5.59
State sand	mineral bulk	µg/L	6.11
Volcanic sand	mineral bulk	µg/L	6.60
Diatomaceous earth	mineral additive	µg/L	9.10
Ecology bioretention standard sand	mineral bulk	µg/L	12.80
Compost	organic bulk	µg/L	25.10
Lava sand (scoria earthtone sand)	mineral bulk	µg/L	51.80
Iron aggregate	mineral additive	µg/L	158.00

µg/L: micrograms per liter

Components are arranged from lowest to highest concentration.

Media components were selected from the SPLP extractions to move forward for the sorption analysis. The justification for those components are as follows.

Component	Run Sorption	Justification
Activated alumina	Yes	Very good performance again for ortho-P and Cu, but elevated NO ₃ . Our best additive for P and Cu capture so far. Use in plant tests if polishing treatment included.
GAC 1230AW	Yes	Very good performance for all contaminants and provides a good (albeit expensive) benchmark.
Shredded cedar bark	No	Ortho-P leaching nearly as high as compost. No significant Cu leaching. Could be promising if vendor can supply shorter fibers that are easier to blend.
High-carbon wood ash (PD 100 + mesh)	Yes	Good results (as before a little high for ortho-P). This remains the best organic additive for metal capture and potentially for water holding capacity and plant growth.
Lava sand (scoria surplus sand)	Yes	Good results and this is a sand we haven't tested yet. Supplier can alter gradation to our specifications. Cost not known yet.
Coco coir	Yes	Good results (as before a little high for ortho-P). This remains our best organic bulk material to-date.
State sand	Yes	Good results (a little high for Cu). This sand has not been tested for sorption. Current gradation coarse for bioretention, but vendor may be able to alter PSD.
Volcanic sand	No	Consistently clean. Will use in Ksat and plant tests, but no need to test because of known low sorption capability.
Diatomaceous earth	No	High-carbon wood ash and DE perform similar functions; however, the high-carbon wood ash SPLP results are better.
Ecology bioretention standard sand	No	We will include this sand in plant tests as a control, but this material has been tested previously. Higher Cu leaching than the other sands in previous tests.

Component	Run Sorption	Justification
Compost	No	We will include compost in plant tests as a control, but this material has been tested previously with known exports N, P, and Cu.
Lava sand (scoria earthtone sand)	No	High NO ₃ and Cu leaching.
iron aggregate	Yes	Extreme leaching of Cu. However, one of our best additives for P and Cu capture in previous experiments. Use in plant tests if polishing treatment included. Contact vendor to determine if differences in feedstock or processing.

3.3. MEDIA COMPONENT SORPTION TESTS

Specialty Analytical Inc. performed sorption analysis for N, P, and Cu on the media components moving forward from Section 3.2. Table 11 summarizes the distribution coefficient (K_d) values by media component, analyte, and time solute was extracted from the sample. The distribution coefficient describes the affinity of the media components for target analytes (N, P, and Cu). The larger the K_d value the greater the affinity and the greater the capacity to sorb the target analyte in solution. Negative numbers in Table 11 indicate release of the analyte from the media component. The values presented in the Table 11 are an average of two (duplicate) samples taken at each time step. Figures 3 through 5 provide a graphic view of the average K_d values by analyte and time solute was extracted from the sample.

Table 11. Average Kd Values for Media Components at 2, 6, and 12 hours.

Average Kd Values for Nitrate-N (mL/g)									
Hours	State Sand	Lava Sand (Scoria Surplus)	Coco Coir	High-Carbon Wood Ash (PD 100 + mesh)	Activated Alumina (100 micron)	GAC 1230AW	Diatomaceous Earth	Iron Aggregate	Shredded Cedar Bark
2	-0.71	-1.40	3.03	1.54	-4.16	246.27	-0.39	3.81	-1.82
6	-1.17	-1.71	3.18	1.62	-4.36	176.28	-1.08	25.23	-1.49
12	-0.49	-1.29	6.31	2.97	-4.11	304.80	-0.62	226.93	0.24
Average Kd Values for Ortho-Phosphorus (mL/g)									
Hours	State Sand	Lava Sand (Scoria Surplus)	Coco Coir	High-Carbon Wood Ash (PD 100 + mesh)	Activated Alumina (100 micron)	GAC 1230AW	Diatomaceous Earth	Iron Aggregate	Shredded Cedar Bark
2	0.51	0.99	-13.28	-9.94	1,597.11	189.26	-6.42	1766.27	-17.97
6	2.06	0.30	-12.72	-6.89	ND	258.89	-6.34	1754.92	-15.76
12	1.82	-0.74	-12.06	-7.91	1,869.26	294.95	-7.27	545.16	-17.20
Average Kd Values for Total Copper (mL/g)									
Hours	State Sand	Lava Sand (Scoria Surplus)	Coco Coir	High-Carbon Wood Ash (PD 100 + mesh)	Activated Alumina (100 micron)	GAC 1230AW	Diatomaceous Earth	Iron Aggregate	Shredded Cedar Bark
2	88.59	30.94	65.94	701.58	11,104.89	370.90	171.47	1,463.89	365.66
6	137.64	42.73	54.94	799.94	24,694.08	1,091.68	244.28	245.41	329.08
12	190.38	56.14	46.64	1,628.95	4,884.46	1,692.72	317.50	115.63	170.94

ND = 0 or no value for B (final solute concentration) in Kd equation ($K_d = (A-B)*V / ((M_s)*B)$).

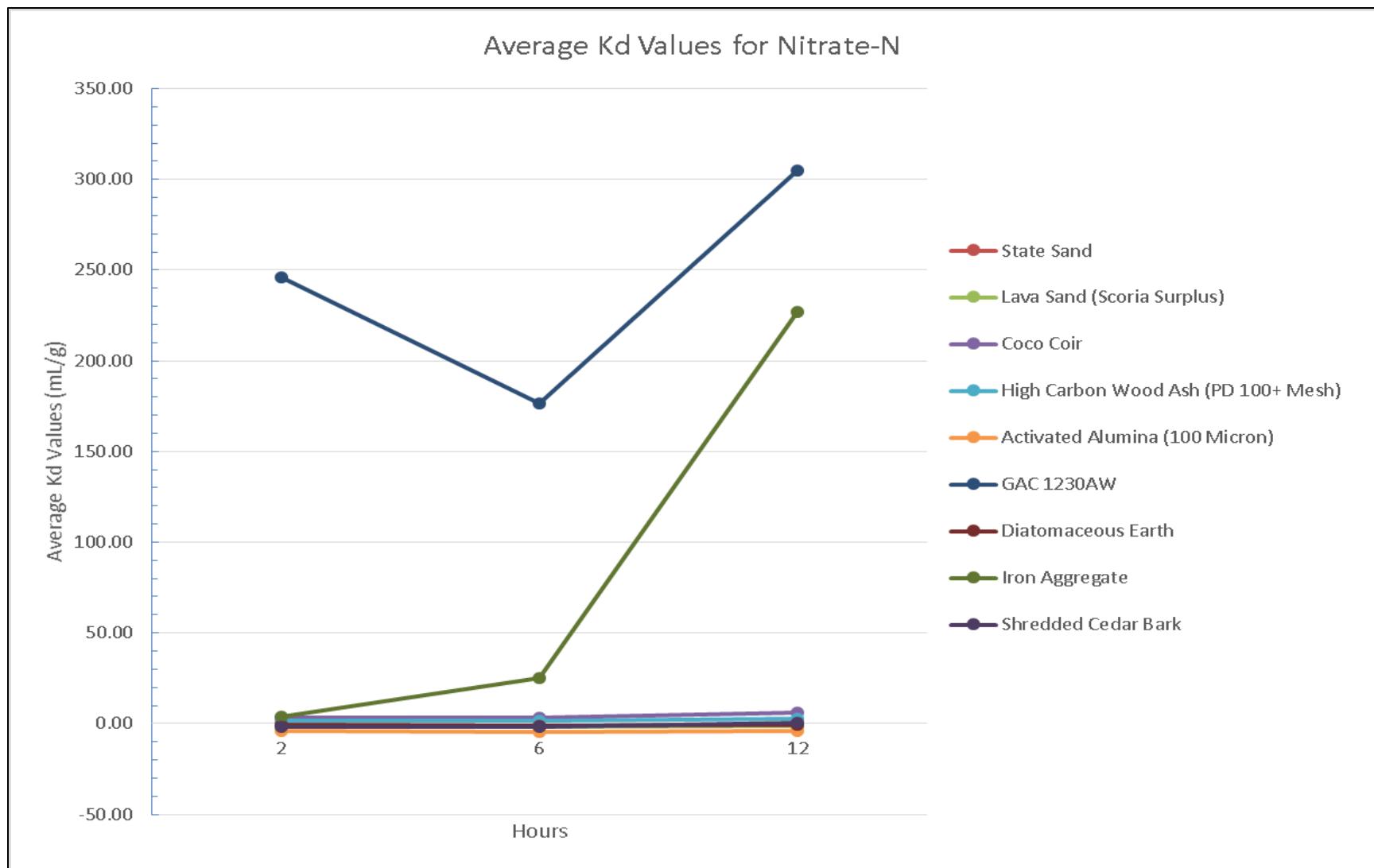


Figure 3. Average Kd Values for Nitrate-N at 2, 6, and 12 hours.

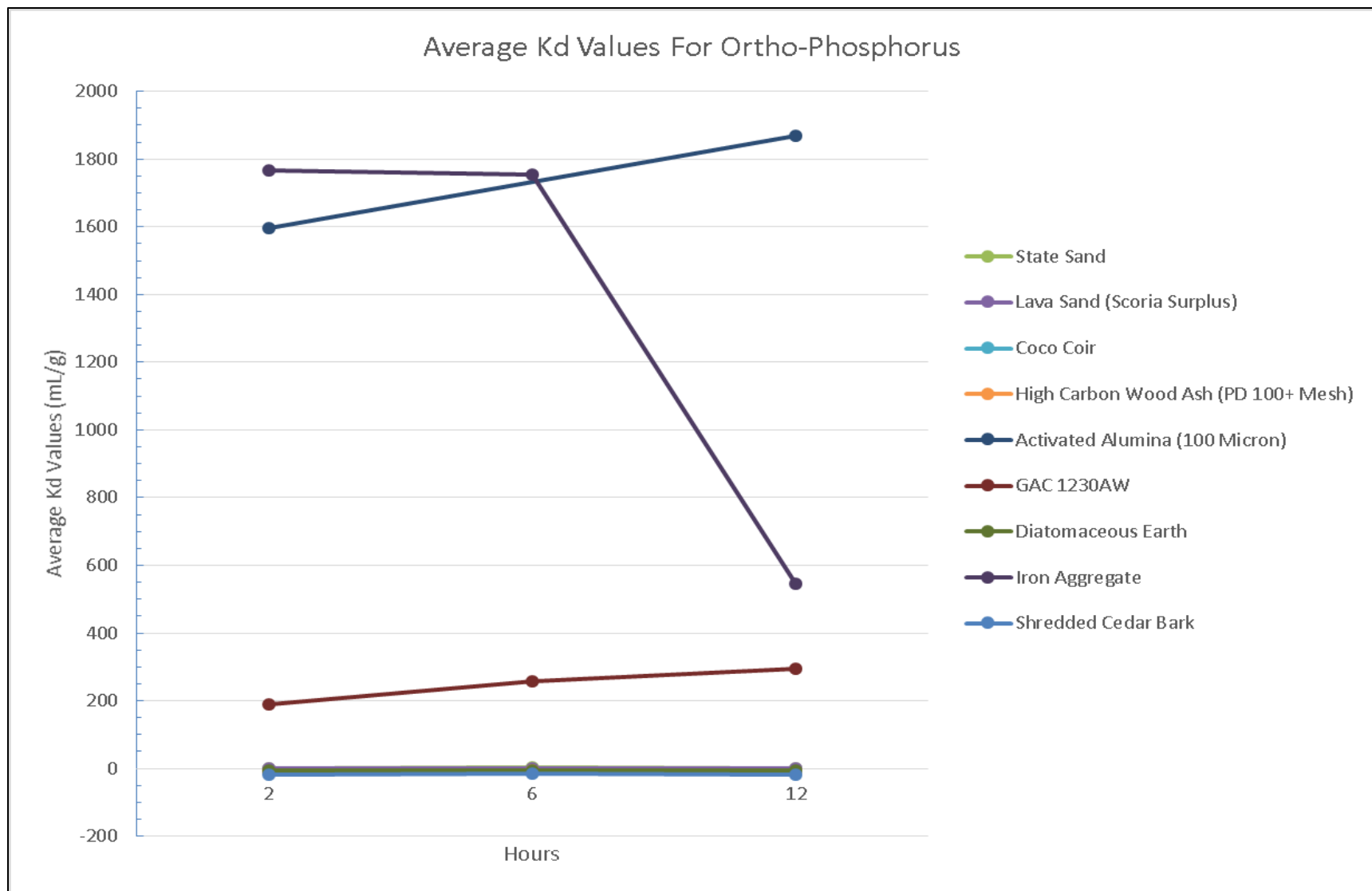


Figure 4. Average Kd Values for Ortho-Phosphorus at 2, 6, and 12 hours.

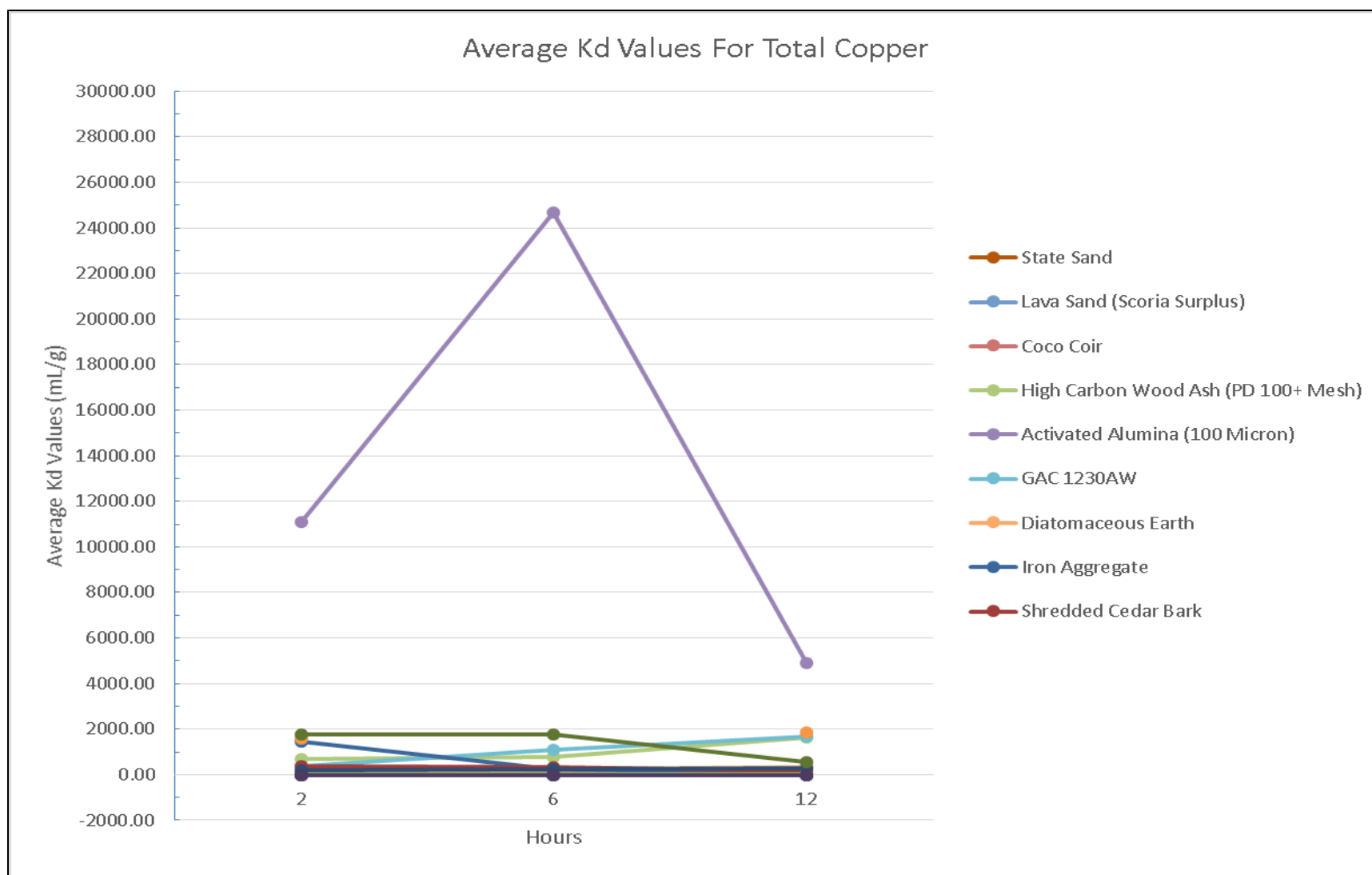


Figure 5. Average Kd Values for Dissolved Copper at 2, 6, and 12 hours.

3.3.1. Kd Values for Nitrate

Nitrate is a highly mobile anion in soil solution. None of the media components showed significant sorption capability for nitrate except for the GAC 1230AW and the iron aggregate at 12 hours. In previous studies (Herrera 2015c), media blends using volcanic sand, coco coir, and high-carbon wood ash provided significant nitrate+nitrite capture. The mechanism for this is not well understood. Given the SPLP extraction results, significant reduction in nitrate+nitrite is not anticipated in blends using the above materials unless nitrate capture is demonstrated again in subsequent water quality treatment experiments with volcanic sand, coir, and high-carbon wood ash or other blends.

3.3.2. Kd Values for Ortho-Phosphorus

As anticipated, the activated alumina and iron aggregate showed strong sorption capacity for phosphate. The Kd values for the iron aggregate dropped sharply after 6 hours. This can be due to several factors, including dissolution of solid material over time therefore increasing sorbent concentration in solution, changing pH, interference from competing ions or preference for the alumina. However, activated alumina Kd values increased slightly over the 12-hour period indicating that alumina is a reliable phosphate sorbent over typical residence times within bioretention.

3.3.3. Kd Values for Dissolved Copper

High-carbon wood ash, GAC, and particularly activated alumina all showed strong sorption capability for dissolved Cu. The activated alumina Kd values dropped sharply after 6 hours. This can be due to several factors, including dissolution of solid material over time therefore increasing sorbent concentration in solution, changing pH, interference from competing ions, or dissolved Cu preference for high-carbon wood ash that exhibits increasing Kd values from 6 to 12 hours.

3.4. MEDIA BLENDS AND KSAT TESTS

Based on the above analyses, best professional judgment, and input from the project advisory group, selected components were combined in blends designed to minimize pollutant flushing, maximize pollutant capture performance, and support plant growth. The saturated hydraulic conductivity was then evaluated for each blend. The composition of each blend is summarized in Table 12.

Table 12. Media Blend Composition and Justification.

No.	Media Blend Abbreviations	Media Blend Treatments ^a	Justification
1	60sand/40comp	60% miles canyon sand/40% compost (control)	Control to compare plant growth with treatments. Note that the 60/40 blend provides optimum plant growth but poor water quality treatment. Therefore, this blend is not viable where the high-performance treatments are applicable and a somewhat misrepresentative control.
2	70vs/20cp/10ash	70% volcanic sand/20% coco coir/10% high-carbon wood ash	Top performer from previous media research (Kitsap study).
3	50ss-vs/40cp/10ash	50% state-volcanic sand mix/40% coco coir/10% high-carbon wood ash	Sand: the state (coarse and high Ksat) and volcanic (finer) sands are two of the three clean sands identified; however PSD of these cannot be altered. Therefore the sands were blended (75%ss/25%vs) to attain a desirable coefficient of uniformity, reduce Ksat, and possibly improved TSS capture. OM content: Coir provides high water holding capacity, some nutrient content and potential N capture; therefore, increasing content in the blend may improve plant health.
4	70ss-vs/20cp/10ash	70% state-volcanic sand mix/20% coco coir/10% high-carbon wood ash	Compare lower coir (organic matter content) for plant growth with blended sand.
5	50ls/40cp/10ash	50% lava sand/50% coco coir/10% high-carbon wood ash	Sand: lava sand is one of three sands that have low N, P and Cu leaching potential. This is the only sand that the supplier can alter the PSD, therefore, providing greater flexibility to meet hydraulic targets. OM content: Coir provides a high water holding capacity, some nutrient content and potential N capture; therefore, increasing content in the blend may improve plant health.
6	70ls/20cp/10ash	70% lava sand/20% coco coir/10% high-carbon wood ash	Compare lower coir (organic matter content) for plant growth with blended sand.
7	70ss-vs/20cp/10ash/ compmulch	70% state-volcanic sand mix/20% coco coir/10% high-carbon wood ash/2-inch compost mulch	This treatment includes lower coir content, and compost mulch to increase nutrients and potentially improve plant growth. The nutrients from the compost mulch may be sorbed by the media below when not taken up by plants.
8	70vs/30comp/p-layer	70% volcanic sand/ 30% compost/polishing drainage layer (medium sand, 5% activated alumina and 5% iron aggregate)	The polishing layer approach is useful for those jurisdictions already deploying compost-based media (Phase 1 communities) and this approach performed well in the Seattle Polishing Layer Study (Herrera 2016). That study used a 12-inch polishing layer. We used a 2-inch layer for this study.

^a All component mixtures are by volume.

PSD = particle size distribution.

Saturated hydraulic conductivity of the blends was evaluated using ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort) to determine optimum moisture content to obtain maximum dry density at 85 percent compaction effort. ASTM D2434 was then used to determine saturated hydraulic conductivity at 85 percent compaction effort (see Table 13 and Figure 6 for results).

Table 13. Media Blend Saturated Hydraulic Conductivity.					
Treatment	Maximum Dry Unit Weight (pounds/cubic foot)	Optimum Moisture Content (percent by mass)	Relative Compaction (percent max dry unit weight)	Ksat (cm/hr)	Ksat (in/hr)
70vs/20cp/10ash	87.3	23.5	85	136.8	54
50ss-vs/40cp/10ash (75%ss and 25%vs)	87.3	23.4	86	61.2	24
70ss-vs/20cp/10ash (75%ss and 25%vs)	100.8	19.3	83	122.4	48
50ls/40cp/10ash	74.7	31.5	81	39.6	16
70ls/20cp/10ash	82.5	23.7	86	68.4	28
50ss-vs/40cp/10ash (50%ss and 50%vs)	80.4	24.9	85	79.2	32
70ss-vs/20cp/10ash (50%ss and 50%vs)	97.4	20.7	85	133.2	52

Note that the blends in Table 13 containing 50 percent state sand and 50 percent volcanic sand were developed specifically to test the influence gradation on Ksat and not used in the plant experiment blends.

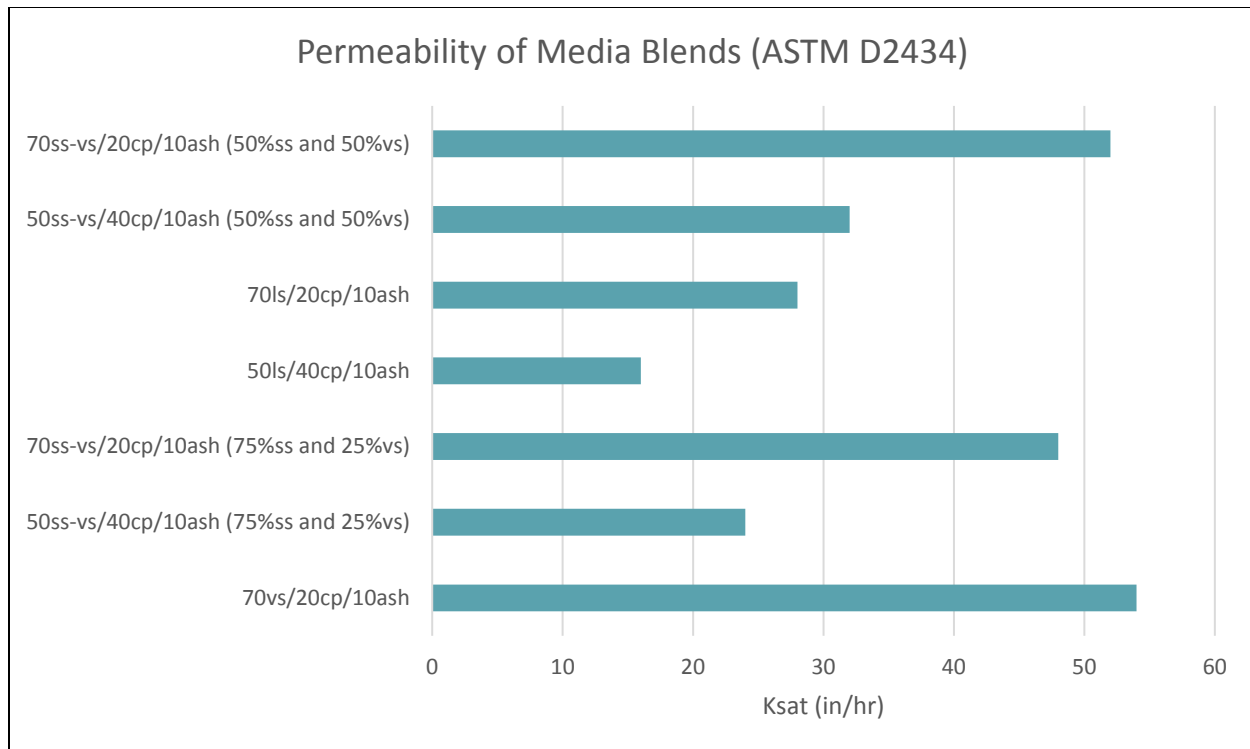
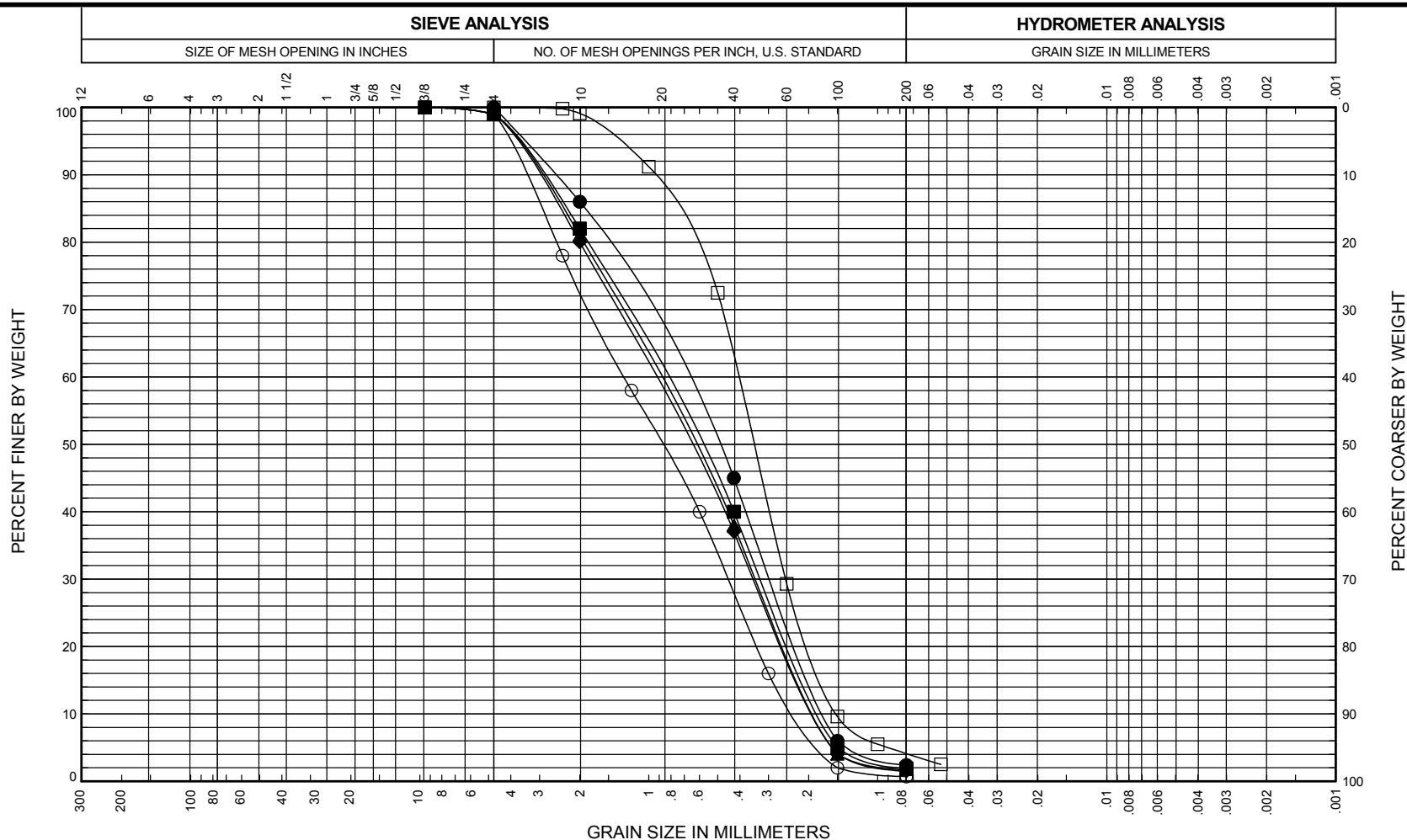


Figure 6. Media Blend Saturated Hydraulic Conductivity.

Note that due to budget constraints and the focus on high-performance, non-compost based media, Ksat was not evaluated for the 60sand/40comp and the 70vs/30comp/p-layer blends. For comparisons to the results from this study, Ksat for two similar polishing layers placed under compost-based media were 33.87 and 25.90 cm/hr (12.94 and 10.20 in/hr) in a previous study (Herrera 2016). In a 2012 study focused on Ksat test methods, several geotechnical labs tested the 60sand/40comp media using ASTM D2434 with results ranging from about 9.1 to 126 cm/hr (3.6 to 49.6 in/hr).

Three different sands were used in the media blends: a coarser state sand, a finer volcanic sand, and a lava sand with a different physical (more porous) characteristic. The state sand and volcanic sands were mixed at different ratios (50/50 or 75 percent state/25 percent volcanic sand) to test how these mixtures would influence Ksat. The coco coir ratio was also altered in these sand blends to test how organic matter would influence Ksat. Increasing and decreasing the coir content was also of interest for altering the water holding capacity and perhaps plant growing capability of the blends. These various blends were charted to assess their gradations coefficient of uniformity and curve in relation to the current bioretention sand specification (see Figure 7).



COBBLES	COARSE	FINE	COARSE	MEDIUM	FINE	FINES: SILT OR CLAY
	GRAVEL		SAND			

BORING AND SAMPLE NO.	GRAVEL %	SAND %	FINES %	% Finer 9.5 mm	% Finer 4.75 mm	% Finer 2.0 mm	% Finer 0.425 mm	% Finer 0.15 mm	% Finer 0.075 mm	D90	D85	D60	D50	D30	D20	D15	D10	D5	Cu	Cc	Alternative Media Bioretention Study	
● 50% Icon/ 50% Walrath	0.0	97.6	2.4		100.0	86.0	45.0	6.0	2.4	2.6	1.9	0.75	0.51	0.28	0.22	0.19	0.17	0.12	4.5	0.6	GRAIN SIZE DISTRIBUTION Icon & Walrath Sand Mixes 21-1-08824-063	
■ 65% Icon/ 35% Walrath	1.0	97.1	1.9	100.0	99.0	82.0	40.0	5.0	1.9	3.0	2.3	0.89	0.61	0.32	0.23	0.20	0.17	0.15	5.1	0.6		
▲ 70% Icon/ 30% Walrath	1.0	97.3	1.7	100.0	99.0	81.0	38.0	4.0	1.7	3.1	2.4	0.94	0.65	0.33	0.24	0.21	0.18	0.15	5.2	0.7		
◆ 75% Icon/ 25% Walrath	1.0	97.5	1.5	100.0	99.0	80.0	37.0	4.0	1.5	3.2	2.5	0.97	0.68	0.34	0.25	0.21	0.18	0.15	5.4	0.7		
○ ICON State Sand	1.0	98.3	0.7	100.0	99.0	73.0	28.1	2.0	0.7	3.5	3.0	1.3	0.88	0.45	0.34	0.29	0.22	0.17	5.7	0.7		
□ Walrath 4120 Sand	0.0				100.0	99.1	62.4	9.6	4.1	0.96	0.79	0.41	0.35	0.25	0.20	0.17	0.15	0.090	2.7	1.0	SHANNON & WILSON, INC. Geotechnical and Environmental Consultants	
																				FIG. DRAFT		

FIG. DRAFT

Figure 7. Gradations and Coefficient of Uniformity (Cu) and Curve (Cc) for Sands Used for the Media Blends.

Note that in Figure 7 above, what is described as Icon sand in the figure is described as state sand in this report, and Walrath sand (figure) is described as volcanic sand (report).

As indicated by the Ksat results, changing the ratio of state (coarser) and volcanic (finer) sands did not significantly influence Ksat. For example, Ksat for the blend with 75 percent state, 25 percent volcanic sand, and 20 percent coir was 122 centimeters per hour (cm/hr) or 48 in/hr and 133 cm/hr (52 in/hr) for the 50/50 percent blend with 20 percent coir. In fact, Ksat was less for the coarser mix, which is likely due to a higher coefficient of uniformity for the 75 percent state/25 percent volcanic sand (see Table 7 for sand coefficient of uniformity). However, the organic matter (coir) content did significantly influence Ksat. For both, Ksat for the sand blends dropped nearly in half when doubling the coco coir content from 20 to 40 percent. Specifically, 122 cm/hr (48 in/hr) for the 70ss-vs/20cp/10ash with 75 percent state sand and 25 percent volcanic sand and 61 cm/hr (24 in/hr) for the 50ss-vs/40cp/10ash with 75 percent state sand and 25 percent volcanic sand.

3.5. PLANT GROWTH ANALYSIS

This section presents results from growth analysis beginning with data obtained from chemical analyses of the irrigation water. Subsequent subsections then describe differences in plant growth across the different treatment based on different measures.

3.5.1. Irrigation Water Analyses

Irrigation water (stormwater) was analyzed for 15 of the 19 watering events. The nutrient input from the stormwater is presented below in Table 14.

Table 14. Nutrient Inputs from Irrigation Water (stormwater).		
Nutrient	Median Concentration (mg/L)	Total Nutrient Load (mg)
Total Kjeldahl Nitrogen	1.1	505
Nitrate-Nitrite	0.08	36
Total Phosphorus	0.206	95
Ortho-Phosphorus	0.068	31

Total load = (16 waterings at 26 liters/watering)(3 waterings at 14.4 liter/watering) = 459.2 liters x median concentration of nutrient.

3.5.2. General Growth Observations

Three *J. patens* plants died within the first 2 months of planting: one death in Treatment 6 row A (70ls/20cp/10ash), one in Treatment 3 row C (50ss-vs/40cp/10ash) and one in Treatment 4 row A (70ss-vs/20cp/10ash). See Appendix D for a diagram of the plant treatment arrangement. All other *J. patens* planted in these treatments survived until the end of the trial, and, therefore, it is unlikely that the early mortalities were due to inadequacies in the media. Rather, these early deaths may have been due to unhealthy bare roots or to the physical disruption that occurred when pooling water caused the media to float. Coconut coir was an especially light soil component; and during the first weeks of watering, some plants in treatments with coconut coir became dislodged due to the media floating in pooled water. One other mortality occurred in

week 24, well into the dry period (*J. patens* growing in Treatment 1 row B [60sand/40comp]). Based on the large size of the other plants in this planter, the *J. patens* in question may have been crowded and/or shaded out.

Appendix F contains a time series of pictures of each treatment from week 4, week 16 (end of wet period and beginning of dry period), and week 25 (end of study) for a visual comparison.

3.5.3. Plant Stem Comparisons

Qualitative evaluation of growth and health were made every 2 months by measuring the height of the longest live stem of each plant (vertical growth evaluation) and counting the number of live shoots of each plant (horizontal growth evaluation).

3.5.3.1. Stem Height

The first measurement of stem height on February 14, 2017, shows that, as expected, the plants in media with compost grew faster than those in media without compost. No significant difference between the height of non-compost plants is seen in any of the three measurements. Observing the trajectory of the plants over time indicate that all three compost treatments continue to grow from the first to the second measurement, while the plants in all non-compost treatments appear to stall in vertical growth after the first measurement. Measurements of vertical grass (*D. cespitosa*) and rush (*J. patens*) growth can be seen in Figures 8 and 9, respectively.

All treatments have a slight decrease in the height of *D. cespitosa* by the end of the dry period as the tallest stalks died or withered. However, the height of *J. patens* increases slightly in all treatments by the end of the dry period. These data support the anecdotal observation that *J. patens* was more robust in the dry period than was *D. cespitosa*, based on other observations of tissue color over time. Final measurements of vertical and horizontal dimensions of both plant types are shown in Table 15. For vertical growth, both grass and rush plants in treatments containing compost reached more than double the height of the plants in non-compost treatments. As previously stated, no significant difference was seen between the height of plants in non-compost treatments; and interestingly, no significant difference was seen between the height of plants in treatments containing compost either. This means that plants in Treatment 7, which contained only a layer of compost on top, grew as tall as plants in Treatment 1, which had 40 percent compost mixed throughout.

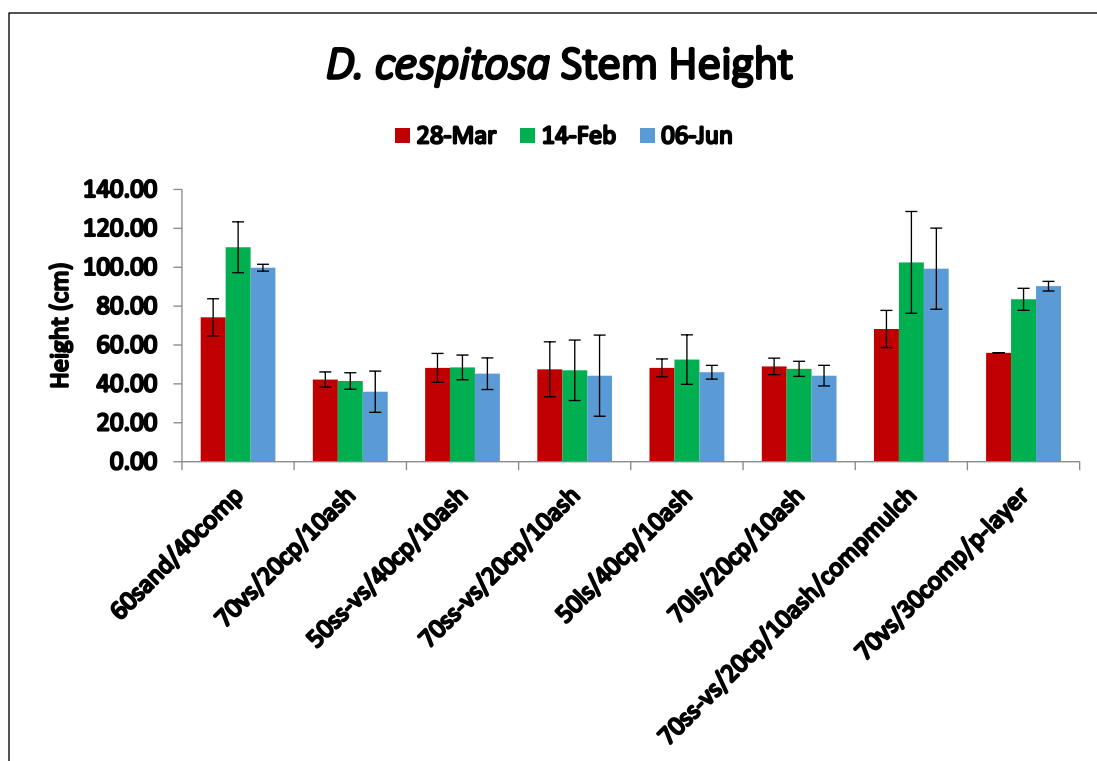


Figure 8. Height of Tallest Live Stem for *D. cespitosa* Over Time.

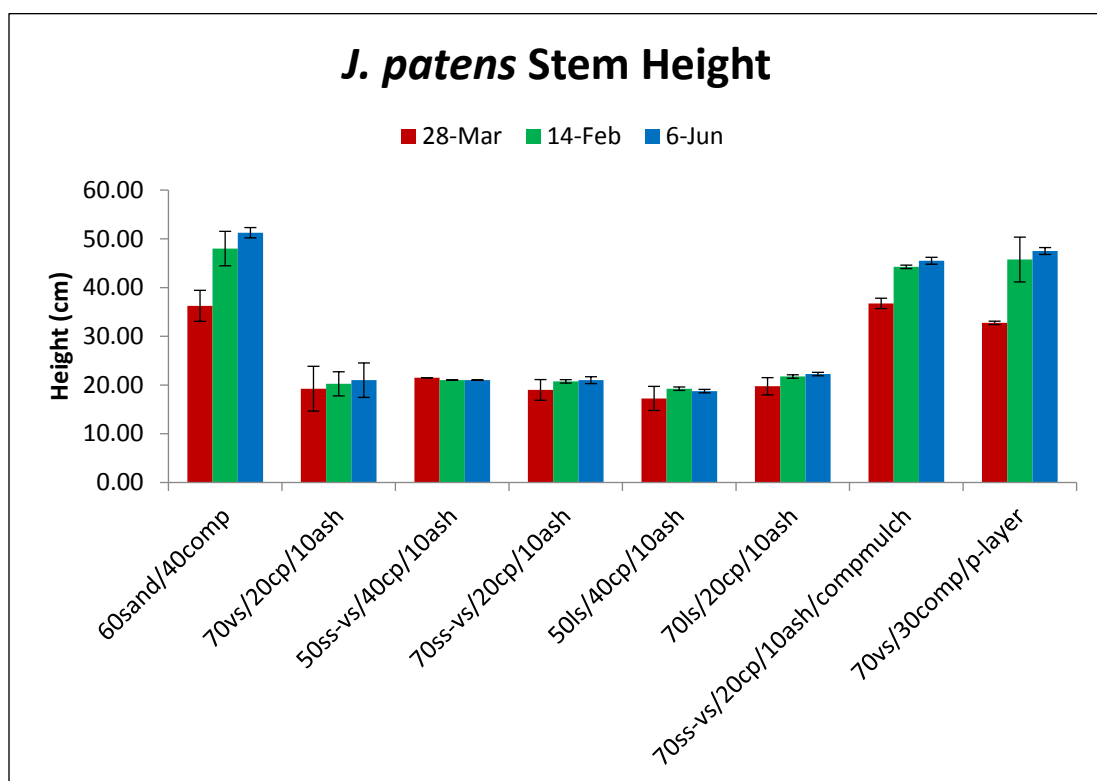


Figure 9. Height of Tallest Live Stem for *J. patens* Over Time.

Table 15. Final Height and Stem Count for <i>D. cespitosa</i> and <i>J. patens</i> .					
No.	Treatment	Height (cm)		Stem Count	
		<i>D. cespitosa</i>	<i>J. patens</i>	<i>D. cespitosa</i>	<i>J. patens</i>
1	60sand/40comp	99.8 ± 1.8	51.3 ± 1.1	59 ± 1	149 ± 33
2	70vs/20cp/10ash	36.0 ± 10.6	21.0 ± 3.5	26 ± 6	24 ± 8
3	50ss-vs/40cp/10ash	45.3 ± 8.1	21.0 ± 0.0	42 ± 4	12 ± 0
4	70ss-vs/20cp/10ash	44.3 ± 20.9	21.0 ± 0.7	28 ± 1	19 ± 6
5	50ls/40cp/10ash	46.0 ± 3.5	18.8 ± 0.4	27 ± 5	9 ± 10
6	70ls/20cp/10ash	44.3 ± 5.3	22.3 ± 0.4	31 ± 12	21 ± 0
7	70ss-vs/20cp/10ash/compmulch	99.3 ± 20.9	45.5 ± 0.7	54 ± 34	130 ± 75
8	70vs/30comp/p-layer	90.3 ± 2.5	47.5 ± 0.7	65 ± 28	191 ± 42

3.5.3.2. Stem Count

Stem counts, used to measure horizontal growth, tell a similar story as height measurements. Stem counts for *D. cespitosa* and *J. patens* are shown over time in Figures 10 and 11, respectively. For *D. cespitosa*, plants in compost treatments did have more stalks throughout than those in non-compost treatments, but the difference was not as substantial with horizontal as with vertical growth. Further, grass stem counts increased throughout the study for all treatments (there was no “stalling” as was seen with vertical growth). However, the opposite was the case for *J. patens*. By the end of the trial, rush plants grown in treatments with compost had significantly more stalks than those grown in non-compost treatments (see Table 11). Rushes grown in non-compost treatments also stalled in horizontal growth after the first measurement, and no significant difference was seen between any of the non-compost treatments. Final measurements of vertical and horizontal dimensions of both plant types are shown in Table 15.

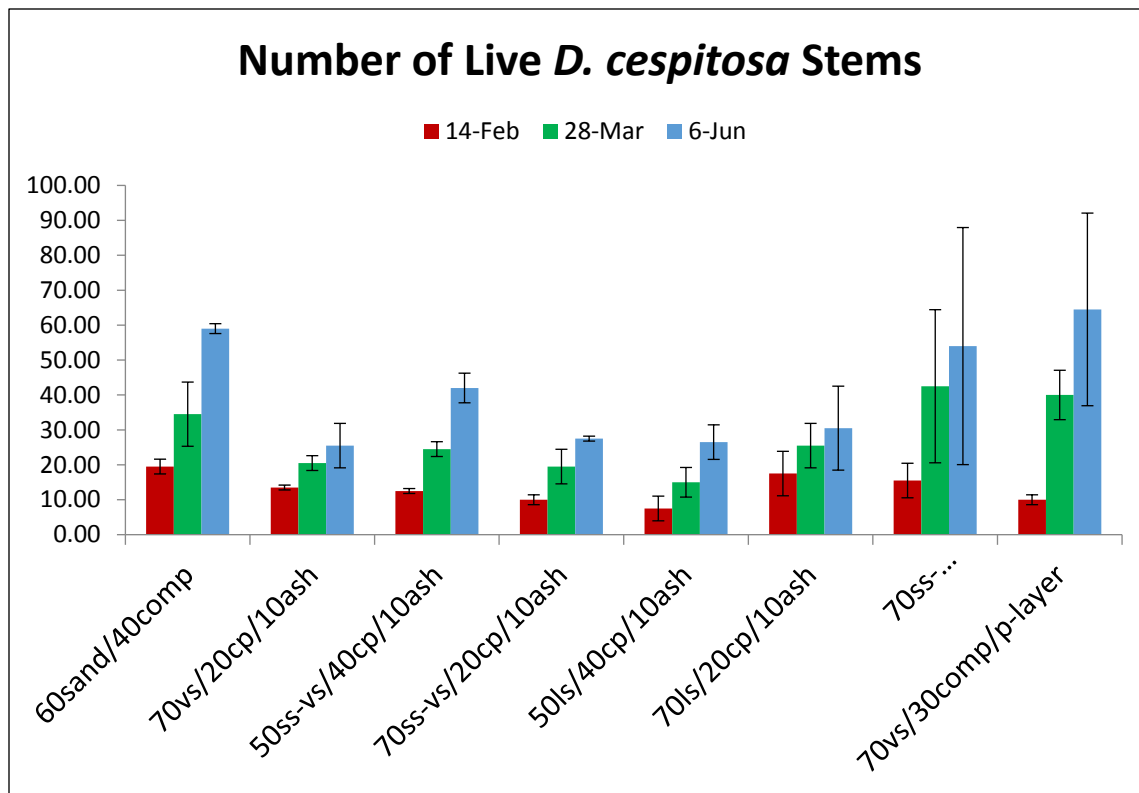


Figure 10. Number of Live *D. cespitosa* Stems Over Time.

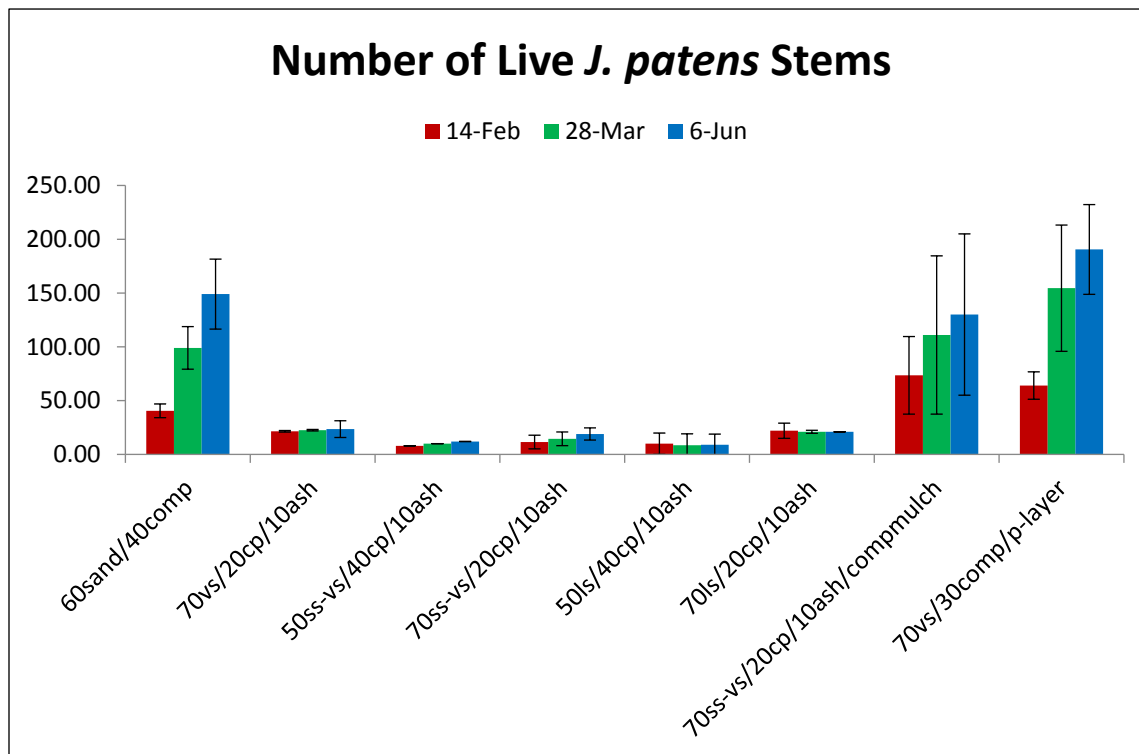


Figure 11. Number of Live *J. patens* Stems Over Time.

3.5.4. Analysis of Nitrogen and Phosphorus Content

The results of the tissue analysis for total N and P in *D. cespitosa* and *J. patens* are shown in Tables 16 and 17, respectively. The letters in the table convey the results of a Tukey HSD means separation that was performed separately for N and P in reed tissue and grass tissue. Means that do not share letters are statistically different. Expected levels of total N and P in tissue vary substantially with plant species, so in this case the plant tissue grown in the 60sand/40comp mix will be used as a reference of “healthy” tissue.

Table 16. Tissue Analysis of Grass (<i>D. cespitosa</i>) Grown in Different Soil Mixtures.					
No.	Treatment	Total N (percent)		Total P (percent)	
1	60sand/40comp	A	0.98 ± 0.06	AB	0.38 ± 0.08
2	70vs/20cp/10ash	B	0.50 ± 0.04	C	0.23 ± 0.00
3	50ss-vs/40cp/10ash	B	0.57 ± 0.12	BC	0.25 ± 0.04
4	70ss-vs/20cp/10ash	B	0.61 ± 0.22	C	0.21 ± 0.02
5	50ls/40cp/10ash	B	0.57 ± 0.08	C	0.23 ± 0.02
6	70ls/20cp/10ash	B	0.48 ± 0.04	C	0.18 ± 0.05
7	70ss-vs/20cp/10ash/compmulch	B	0.59 ± 0.07	ABC	0.25 ± 0.03
8	70vs/30comp/p-layer	AB	0.74 ± 0.08	A	0.38 ± 0.06

Mean, standard deviation, and Tukey HSD statistical groups are shown for total N (percent) and total P (percent). If two treatments share a letter, they are NOT statistically different.

Table 17. Tissue Analysis of Rushes (<i>J. patens</i>) Grown in Different Soil Mixtures.					
No.	Treatment	Total N (percent)		Total P (percent)	
1	60sand/40comp	A	1.54 ± 0.16	A	0.41 ± 0.07
2	70vs/20cp/10ash	C	0.81 ± 0.03	C	0.20 ± 0.02
3	50ss-vs/40cp/10ash	C	0.71 ± 0.01	C	0.19 ± 0.00
4	70ss-vs/20cp/10ash	C	0.76 ± 0.02	BC	0.23 ± 0.02
5	50ls/40cp/10ash	–	not enough tissue	–	not enough tissue
6	70ls/20cp/10ash	C	0.75 ± 0.16	BC	0.24 ± 0.02
7	70ss-vs/20cp/10ash/compmulch	B	1.15 ± 0.07	AB	0.31 ± 0.02
8	70vs/30comp/p-layer	A	1.47 ± 0.07	A	0.36 ± 0.03

Mean, standard deviation, and Tukey HSD statistical groups are shown for total N (percent) and total P (percent). If two treatments share a letter, they are NOT statistically different.

There is a clear divide between treatments with compost (1, 7, and 8) and treatments without, which is supported by Tukey’s multiple comparison test for both the grass and rush species (see Tables 16 and 17). Plants grown in Treatments 1 (60sand/40comp) and 8 (70vs/30comp/p-layer) had significantly higher total N concentration than plants grown in the remaining treatments. For rush tissue (*J. patens*), Treatment 7 (70ss-vs/20cp/10ash/compmulch) had statistically lower total N concentrations than Treatments 1 and 8, but statistically higher total N concentrations than the remaining treatments, all of which performed similarly to one another. For grass tissue (*D. cespitosa*), Treatment 7 (70ss-vs/20cp/10ash/compmulch) performed similarly to all non-

compost treatments for N concentrations. Figure 12 provides a visual comparison of the total N concentration of plant tissue grown in each BSM treatment.

Again, the presence or absence of compost made the largest difference for P concentrations in the plant tissue. For the grass tissue (*D. cespitosa*), Treatments 1 (60sand/40comp) and 8 (70vs/30comp/p-layer) were statistically higher than all the non-compost treatments except Treatment 3 (50ss-vs/40cp/10ash). The P concentration of grass tissue in Treatment 7 (70ss-vs/20cp/10ash/compmulch) was variable, such that Treatment 7 was statistically similar to all treatments, both those with and without compost. A similar pattern is seen for total P concentration in rush tissue (*D. cespitosa*): Treatments 1 (60sand/40comp) and 8 (70vs/30comp/p-layer) were statistically higher than all the non-compost treatments. All non-compost treatments had statistically similar P concentrations; and for rush tissue, Treatment 7 (70ss-vs/20cp/10ash/compmulch) performed similarly to Treatments 1, 4, 6, and 8. Figure 13 provides a visual comparison of the total P concentration of plant tissue grown in each BSM treatment.

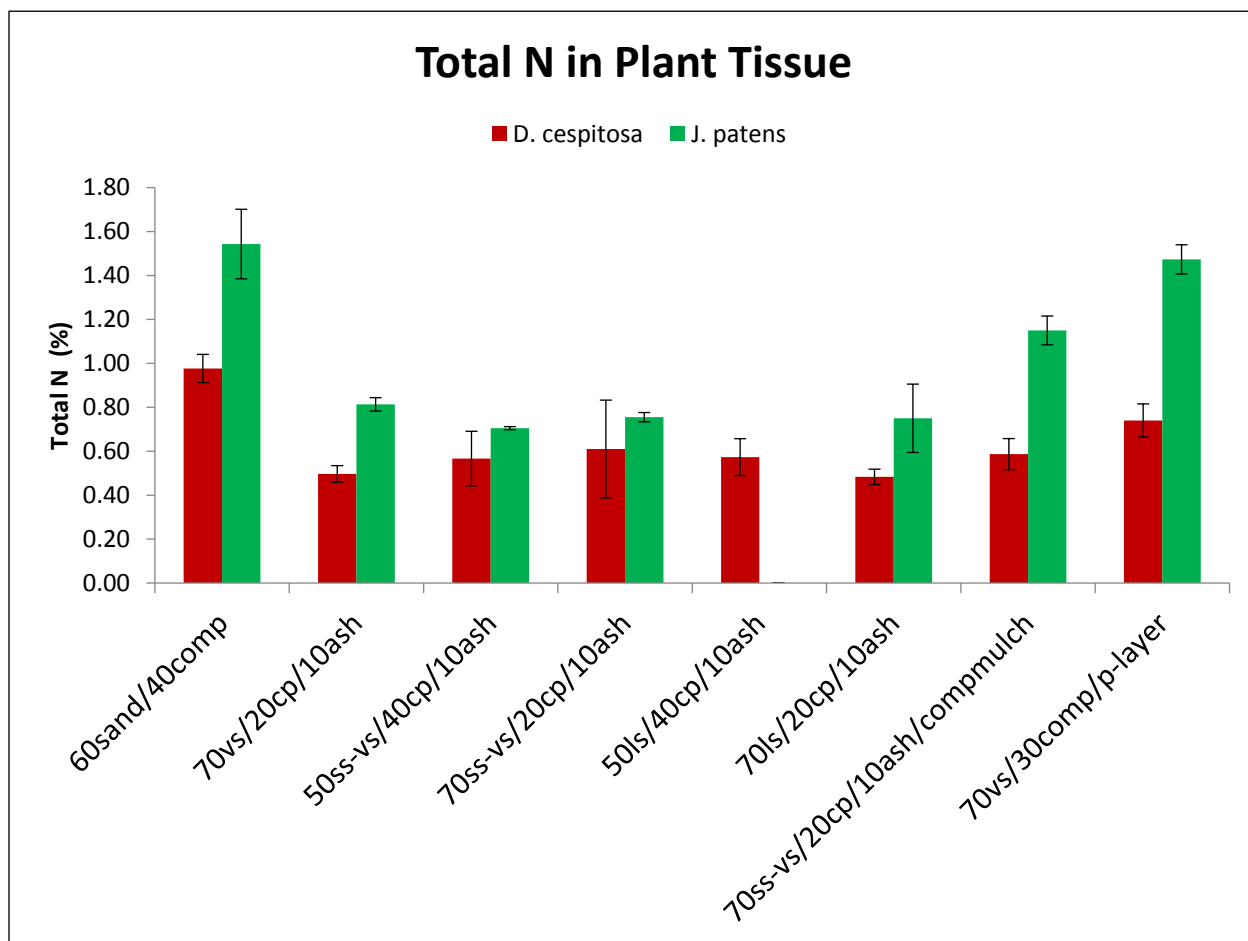


Figure 12. Total N (percent) of Grass (*D. cespitosa*) and Rush (*J. patens*) Tissue in Each Media Treatment.

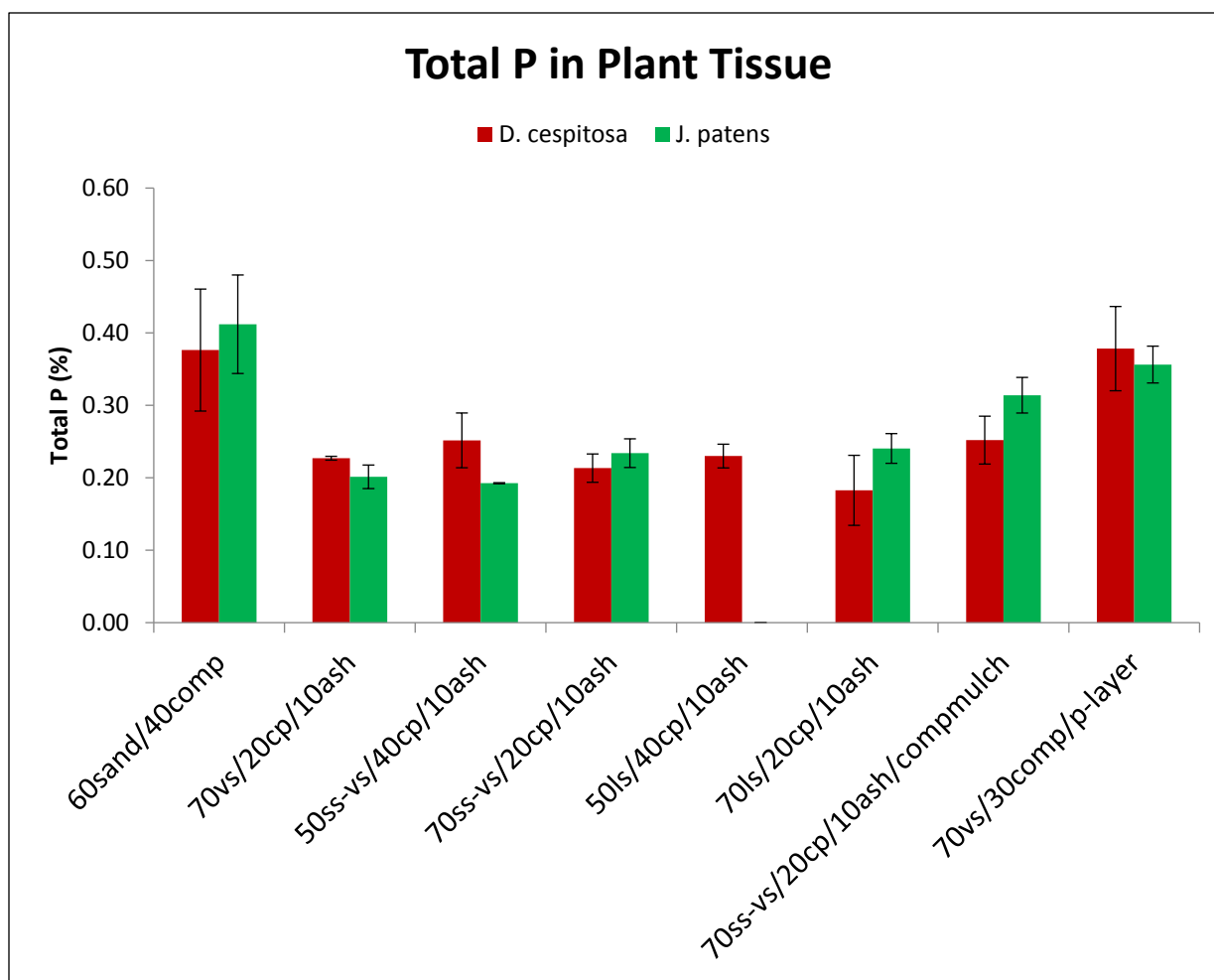


Figure 13. Total P (percent) of Grass (*D. cespitosa*) and Rush (*J. patens*) Tissue in Each Media Treatment.

3.5.5. Plant Biomass

After 6 months the plants were removed from the buckets and the roots were carefully separated from the media and washed. The whole plant was placed on a grid to visually compare growth and then the stems and roots separated and placed in paper bags for drying. Stems and roots were placed in a drying oven at 105°C for 18 hours and then weighed. Figures 14 through 19 below provide the total biomass distribution of composite samples consisting of all plants for each species in each treatment. For example, all six *D. cespitosa* are composited into one sample for Treatment 7 (70ss vs/20cp/10ash/compmulch) (2 *D. cespitosa*/rep x 3 reps) and all six *J. patens* are composited. Note that during the sampling, cementing or caking of the polishing layer was observed in one of the polishing layer treatments (70vs/30comp/p-layer) indicating that the 5 percent iron content may have been too high.

Figure 14. Deschampsia Roots.

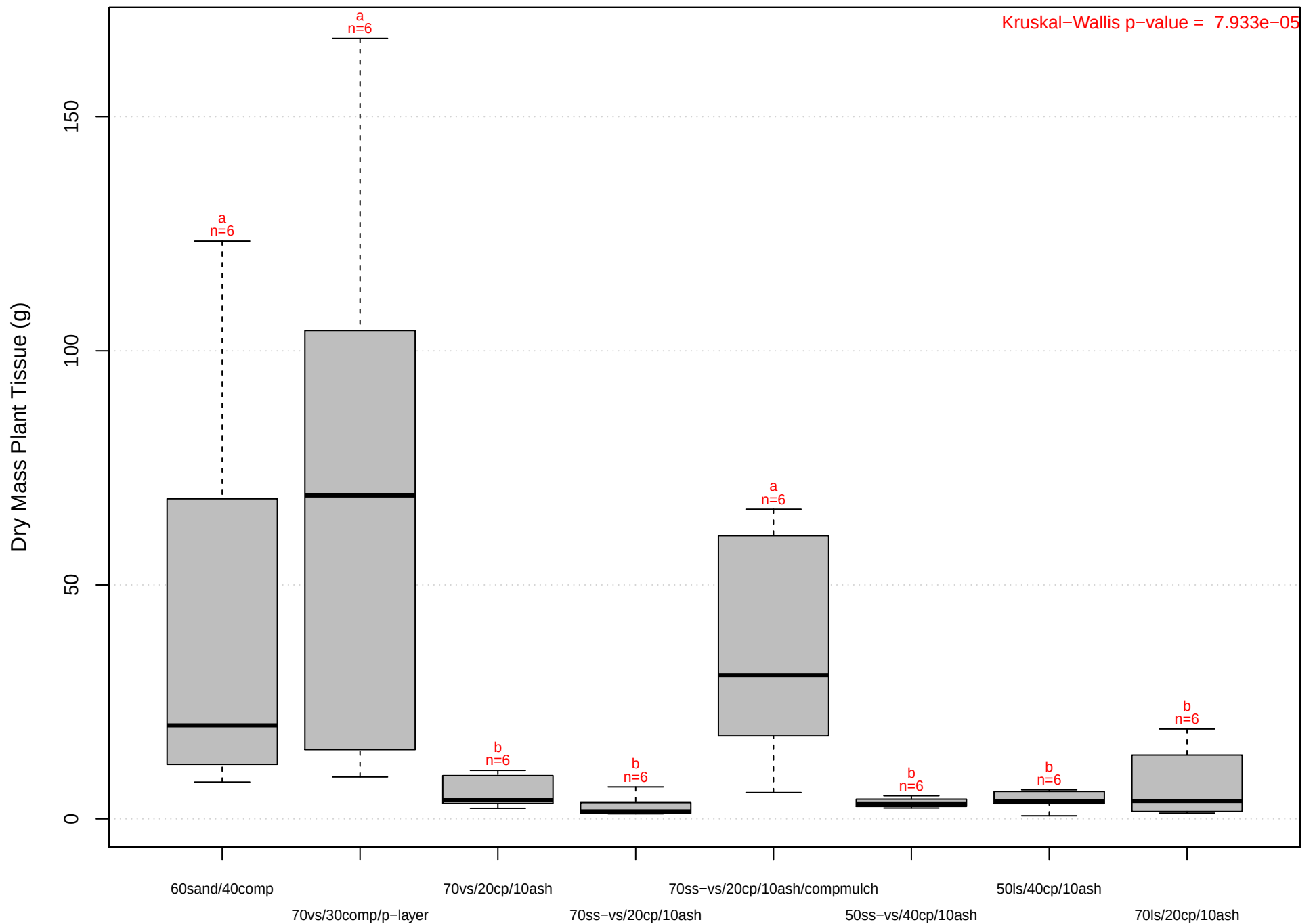


Figure 15. Juncus Roots.

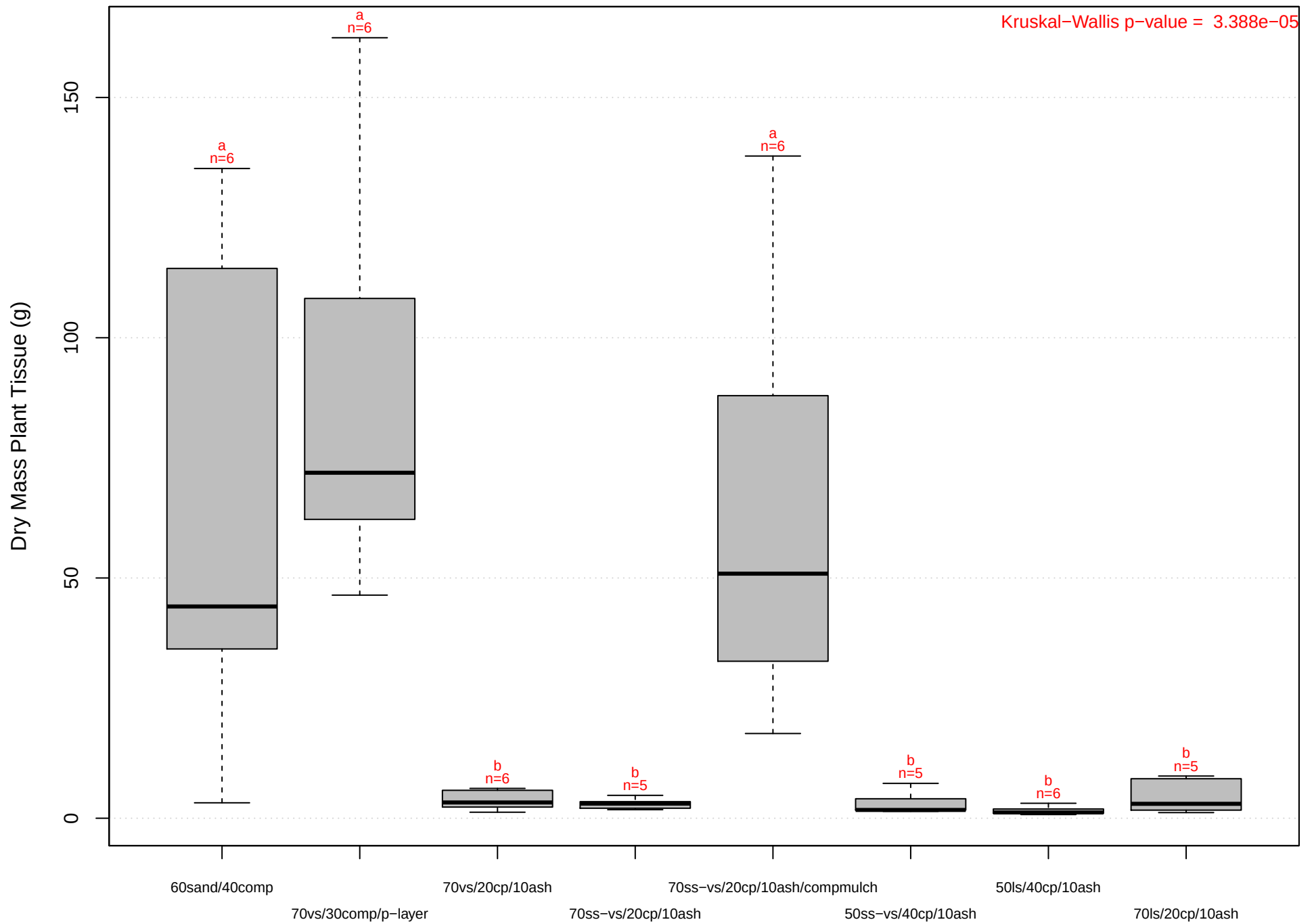


Figure 16. Deschampsia Stems.

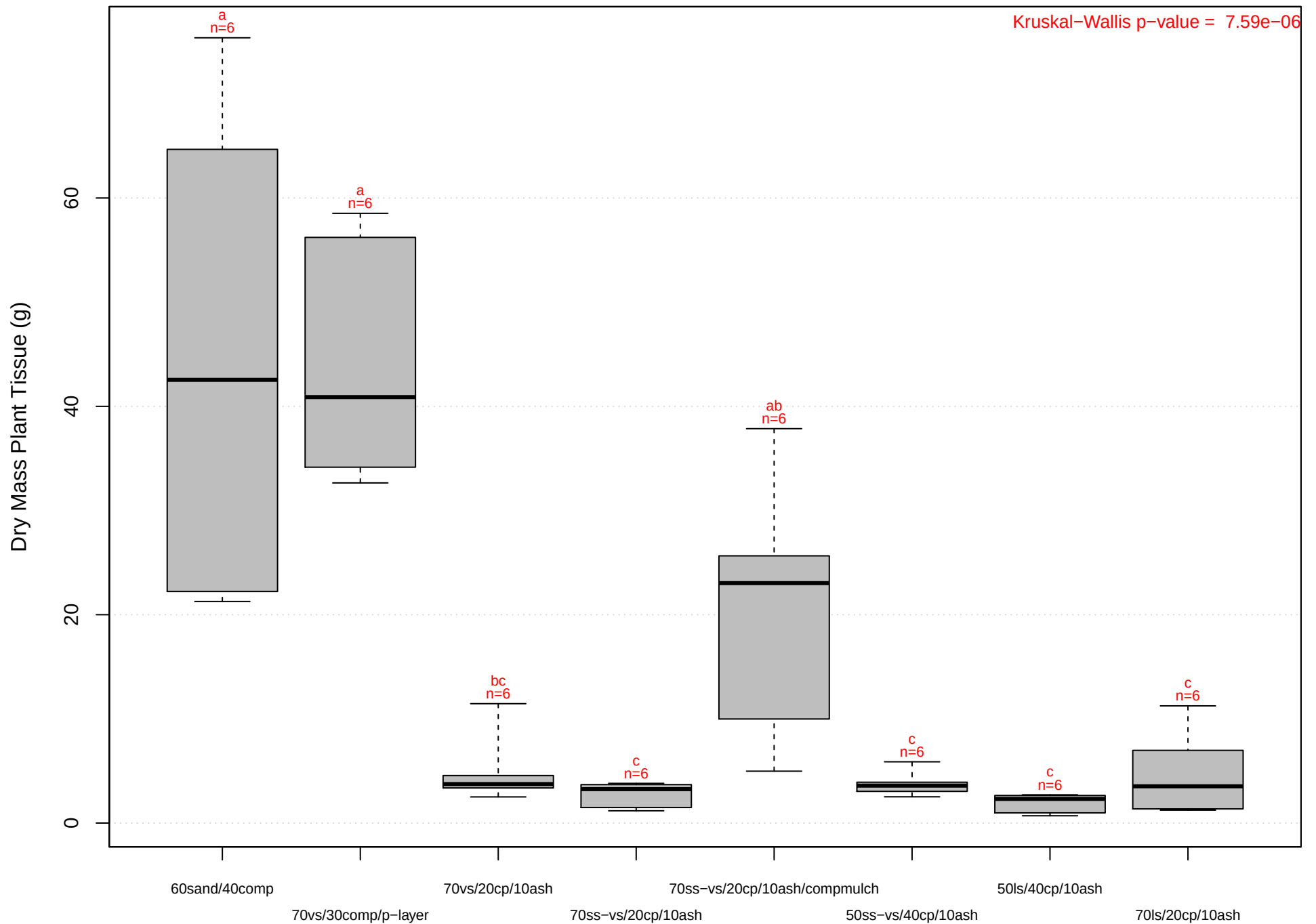


Figure 17. Juncus Stems.

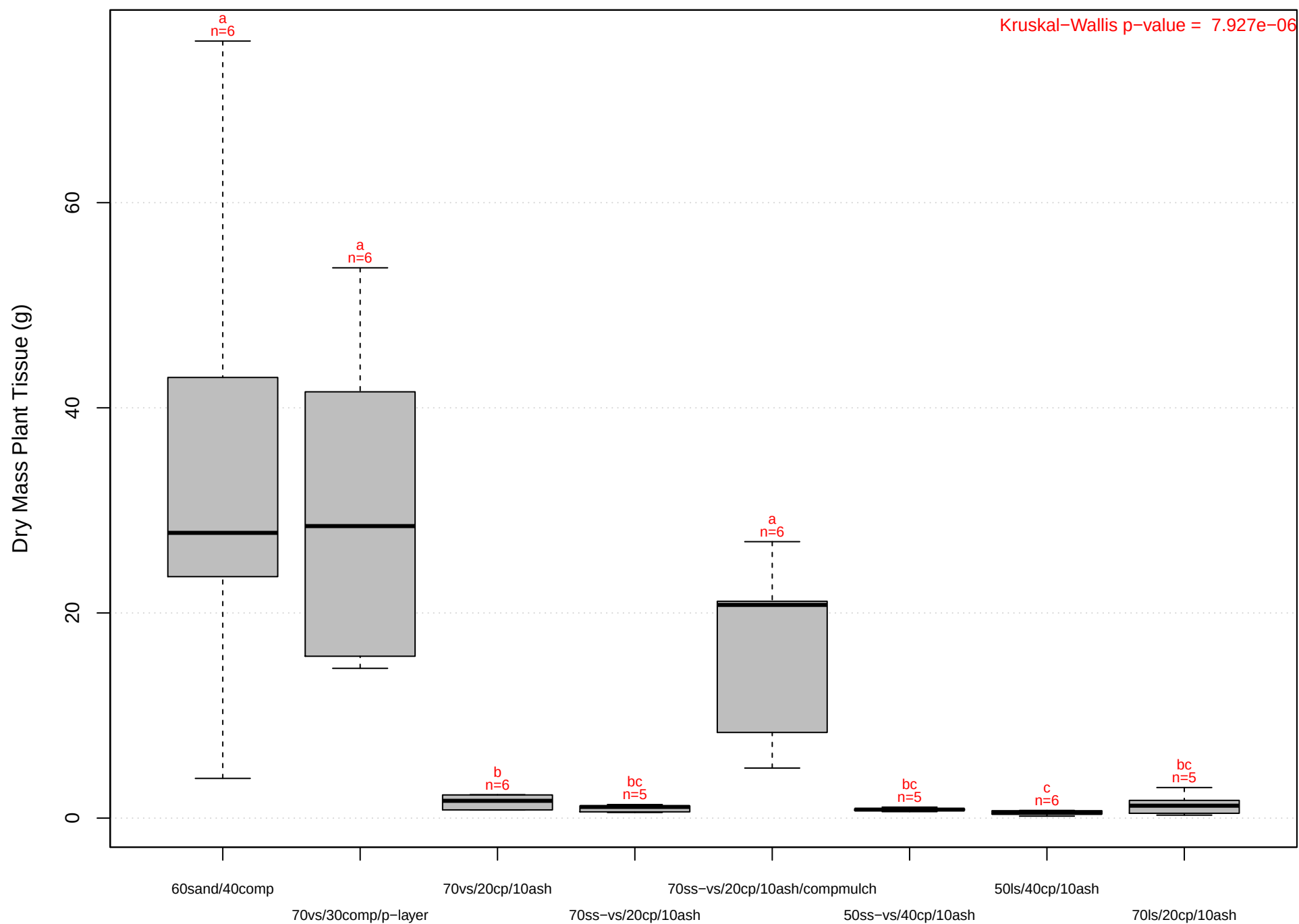


Figure 18. Deschampsia Total Mass.

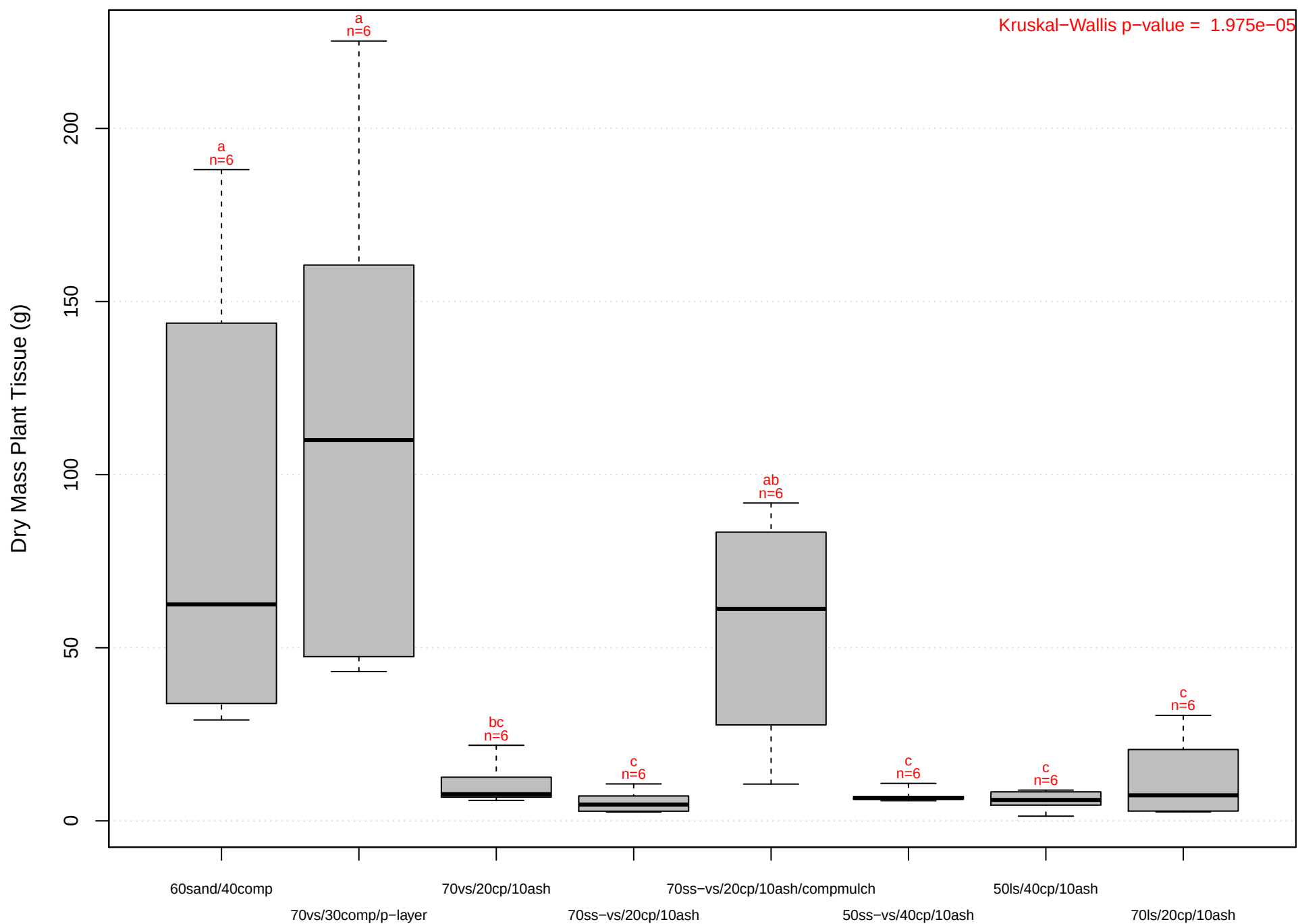
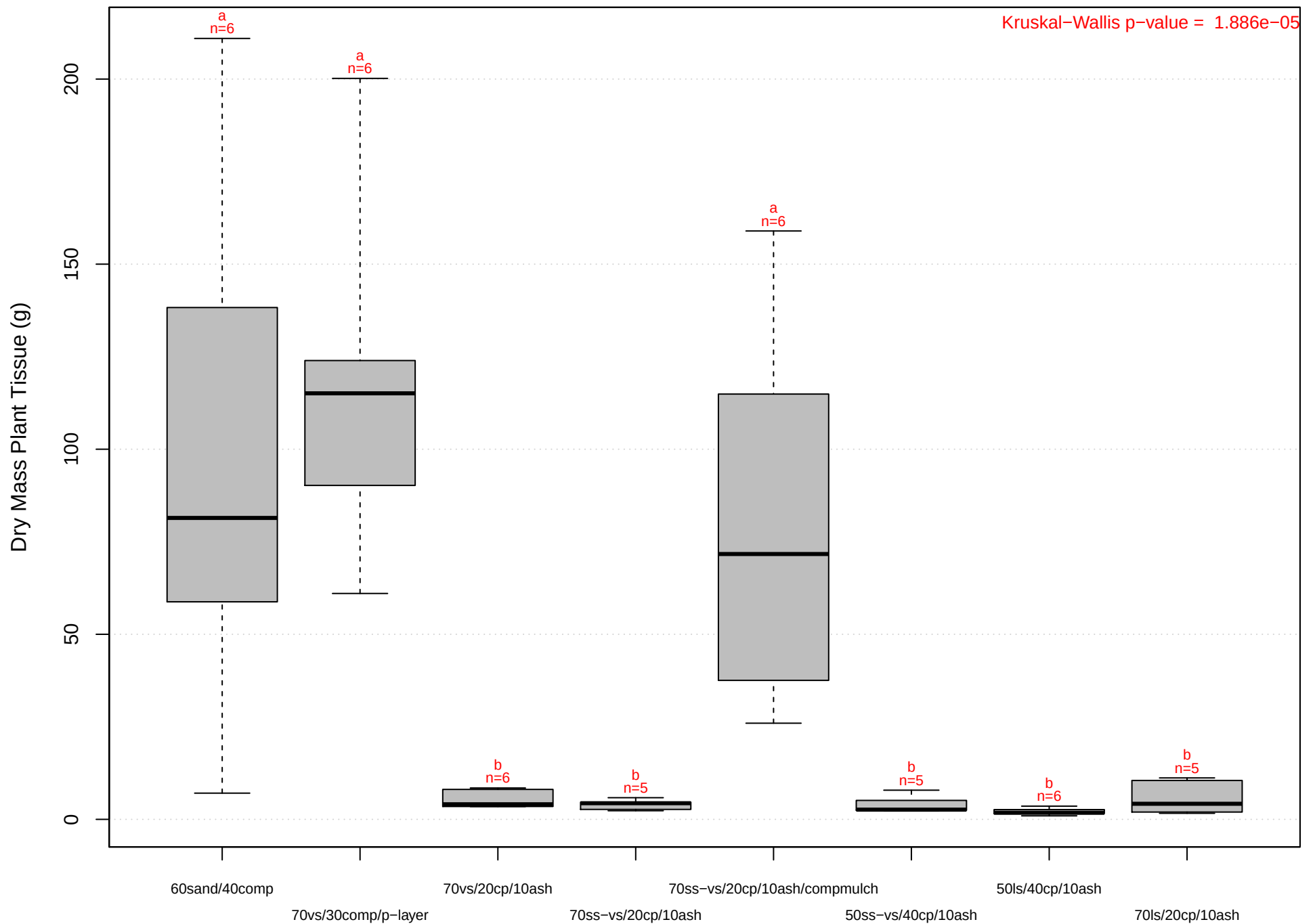


Figure 19. Juncus Total Mass.



The plant biomass analyses for stems and roots shows a clear division between compost-based media (including compost mulch media) and non-compost media. All compost-based media performed statistically the same for stem and root biomass development and all non-compost media the same as well. The difference in biomass production between the compost and non-compost media was significant. For example, mean biomass for Treatment 8 (70vs/30comp/p-layer) was 58.41 grams and 3.93 grams for Treatment 2 (70vs/20cp/10ash. Just considering mean values, Treatment 8 with 30 percent compost produced the most biomass of any treatment including Treatment 1 with 40 percent compost. This indicates that either less compost is necessary in compost-based media for optimum plant growth or that the polishing layer at the bottom of Treatment 8 creates a soil environment conducive to optimum nutrient uptake.

Most noteworthy is that Treatment 7 (70ss-vs/20cp/10ash/compmulch) performed statistically similarly to the other compost-based media with either 30 or 40 percent compost mixed throughout the media column. While this media mixture performed very well for plant growth, the water quality performance is not known.

3.5.6. General Plant Health

Taken together the plant size, tissue analysis, and biomass indicate that there is no significant difference in plant growth or health between the five, non-compost treatments. The treatments containing compost were expected to have higher biomass yield with healthier plant tissue than those without. But the subjective question remains whether plants grown in the non-compost treatments are “good enough” for a functioning bioretention system. More specifically, is a plant that is aesthetically pleasing and survives through mild stress good enough for a bioretention system whether or not the plant grows to its full potential.

There was limited mortality in this study. The three deaths that were seen in the weeks following the planting were likely due to the physical problem of the light soil mixture floating on pooling water and thereby uprooting the new plants during watering. This problem could be solved by simply including a layer of mulch made of gravel or some other dense material. There was no visible sign of chlorosis for all plants that survived during the 4-month wet period. All stalks were green and appeared healthy until the dry period began. The limited mortality and lack of severe chlorosis shows that all of the soil mixtures used in this study are capable of supporting plants under “wet period” conditions.

While the non-compost treatments in general sustained healthy looking plants, the measurements over time show that they did not support much growth. While the plants in the compost treatments grew steadily over the course of the study, the plants in the non-compost treatments were stunted almost immediately, showing very limited growth after week 5. This indicates that plants will not grow to full potential size in these media at least until the media develops more structure and organic matter inputs decompose for increased nutrient availability. Additionally, an important finding is that increasing organic matter (coir) to improve water holding capacity did not improve plant health for the non-compost blends.

Plants in the non-compost treatments appear to withstand the dry period at least as well as those in treatments with compost. The dry period watering schedule was stressful enough to result in chlorosis in both the grass and rush plants in all treatments by the end of the study. However, the rate of yellowing was not substantially different from one treatment to another (see Appendix F for images of the plants over time). Therefore, all treatments in this study can support plants through a drought period; however, the stem count and height were significantly less in the non-compost media than the compost based media by the end of the study.

Finally, the performance of Treatment 7 (70ss-vs/20cp/10ash/compmulch) is promising. With a layer of compost mulch, Treatment 7 produced plants as large as Treatments 1 and 8, which had 40 percent and 30 percent compost, respectively, mixed throughout the planter.

4. CONCLUSIONS AND RECOMMENDATIONS

This grant project implements recommendations and next steps of previous bioretention media studies including *Analysis of Bioretention Soil Media for Improved Nitrogen, Phosphorus, and Copper Retention* (Herrera 2015c) and the *Pacific Northwest Bioretention Performance Synthesis Report* (Herrera 2015a). Specifically, this study tests media components for potential contaminant export and sorption capability and blends for hydraulic conductivity and plant growth. Based on the results from these experiments, the following major study conclusions are identified.

4.1. MEDIA COMPONENTS

1. Three sands (one medium to fine and one with coarser particle size distribution and one with a porous structure) have now been identified that do not leach contaminants. Two (volcanic and state sands) have been tested multiple times with good SPLP extraction results for each analysis. The porous scoria sand particle size distribution can be altered by the supplier. These three sands should move forward and provide the mineral aggregate component for Phase 2 media blends.
2. Activated alumina and iron aggregate continue to exhibit strong sorption capability for ortho-P in sorption tests. Activated alumina, iron aggregate, and high-carbon wood ash show strong sorption capability for total Cu. All these materials also exhibit low leaching potential. These three materials should move forward to Phase 2 media blends as organic additives (high-carbon wood ash) or polishing layer components (alumina and iron).

4.2. MEDIA BLENDS

1. Saturated hydraulic conductivity is a balance between particle size and particle size distribution (coefficient of uniformity), compaction, and other factors. The sand blends developed for this study were not strongly influenced by more or less coarse material in the blend. Instead coefficient of uniformity appeared to offset the potential to increase Ksat with the addition of coarser aggregate. However, organic matter (coco coir) in these blends did strongly influence Ksat. At the same time, additional organic matter did not make a significant difference for plant health and vigor. Accordingly, a maximum of 20 to 30 percent organic matter is recommended for blends in Phase 2.
2. As noted in Section 3.5.4, cementing or caking was observed in one of the polishing layer replicates, indicating that 5 percent iron content by volume was too high. Accordingly,

polishing layer treatments should contain no more than 2 percent iron by volume and trials with only activated alumina should be evaluated.

4.3. PLANTS

1. Plants survived in all treatments. But the subjective question remains whether plants grown in the non-compost treatments are “good enough” for a functioning bioretention system. More specifically, is a plant that is aesthetically pleasing and survives through mild stress good enough for a bioretention system whether or not the plant grows to its full potential? While this question will remain as plant studies progress, one treatment shows promise to support healthy plant growth nearly equal to compost-based media. The 70 percent volcanic sand/20 percent coco coir/10 percent high-carbon wood ash with a compost mulch performed statistically similarly to the media with 30 to 40 percent compost. This high-performance media, without the compost mulch, performed very well for low leaching potential and very good pollutant capture in a previous study (Herrera 2015c). However, the contaminant flushing or capture performance of this approach has not been tested. Accordingly, the high-performance media blends that incorporate clean sands, coir, and ash should move ahead to Phase 2 for more flushing and contaminant capture analyses with and without a compost mulch.

4.4. SUMMARY RECOMMENDATIONS AND PHASE 2

Many of the media components evaluated in previous studies tested well in this study. Accordingly, confidence in these media components for minimal leaching potential and binding target contaminants has increased. An exception to this was the iron aggregate for leaching dissolved Cu. Discussions with the material supplier to confirm feedstocks and processing as well further testing is necessary to rely on iron aggregate for polishing layer applications.

All the non-compost media supported plants. The ability of compost-based media to support superior plant growth was not in question, but rather the ability of high-performance, low-nutrient media to support adequate plant growth. The question of what is adequate will vary across users and settings. The timeframe for the plant study was short and the plant palette limited to two plant species. Additionally, the treatments were purposely limited to media alone rather than including and organic mulch (e.g. arborist wood chips) typical to actual installations. The exception to this was the use of a compost mulch on the 70 percent volcanic sand/20 percent coco coir/10 percent high-carbon wood ash.

Given the results of this and previous studies, next steps for Phase 2 should include:

- Final leaching and sorption analysis of media components,
- The Ksat for all media blends test well above the 30.5 cm/hr (12 in/hr) maximum Ksat recommended by Ecology. While the 30.5 cm/hr will remain for design purposes,

decisions must be made by Ecology and the advisory group concerning the appropriate actual Ksat target range for the blending, flushing and dosing of media blends in Phase 2.

- Include orifice and/or other hydraulic controls to attain more reliable Ksat ranges in Phase 2 column tests and full-scale pilots.
- Continue to test the polishing layer approach using reduced iron aggregate volumes and activated alumina alone.
- Flush and dose media blends that have demonstrated superior pollutant capture combined with elements that potentially improve plant health. For example, the 70 percent volcanic sand/20 percent coco coir/10 percent high-carbon wood ash with a compost mulch (which performed statistically similarly to the media with 30 to 40 percent compost) should be evaluated for water quality treatment. However, other components that may support improved plant health such as wood chips or slow release nutrients should also be included in the experimental blends and assessed for treatment performance.

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APPENDIX A

Quality Assurance Project Plan

QUALITY ASSURANCE PROJECT PLAN

**BIORETENTION MEDIA COMPONENT ANALYSIS TO
IMPROVE RUNOFF TREATMENT**

**Prepared for
Kitsap County**

Prepared by
Herrera Environmental Consultants, Inc.



QUALITY ASSURANCE PROJECT PLAN

BIORETENTION MEDIA COMPONENTS ANALYSIS TO IMPROVE RUNOFF TREATMENT

**Prepared for
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2200 Sixth Avenue, Suite 1100
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April 10, 2017

TITLE AND APPROVAL SHEET

Title: Quality Assurance Project Plan: Bioretention Media Component Analysis to Improve Runoff Treatment

Author: Herrera Environmental Consultants, Inc., Seattle, Washington

Date: September 20, 2016

Approved by:

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Curtis Hinman, Herrera Environmental Consultants

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John Lenth, Herrera Environmental Consultants

University of Washington Plant Experiment Manager: _____ Date: _____
Sally Brown, University of Washington

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Mark Harris, Analytical Resources Inc.

Laboratory Manager: _____ Date: _____
Marty French, Specialty Analytical

Laboratory Manager: _____ Date: _____
Joe Laprade, Shannon and Wilson

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1. INTRODUCTION

The current Washington State, Phase I municipal National Pollutant Discharge Elimination System (NPDES) stormwater permit requires the use of low impact development (LID) practices as the first option for managing stormwater where feasible effective January 1, 2017.

Bioretention is the most widely applicable and flexible Best Management Practice (BMP) in the suite of LID practices. Bioretention systems may include under-drains, especially in areas with soils that are less suitable for infiltration. In these cases, a portion of the treated runoff is discharged back into the stormwater conveyance system rather than infiltrated.

Bioretention is currently classified in the *Stormwater Management Manual for Western Washington* (SWMMWW) (Ecology 2012b) as a basic (solids removal) and enhanced (copper and zinc removal) treatment BMP. The guidelines in the SWMMWW for the composition of bioretention media include sand and compost. While bioretention using compost-based media can provide very good water quality treatment for some contaminants (e.g., sediment, zinc, hydrocarbons, and likely bacteria), regional and national research indicate nitrogen (N), phosphorus (P), and copper (Cu) may be exported from these systems (Herrera 2016, Geosyntec 2013).

This grant project will implement the recommendations and next steps of previous bioretention media studies with the ultimate goal to develop recommendations for new statewide, high-performance bioretention soil media (BSM) specifications that reduces contaminant flushing; meets Washington State Department of Ecology's (Ecology) treatment objectives for total suspended solids (TSS), total and dissolved Cu and Zn, and phosphorus; grows plants, is affordable and available; and minimizes toxicity to aquatic organisms.

The project is funded by Grants of Regional and Statewide Significance (GRSS) through Washington State Department of Ecology (Ecology), and is Phase 1 of a two-part study to test media components and blends for hydraulic conductivity and plant growth followed by Phase 2 (not yet funded) to test media blends for flushing, pollutant capture, and the ability to protect aquatic organisms. Kitsap County is the grant recipient and Herrera Environmental Consultants is the technical lead.

Each environmental study conducted by or for Ecology must have an approved Quality Assurance Project Plan (QAPP) describing the objectives of the study and the procedures to achieve those objectives. The following QAPP was prepared in accordance with Ecology's *Guidelines for Preparing Quality Assurance Project Plans* (Ecology 2004), and documents sample collection, processing, and analysis procedures to ensure that resulting data are scientifically and legally defensible. This document is organized as follows:

- Background
- Project Description
- Organization and Schedule
- Quality Objectives
- Experimental Design
- Sampling Procedures
- Measurement Procedures
- Quality Control
- Data Management Procedures
- Audits and Reports
- Data Verification and Validation
- Data Quality Assessment
- References

2. BACKGROUND

This section provides a description of the bioretention media study and briefly summarizes the results of previous laboratory testing and field monitoring.

2.1. TECHNOLOGY DESCRIPTION

Bioretention facilities are shallow landscaped depressions with a designed soil mix and plants adapted to the local climate and soil moisture conditions that receive stormwater from a small contributing area. These systems are designed to more closely mimic natural forested conditions where healthy soil and vegetation promote the infiltration, storage, filtration, and slow release of stormwater flows. Within the low Impact development approach, bioretention areas are designed as small-scale, dispersed systems that are integrated into the site as a landscape amenity (see Figure 1).



Figure 1. Typical Bioretention Application.

2.2. RESULTS OF PREVIOUS STUDIES

While bioretention can provide very good water quality treatment for many contaminants (e.g., sediment, zinc, hydrocarbons, and likely bacteria), regional and national research indicate nitrogen (N), phosphorus (P), and copper (Cu) may be exported from these systems (Herrera 2012; Jonasson et al. 2010; Trowsdale and Simcock 2011). The sources of N, P, and Cu can be various materials including mineral aggregates, and natural and engineered amendments (Herrera 2015c; Pitt and Clark 2010); however, compost provides the largest contribution of these contaminants (Herrera 2014, 2015a, 2015b, 2015c). Export of N, P, and Cu is of particular concern for bioretention installations with under-drains that discharge to receiving waters and bioretention installations with or without under-drains located close to shallow groundwater drinking water supply wells or in proximity to phosphorus and nitrogen sensitive receiving waters.

Analysis of Bioretention Soil Media for Improved Nitrogen, Phosphorus, and Copper Retention conducted by Herrera in partnership with Kitsap County in 2014–15 (Herrera 2015c) focused on the selection, pollutant export, and pollutant capture characteristics of new BSM components and media blends for high performance water quality treatment. Findings from that research suggest that some of the new media blends significantly reduce the export of N, P, and Cu compared to the currently prescribed BSM, which includes 60 percent sand and 40 percent compost. The Kitsap-sponsored study was limited in scope and did not include: chemical (with the exception of leaching tests) or physical characterization of the media components; hydraulic analysis; plant growth tests using plants typical to western Washington bioretention systems; selection of appropriate metrics to describe the media components and blends in a specification; and toxicity testing to evaluate how well these new blends protect targeted aquatic organisms from acute toxicity (biological effectiveness).

Following the Kitsap study, Herrera developed a draft BSM synthesis report (Pacific Northwest Bioretention Performance Synthesis Report) to summarize knowledge and data gaps learned through several recent regional research projects (Herrera 2015a). The Kitsap study and the draft BSM synthesis report provided recommendations for next steps to develop a high-performance BSM. This grant project will implement the recommendations and next steps of these previous bioretention media studies with the ultimate goal to develop new statewide specifications for a high-performance BSM.

3. PROJECT DESCRIPTION

The ultimate goal of these bioretention media studies (Phase 1 and Phase 2) is to develop new statewide specifications for a high-performance BSM that reduces contaminant flushing; meets Washington State Department of Ecology's (Ecology) treatment objectives for total suspended solids (TSS), dissolved Cu and Zn, and phosphorus; grows plants, is affordable and available; and minimizes toxicity to aquatic organisms. As part of this larger effort, the objectives of this project will be to:

- Analyze the leaching potential of N, P, and Cu from individual bioretention media components using weak acid and deionized water extraction.
- Analyze the sorption capacity of individual bioretention media components for N, P, and Cu.
- Test and adjust the saturated hydraulic conductivity (Ksat) of media blends (developed from components selected in the two analyses above) to an acceptable range.
- Assess the ability of media blends (developed from components selected in the three analyses above) to grow plants.

Qualitative criteria for media component and media blends include:

- **Leaching:** media components that leach the minimum amount of N, P, and Cu will be considered first for testing in the media blends (see Section 6.1.2 for leaching analysis details).
- **Sorption:** materials with higher sorption capacity for N, P and Cu will be considered first for testing in media blends (see Section 6.1.3 for sorption analysis details).
- **Hydraulic performance:** media blends must have a minimum Ksat greater than 4 inches/hour. The maximum Ksat value will be determined by the project team (see Section 6.1.4 for Ksat details).
- **Sustainability:** the availability, transportation requirements, manufacturing and/or extraction processes will be considered for each media component.
- **Cost:** media components with the minimum cost per unit used in the media blends will be considered first for testing in media blends. Cost will be considered along with the above criteria to attain the best balance of cost to optimum performance.

Optimizing bioretention media to best manage these contaminants will provide the region and state with a high performance and affordable water quality treatment practice that captures multiple pollutants of concern and is adaptable to rural, suburban, and ultra-urban settings. The project will support continued coordination among State and local jurisdictions that are developing and implementing bioretention systems, and with input from those partners, refine and conduct testing of individual bioretention components and media mixtures to improve retention of N, P, and Cu. Specifically the project will:

- Provide a scientific basis for determining the appropriate design of bioretention media.
- Refine and expand the application of an effective flow control and water quality treatment tool for meeting Minimum Requirements 5, 6, and 7 in Appendix 1 of the permit.
- Develop recommendations for updating “Design Criteria for Custom Bioretention Soil Mixes,” the “Default Bioretention Soil Media” and the default bioretention soil mix infiltration rate/correction factor presented in Section 7.4 of Volume V of the 2012 SWMMWW.
- Develop recommendations for updating bioretention soil media in the 2012 Low Impact Development Technical Guidance Manual for Puget Sound.
- Improve design review and permitting of bioretention with updated design criteria.

4. ORGANIZATION AND SCHEDULE

This study is funded by the 2015–17 Biennial Municipal Stormwater GRSS funding program. The GRSS provides support for Phase I and Phase II local governments to implement their stormwater management programs pursuant to requirements of the NPDES stormwater permit. Kitsap County is the grant recipient, and Herrera Environmental Consultants, Inc. (Herrera) is the technical lead and will design and conduct the media evaluation in cooperation with project partners. Analytical Resources Inc., Specialty Analytical, Inc., and Shannon and Wilson, Inc. will provide analytical laboratory services for the water quality and Ksat analysis. Project organization and personnel for this study are identified in Table 1.

Table 1. Project Organization and Key Personnel.		
Title	Name	Affiliation
Client Project Manager	Chris May	Kitsap County
Herrera Principal-in-Charge	John Lenth	Herrera Environmental Consultants
Herrera Project Manager	Curtis Hinman	Herrera Environmental Consultants
Herrera Water Quality Data Quality Assurance Lead	Gina Catarra	Herrera Environmental Consultants
Herrera Technical Support	Dylan Ahearn	Herrera Environmental Consultants
Herrera Data Management Lead	Kristen Matsumura	Herrera Environmental Consultants
Research Associate Professor	Sally Brown	University of Washington
Analytical Lab Quality Assurance Officer	Mark Harris	Analytical Resources, Inc.
Specialty Analytical Lab Quality Assurance Officer	Marty French	Specialty Analytical
Soils Lab Manager	Joe Laprade	Shannon and Wilson

Project partners include Kitsap County, City of Seattle, City of Redmond, King County, Thurston County, City of Tacoma, Seattle University, University of Washington, and Washington Department of Ecology.

4.1. RESPONSIBILITIES

4.1.1. Client Project Manager – Chris May

Chris May is the Project Manager for Kitsap County (the grant recipient) and will oversee project progress and review and comment on the technical work and deliverables. He will be the primary point of contact for Kitsap County.

4.1.2. Herrera Principal-in-Charge – John Lenth

John Lenth will provide senior quality assurance review of technical work and deliverables throughout all phases of the project.

4.1.3. Herrera Project Manager and Technical Lead – Curtis Hinman

Curtis Hinman will direct all technical work and coordinate all field work related to this project including laboratory and field experimental design.

4.1.4. Herrera Water Quality Data Quality Assurance Lead – Gina Catarra

Gina Catarra will independently review water quality data entry (laboratory reports compared to electronic files) and will review quality assurance worksheets to determine appropriate response actions to any quality assurance issues.

4.1.5. Herrera Technical Support – Dylan Ahearn

Dylan Ahearn will provide technical support for experimental design. He will also perform a final quality assurance review on these data to assess their accuracy and determine their usability for subsequent analysis related to system performance evaluations.

4.1.6. Herrera Data Management Lead – Kristen Matsumura

Kristen Matsumura will manage data and perform statistical analysis as needed.

4.1.7. Herrera Field Sampling Support – Alex Svendsen

Alex Svendsen will be responsible for collecting and delivering stormwater to University of Washington for the plant study.

4.1.8. Analytical Laboratory Quality Assurance Officer – Joe Laprade

Joe Laprade will assist with study strategies and coordinate the lab assessment for the hydraulic conductivity at Shannon and Wilson.

4.1.9. Analytical Laboratory Quality Assurance Officer – Mark Harris

Mark Harris will track samples and results in the laboratory; provide properly cleaned sample bottles with appropriate preservatives; evaluate laboratory compliance with this QAPP and laboratory quality assurance plan; report discrepancies and transmit laboratory results to the Herrera Project Manager.

4.1.10. Analytical Laboratory Quality Assurance Officer – Marty French

Marty French will track samples and results in the laboratory; provide properly cleaned sample bottles with appropriate preservatives; evaluate laboratory compliance with this QAPP and laboratory quality assurance plan; report discrepancies and transmit laboratory results to the Herrera Project Manager.

4.1.11. Plant Study Co-Lead – Sally Brown

Sally Brown will co-lead the plant study with Curtis Hinman and coordinate the plant study at University of Washington with Herrera.

4.2. CONTACTS

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4.3. SCHEDULE

The estimated project schedule for the study is outlined in Table 2.

Table 2. Project Milestones.	
Project Milestone	Date Completed
Draft QAPP for project partner review	August 25, 2016
Final QAPP	September 8, 2016
Select media components	September 20, 2016
Complete leaching analysis of media components	October 4, 2016
Complete sorption analysis of media components	October 18, 2016
Complete Ksat analysis of media blends	November 8, 2016
Complete plant growth analysis	June 1, 2017
Complete data analysis	June 8, 2017
Complete preliminary report	May 15, 2017
Complete final report with media recommendations	June 15, 2017

5. QUALITY OBJECTIVES

The goal of this QAPP is to ensure that data collected through this study are scientifically accurate and legally defensible. To meet this goal, the collected data will be evaluated using the following quality assurance objectives:

- **Precision:** A measure of the variability in the results of replicate measurements due to random error.
- **Bias:** The systematic or persistent distortion of a measurement process that causes errors in one direction (i.e., the expected measurement is different from the true value).
- **Representativeness:** The degree to which the data accurately describe the conditions being evaluated based on the selected sampling locations, sampling frequency, and sampling methods.
- **Completeness:** The amount of data obtained from the measurement system.
- **Comparability:** The ability to compare data from the current project to data from other similar projects, regulatory requirements, and historical data.

Method Quality Objectives (MQOs) are performance or acceptance criteria that are established for each of these quality assurance objectives. The specific MQOs that have been identified for this project are described below and summarized in Tables 3 and 4.

5.1. PRECISION

Precision will be assessed using laboratory and field duplicates. Precision for laboratory duplicates will be ± 25 percent relative percent difference (RPD) for TSS, ± 10 percent for pH, ± 35 percent for bacteria, and ± 20 percent for all other water quality parameters. Precision for field duplicates will be ± 15 percent RPD for pH and ± 25 percent for all other water quality parameters. In all cases, the RPD of duplicate samples will be calculated using the following equation:

$$RPD = \frac{(C_1 - C_2) \times 100\%}{(C_1 + C_2) / 2}$$

where: RPD = relative percent difference

C_1 = larger of two values

C_2 = smaller of two values

The relative percent difference will be less than or equal to the indicated percentages for values greater than 5 times the reporting limit and ± 2 times the reporting limit for values less than or equal to 5 times the reporting limit.

Table 3. Method Quality Objectives for Water Quality Data.

Parameter	Reporting Limit	Units	Method Blank	Rinsate Blank	Control Standard Recovery	Matrix Spike Recovery	Laboratory Duplicate RPD ^a
Total suspended solids	1.0	mg/L	<RL	<2 x RL	90–110%	NA	≤20% or ±2 x RL
pH	NA	std. units	<RL	NA	NA	NA	≤10% or ±2 x RL
Total Kjeldahl Nitrogen	1.0	mg/L	<RL	<2 x RL	90–110%	75–125%	≤20% or ±2 x RL
Nitrate-nitrite	0.01	mg/L	<RL	<2 x RL	90–110%	75–125%	≤20% or ±2 x RL
Total phosphorus	0.008	mg/L	<RL	<2 x RL	90–110%	75–125%	≤20% or ±2 x RL
Ortho-phosphorus	0.004	mg/L	<RL	<2 x RL	90–110%	75–125%	≤20% or ±2 x RL
DOC	1.5	mg/L	<RL	<2 x RL	90–110%	75–125%	≤20% or ±2 x RL
Hardness	0.33	mg/L	<RL	NA	80–120%	75–125%	≤20% or ±2 x RL
Cadmium, dissolved	0.1	µg/L	<RL	<2 x RL	80–120%	75–125%	≤20% or ±2 x RL
Cadmium, total							
Copper, dissolved	0.5	µg/L	<RL	<2 x RL	80–120%	75–125%	≤20% or ±2 x RL
Copper, total							
Zinc, dissolved	4	µg/L	<RL	<2 x RL	80–120%	75–125%	≤20% or ±2 x RL
Zinc, total							
Polycyclic aromatic hydrocarbons	1.0	µg/L	<RL	<2 x RL	30–120%	30–120%	≤30% or ±2 x RL
Total petroleum hydrocarbons (diesel)	0.25	mg/L	<RL	<2 x RL	56–103%	56–103%	≤30% or ±2 x RL
Total petroleum hydrocarbons (motor oil)	0.5	mg/L	<RL	<2 x RL	30–160%	30–160%	≤30% or ±2 x RL
Fecal Coliform bacteria	2 ^b	CFU/100 mL	<RL	NA	NA	NA	≤35% or ±2 x RL
E. coli bacteria	2 ^b	CFU/100 mL	<RL	NA	NA	NA	≤35% or ±2 x RL

^a The relative percent difference will be less than or equal to the indicated percentage for values greater than 5 times the reporting limit, and ±2 times the reporting limit for values less than or equal to 5 times the reporting limit.

^b Reporting limit will be dependent on dilution used in analysis.

CFU/100 mL

std. units = standard units

mg/L = milligrams per liter

RL = reporting limit

µg/L = micrograms per liter

RPD = relative percent difference

NA = not applicable

DOC = dissolved organic carbon

Table 4. Method Quality Objectives for Plant Tissue Analysis.				
Parameter	Reporting Limit	Units	Method Blank	Laboratory Duplicate
Biomass	0.01	g	na	na
Nitrogen	0.03	mg/mg	na	na
Phosphorus	10	mg/kg	na	na

5.2. BIAS

Bias will be assessed based on analyses of method blanks, matrix spikes, and control standards. Method blank values will not exceed the reporting limit. The percent recovery of matrix spikes will be ± 25 percent for total phosphorus, ortho-phosphorus, hardness, and total and dissolved metals. Duplicate matrix spikes will also be run on a portion of the samples. The laboratory control sample recovery will be ± 10 percent for TSS, total phosphorus, ortho-phosphorus, hardness, and total and dissolved metals. Percent recovery for matrix spikes will be calculated using the following equation:

$$\%R = \frac{(S - U) \times 100\%}{C_{sa}}$$

where: %R = percent recovery

S = measured concentration in spike sample

U = measured concentration in un-spiked sample

C_{sa} = actual concentration of spike added

If the analyte is not detected in the un-spiked sample, then a value of zero will be used for U in the equation.

Percent recovery for control standards will be calculated using the following equation:

$$\%R = \frac{(M) \times 100\%}{T}$$

where: %R = percent recovery

M = measured value

T = true value

5.3. REPRESENTATIVENESS

Synthetic Precipitation Leaching Protocol (SPLP) will be conducted for up to 14 media components. A maximum of eight media blends will be selected consisting of various

proportions of selected media components. The SPLP Extractions for media components and treatment blends for the plant study will be replicated a minimum of three times. The treatments for the plant study will be placed in a random block design. While compressed, a 6-month growth period for the plant study is considered adequate to meet sampling program objectives.

5.4. COMPLETENESS

A minimum of 95 percent of the samples submitted to the laboratory will be judged valid. An equipment checklist and Chain of Custody forms will be used to prevent loss of data resulting from missing containers, inoperable delivery and collection apparatus or sample delivery.

5.5. COMPARABILITY

Standard sampling procedures, analytical methods, units of measurement, and reporting limits will be applied to meet the goal of data comparability. The results will be tabulated in standard spreadsheets to facilitate analysis and comparison with comparable bioretention media studies.

6. EXPERIMENTAL DESIGN

This section of the QAPP provides information on the study design including: overall approach and phases of the study, SPLP, sorption, and Ksat methods, and description of the plant study.

6.1. SAMPLE PROCESS DESIGN

Overall the study approach is designed to optimize bioretention media for N, P, and Cu capture, to operate within an acceptable Ksat range and support plants. There are four primary tasks to the study:

1. Conduct a rapid survey of potential bioretention media components based on pollutant capture capability, cost, availability, and sustainability. Select individual media components from survey and project partner input.
2. Conduct Synthetic Precipitation Leaching Protocol (SPLP Method 1312) to determine N, P, and, Cu leaching potential of selected components. Select the media components that minimize leaching potential, and that are estimated to provide adequate hydraulic conductivity and support plants.
3. Combine selected components into media blends and assess the Ksat (permeability) of those blends. Adjust the blends if necessary to meet acceptable Ksat range determined by project team.
4. Conduct plant growth tests with media blends that meet the Ksat objectives.

6.1.1. Rapid Survey of Media Components

The BSM components from the previous media research (Herrera 2015c) that exhibit the best TSS, metals, and nutrient removal will be selected for additional media testing. Any new media components will be selected using a rapid survey of the scientific literature and project partner input for treatment effectiveness of target stormwater pollutants. Additionally, practical considerations will include availability, sustainability, and cost. A broad range of bioretention media components will be considered and included in the survey.

The media components will be organized into a matrix by three categories: bulk aggregate (e.g., sands); bulk organic (e.g., compost) that comprise the majority of the media blends; and amendments that provide specific pollutant capture and/or hydraulic characteristics, and comprise less of the overall volume. A maximum of 14 bioretention media components (e.g., 4 bulk aggregates, 4 bulk organic materials, and 6 amendments) will be selected based on minimal leaching and pollutant capture in previous research, availability, and cost.

6.1.2. Media Component Leaching Tests

The leaching potential for N, P, and Cu for selected media components will be assessed using a SPLP extraction. The analysis will be performed at Analytical Resources Inc. (ARI), an Ecology certified laboratory. The SPLP analysis will be conducted for total kjeldahl nitrogen (TKN), nitrate-nitrite, ortho-phosphorus (ortho-P), and dissolved Cu using two procedures:

- Metals – weak acid ($\text{H}_2\text{SO}_4/\text{HNO}_3$) extraction using a pH recommended for western US
- Nutrients – deionized water extraction

Suppliers will be identified for media components selected from the survey process described in Section 6.1.1. Samples of the selected media components will then be collected from suppliers and, where possible, samples will be collected by Herrera staff from multiple locations in material stockpiles and composited for analysis.

A maximum of 14 components (e.g., 4 bulk aggregate, 4 bulk organic, and 6 amendments) will be selected from the SPLP analysis using the following criteria: $\text{Cu} \leq 5 \mu\text{g/L}$; $\text{NO}_3\text{-NO}_2 \leq 0.1 \text{ mg/L}$; and $\text{TP} \leq 0.1 \text{ mg/L}$. If none of the components initially selected meet these criteria, additional components will be considered for SPLP analysis. If none of the components initially or subsequently selected meet these criteria, then components with the lowest concentrations will be selected and proprietary and non-proprietary components will be considered for use as a polishing layer to reduce effluent concentrations from the media blends comprised of the components with the lowest SPLP concentrations. Results will be reviewed by the project partners to consider SPLP analysis, media component cost, and sustainability for final recommendations.

One SPLP analysis will be conducted per media component; accordingly, no statistical analysis will be performed on the leaching results.

6.1.3. Media Component Sorption Tests

Media components meeting criteria in Section 6.1.2 from the SPLP analysis will be selected for sorption tests. Equilibrium batch studies to assess total Cu, nitrate as N and ortho-P removal capability will be conducted on each component. The batch studies will focus on kinetic processes to determine the time required to reach sorption equilibrium using a sorption fluid. Fourteen media components are anticipated for testing. See Table 5 for the sorption fluid composition.

Dissolved organic carbon (DOC) is a strong sorbent and will be added to the sorption solution to simulate this component of actual stormwater and assess DOC interference.

Table 5. Sorption Fluid Composition (20 L).	
Standards	Concentration
Dissolved organic carbon (Suwannee River natural organic material)	4,000 µg/L
Phosphorus	100 µg/L
Nitrate (potassium nitrate)	1,000 µg/L
Copper (cupric sulfate pentahydrate)	100 µg/L
Buffer (sodium bicarbonate)	0.185 mg/L
Interference ions (sodium chloride)	1.0 mg/L

A distribution coefficient, which describes the affinity of the media components for target analytes, will be developed from the sorption analysis. The coefficient is calculated as follows:

$$K_d = (A-B) \cdot V / ((M_s) \cdot B)$$

where:

K_d = distribution coefficient (mL/g)

A = initial concentration of the solute defined as the mean concentration of the blanks (µg/mL)

B = final concentration of the solute after 2, 6, and 12 hours in contact with the media (µg/mL)

V = Volume of the solution used (mL)

M_s = mass of soil expressed on an oven-dried basis (g)

6.1.4. Combine Components and Conduct Ksat Tests

Media components meeting criteria in Section 6.1.2 and 6.1.3 analyses will be combined into media blends to test K_{sat} . A minimum target for hydraulic conductivity will be 4 inches/hour (4 inch/hour x the maximum correction factor for BSM of 0.25 = 1 inch/hour or Ecology's recommended minimum K_{sat} for BSM). A maximum range will be determined by the project team. K_{sat} tests will be conducted using Standard Test Method for Permeability of Granular Soils (ASTM D2434 modified approach) on each trial blend. A maximum of 10 media blends will be analyzed for saturated hydraulic conductivity.

Coefficient of Uniformity, Guidelines for Filter Media in Biofiltration Systems (FAWB 2009), material availability, best professional judgment will be used to estimate proper gradation of components. A maximum of 10 trial media blends are anticipated for testing. If necessary the particle size distribution in the media blends (with an emphasis on bulk mineral aggregate) will be adjusted to attain desired results.

6.1.5. Plant Growth Analysis

Media components meeting criteria in Sections 6.1.2, 6.1.3, and 6.1.4 will be combined into media blends to conduct plant growth tests. The plant study will be conducted for approximately 6 months. Media and plants will be placed in 45.42-liter (12-gallon) buckets and grown in the Center for Urban Horticulture greenhouse under controlled conditions for duration of study. A maximum of eight media blends will be used for the plant tests. Each treatment will be replicated three times.

Stormwater will be used to irrigate the plants and will be analyzed for total phosphorus (TP), ortho-P, nitrate+nitrite, and TKN. See Tables 4 and 6 for Method Quality Objectives and Detection Limits for these analytes.

Plant analysis, to assess the comparative health of plants in various treatments, will include chlorophyll *a*, total carbon, total nitrogen, and total biomass. Typical plants used in bioretention systems in western Washington will be selected for the experiment. **Criteria to select plants for the study will include:**

- Primarily consider plants recommended for zone 1 (bottom of bioretention area) and perhaps zone 2.
- Plants should have lower nutrient requirements.
- Relatively fast growing (necessary to assess growth within the 6 month timeframe for the study).
- Very small shrubs or grasses (necessary to fit in 45.42-liter buckets).
- Plants must be readily available.
- Ideally, selected plants can be propagated/cloned easily.

Blends not supporting adequate plant growth will be assessed for elimination from the study or augmented for further testing.

The plant water regime will simulate two rainfall patterns typical for City of Seattle: 1) total average volume for the period November through February; and 2) total average volume for the period July through August. The period November through February simulates winter conditions with a total volume of approximately 571 liters per plant container and 26 liters per container each watering (once every 6 days) for approximately 16 weeks. The period July through August simulates dry summer conditions with a total volume of 56 liters and 14 liters per container each watering (once every 21 days) for 8 weeks. Watering volumes are determined by the following:

Plant container Area x Drainage Area Ratio x Runoff Ratio x Bypass)/1000

where:

Plant Container Area = 923.99 cm²

Drainage to Bioretention Area Ratio = 15/1

Runoff Ratio = 0.9

Bypass = 0.91

1000 = conversion for cubic centimeters to liters

7. SAMPLING PROCEDURES

This section of the QAPP describes laboratory sampling procedures necessary to ensure the quality and representativeness of the collected samples. This section includes information on laboratory safety, flow monitoring, and water sampling.

7.1. LABORATORY SAFETY PROCEDURES

The plant study will be conducted at University of Washington (UW) Center for Urban Horticulture. Personnel will follow safety requirements for UW as outlined in their laboratory procedures.

7.2. OBTAIN AND SAMPLE MEDIA COMPONENTS

Individual media components selected from the survey process described in Section 6.1.1 will be collected from producers or suppliers of those materials. For suppliers not located in this region, representatives will be contacted by Herrera staff and samples collected and shipped by the suppliers. For local suppliers with bulk aggregate or organic materials, Herrera staff will collect samples on-site from various representative locations in those material piles and composite into a single sample. Samples will be collected using stainless steel scoops, mixed in stainless steel bowls, and composited into plastic containers. All containers will be pre-cleaned using the following process: Liquinox detergent rinse, deionized water rinse, 10 percent hydrochloric acid rinse, and a final rinse with deionized water.

7.3. MEDIA COMPONENT LEACHING TESTS

Samples of the media components selected from the survey process described in Section 6.1.1 and collected from suppliers will be assessed for leaching potential using SPLP Extraction Method 1312. In general, the procedure is the following:

- If particle size reduction is needed, crush, cut, or grind the sample to pass through a 9.5-mm (0.375-inch) sieve.
- Weigh 40.0 grams of solids into in a 1-liter HDPE extraction bottle.
- Add a volume of extraction fluid equal to (20 times the weight of sample). Extraction fluids are dependent on analyte and include:
 - o Metals – weak acid ($\text{H}_2\text{SO}_4/\text{HNO}_3$) extraction using a pH recommended for western US
 - o Nutrients – deionized water extraction

- Place samples in tumbler and rotate at 30 rpm (± 2) for 18 hours (± 2).
- Following extraction, the liquid extract is filtered through a 0.6- to 0.8- μm glass fiber filter.

7.4. MEDIA COMPONENT SORPTION TESTS

Samples of media components passing the leaching tests described in Sections 6.1.2 and 7.3 will be assessed for contaminant sorption using a method based on ASTM D4545-03 and modified by Herrera and Specialty Analytical.

In general, samples for the contaminant sorption analysis are air dried for 7 days and passed a 2 mm sieve size prior to tumbling in a 1:20 ratio of sample to sorption solution (see Section 6.1.3 for sorption solution composition). After 2, 6, and 12 hours of tumbling, a small aliquot of sample is taken and filtered through a 0.45- μm filter. Samples are preserved and stored in proper containers for individual analytical methods. Specific procedures are the following:

- Weigh out a portion of sample into an aluminum weight dish and record the weight.
- Allow sample to air dry for 7 days or until constant weight (less than 5 percent change in weight in 24 hours).
- All samples must pass 2-mm sieve size. Use a mortar and pestle to crush samples of larger size.
- Mix the sieve material and determine the moisture content. Determine the mass of the media sample, corrected for the moisture content.
- Weigh out 50 grams of samples and duplicates. Combine 1,000 mL of sorption fluid into a 1-liter polypropylene bottle. Weight of sorption fluid = 20 times weight of solids to be extracted.
- Once the sorption fluid is added to the samples, the samples are immediately tumbled. At 2, 6, and 12 hours and an aliquot of the sample is filtered through a 0.45- μm filter and prepared for analyses.

7.5. MEDIA COMPONENT BLENDING

Media components passing analyses described in Sections 6.1.2, 6.1.3, 7.3, and 7.4 will be blended into media treatments for Ksat tests and the plant study. The blends will include bulk aggregate and organic materials and additives to achieve specific N, P, and Cu capture objectives. Physical characteristics of components and proportion of components will be selected considering gradation to minimize migration of fine fractions and organic material, prevent excessively high or low hydraulic conductivity and attain desired pollutant capture.

Blending will be by volume and the mass of the component volumes recorded if needed for additional analyses (e.g., mass of contaminant captured per mass of media).

7.6. SATURATED HYDRAULIC CONDUCTIVITY TESTS

Saturated hydraulic conductivity will be evaluated for each media blend. The Ksat tests will be conducted using Standard Test Method for Permeability of Granular Soils (ASTM D2434 modified approach) on each trial blend. In general, the test follows the below procedures:

Determine maximum dry density values for compaction of bioretention soil sample using Proctor method ASTM D1557 Method C (6-inch mold). Sample preparation for the Proctor test shall be amended in the following ways:

- Maximum grain size within the sample shall be no more than 0.5 inches in size.
- Snip larger organic particles (if present) into 0.5-inch-long pieces.
- When adding water to the sample during the Proctor test, allow the sample to pre-soak for at least 48 hours to allow the organics to fully saturate before compacting the sample.

ASTM D2434 shall be used and amended in the following ways:

- Apparatus:
 - o Use a 6-inch mold for the test.
 - o If using porous stone disks for the testing, the permeability of the stone disk shall be measured before and after the soil tests to ensure clogging or decreased permeability has not occurred during testing.
 - o Use the confined testing method with 5- to 10-pound force spring.
 - o Use de-aired water.
- Sample:
 - o Maximum grain size within the sample shall not be more than 0.5 inches in size.
 - o Snip larger organic particles (if present) into 0.5-inch-long pieces.
 - o Pre-soak the sample for at least 48 hours prior to loading it into the mold. During the pre-soak, the moisture content shall be higher than optimum moisture but less than full saturation (i.e., there shall be no free water). This pre-soak ensures the organics have been fully saturated at the time of the test.

- Preparation of Sample:
 - o Place soil in cylinder via a scoop.
 - o Place soil in 1-inch lifts and compact using a 50.8-mm-(2-inch)-diameter round tamper. Pre-weigh how much soil is necessary to fill 1-inch lift at 85 percent of maximum dry density, then tamp to 1-inch thickness. Once mold is full, verify that density is at 85 percent of maximum dry density (+ or -0.5 percent). Apply vacuum (508 mm or 20 inches Hg) for 15 minutes before inundation.
 - o Inundate sample slowly under a vacuum of 508 mm (20 inches) Hg over a period of 60 to 75 minutes.
 - o Slowly remove vacuum (>15 seconds).
 - o Sample shall be soaked in the mold for 24 to 72 hours before starting test.
- Procedure:
 - o The permeability test shall be conducted over a range of hydraulic gradients between 0.1 and 2.
 - o Steady state flow rates shall be documented for four consecutive measurements before increasing the head.
 - o The permeability test shall be completed within 1 day (1-day test duration).

7.7. PLANT GROWTH ANALYSIS

Media components meeting criteria in Sections 6.1.2, 6.1.3, and 6.1.4 will be combined into media blends to conduct plant growth tests. The plant study will be conducted for approximately 6 months.

Media and plants will be placed in 45.42-liter (12-gallon) buckets and grown in the Center for Urban Horticulture greenhouse under controlled conditions for duration of study. Each treatment will be replicated three times, and treatments will be arranged in a random block design.

A 45.7-centimeter (cm) (18-inch) layer of media will be placed on top of a 5-cm (2-inch) drainage layer of Type 26 (or other coarse sand or fine gravel) in each bucket leaving approximately 2.5 cm (1 inch) of freeboard for ponding of influent water. *Deschampsia cespitosa* (Tufted hairgrass) and *Juncus patens* (California grey rush), two species typically used in bioretention systems in western Washington will be selected for the experiment. Plants will be bareroot stock delivered from a local nursery, in bundles of 50. Bareroot plants will be used to minimize contamination of the treatment media by planting soil. The roots will be loosened and

straightened to prevent roots from growing in a circular, constrained pattern. Each plant will be photographed prior to planting in front of a gridded backdrop. Initial photographs will provide a point of reference to compare with subsequent photos for determining plant health and vigor at the end of the project. Buckets will be filled with media and 4 plants will be planted in each bucket (two *D. cesptiosa* and two *J. patens*). The greenhouse photo period will be 12 hours from 7 a.m. to 7 p.m., and the temperature range will be 68 to 72 degrees Fahrenheit. High-pressure sodium (400 watt) lights will be used for the light source.

Each batch of stormwater used to irrigate the plants will be analyzed for pH, TP, Ortho-P, NO₃-NO₂, and TKN. Plant analysis, to assess the comparative health of plants in various treatments, will include chlorophyll *a*, total carbon, total nitrogen, and total biomass.

Plants will be watered once at planting with tap water, then once per week starting 1 week after initial watering for 16 weeks. Each planter will receive approximately 26 liters (5.7 gallons) gallons of water per week at each watering. Stormwater for plant watering will be collected at City of Redmond's Maintenance and Operations Facility (18080 NE 76th Street Redmond, WA 98052) and delivered weekly in a 747 liter HDPE tank by Herrera. Stormwater from the tank will be pumped into LDPE plastic carboys for watering the plants. After approximately 16 weeks, plants will be stressed by reducing the watering regime to once every 3 weeks. Each planter will receive approximately 14.4 liters (3.2 gallons) gallons of water at each watering. Stormwater will continue to be used for watering unless not available. If stormwater is not available tap water will be used for watering. Stressing is intended to simulate the dryer conditions of summer, and will continue for 8 weeks.

Samples will be collected from the stormwater used to water the plants prior to each watering and delivered for analysis to Analytical Resources Inc. (approximately 20 samples). The sample for water quality analysis will be collected by taking a grab sample from the top, middle and bottom of the delivery tank, composited into one 20-liter (4.40-gallon) LDPE sample bottle, and stored at 3 degrees Celsius until delivery to the lab.

Starting approximately 2 months after planting pictures will be taken once per month of all replicates for each treatment to compare growth. Pictures will be taken from above and to the side of the plants. Pictures from the side will be taken with a grid background.

At approximately 2 months after planting and at the end of the wet watering period measurements of the longest live stalks will be recorded and the number of live stalks counted for one rep in each treatment.

At the end of the study all plants will be harvested at 2 cm (0.79 inches) above the soil. The harvest will be rinsed and dried in a drying oven at 105 degrees Celsius, then weighed to determine dry biomass. A representative sample of this biomass will be ground into a fine powder using a mortar and pestle and analyzed for carbon (C) and nitrogen (N) content by combustion using a Perkin Elmer CHN analyzer model 2400. The dried biomass will also be analyzed for total phosphorus (P) content as follows. Samples (2 g) will be dry ashed in a muffle furnace and then dissolved in a concentrated acid solution. The solution is then filtered and run

for total elemental concentrations (including P) using a Thermo Scientific Co. inductively coupled plasma mass spectrometer (ICP-MS) Model 6300. Additionally, the plant roots will be harvested, rinsed and pictures taken on the grid used at planting to assess root growth.

7.7.1. Laboratory Forms

For each stormwater delivery and sample, personnel will record the following information on a standardized field form before and after sampling:

- Date.
- Time of sample collection.
- Name(s) of field personnel present.
- All cleaning and preparation procedures.
- Sample volume collected in sample bottles.
- Unusual conditions (e.g., odor, color, turbidity, equipment leaks or spills).
- Modifications of, or unusual, sampling procedures.
- Any miscellaneous factors that might influence samples.

7.7.2. Sample Containers and Preservation

Twenty-liter LDPE plastic carboys will be used for sample collection. The analytical laboratory will clean the sample bottles. Spare sample bottles will be carried by personnel conducting the testing in case of breakage or possible contamination. Sample containers and preparation will follow Code of Federal Regulations [40 CFR 136] guidelines. Refer to Table 5 in the *Measurement Procedures* section for information on recommended sample containers.

7.7.3. Sample Identification and Labeling

All sample containers will be labeled with the following information, using waterproof labels and indelible ink and placed on dry sample container lids:

- Column/sample ID
- Date of sample collection (month/day/year)
- Time of sample collection (military format)

7.7.4. Chain-of-Custody

After samples have been obtained and the collection procedures properly documented, a written record of the chain-of-custody of each sample will be completed by laboratory personnel to ensure that samples have not been tampered with or compromised in any way and to track the requested analysis for the analytical laboratory. Information necessary in the chain-of-custody includes:

- Name(s) of field personnel.
- Date and time of sample collection,
- Location of sample collection.
- Printed names, signatures and contact information of field personnel and laboratory personnel handling the samples.
- Laboratory analysis requested and control information (e.g., duplicate or spiked samples) and any special instructions (e.g., time sensitive analyses).

Sample custody will be tracked in the laboratory through the entire analytical process, and the signed chain-of-custody forms and analytical results returned to the Herrera project manager. The Herrera monitoring lead will record the date and time of sample deliveries for the project file.

7.7.5. Sample Delivery

Immediately after collection, samples will be clearly labeled and delivered to ARI in Tukwila, Washington. Samples will be capped to prevent contamination and kept on ice to maintain a temperature of 6 degrees Celsius or less. At ARI samples will be churn split into bottles prepared by ARI.

8. MEASUREMENT PROCEDURES

Laboratory analytical procedures will follow methods approved by the US Environmental Protection Agency (EPA) (APHA et al. 1992, 1998; US EPA 1983, 1984). These methods provide reporting limits that are below the state and federal regulatory criteria or guidelines and will allow direct comparison of the analytical results with these criteria. Preservation methods, analytical methods, reporting limits, and sample holding times are presented in Table 6.

Samples for parameters requiring filtration (i.e., Ortho-P, dissolved Cu, and dissolved zinc) will be delivered to the laboratory within 4 hours of their collection. Upon their receipt, laboratory personnel will immediately filter and preserve these samples.

ARI, the laboratory identified for this project, is certified by Ecology and participates in audits and inter-laboratory studies by Ecology and EPA. These performance and system audits have verified the adequacy of the laboratory's standard operating procedures, which include preventive maintenance and data reduction procedures.

The laboratory will report the analytical results within 30 days of receipt of the samples. The laboratory will provide sample and quality control data in standardized reports suitable for evaluating the project data. The reports will also include a case narrative summarizing any problems encountered in the analyses.

Table 6. Methods and Detection Limits for Water Quality Analyses.									
Analyte	Analytical Method	Method Number ^a	Volume of Water Required for Analysis	Field Sample Container	Pre-Filtration Holding Time	Total Holding Time ^b	Preservation	Reporting Limit	Units
Total suspended solids	Gravimetric ^c	SM 2540 D	1 L	HDPE	7 days	7 days	Cool, ≤6°C	1.0	mg/L
pH	Meter	SM 4500 H+B	100 ml	HDPE	15 minutes	15 minutes	Cool, ≤6°C	NA	std. units
Total Kjeldahl Nitrogen	Colormetric	SM 4500-Norg D	100 mL	HDPE		28 days	Cool, ≤6°C; H ₂ SO ₄ to pH<2	1.0	mg/L
Nitrate-nitrite	Colorimetric	SM 4500 NO3 I	200 mL	HDPE	48 hours	28 days	Cool, ≤6°C; H ₂ SO ₄ to pH<2	0.01	mg/L
Total phosphorus	Colorimetric	SM 4500-P-E	200 mL	HDPE	NA	28 days	Cool, ≤6°C; H ₂ SO ₄ to pH<2	0.008	mg/L
Ortho-phosphorus	Colorimetric	EPA 365.2	200 mL	HDPE	4 hours ^d	48 hours	Cool, ≤6°C; H ₂ SO ₄ to pH<2	0.004	mg/L
DOC	Combustion	SM 5310B	50 mL	Amber Glass	24 hours	28 days	Filter, Cool, ≤6°C; H ₂ SO ₄ to pH<2	1.5	mg/L
Hardness	Calculation	EPA 6010	100 mL	HDPE	NA	6 months	Cool, 4°C, HNO ₃ to pH <2	0.33	mg/L
Cadmium, dissolved	ICP-MS	EPA 200.8	200 mL	HDPE	4 hours ^d	6 months	Filter, Cool, ≤6°C; HNO ₃ to pH<2	0.1	µg/L
Copper, dissolved					4 hours ^d			0.5	
Zinc, dissolved					4 hours ^d			4	
Cadmium, total					NA		Cool, ≤6°C; HNO ₃ to pH<2	0.1	
Copper, total					NA			0.5	
Zinc, total					NA			4	
Polycyclic aromatic hydrocarbons					GC/MS			EPA 8270D	
Total petroleum hydrocarbons (diesel)	GC/FID	NWTPH-Dx ^e	2 x 500 mL	1 L glass bottle	7 days	7 days	Maintain ≤4°C, H ₂ SO ₄ to pH <2	0.25	mg/L
Total petroleum hydrocarbons (motor oil)			2 x 500 mL					0.5	mg/L
E. coli	Membrane filtration	SM 9223 B	250 mL	250 mL HDPE bottle	8 hours	8 hours ^f	Cool, ≤6°C	1 ^g	CFU/100 mL
Fecal coliform bacteria	Membrane filtration	SM 9222 D	250 mL	250 mL HDPE bottle	8 hours	8 hours ^f	Cool, ≤6°C	1 ^g	CFU/100 mL

^a SM method numbers are from APHA et al. 1998; EPA method numbers are from US EPA 1983, 1984. The 18th edition of Standard Methods for the Examination of Water and Wastewater (APHA et al. 1992) is the current legally adopted version in the Code of Federal Regulations (CFR). However, the 20th edition provides additional guidance on certain key items. For this reason, the 20th edition is referenced in this table as the best available guidance. An equivalent standard method can be substituted. NWTPH-Dx method is from the Washington State Department of Ecology (Ecology 2007).

^b Holding time specified in EPA guidance (US EPA 1983, 1984) or referenced in Standard Methods for equivalent method.

^c A G4 glass fiber filter will be used for the total suspended solids and suspended sediment concentration filtration.

^d EPA requires filtering for dissolved metals, nutrients, and pH measurement to be performed within 15 minutes of the collection of the last aliquot. Due to logistical consideration related to the collection of flow-weighted composite sampling, this goal may be difficult to meet.

^e Washington State Department of Ecology methods (Ecology 2007) includes silica gel extract cleanup step.

^f Incubation must start prior to 8 hours.

^g Reporting limit will be dependent upon dilution used in analysis.

C = Celsius

ICP-MS = inductively coupled plasma/mass spectrometry

GC/MS = gas chromatography/ mass spectrometry

L = liter

mg/L = milligrams per liter

NA = not applicable

µg/L = micrograms per liter

DOC = dissolved organic carbon

9. QUALITY CONTROL

This section includes information on field quality assurance/quality control (QA/QC) and laboratory quality control.

9.1. FIELD QUALITY CONTROL

This section summarizes the QA/QC procedures that laboratory personnel will implement to evaluate sample contamination and sampling precision and to maintain and calibrate monitoring equipment.

9.1.1. Bottle Blanks

One sample bottle blank will be collected at the beginning, middle, and end of the plant experiments. The bottle blank will be collected by filling sample bottles with reagent-grade water using a similar volume dispensed for each plant container.

9.2. LABORATORY QUALITY CONTROL

This section summarizes the quality control procedures the laboratory will perform and report with the analytical results. Accuracy of the laboratory analyses will be verified using blank analyses, duplicate analyses, laboratory control spikes and matrix spikes in accordance with the EPA methods employed. Analytical Resources, Inc. will be responsible for conducting internal quality control and quality assurance measures in accordance with their own quality assurance plans.

Water quality results will first be reviewed at the laboratory for errors or omissions. Laboratory quality control results will be reviewed by the laboratory to verify compliance with acceptance criteria. The laboratory will also validate the results by examining the completeness of the data package to determine whether method procedures and laboratory quality assurance procedures were followed. The review, verification, and validation by the laboratory will be documented in a case narrative that accompanies the analytical results.

Data will be reviewed and validated within 7 days of receiving the results from the laboratory. This review will be performed to ensure that all data are consistent, correct and complete, and that all required quality control information has been provided. Specific quality control elements for the data (see Tables 3 and 4) will also be examined to determine if MQOs for the project have been met.

Results from these data validation reviews will be summarized in quality assurance worksheets (see example in Appendix A) that are prepared for each sample batch. The Herrera project manager and Herrera quality assurance lead for water quality data will be jointly responsible for identifying and initiating corrective action. Values associated with minor quality control problems will be considered estimates and assigned *J* qualifiers. Values associated with major quality control problems will be rejected and qualified with an *R*. Estimated values may be used for evaluation purposes, but rejected values will not be used. The following sections describe in detail the data validation procedures for quality control.

10. DATA MANAGEMENT PROCEDURES

Analytical Resources, Inc. will report the analytical results within 30 days of receipt of the samples. The laboratory will provide sample and quality control data in standardized reports that are suitable for evaluating the project data. These reports will include all quality control results associated with the data. The reports will also include a case narrative summarizing any problems encountered in the analyses, corrective actions taken, changes to the referenced method, and an explanation of data qualifies.

Laboratory data will be entered from the lab electronic data spreadsheets into the project database for all subsequent data management and archiving tasks. Herrera's quality assurance lead for water quality data will perform an independent review to ensure that the data were entered without error. Specifically, 10 percent of the sample values will be randomly selected for rechecking and crosschecking with laboratory reports. If errors are detected, they will be corrected, and then an additional 10 percent will be selected for validation. This process will be repeated until no errors are found in the data.

11.AUDITS AND REPORTS

This section provides information on audits and reports that will be part of this monitoring program.

11.1. AUDITS

Audits performed for water quality data will occur within 7 business days of receiving results from the laboratory. This review will be performed to ensure that all data are consistent, correct, and complete, and that all required quality control information has been provided. Specific quality control elements for the data (see Tables 3 and 4) and raw data will also be examined to determine if the MQOs for the project have been met. Results from these audits will be documented in QA worksheets (see Appendix A) that will be prepared for each batch of samples.

In the event that a potential QA issue is identified through these audits, Herrera's data quality assurance lead will review the data to determine if any response actions are required. Response actions in this case might include the collection of additional samples, reanalysis of existing samples if not yet past holding time, or advising the laboratory that methodologies or QA/QC procedures need to be improved.

11.2. REPORTS

Herrera will prepare a preliminary and final report for project partner (including Ecology) review.

12. DATA VERIFICATION AND VALIDATION

Data verification and validation will be performed on the water quality data that are collected through the duration of this project. The specific procedures that will be used to verify and validate each type of data are described in the following sections.

12.1. VERIFICATION AND VALIDATION METHODS FOR WATER QUALITY DATA

Data will be reviewed and audited within 7 business days of receiving the results from the laboratory. This review will be performed to ensure that all data are consistent, correct and complete, and that all required quality control information has been provided. Specific quality control elements for the data (see Tables 3 and 4) will also be examined to determine if the MQOs for the project have been met. Results from these data validation reviews will be summarized in quality assurance worksheets that are prepared for each sample batch (see Appendix A). Values associated with minor quality control problems will be considered estimates and assigned *J* qualifiers. Values associated with major quality control problems will be rejected and qualified *R*. Estimated values may be used for evaluation purposes, while rejected values will not be used. The following sections describe in detail the data validation procedures for these quality control elements:

- Completeness
- Methodology
- Holding times
- Bottle blanks
- Reporting limits
- Matrix spikes
- Control standards
- Sample representativeness

12.1.1. Completeness

Completeness will be assessed by comparing valid sample data with this quality assurance project plan and the chain-of-custody records. Completeness will be calculated by dividing the number of valid values by the total number of values. If less than 95 percent of the samples submitted to the laboratory are judged to be valid, then more samples will be collected until at least 95 percent are judged to be valid.

12.1.2. Methodology

Methodologies for analytical procedures will follow EPA-approved methods (APHA et al. 1992, 1998; US EPA 1983, 1984) specified in Table 5. Field procedures will follow the methodologies described in this QAPP. Any deviations from these methodologies must be approved by Ecology and documented in an addendum to this QAPP. Deviations that are deemed unacceptable will result in rejected values (*R*) and will be corrected for future analyses.

12.1.3. Holding Times

Holding times for each analytical parameter in this study are summarized in Table 6. Holding time compliance will be assessed by comparing sample collection dates and times to filtration (pre-filtration) and analytical (post-filtration or total) dates and times. Sample collection times will be based on the date and time that the last aliquot was collected, but start of sampling date and time will be recorded as well.

12.1.4. Pre-Filtration Holding Times

Samples requiring filtration should be filtered within 4 hours of collection. EPA requires that dissolved metals and Ortho-P should be filtered within 15 minutes of the collection of the last aliquot. Meeting this holding time goal would be difficult for this project. Consequently, dissolved metals and Ortho-P samples that are filtered within 4 hours will be flagged as estimated values (*J*). Dissolved metals and Ortho-P samples that are filtered after this 4-hour limit will be considered rejected (*R*).

12.1.5. Post-Filtration or Total Holding Times

- For analytes with holding times in excess of 7 days:
 - o Data from samples that exceed the specified maximum post-filtration holding times by less than 48 hours will be considered estimates (*J*). Data from samples that exceed the maximum post-filtration holding times by more than 48 hours will be rejected values (*R*).

- For analytes with holding equal to or less than 7 days:
 - o Data from samples that exceed the specified maximum post-filtration holding times by less than 24 hours will be considered estimates (*J*). Data from samples that exceed the maximum post-filtration holding times by more than 24 hours will be rejected values (*R*).

12.1.6. Method Blanks

Method blank values will be compared to the MQOs that have been identified for this project (see Tables 3 and 4). If an analyte is detected in a method blank at or below the reporting limit, no action will be taken. If blank concentrations are greater than the reporting limit, the associated data will be labeled with a *U* (in essence increasing the reporting limit for the affected samples), and associated project samples within 5 times the de facto reporting limit will be flagged with a *J* (G. Grepogrove, Manchester Laboratory, personal communication, September 4, 2007). In each of these cases, the de facto reporting limit for that analyte will be recorded along with the raw data, equipment will be decontaminated, and samples will be rerun if possible.

12.1.7. Bottle Blanks

Bottle blank concentrations will be compared to the MQOs that have been identified for this project (see Tables 3 and 4). If concentrations are detected in the bottle blanks that exceed 2 times the reporting limit, the lab will be contacted to review cleaning procedures, test for bottle contamination before next sample collection and associated samples collected since the previous bottle blank that are within 5 times the new reporting limit will be flagged with a *J*.

12.1.8. Reporting Limits

Both raw values and reporting limits will be presented in each laboratory report. If the proposed reporting limits are not met by the laboratory, the laboratory will be requested to reanalyze the samples or revise the method, if time permits. Proposed reporting limits for this project are summarized in Table 6.

12.1.9. Duplicates

Duplicate results exceeding the MQOs for this project (see Table 3) will be recorded in the raw data tables, and noted in the quality assurance worksheets; and associated values will be flagged as estimates (*J*). If the objectives are severely exceeded (such as more than twice the objective), then associated values will be rejected (*R*).

12.1.10. Matrix Spikes

Matrix spike results exceeding the MQOs for this project (see Table 3) will be noted in the quality assurance worksheets, and associated values will be flagged as estimates (*J*). However, if the percent recovery exceeds the MQOs and a value is less than the reporting limit, the result will not be flagged as an estimate. Non-detected values will be rejected (*R*) if the percent recovery is less than 30 percent.

12.1.11. Control Standards

Control standard results exceeding the MQOs for this project (see Tables 3 and 4) will be noted in the quality assurance worksheets, and associated values will be flagged as estimates (*J*). If the objectives are severely exceeded (such as more than twice the objective), then associated values will be rejected (*R*).

13. DATA QUALITY ASSESSMENT

Separate subsections herein describe the procedures that will be used to assess the usability of the data and analyze the data.

13.1. DATA USABILITY ASSESSMENT

The Herrera quality assurance officer will provide an independent review of the water quality QC data from each sampling event using the MQOs that have been identified in this QAPP. The results will be presented in a water quality data quality assessment report (see *Audits and Reports* section). The data quality assessment report will summarize quality control results, identify when data quality objectives were not met, and discuss the resulting limitations (if any) on the use or interpretation of the data. Specific quality assurance information that will be noted in the data quality assessment report includes the following:

- Changes in and deviations from the QAPP.
- Results of performance or system audits.
- Significant quality assurance problems and recommended solutions.
- Data quality assessment results in terms of precision, bias, representativeness, completeness, comparability, and reporting limits.
- Discussion of whether the quality assurance objectives were met, and the resulting impact on decision-making.
- Limitations on use of the measurement data.

13.2. DATA ANALYSIS PROCEDURES FOR MEDIA COMPONENTS AND WATER QUALITY

Data analysis will be performed to document the leaching and sorption potential of the media components and quality of the influent water for the plant experiments. The data for the leaching and sorption potential will be used to simply rank those component potentials. The data for the plant experiment influent water will be used to assess the nutrient inputs of that water with one sample taken at each influent water delivery. Accordingly, the following basic, summary statistics will be provided:

- Leaching data: rank media components from lowest to highest leaching potential.
- Sorption data: basic summary statistics (minimum, maximum, mean and median).
- Plant influent water: basic summary statistics (minimum, maximum, mean and median).

13.3. DATA ANALYSIS PROCEDURES FOR PLANT EXPERIMENTS

Statistical analyses will be performed to determine whether there are significant differences in plant growth characteristics for each media blend. Metrics used to assess the comparative growth and health of plants in various treatments, will include chlorophyll a, total carbon, total nitrogen and total biomass. The specific null hypothesis (H_0) and alternative hypothesis (H_a) for these analyses are as follows:

H_0 : Plant growth characteristics are equal among media treatments.

H_a : Plant growth characteristics are not equal among media treatments.

Data analysis will begin with visual assessment using boxplot distributions. If normally distributed, the data will be analyzed using one-factor analysis of variance (ANOVA) and a mixed model, two-way ANOVA where appropriate. Because an ANOVA test is considered a parametric procedure, there are several underlying assumptions that must be met when this approach is used; most notably, the data must have a normal distribution and each treatment group must have an equal variance. If the data is a non-normal distribution, the Kruskal-Wallis Test will be computed by using a large-sample approximation, ranking the data and performing a parametric test on the ranks.

Where a significant difference in plant growth is detected due to the media treatment factor, follow-up Tukey HSD multiple comparison tests will be performed to determine which specific media treatments have different plant growth performance relative to the others. Statistical significance in all these tests was assessed based on an alpha (α) level of 0.05.

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APPENDIX A

Quality Assurance Worksheet

Data Quality Assurance Worksheet

Plant Experiment:			Entry Date		Page	1	of	2
Laboratory/Parameters:	See below		Checked By:					
Sample Date/Sample ID:			Sample Collection Time:					

Parameter	Completeness/ Methodology	Pre-Filter Holding Time		Total Holding Time		Lab Method Blanks/ Reporting Limit		Surrogate Recovery (percent recovery)		Matrix Spikes (percent recovery)		Lab Duplicates (RPD)**		Field Duplicates (RSDp)***		Rinsate Blanks		Lab Control Standard (percent recovery)		ACTION
		Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	
pH	SM 4500 H+B		15 min‡		15 min		NA		NA		NA		≤10% or ±2 x RL		≤35%		NA		NA	
Total Suspended Solids	SM 2540D		7 dy		7 dy		≤1.0 mg/L		NA		NA		≤20% or ±2 x RL		≤35%		NA		±10	
DOC	SM 5310B		24 hr		28 dy		≤1.5 mg/L		NA		±25		≤20% or ±2 x RL				<2 x RL		±10	
TP	SM 4500-P-E		NA		28 dy		≤0.008 mg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±10	
Ortho-P	EPA 365.2		15 min‡		48 hr		≤0.004 mg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
TKN	SM 4500- Norg D		NA		28 dy		≤0.6 mg/L		NA		±25		≤20% or ±2 x RL		≤35%		NA		±20	
Nitrate+Nitrite	SM 4500 NO3 I		48 hr		28 dy		≤0.01 mg/L		NA		±25		≤20% or ±2 x RL		≤35%		NA		±10	

* As CaCO₃

** The relative percent difference (RPD) must be less than or equal to the indicated percentage for values that are greater than 5 times the reporting limit. RPD must be ±2 times the reporting limit for values that are less than or equal to 5 times the reporting limit.

*** The pooled relative standard deviation (RSDp) will only be calculated for values that exceed 5 times the RL. Reported values are for the following pooled duplicates: _____.

‡ EPA requires field filtering within 15 minutes of collection of the last aliquot. This is generally not feasible with flow weighted composite sampling.

Data Quality Assurance Worksheet

Plant Experiment:			Entry Date		Page	2	of	2
Laboratory/Parameters:	See below		Checked By:					
Sample Date/Sample ID:			Sample Collection Time:					

Parameter	Completeness/ Methodology	Pre-Filter Holding Time (days)		Total Holding Time (days)		Lab Method Blanks/ Reporting Limit		Surrogate Recovery (percent recovery)		Matrix Spikes (percent recovery)		Lab Duplicates (RPD)**		Field Duplicates (RSDp)***		Rinsate Blanks		Lab Control Standard (percent recovery)		ACTION
		Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	Reported	Goal	
Metals diss. (Cd)	EPA 200.8		12 hr‡		6 mo		≤0.1 µg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
Metals total (Cd)	EPA 200.8		NA		6 mo		≤0.1 µg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
Metals diss. (Cu)	EPA 200.8		12 hr‡		6 mo		≤0.5 µg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
Metals total (Cu)	EPA 200.8		NA		6 mo		≤0.5 µg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
Metals diss. (Zn)	EPA 200.8		12 hr‡		6 mo		≤4.0 µg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
Metals total (Zn)	EPA 200.8		NA		6 mo		≤4.0 µg/L		NA		±25		≤20% or ±2 x RL		≤35%		≤2 x RL		±20	
PAH	EPA 8270D		NA		7 dy		≤1.0 µg/L		23–120		30–115		≤30% or ±2 x RL		≤45%		≤2 x RL		30–115	
TPH (diesel)	NWTPH-Dx		7 dy		7 dy		≤0.25 mg/L		35–131		56–103		≤30% or ±2 x RL		≤45%		≤2 x RL		56–103	
TPH (motor oil)	NWTPH-Dx		7 dy		7 dy		≤0.5 mg/L		NA		30–160		≤30% or ±2 x RL		≤45%		≤2 x RL		30–160	
E. coli	SM 9223 B		8 hr		8 hr		<RL		NA		NA		≤35% or ±2 x RL		NA		NA		NA	
Fecal coliform bacteria	SM 9222D		6 hr		6 hr		2 CFU/ 100 mL		NA		NA		≤35% or ±2 x RL		≤35%		NA		NA	

* As CaCO₃

** The relative percent difference (RPD) must be less than or equal to the indicated percentage for values that are greater than 5 times the reporting limit. RPD must be ±2 times the reporting limit for values that are less than or equal to 5 times the reporting limit.

*** The pooled relative standard deviation (RSDp) will only be calculated for values that exceed 5 times the RL. Reported values are for the following pooled duplicates: _____.

‡ EPA requires field filtering within 15 minutes of collection of the last aliquot. This is generally not feasible with flow weighted composite sampling.

APPENDIX B

Media Component Matrix

Table B-1. Bioretention Media Components.

Common Name	Component	Material Composition	Source/Process	Vendor	Source Location	Cost/Unit (CY Delivered)	Quantity for Cost Estimate	Estimated % Use in BSM (low)	Estimated % Use in BSM (high)	Target Pollutants	Treatment Mechanism	Project	Tests Completed or in Progress					Performance Notes	Recommended	
													Leaching or Flushing	Hydraulic Conductivity	Stormwater Dosing	Polishing	Pilot Testing		2015 Study	2017 Study
Activated alumina	Mineral additive	Aluminum hydroxide (1)	Dehydroxylating aluminum hydroxide. Process results in a highly porous material (1) that is 98-99% alumina and 1-2% soda.	Axens, Inc. (eastern U.S.) Contact: Bill Reidbreid@axensna.com	Eastern US and Canada.	\$1,750.00	<100 CY	5	10	Fluoride, arsenic, selenium, beryllium, and natural organic matter (10). Phosphorus (11).	sorption, filtration	Port of Olympia and Seattle Polishing Layer Study	X	X	X	X		Best performance for P capture (17, 23). Some have reported possibility to raise pH to 8-10 (16). No increase in pH in local trails (22).	Yes	Yes
Bauxite	Mineral additive	Hydrous aluminum oxides and aluminum hydroxides (13).	Strip-mined.	Not targeted for testing	Australia, Brazil, China, India, etc.	Not targeted for testing	Not targeted for testing	5	20	Phosphorus	sorption and/or precipitation (pH dependent...neutral to lower pH favors Al and Fe adsorption)							Principle source of aluminum.	No	No
Bayoxide E33	Mineral additive			AdEdge	Atlanta, Georgia															
Biochar	Organic additive	Ligno-cellulosic product that may be created from multiple types of raw material (e.g., bamboo, Douglas fir, reeds, etc.)	Any ligno-cellulosic material burned at specific temperature and in a low- or no-oxygen environment. Specifically will analyze Environmental Ultra.	Biochar Supreme (Everson, WA), Walrath.	Western WA, Canada or.	\$300.00	>300 CY	5	20	Varies by feedstock and burn process.	Filtration, Sorption, complexation and promotes biological activity thus uptake.	Port of Olympia	X	X	X	X		High variability among sources for P export, pollutant capture and hydraulic conductivity (17). Specifically will analyze Environmental Ultra that has high surface area.	Yes	No
Blast furnace slag	Mineral additive	Typically 33-43% calcium oxide and 9-16% aluminum oxide (13).	By-product of iron ore processing.	Not targeted for testing	Steel manufacturers.	Not targeted for testing	Not targeted for testing	5	20	Phosphorus	Sorption and/or precipitation (pH dependent...lower pH favors Al and Fe adsorption, higher pH favors calcium precipitation).							Some studies have found significant reduction in infiltration capability using slag (14). Potential for metal leaching (13).	No	No
C-33 sand	Bulk aggregate	Usually common silica sand.	Various mining processes (dredging, excavation). C-33 is an ASTM specification for concrete aggregates generally with no more than 4% passing the 100 sieve and a uniformity coefficient that is ≤ 4.	Cadmin (Redmond plant)	Likely western Washington pits.	Not targeted for testing	Not targeted for testing	50	80	Particulates, metals	Filtration.	Port of Olympia		X	X				No	No
Carbonate sands	Bulk aggregate	Calcium carbonate (1).	Skeletal remains of plants or animals or weathered rock with a high calcium carbonate content (1).	No source identified	No source identified	No source identified	No source identified	50	80	Phosphorus	Sorption and/or precipitation (pH dependent...higher pH favors calcium precipitation).								No	No
Coco peat	Primary additive	Coconut husks and sphagnum peat.	Coir waste from coir fiber industries is washed, heat-treated, screened, graded, and processed into coco peat products of various granularity and denseness.	No source identified	India, southeast Asia and south Pacific, New Zealand (1).	No source identified	No source identified	5	20	Metals.		Port of Olympia						High water holding capacity. Low nutrient content. May have naturally occurring beneficial fungi (Trichoderma) that protects plants from pathogens (e.g. pythium) (1). May lower pH significantly (19).	No	No
Coco coir fiber (may or may not include pith)	Bulk organic	Coconut husk and coconut husk pith.	Fibrous layer of the fruit is separated from the hard shell manually (~2,000 husk/day) or by machine (~2,000 coconuts/hour) (1).	Sunlight Supply (Vancouver, WA). Using CocoGro for testing.	India, southeast Asia and south Pacific (1).	\$130-\$150.00	>200 CY	20	40	Not known (primarily applied for soil structure).	Not known.	Kitsap BSM and Redmond Study 2014-15. BSM Study Phase 1 2016-17.	X	X	X		X	While primarily a soil structure and water holding capacity amendment the material should be assessed for leaching if commonly applied.	Yes	Yes
Compost	Bulk organic	Usually yard trimmings or yard trimmings with food waste. Will not include manure- or biosolids-based composts.	Biologic decomposition.	Several local vendors and producers, Walrath.	Several local vendors and producers.	\$24.00	>300 CY	5	20	Metals, hydrocarbons, bacteria.	Filtration, sorption, complexation and promotes biological activity thus uptake.	Kitsap BSM and Redmond Study 2014-15. BSM Study Phase 1 2016-17.	X	X	X	X	X	Flushing and leaching of Cu, P and N observed (21).	Yes (selected for comparative performance)	Yes (selected for comparative performance)

Table B-1 (continued). Bioretention Media Components.																				
Common Name	Component	Material Composition	Source/Process	Vendor	Source Location	Cost/Unit (CY Delivered)	Quantity for Cost Estimate	Estimated % Use in BSM (low)	Estimated % Use in BSM (high)	Target Pollutants	Treatment Mechanism	Project	Tests Completed or in Progress					Performance Notes	Recommended	
													Leaching or Flushing	Hydraulic Conductivity	Stormwater Dosing	Polishing	Pilot Testing		2015 Study	2017 Study
Corliss pipe bedding sand	Bulk aggregate	Not known	Various mining processes (dredging, excavation).	Corliss (Puyallup)	Puyallup	\$25.00	>100 CY	50	80	Particulates, metals	Filtration, sorption.	Kitsap BSM Study 2014-15	X					Initial SPLP screening indicates N, P and Cu at detection limits.	Yes	No
Corliss utility sand	Bulk aggregate	Not known	Various mining processes (dredging, excavation).	Corliss (Puyallup)	Puyallup	\$26.65	>100 CY	50	80	Particulates, metals	Filtration, sorption.	Kitsap BSM Study 2014-15	X					Initial SPLP screening indicates N, P and Cu at detection limits.	Yes	No
Crushed brick	Mineral additive	Clay-bearing soil, sand and lime, or concrete material that is fire hardened or air dried (1).	Recycled or new brick crushed to specific gradation.	RealGoods Company (Daniel Wheeler, 814-676-0700)	Oil City, PA	not known		5	20	Phosphorus.	Sorption, filtration	Kitsap BSM Study 2014-15	X					Initial SPLP screening indicates high N leaching potential (22).	Yes	No
Dakota peat	Bulk organic	Decomposed reeds and sedges from ancient swamp lands.	Harvested from old ditched and drained farmland (now shrublands). Field is tilled dried and vacuum harvested (generally to 24" depth).	Dakota Peat (Grand Forks, ND)	Red River Valley in NW MN.	\$300.00	<100 CY	5	20	Metals.	Filtration, sorption, complexation and promotes biological activity thus uptake.	Kitsap BSM Study 2014-15	X					Harvested area is returned to habitat (e.g. water fowl) in cooperation with MN DNR. Excellent metals capture at high flow rates (19). May lower pH significantly (19). May export P and Ortho-P (19). Initial SPLP extraction indicates very high N export potential (22).	Yes	No
Diatomaceous earth (Diatomite)	Mineral additive	Approximately 80-90% silica, 2-4% alumina and 0.5-2% iron oxide (1).	Skeletal remains of diatoms	Walrath (Puyallup). Envirotech Soil Solutions George Serril 503-723-9790 http://www.axisplayball.com/more_about_axis.htm#AXIS:32Specifications	Several sites in western US.	\$300.00	>300 CY	5	20	Bacteria, fine particulates, phosphorus.	Adsorption and/or precipitation (pH dependent...higher pH favors calcium precipitation). Filtration.	Kitsap BSM Study 2014-15	X	X	X			For wastewater treatment DE is mixed in a slurry and fed onto a fine screen (septum). The DE coats the septum and creates a microscopic filter (3). Discharge of DE from filters controlled by DOE in current SWMMWW. Air borne particle and lung disease guidelines necessary for handling. High water holding capacity and improved plant growth.	Yes	Yes
Eastern OR basalt sand	Bulk aggregate	Basalt is an aphanitic igneous rock with less than 20% quartz and less than 10% feldspathoid by volume, and where at least 65% of the feldspar is in the form of plagioclase. Rapidly weathers to brown or rust-red due to oxidation of its mafic (iron-rich) minerals into rust (1).	Common extrusive igneous (volcanic) rock formed from the rapid cooling of basaltic lava exposed at or very near the earth's surface (1).	not known	not known	not known		50	80			Kitsap BSM Study 2014-15	X						No	No
Ecology bioretention sand specification/gradation	Bulk aggregate	Silicate minerals (most commonly quartz and smaller percentages of other minerals such as feldspars) (4).	Various mining processes (dredging, excavation).	Several local suppliers (primary supplier currently Miles Sand and Gravel and Walrath. Miles Canyon for Kitsap BSM Study 2014-15).	Western Washington.	\$40.00	>300 CY	50	80	Phosphorus (sand filters including biological activity).	Filtration and biological uptake.	Kitsap BSM Study 2014-15. BSM Study Phase 1 2016-17.	X					Flushing and leaching of Cu, P and N observed (21).	Yes (selected for comparative performance)	Yes (selected for comparative performance)
Expanded shale	Mineral additive	Depending on parent materials: Hydrous aluminum silicates, feldspar, quartz, carbonates and/or micas.	Crushed clay, shale or slate exposed to high heat (3,600 F).	Walrath (Puyallup)	Utelite, Inc UT.	\$78.00	Not targeted for testing	10	20			Port of Olympia			X			Elevates pH (17).	No	No

Table B-1 (continued). Bioretention Media Components.

Common Name	Component	Material Composition	Source/Process	Vendor	Source Location	Cost/Unit (CY Delivered)	Quantity for Cost Estimate	Estimated % Use in BSM (low)	Estimated % Use in BSM (high)	Target Pollutants	Treatment Mechanism	Project	Tests Completed or in Progress					Performance Notes	Recommended	
													Leaching or Flushing	Hydraulic Conductivity	Stormwater Dosing	Polishing	Pilot Testing		2015 Study	2017 Study
Fly ash	Mineral additive		Residual of combustion from coal power plants.	Not targeted for testing	Not targeted for testing	Not targeted for testing	Not targeted for testing	5	20	Phosphorus								Potential for metal leaching (13).	No	No
G2 Media	Mineral additive	Diatomaceous earth and ferric hydroxide.	Ferric hydroxide is chemically bonded to DE.	ADI International	New Brunswick, Canada	\$2700 (not delivered)	Not targeted for testing	5	10	Phosphorus	Sorption								No	No
Granular activated carbon	Organic additive	Carbonaceous (e.g. nutshells, coconut husk or wood) (1).	Physical (e.g. hot gasses) or chemical (e.g. acid, base or salt) activation to increase porosity and surface functional groups.	Charcoal House, (Crawford, NE). Use 1230AW GAC from Charcoal House for analysis. 8x16 mesh http://www.buyactivatedcharcoal.com/product/granular_activated_charcoal/coconut/8x16_mesh	Unknown	\$718.20	<100 CY	5	20	Organic compounds, natural organic matter, mercury and Cd (1, 9).	Sorption, filtration	Port of Olympia and Kitsap BSM Study 2014-15. BSM Study Phase 1 2016-17.	X	X	X	X		Powdered and granulated forms available (granulated likely best material for bioretention application) (1). Performance determined by surface area and chemical characteristics (e.g. surface functional groups). Improved N03-N02 capture in media mixtures and Cu capture when tested individually (19). May release (19) or export P (17).	Yes	Yes
Hi-clay alumina	Mineral additive	Minimum 20-40% Al2O3.	By-product of commercial alum production (1).	Not targeted for testing	CA, MT, UT, CO, Argentina.	Not targeted for testing	Not targeted for testing	5	20	Phosphorus	Sorption and/or precipitation (pH dependent...neutral to lower pH favors Al and Fe adsorption)								No	No
High carbon wood ash	Organic additive	Ligno-cellulosic product that may be created from multiple types of raw material (e.g., tree slash, etc.)	Any ligno-cellulosic material burned at specific temperature and in an oxygen environment. Specifically will analyze products from Biological Carbon	Biological Carbon LLC. Use PD and AS 100+ mesh for analysis.	Philomath, OR	\$400.00	1 CY	5	20	Varies by feedstock and burn process.	Filtration, sorption, complexation and promotes biological activity thus uptake.	Kitsap BSM Study 2014-15. BSM Study Phase 1 2016-17.	X	X	X			Initial leaching trials indicate some potential for ortho-P leaching (higher than GAC 1230AW, but lower than biochar (22).	Yes	Yes
Imbrium/Contech Sorptive media	Mineral additive			Not targeted for testing	Contec.	Not targeted for testing		5	10		Sorption and precipitation.								No (Contech will not release material for testing).	No (Contech will not release material for testing).
Iron aggregate	Mineral additive	Iron particles (97% Fe)	Waste from machine and mill operations. Material is then cleaned and sieved.	Connelly-GPM, Inc.	Chicago, IL	\$1,992.00	1 CY	5	10	Phosphorus, copper.	Sorption, precipitation.	Seattle Polishing Layer Study 2015	X	X	X	X			No	Yes
Iron-coated sand	Mineral additive	Usually common silica sand coated with hydrated iron oxide.	Mixing iron oxides with sand and acids or bases and applying heat.	No source identified	No source identified	No source identified	No source identified	5	10	Metals (Cu) (6), humic acids (7), phosphorus (8).	Sorption, filtration							Coating process determines Fe density and performance.	No source identified	No source identified
Iron-coated wood chips	Bulk organic	Horse manure and ferrous gluconate	Ferrous gluconate incorporated onto composted manure. Process facilitated by bacteria.	Experimental stage (no vendor)	Eastern Washington	\$70.00	1 CY	5	20	Phosphorus, lead.	Sorption	Kitsap BSM Study 2014-15	X	X	X			Exported Cu during dosing trials (22).	Yes	No
Lava sand	Bulk aggregate		Crushed product from lava rock. Lava rock from volcanic cinder pit exposed to steam.	Palmer Coking Coal and Walrath	Goldendale, WA	\$78.30	>5 CY	50	80	Possibly Phosphorus	Sorption	Kitsap BSM Study 2014-15	X	X	X			Treatments with this material exported copper during dosing experiments.	Yes	Yes
Lava sand (scoria surplus sand)			Crushed product from lava rock. Lava rock from volcanic cinder pit exposed to steam.	Stein Hauge, Martin's Feed, PO Box 206 Lynden, WA 98264	Goldendale, WA			50	80	Possibly Phosphorus	Sorption	BSM Study Phase 1 (2016-17)	X	X					NA	Yes
Lava sand (scoria earthtone sand)			Crushed product from lava rock. Lava rock from volcanic cinder pit exposed to steam.	Stein Hauge, Martin's Feed, PO Box 206 Lynden, WA 98264	Goldendale, WA			50	80	Possibly Phosphorus	Sorption	BSM Study Phase 1 (2016-17)	X	X					NA	Yes
Loamy sand topsoil	Bulk aggregate	Varies with source. See soil classification	Varies, often removed during land clearing.	Various western WA locations	Various western WA locations.	\$20.00	>300 CY	10	50	Treatment capabilities for various pollutants.	All stormwater treatment mechanisms if media is biologically active.							Flushing and leaching of Cu, P and N observed.	No	No

Table B-1 (continued). Bioretention Media Components.

Common Name	Component	Material Composition	Source/Process	Vendor	Source Location	Cost/Unit (CY Delivered)	Quantity for Cost Estimate	Estimated % Use in BSM (low)	Estimated % Use in BSM (high)	Target Pollutants	Treatment Mechanism	Project	Tests Completed or in Progress					Performance Notes	Recommended	
													Leaching or Flushing	Hydraulic Conductivity	Stormwater Dosing	Polishing	Pilot Testing		2015 Study	2017 Study
NXT-2 (lanthunum coated DE)	Mineral additive	Lanthunum (metallic element #57)-iron oxyhydroxide and diatomaceous earth (calcium carbonate).	Manufactured metallic element from monazite and bastnasite...atomic #57 (13).	EP Minerals (Reno, NV)	Nevada	\$8,370.00	small	5	20	Arsenic and phosphorus (13).								Does not alter pH and reaction is less pH dependent (13).	No	No
Oyster shells	Mineral additive	Primarily CaCo3.	By-product of local oyster growers.	Several in western WA. Used Gold Coast Oyster LLC	Western Washington	\$75.00	>300 CY	5	20	Phosphorus, metals.	Sorption and precipitation.	Kitsap BSM Study 2014-15	X					Good performance from oyster shells heated in an air atmosphere and very good performance from shells conditioned by pyrolysis in a nitrogen environment (converted CaCo3 to Ca oxide at surface (20). Initial leaching indicates nitrate export potential (22).	Yes	No
Perlite	Mineral additive	Silcon dioxide, aluminum oxide, sodium oxide and iron oxide.	Expanded amorphous volcanic glass.	Walrath (Puyallup), Great Western Supply (Olympia).	Lakeview, OR (south-central OR)	\$45.00	Not targeted for testing	10	20	TSS, oil and grease.		Port of Olympia						Helps prevent soil compaction. Low water holding capacity.	No	No
Phoslock	Mineral additive	Modified bentonite clay containing lanthanum.	Proprietary phosphorus capture media.	Not targeted for testing	SePRO, CSIRO Land and Water.	Not targeted for testing				Phosphorus	Sorption and precipitation.								No	No
Phos-phosorb	Mineral additive	Heat expanded volcanic rock (Perlite) and activated alumina.	Proprietary phosphorus capture media.	Not targeted for testing	Contec.	Not targeted for testing				Phosphorus, TSS.	Sorption and precipitation.								No (Contech will not release material for testing).	No (Contech will not release material for testing).
Play sand	Bulk aggregate	Usually common silica sand.	Various mining processes (dredging, excavation). Specific process unknown.	Home Depot	Unknown.	Not targeted for testing	Not targeted for testing	50	80	Particulates, metals	Filtration, sorption.	Port of Olympia			X				No	No
Pumice	Mineral additive	Silicic (igneous rock with ≥ 65% silica) or felsic (igneous rock with ≥75 % felsic minerals...quartz, orthoclase and plagioclase), but basaltic and other compositions are known. (1).	Super-heated, highly pressurized rock violently ejected from volcanoes (1).	Hess Pumice (ID)	Mined in ID, CA, OR, Canada.	\$41.24	Not targeted for testing	10	20	Particulates, metals (with Fe additive) (18).	Filtration, sorption.	Port of Olympia			X			Highly porous. May export metals and TP (17). Environmental concerns due to high demand and mining in environmentally sensitive areas (1).	No	No
Red mud	Mineral additive	Primarily iron, calcium and titanium oxides (13).	By-product of bauxite refining.	Not targeted for testing	Australia, Brazil, China, India, etc.	Not targeted for testing	Not targeted for testing	5	20	Phosphorus	Sorption and/or precipitation (pH dependent...lower pH favors Al and Fe adsorption, higher pH favors calcium precipitation).							Toxic waste product with difficult disposal issues. May have high concentrations of arsenic and chromium. Can have high pH (10-13).	No	No
Rhyolite sand	Bulk aggregate	Quartz, alkali feldspar and plagioclase	High viscous lava. Volcanic plugs, dikes and breccias.	Walrath (Puyallup)	Nevada	\$200.00	<100 CY	50	80	Possibly nutrients and metals (19).	Likely sorption.	Kitsap BSM Study 2014-15	X					May provide better pollutant capture than silica sands (19). Did not export P or Ortho-P (19). Initial leaching trials indicate some nitrate export potential (22).	Yes	No
Shedded cedar bark	Organic additive	Finely shredded bark	Shredded (often multiple times) timber harvest waste	Swansons (Longview, WA)	Southwest Washington			5	10	Not known (primarily applied for soil structure).	Not known.		X					While primarily a soil structure and water holding capacity amendment the material should be assessed for leaching if commonly applied. Fairly high ortho-P concentration for SPLP extraction.	No	No

Table B-1 (continued). Bioretention Media Components.																				
Common Name	Component	Material Composition	Source/Process	Vendor	Source Location	Cost/Unit (CY Delivered)	Quantity for Cost Estimate	Estimated % Use in BSM (low)	Estimated % Use in BSM (high)	Target Pollutants	Treatment Mechanism	Project	Tests Completed or in Progress					Performance Notes	Recommended	
													Leaching or Flushing	Hydraulic Conductivity	Stormwater Dosing	Polishing	Pilot Testing		2015 Study	2017 Study
Snohomish Co filter sand	Bulk aggregate	Usually common silica sand.	Various mining processes (dredging, excavation). Snoho Co filter sand is used for stormwater filter media and is a moderately well-graded sand with 4% or less passing the 100 sieve.	CADMAN, Inc (western WA)	Western Washington	\$38.48	Not targeted for testing	50	80	Particulates	Filtration.	Port of Olympia		X	X			Can export metals and TP (17).	No	No
State Sand	Bulk aggregate	Native pit sand	Washed several times; well-graded with 2% passing through the 100 sieve	ICON Materials (Auburn, WA)	Auburn mine	\$28.60	300 CY	50	80	Particulates	Filtration.							Initial leaching trials indicate low flushing potential.	No	Yes
Volcanic sand	Bulk aggregate	Varies: olivine, pyroxene and magnetite. Usually Fe rich (4).	Eroded from volcanic terrain or product of eruption.	Walrath (Puyallup)	Southwest Washington (Mt Saint Helens origin)	\$30.00	>200 CY	50	80	Possibly bacteria (5).	Filtration.	Kitsap BSM Study 2014-15. BSM Study Phase 1 2016-17.	X	X	X	X		May provide better pollutant capture than silica sands (19). Initial trials indicate low export potential for N, P and Cu (22).	Yes	Yes
Washed sand	Bulk aggregate		Excavation	Palmer Coking Coal	Black Diamond, WA	\$44.50	>3 CY	50	80	Phosphorus (sand filters including biological activity).	Filtration.	Kitsap BSM Study 2014-15	X	X	X	X		No longer available.	Yes	No (no longer available)
Water treatment residuals	Mineral additive	Aluminum or iron hydroxides coagulated with various particulates suspended in natural waters (silt, clay, organic matter).	Drinking water treatment plant intakes to settle suspended material.	Drinking water treatment plants (western WA).	Drinking water treatment plants throughout WA.	Material usually free. Transportation costs unknown.	Not targeted for testing	5	20	Phosphorus	Sorption and/or precipitation (pH dependent...neutral to lower pH favors Al and Fe adsorption)	Port of Olympia			X			Good P capture performance. Exports Cu (17).	No	No
Zeolite	Mineral additive	Aluminosilicate	Industrial crystallatation of silica-alumina or volcanic rock reacting with alkaline water (1).	Walrath (Puyallup)	Mined in CA, ID, WY, NV, AZ, OR.	\$449.00	<100 CY	5	20	Nitrogen compounds (1), humic acids (2), metals (2), phosphorus (14), some organics.	Molecular sieving, ion exchange (1), sorption, cation exchange (2). Possible to modify zeolite (e.g. acid treatment) for OM and anion capture (2).	Kitsap BSM Study 2014-15	X					Has regular pore structure that can selectively sort molecules based primarily on size (1). High water holding capacity (1). May be modified to be "aluminum-loaded" (2). There are many different types of Zeolite with different performance characteristics. May be issue with ion exchange, release of Na and leaching of metals. Did not export Cu, P or Ortho-P (19). Initial trials indicate potential to export nitrate (22).	Yes	No

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APPENDIX C

Sorption Kd Value Table

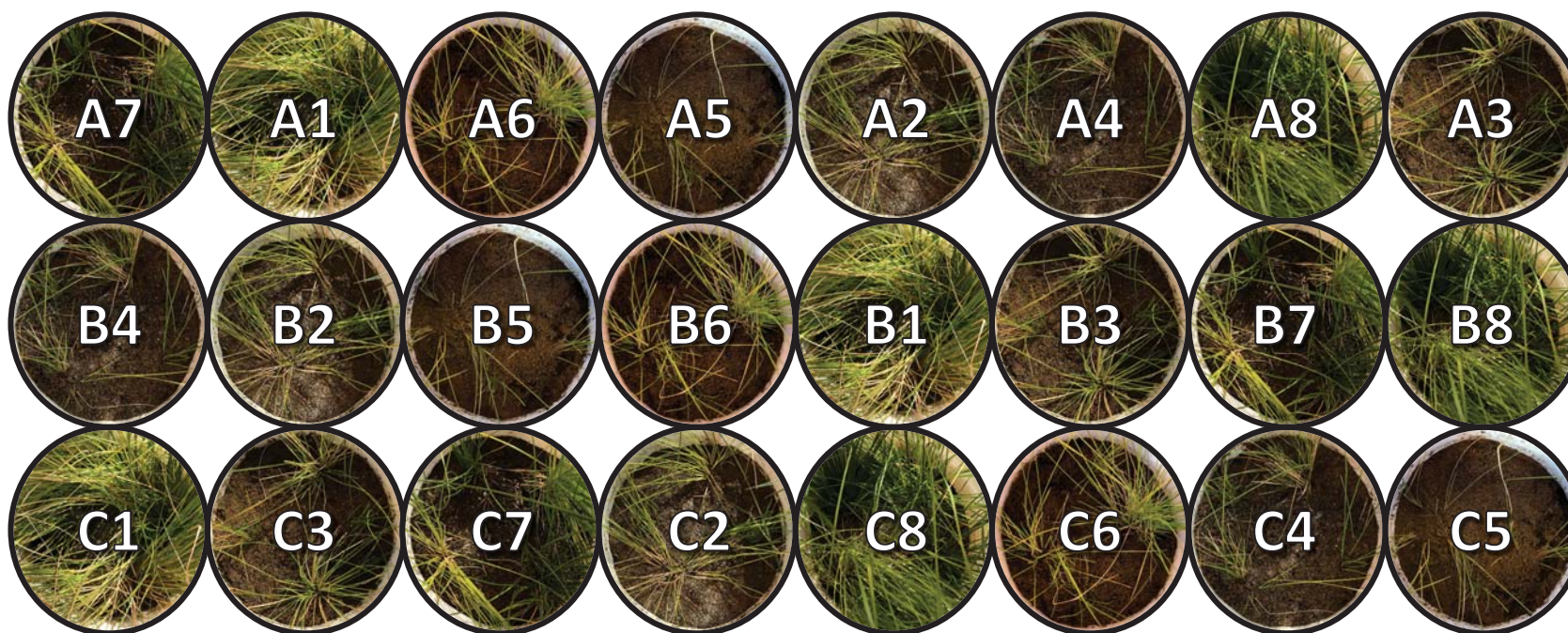
Table C-1. Kd Values for Media Components: 15-06110-000.

Polishing Layer Component	Nitrate 2h (mL/g)	Nitrate 6h (mL/g)	Nitrate 12h (mL/g)	Ortho-P 2h (mL/g)	Ortho-P 6h (mL/g)	Ortho-P 12h (mL/g)	Total Copper 2h (mL/g)	Total Copper 6h (mL/g)	Total Copper 12h (mL/g)
state sand	-0.67	-1.15	-0.55	0.03	0.42	2.03	79.86	137.67	177.21
state sand	-0.74	-1.20	-0.43	0.99	3.70	1.61	97.33	137.61	203.55
Average Kd Value	-0.71	-1.17	-0.49	0.51	2.06	1.82	88.59	137.64	190.38
lava sand (scoria surplus sand)	-1.41	-1.70	-1.28	1.58	0.21	-0.83	31.46	42.00	53.53
lava sand (scoria surplus sand)	-1.40	-1.72	-1.29	0.40	0.40	-0.66	30.41	43.46	58.76
Average Kd Value	-1.40	-1.71	-1.29	0.99	0.30	-0.74	30.94	42.73	56.14
coco coir	2.74	3.04	6.23	-13.02	-12.57	-12.25	62.40	53.68	48.71
coco coir	3.31	3.32	6.39	-13.54	-12.87	-11.88	69.47	56.20	44.57
Average Kd Value	3.03	3.18	6.31	-13.28	-12.72	-12.06	65.94	54.94	46.64
high carbon wood ash PD 100+ mesh	1.30	1.54	2.68	-10.65	-7.34	-7.82	644.72	815.13	1888.00
high carbon wood ash PD 100+ mesh	1.77	1.69	3.26	-9.23	-6.45	-8.00	758.44	784.75	1369.90
Average Kd Value	1.54	1.62	2.97	-9.94	-6.89	-7.91	701.58	799.94	1628.95
activated alumina (100 micron)	-3.64	-4.06	-3.81	1536.09	0.00	2080.39	9613.78	20834.80	3875.78
activated alumina (100 micron)	-4.67	-4.67	-4.41	1658.13	0.00	1658.13	12595.99	28553.36	5893.14
Average Kd Value	-4.16	-4.36	-4.11	1597.11	0.00	1869.26	11104.89	24694.08	4884.46
GAC 1230AW	241.75	269.59	282.45	192.15	246.95	294.95	648.16	1984.82	2817.87
GAC 1230AW	250.78	82.97	327.15	186.37	270.83	294.95	93.65	198.55	567.57
Average Kd Value	246.27	176.28	304.80	189.26	258.89	294.95	370.90	1091.68	1692.72
diatomaceous earth	-0.47	-1.11	-0.76	-6.49	-5.32	-7.64	165.93	241.42	313.12
diatomaceous earth	-0.31	-1.05	-0.48	-6.34	-7.37	-6.91	177.01	247.14	321.87
Average Kd Value	-0.39	-1.08	-0.62	-6.42	-6.34	-7.27	171.47	244.28	317.50
iron aggregate	3.50	24.84	207.42	1616.23	1748.36	600.48	810.88	250.59	124.52
iron aggregate	4.12	25.62	246.43	1916.32	1761.47	489.84	2116.89	240.24	106.75
Average Kd Value	3.81	25.23	226.93	1766.27	1754.92	545.16	1463.89	245.41	115.63
shredded cedar bark	-1.27	-1.97	0.14	-18.00	-15.09	-17.03	337.32	311.83	135.09
shredded cedar bark	-2.37	-1.02	0.35	-17.94	-16.44	-17.37	394.00	346.34	206.80
Average Kd Value	-1.82	-1.49	0.24	-17.97	-15.76	-17.20	365.66	329.08	170.94

APPENDIX D

Plant Study Treatment Placement

Greenhouse Window



Treatment Layout

Treatment Number	Treatment Composition
1	60% miles canyon sand/40% CG compost (control)
2	70% volcanic sand/20% coco coir/10% high carbon wood ash
3	50% state-volcanic sand mix/40% coco coir/10% high carbon wood ash
4	70% state-volcanic sand mix/20% coco coir/10% high carbon wood ash
5	50% lava sand/50% coco coir/10% high carbon wood ash
6	70% lava sand/20% coco coir/10% high carbon wood ash
7	70% state-volcanic sand mix/20% coco coir/10% high carbon wood ash/1" or 2" compost mulch
8	70% volcanic sand/30% compost/polishing drainage layer (medium sand, 5% activated alumina and 5% iron aggregate)

APPENDIX E

Plant Selection Tables

Table E-1. Bioretention Media Study Plant Drought Tolerance, Nutrient Requirements, and Growth Rate.														
Scientific Name	Common Name	pH		C:N Ratio	Nitrogen Fixation	Anaerobic Tolerance	Drought Tolerance	Fertility Requirement	Moisture Use	Salinity Tolerance	Root Depth, Minimum (inches)	Shape and Orientation	Growth Rate	Source
		Min.	Max.											
<i>Amelanchier alnifolia</i>	Western serviceberry	4.8	8.4	M	None	None	L	M	M	L	24	Erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=AMAL2
<i>Carex exsiccata</i>	Western inflated sedge	4.5	7.5	M	None	High	L	L	H	L	16	Tufts to 36 inches, sometimes spreading on short rhizomes	Rapid	http://eol.org/pages/1123111/data http://soundnativeplants.com/nursery/species-descriptions/grasses-rushes-sedges/ http://biology.burke.washington.edu/herbarium/imagecollection.php?Genus=Carex&Species=exsiccata
<i>Carex obnupta</i>	Slough sedge	5.5	7.0	H	None	None	L	L	H	M	12	Erect	Rapid	http://plants.usda.gov/java/charProfile?symbol=CAOB3
<i>Carex oshimensis</i> 'Evergold'	Vegetated Japanese sedge	4.0	9.0	H	None	Moderate	M	L	M	L	12	Low, grass-like, dense	Moderate	http://plants.minorsgardencenter.com/12100004/Plant/3387/Evergold_Japanese_Sedge http://www.loganlabs.com/doc/general-guidelines-ornamental.pdf
<i>Carex stipata</i>	Sawbeak sedge, prickly sedge, awlbeak sedge	4.9	7.9	H	Yes	High	M	L	H	L	12	Reaches 2 to 3 feet tall.	Rapid	http://davesgarden.com/guides/pf/go/72829/#b https://www.provenwinners.com/plants/carex/orange-sedge-carex-testacea https://kb.osu.edu/dspace/bitstream/handle/1811/44819/v107n3_39.pdf?jsessionid=10B8A8FA89CE61E4D6A9E77437D03994?sequence=1
<i>Carex testacea</i>	Orange New Zealand sedge	6.6	7.5	H	None	Moderate	M	M	M	L	12	Upright, up to 30 inches	Moderate	https://www.provenwinners.com/plants/carex/orange-sedge-carex-testacea http://www.monrovia.com/plant-catalog/plants/1129/orange-new-zealand-sedge/
<i>Cornus sericea</i> 'Kelseyi'	Dwarf red-twig dogwood	4.8	7.5	H	None	H	L	L	H	None	20	Semi-erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=COSES
<i>Deschampsia cespitosa</i> 'Northern lights'	Tufted hair grass	3.5	7.5	?	No, but takes up heavy metals	Moderate	H	L	M	M	12	12 inches tall (cultivar) – 60 inches (species)	Rapid	http://plants.usda.gov/factsheet/pdf/fs_dece.pdf
<i>Eleocharis ovata</i>	Ovate spikerush	4.6	6.8	H	None	High	None	L	M	L	6	Bunching, low	Moderate	http://eol.org/pages/1123111/data
<i>Eleocharis palustris</i>	Creeping spike-rush	4.0	8.0	H	None	H	L	M	H	L	14	Erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=ELPA3
<i>Iris douglasiana</i>	Douglas iris	5.0	8.0	H	None	M	M	M	M	M	6	Rhizomatous, spreading	Moderate	http://plants.usda.gov/plantguide/pdf/cs_irdo.pdf
<i>Iris sibirica</i> 'Bennerup Blue'	Bennerup Blue Siberian iris	6.1	7.8		None	H	M	M	M	L	6	Rhizomatous, spreading	Moderate	http://davesgarden.com/guides/pf/go/880/ http://eol.org/pages/590486/details
<i>Iris sibirica</i> 'Baby Sister'	Baby Sister Siberian iris	6.1	7.8		None	H	M	M	M	L	6	Rhizomatous, spreading	Moderate	http://davesgarden.com/guides/pf/go/880/ http://eol.org/pages/590486/details
<i>Juncus effusus</i>	Soft rush or common rush	5.5	8.8	M	None	M	M	M	M	L	24	Erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=JUUF

Table E-1 (continued). Bioretention Media Study Plant Drought Tolerance, Nutrient Requirements and Growth Rate.														
Scientific Name	Common Name	pH		C:N Ratio	Nitrogen Fixation	Anaerobic Tolerance	Drought Tolerance	Fertility Requirement	Moisture Use	Salinity Tolerance	Root Depth, Minimum (inches)	Shape and Orientation	Growth Rate	Source
		Min.	Max.											
<i>Juncus ensifolius</i>	Dagger-leaf rush	6.0	8.0	M	None	H	L	L	H	M	11	Erect	Moderate	http://eol.org/pages/634844/data http://plants.usda.gov/core/profile?symbol=JUEN
<i>Juncus patens</i> 'Elk Blue'	Spreading rush	4.6	6.5	H	None	H	H	L	M	L	6	Clumping, erect	Rapid	http://www.theodorepayne.org/mediawiki/index.php?title=Juncus patens %27Elk Blue%27 http://www.smgrowers.com/products/plants/plantdisplay.asp?plant_id=893
<i>Juncus tenuis</i>	Slender rush	4.5	7	M	None	L	L	L	M	L	6	Erect	Slow	http://plants.usda.gov/java/charProfile?symbol=JUTE
<i>Liriope muscari</i>	Big blue lilyturf	5.0	8.0	H	None	L	M	H	M	L	12	Erect, low growing	Moderate	http://plants.usda.gov/java/charProfile?symbol=LIMU6
<i>Mahonia aquifolium</i> 'compacta'	Compact or dwarf tall Oregon grape	5.0	8.0	H	None	L	H	M	M	L	20 (for sp., info on 'compacta' not available)	Semi-erect, woody shrub	Moderate	http://plants.usda.gov/core/profile?symbol=MAAQ2
<i>Philadelphus lewisii</i>	Mock-orange	7.0	8.0	H	None	L	M	L	L	None	6	Erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=PHLE4
<i>Rosa nutkana</i>	Nootka rose	6.5	7.0	M	None	L	L	L	H	L	6	Erect	Rapid	http://plants.usda.gov/java/charProfile?symbol=RONU
<i>Rubus spectabilis</i>	Salmonberry	5.7	7.2	H	None	M	H	L	M	None	10	Semi-erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=RUSP
<i>Schoenoplectus acutus</i> (<i>Scirpus acutus</i>)	Hardstem bulrush	5.2	8.5	H	None	H	M	L	H	L	14	Erect, rhizomatous	Moderate	http://plants.usda.gov/plantguide/pdf/pg_scac3.pdf
<i>Scirpus microcarpus</i>	Small-fruited bulrush	5.4	7.4	H	None	H	None	L	M	None	12	Erect, rhizomatous	Rapid	http://eol.org/pages/469325/data
<i>Sisyrinchium idahoense</i>	Idaho blue-eyed grass	6.4	8.2	M	None	M	L	M	H	None	8	Erect	Moderate	http://plants.usda.gov/java/charProfile?symbol=SIID
<i>Spiraea douglassii</i>	Douglas spirea	5.5	7.5	H	None	H	M	M	L	None	16	Upright shrub, spreading	Moderate	http://eol.org/pages/634454/data http://plants.usda.gov/core/profile?symbol=SPDO
<i>Symphoricarpos albus</i>	Snowberry	6.0	7.8	M	None	None	H	M	M	M	18	Rounded	Moderate	http://plants.usda.gov/java/charProfile?symbol=SYAL

Table E-2. Bioretention Media Study Plant Drought Tolerance, Nutrient Requirements, and Growth Rate.																	
Rank	Scientific Name	Common Name	Photo	Zone			Exposure			Native	Typical Width	Typical Height	Time of Bloom	Plant Characteristics	Macro-Nutrient Requirements	Suggested By	Use
				1	2	3	F	P	S								
1	<i>Amelanchier alnifolia</i>	Western serviceberry			x	x	x	x		x	8' to 20'	5' to 10'	April to May	Large white flower clusters; purple to blue-black berries; attracts native birds.	Medium	Deb Guenther	No (low DT)
1	<i>Carex exsiccata</i>	Western inflated sedge		x			x			x	36"	36"	June to August	Also called <i>C. vesicaria</i> var. <i>major</i> . Perennial, can form large clumps. OBL wetland species.	Medium	Mark Maurer (never used it)	No (low DT, not readily available)
7	<i>Carex obnupta</i>	Slough sedge		x	x		x	x		x	12" to 36"	To 48" spreading	April to May	Shiny foliage; excellent soil binder; can spread rapidly.	Not known	Henry Stevens, Juli Hartwig, SVR/MIG, Mark Brumbaugh, Mark Maurer, Jason King, Jenny Morgan	Possible (low nutrient, rapid GR)
1	<i>Carex oshimensis</i> "Evergold"	Vegetated Japanese sedge			x	x	x	x	x		24" to 36"	12" to 24"	Late spring or early summer	Deep green variegated creamy white band on foliage that turns to yellow; great accent plant; good for edges and borders.	Not known	Kas Kinkead	Possible (low nutrient, moderate DT)
2	<i>Carex stipata</i>	Sawbeak sedge		x				x		x	10" to 3'	10" to 3'	June	Wet soils; excellent soil binder.	Not known	Kate Forester, Mark Maurer	Possibly (low nutrient, moderate DT, rapid GR)
1	<i>Carex testacea</i>	Orange New Zealand sedge		x	x	x	x	x	x		12" to 15"	To 15" spreading	Early summer	Mounding form; orange-brown/bronze color in spring and summer; more intensive orange in winter.	Not known	Mark Brumbaugh	Possibly (moderate nutrient, moderate DT, moderate GR) Color spectrum?
6	<i>Cornus sericea</i> "Kelseyi"	Dwarf red-twig dogwood		x	x	x	x	x		x	1.5' to 3'	3' spreading	May to June	Small white flowers; berry-like fruit; compact form; good groundcover; striking winter color with red stems.	Not known	Kas Kinkead, Deborah Peters, Mark Brumbaugh, Deb Guenther, Joy Rodriguez, Drena Donafrio	Possibly (low nutrient, but low DT, moderate GR)

Table E-2 (continued). Bioretention Media Study Plant Drought Tolerance, Nutrient Requirements and Growth Rate.																	
Rank	Scientific Name	Common Name	Photo	Zone			Exposure			Native	Typical Width	Typical Height	Time of Bloom	Plant Characteristics	Macro-Nutrient Requirements	Suggested By	Use
				1	2	3	F	P	S								
2	<i>Deschampsia cespitosa</i> "Northern lights"	Tufted hair grass			x	x	x	x		x	6" to 12"	6" to 12"	Late spring to early summer	Stunning, grassy foliage with creamy white variegation that turns pink in winter (attractive in winter months): several other cultivars available.	Not known	Mark Maurer, Jason King	Yes (low nutrient, high DT, rapid GR)
1	<i>Eleocharis ovata</i>	Ovate spikerush		x	x		x	x		x	1.5'	1.5'	Late summer	Annual, low growing and bunching. Semi-erect.	Low	Jason King	Possibly (low nutrient, not DT, moderate GR)
2	<i>Eleocharis palustris</i>	Creeping spike-rush		x			x			x	To 3.5'	To 1.5'	June to September	Wet soils to shallow water; perennial forming small clumps.	Low	Kate Forester, Mark Maurer	No (poor DT)
1	<i>Iris douglasiana</i>	Douglas iris		x	x	x	x	x		x	12" to 24"	18" to 24"	Early spring	Purple and blue flowers, narrow foliage in clumps similar to coarse grass; do not use non-native and invasive yellow-flag iris.	Not known	Deborah Peters	No (may die back naturally by end of experiment)
1	<i>Iris sibirica</i> "Bennerup blue"	Bennerup Blue Siberian iris			x	x	x				18" to 24"	24 to 36"	Spring-summer	Showy flowers, grassy-like foliage.	Not known	SVR/MIG	No (may die back naturally by end of experiment)
1	<i>Iris sibirica</i> "Baby Sister"	Baby Sister Siberian iris			x	x	x				4-6 or 1/2 gallon	24 to 30	Spring-summer	Showy flowers, grassy-like foliage.	Not known	SVR/MIG	No (may die back naturally by end of experiment)
4	<i>Juncus effusus</i>	Soft rush or common rush		x			x	x		x	1' to 2'	1' to 2'	Summer	Wet soils; evergreen perennial; hardy and adaptable; drought-tolerant; small, non-showy flowers.	Medium	Kas Kinkead, Mark Brumbaugh, Jason King, Jenny Morgan	No (invasive)

Table E-2 (continued). Bioretention Media Study Plant Drought Tolerance, Nutrient Requirements and Growth Rate.																	
Rank	Scientific Name	Common Name	Photo	Zone			Exposure			Native	Typical Width	Typical Height	Time of Bloom	Plant Characteristics	Macro-Nutrient Requirements	Suggested By	Use
				1	2	3	F	P	S								
3	<i>Juncus ensifolius</i>	Dagger-leaf rush		x			x			x	6" to 15"	6" to 9" spreading	Summer	Flattened stems like an iris; dark brown flowers small and rounded like pom-poms; yellow-orange fall color.	Medium	Kate Forester, Mark Maurer, Deborah Peters	No (low DT)
4	<i>Juncus patens</i> "Elk Blue"	Spreading rush		x	x			x		x	12" to 24"	18" to 24" spreading	May to August	Spiky, blue-green grass-like foliage; other cultivars readily available.	Not known	Kas Kinkead, Henry Stevens, SVR/MIG, Deb Guenther	Yes (moderate nutrient, high DT, fast GR)
3	<i>Juncus tenuis</i>	Slender rush		x	x		x			x	6" to 20"	6" to 30"	May to September	Soft, bright green foliage and delicate flowers.	Not known	Kate Forester, Jenny Morgan, Joy Rodriguez	No (slow grower)
1	<i>Liriope muscari</i>	Big blue lilyturf			x	x	x	x			0.75 to 1'	1' to 1.5'	August to September	Low growing dark green grassy foliage with blue/purple spikes in summer.	Medium	Henry Stevens	No (high nutrient and no experience with this plant)
1	<i>Mahonia aquifolium</i> "compacta"	Compact or dwarf tall Oregon grape			x	x	x	x		x	2' to 3'	3' to 4'	April to June	Dwarf form of sun-loving native Oregon grape has same flowers; stays compact.	Low	Kas Kinkead	Possible (high DT, moderate nutrient, moderate GR)
1	<i>Philadelphus lewisii</i>	Mock-orange			x	x	x	x		x	5' to 10'	5' to 10'	June to July	Fragrant white flowers; makes thickets.	Low	Deb Guenther	Possibly (moderate DT, low nutrient moderate GR, but large)
1	<i>Rosa nutkana</i>	Nootka rose			x		x	x		x	6' to 10'	6' to 10'	April to June	Moist to fairly dry soils; tolerates inundation and saturated soils; aggressive spreader; fruits persist; less thorny than <i>R. rugosa</i> .	Low	Deb Guenther	Possibly (moderate DT, low nutrient, rabid GR, but large)

Table E-2 (continued). Bioretention Media Study Plant Drought Tolerance, Nutrient Requirements and Growth Rate.																	
Rank	Scientific Name	Common Name	Photo	Zone			Exposure			Native	Typical Width	Typical Height	Time of Bloom	Plant Characteristics	Macro-Nutrient Requirements	Suggested By	Use
				1	2	3	F	P	S								
1	<i>Rubus spectabilis</i>	Salmonberry		x	x	x		x	x	x	5' to 10'	10' spreading	February to April	Magenta flowers; yellow-orange fruits are early nectar source for hummingbirds; spreads aggressively and makes thickets; good soil binder.	low	Drena Donafrio	Possibly (high DT, low nutrient, rapid GR, but large)
3	<i>Schoenoplectus acutus</i> (<i>Scirpus acutus</i>)	Hardstem bulrush		x			x			x	4' to 10'	4' to 10'	–	Wet soils; favors prolonged inundation; excellent soil binder. Forms very dense stands; can form a monoculture.	Medium	Jenny Morgan, Mark Brumbaugh, Juli Hartwig	No (likes wetter environment)
3	<i>Scirpus microcarpus</i>	Small-fruited bulrush		x				x	x	x	24" to 36"	12" to 24" spreading	June to August	Large, round flower clusters persist over winter; attractive in combination with spiky flowers; good soil binder; spreads aggressively.	Low	Juli Hartwig, Jenny Morgan, Deb Guenther	Possibly (high DT, low nutrient, rapid GR)
1	<i>Sisyrinchium idahoense</i>	Idaho blue-eyed grass		x	x	x	x	x	x	x	1'	1.7'	Mid-spring to mid-summer	Small perennial with grassy foliage and star shaped blue/violet flowers with yellow "eyes." Attractive and great source for pollinators.	Medium	Kate Forester	No (others are hardier)
2	<i>Spiraea douglassii</i>	Douglas spirea		x	x		x	x		x	4' to 7'	6' to 10' spreading	June to August	Spikes of rosy-pink flower clusters; great for butterflies; can self-seed readily and may spread and crowd out other plants in consistently wet soils.	Low	Deborah Peters, Kate Forester	Possibly (moderate DT, moderate nutrient, moderate GR, but large)
3	<i>Symphoricarpos albus</i>	Snowberry			x	x	x	x	x	x	2' to 6'	6' spreading	April to June	White berries from summer to winter; clusters of pink flowers are great for pollinators; great combined with red-twig dogwood and Oregon grape; spreads and forms thickets.	Medium	Mark Brumbaugh, Deb Guenther, Drena Donafrio	Possibly (high DT, moderate nutrient, moderate GR, but large)

Exposure: F = full sun; P = partial sun; S = shade

Zone: 1 = bottom or bioretention cell; 2 = side slope usually above ponding depth; 3 = Top of cell slope

APPENDIX F

Plant Image Time Series

Table 1. Row A – Treatment 1.



Treatment:

60% Ecology sand, 40% Cedar Grove compost

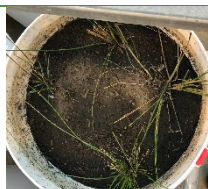
Field Notes:

As with all compost-media blends, A1 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

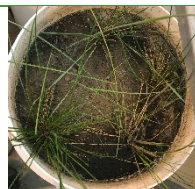
Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 7



Week 10



Week 15



Week 19



Week 23



Week 27



J-1



J-2



D-1



D-2

Table 2. Row A – Treatment 2.

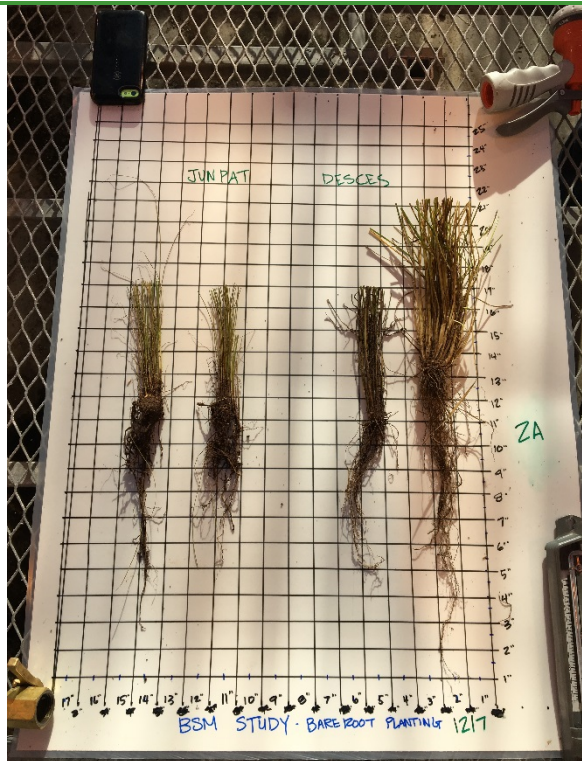
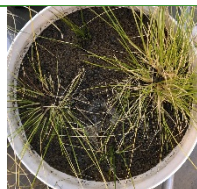
			Treatment: 70% volcanic sand, 20% coco coir, 10% high-carbon wood ash Field Notes: Key: J = <i>Juncus patens</i> D = <i>Deschampsia cespitosa</i>		
					
Week 7	Week 10	Week 15	Week 19	Week 23	Week 27
	No Image				
J-1	J-2		D-1	D-2	

Table 3. Row A – Treatment 3.

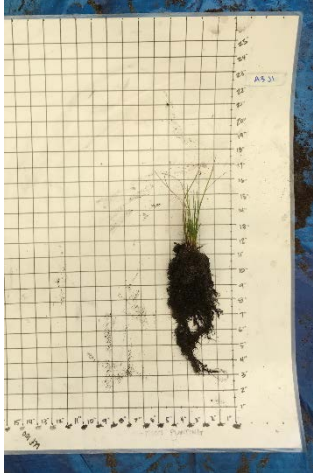
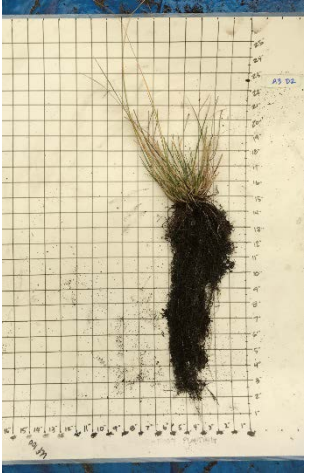
						Treatment: 50% state sand/volcanic sand*, 40% coco coir, 10% high-carbon wood ash *75% state sand, 25% volcanic sand Field Notes: Key: J = <i>Juncus patens</i> D = <i>Deschampsia cespitosa</i>
						
Week 7	Week 10	Week 15	Week 19	Week 23	Week 27	
						
J-1	J-2	D-1	D-2			

Table 4. Row A – Treatment 4.



Treatment:

70% state sand/volcanic sand*, 20% coco coir, 10% high-carbon wood ash

*75% state sand, 25% volcanic sand

Field Notes:

One *J. patens* found deceased on 2/7/17.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 7



Week 10



Week 15



Week 19



Week 23

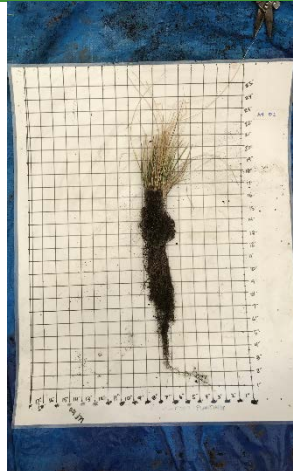


Week 27

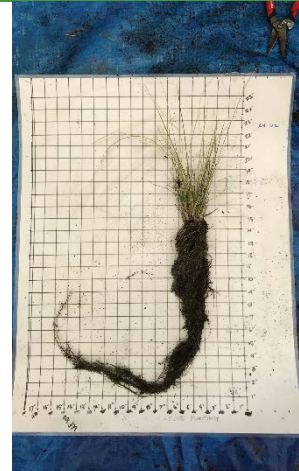


J-1

Deceased



D-1



D-2

Table 5. Row A – Treatment 5.



Treatment:

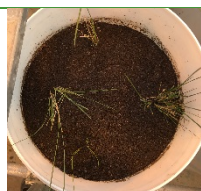
50% lava sand, 40% coco coir, 10% high-carbon wood ash

Field Notes:

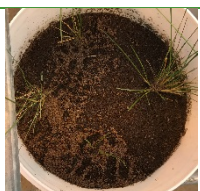
Key:

J = *Juncus patens*

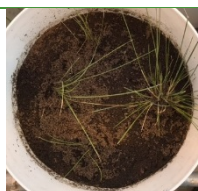
D = *Deschampsia cespitosa*



Week 7



Week 10



Week 15



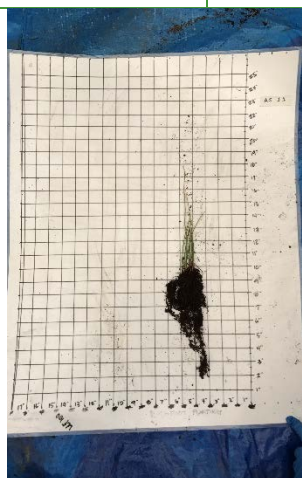
Week 19



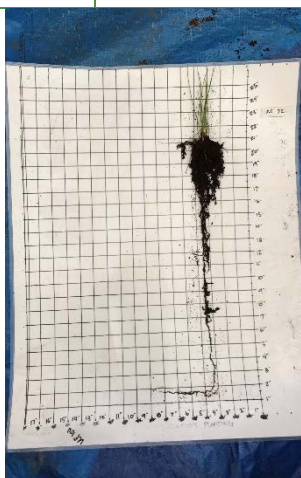
Week 23



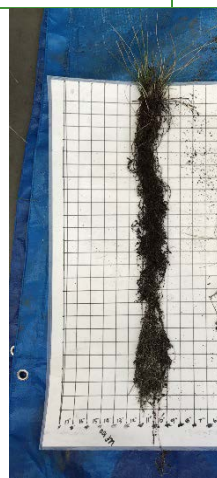
Week 27



J-1



J-2



D-1



D-2

Table 6. Row A – Treatment 6.



Treatment:

70% lava sand, 20% coco coir, 10% high-carbon wood ash

Field Notes:

One *J. patens* found deceased on 1/10/17.

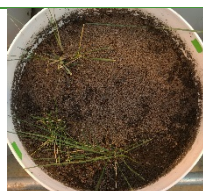
Key:

J = *Juncus patens*

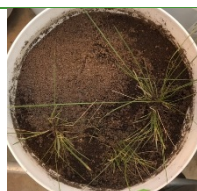
D = *Deschampsia cespitosa*



Week 7



Week 10



Week 15



Week 19



Week 23

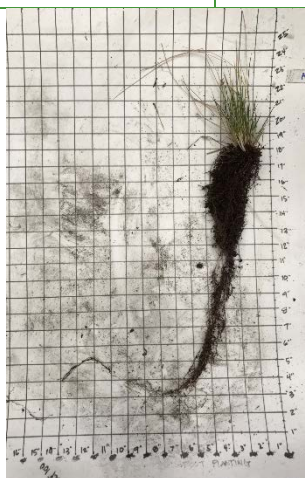


Week 27

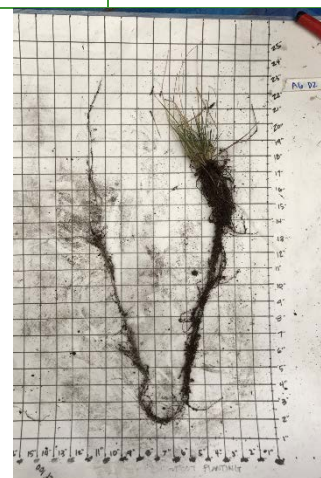


J-1

Deceased



D-1

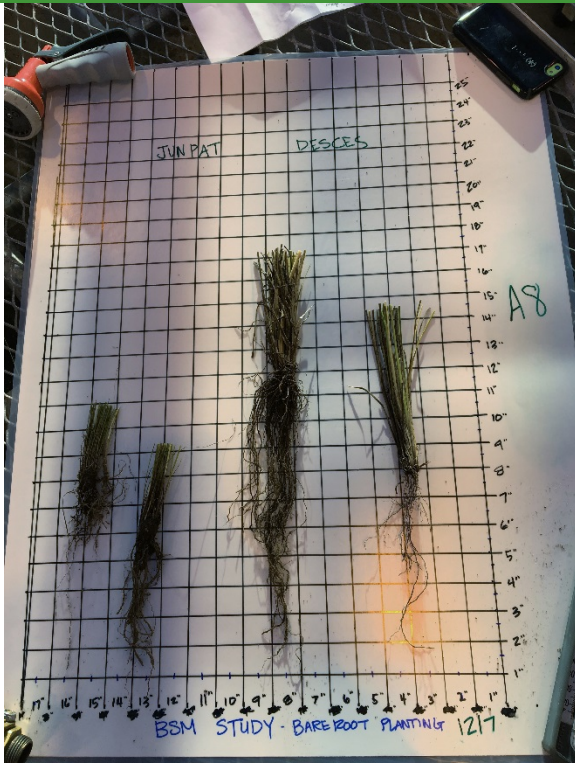


D-2

Table 7. Row A – Treatment 7.

				Treatment: 70% state sand/volcanic sand mix*, 20% coco coir, 10% high-carbon wood ash, 2-inches of compost mulch *50% state sand, 50% volcanic sand Field Notes: As with all compost-media blends, A7 had a higher occurrence of bugs (flies, snails, spiders) than other treatments. Mushrooms were observed growing on 1/24/17. Key: J = <i>Juncus patens</i> D = <i>Deschampsia cespitosa</i>			
							
Week 7	Week 10	Week 15	Week 19	Week 23	Week 27		
							
J-1	J-2	D-1	D-2				

Table 8. Row A – Treatment 8.



Treatment:

70% volcanic sand, 30% compost, p-layer*

*medium sand, 5% activated alumina, 5% iron aggregate

Field Notes:

As with all compost-media blends, A8 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 7



Week 10



Week 15



Week 19



Week 23



Week 27



J-1



J-2



D-1



D-2

Table 9. Row B – Treatment 1.



Treatment:

60% Ecology sand, 40% Cedar Grove compost

Field Notes:

As with all compost-media blends, B1 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

J. patens deceased prior to final sampling.

Key:

J = *Juncus patens*

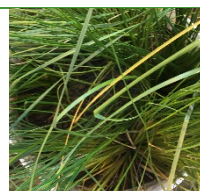
D = *Deschampsia cespitosa*



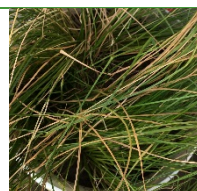
Week 10



Week 15



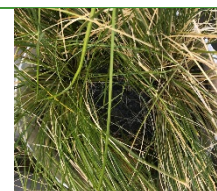
Week 18



Week 21



Week 23



Week 27



J-1



J-2



D-1



D-2

Table 10. Row B – Treatment 2.

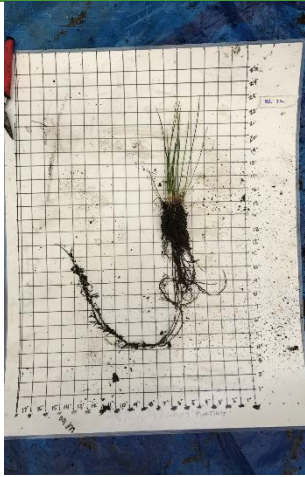
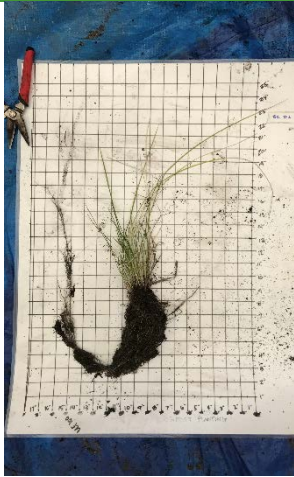
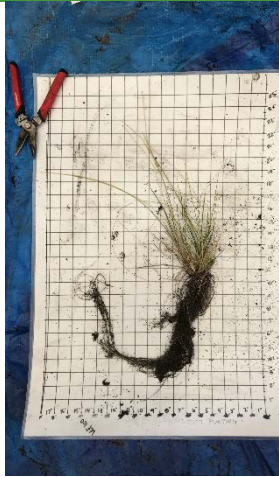
					
Treatment: 70% volcanic sand, 20% coco coir, 10% high-carbon wood ash Field Notes: Key: J = <i>Juncus patens</i> D = <i>Deschampsia cespitosa</i>					
					
Week 10	Week 15	Week 18	Week 21	Week 23	Week 27
No image					
J-1	J-2	D-1	D-2		

Table 11. Row B – Treatment 3.



Treatment:

50% state sand/volcanic sand*, 40% coco coir, 10% high-carbon wood ash

*75% state sand, 25% volcanic sand

Field Notes:

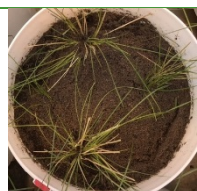
Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



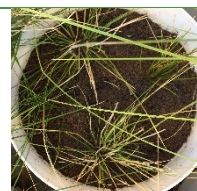
Week 10



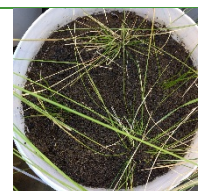
Week 15



Week 18



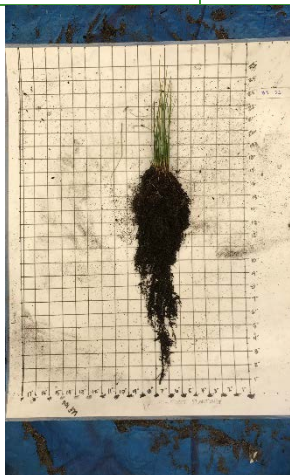
Week 21



Week 23



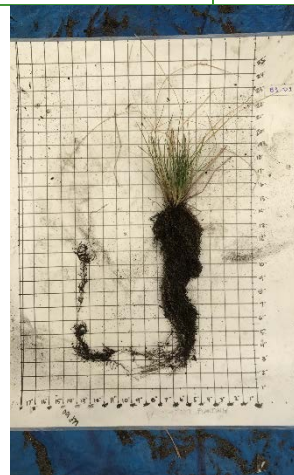
Week 27



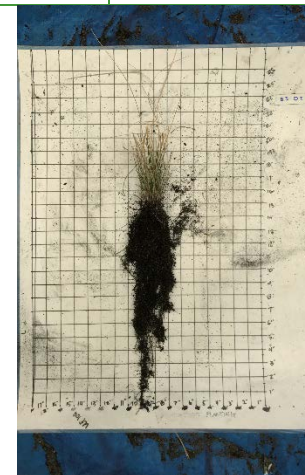
J-1

No image

J-2



D-1



D-2

Table 12. Row B – Treatment 4.



Treatment:

70% state sand/volcanic sand*, 20% coco coir, 10% high-carbon wood ash

*75% state sand, 25% volcanic sand

Field Notes:

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 10



Week 15



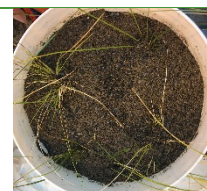
Week 18



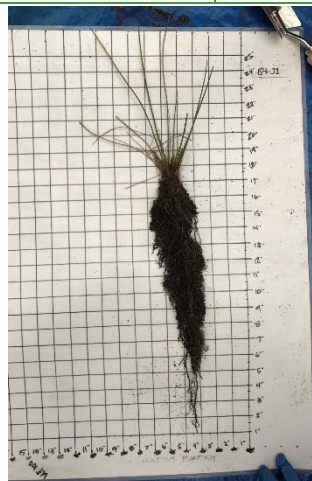
Week 21



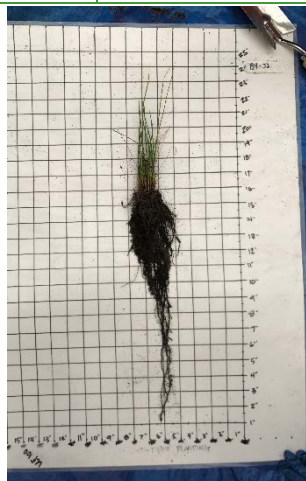
Week 23



Week 27



J-1



J-2

No image

D-1



D-2

Table 13. Row B – Treatment 5.



Treatment:

50% lava sand, 40% coco coir, 10% high-carbon wood ash

Field Notes:

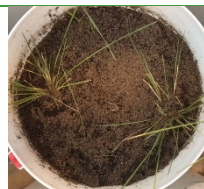
Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



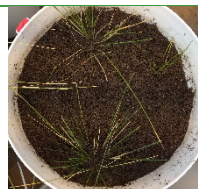
Week 10



Week 15



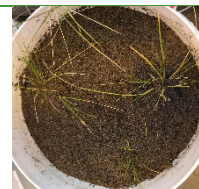
Week 18



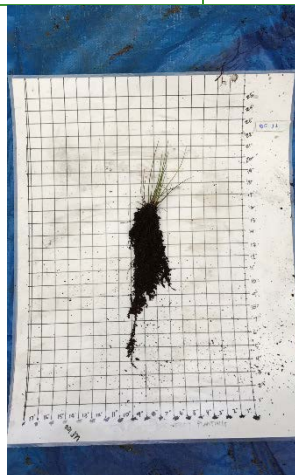
Week 21



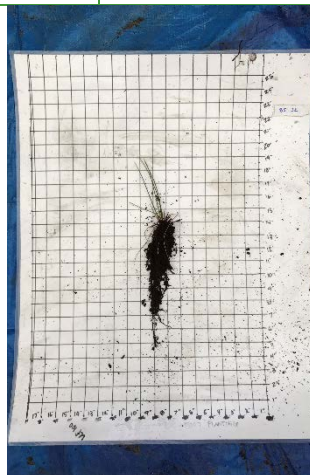
Week 23



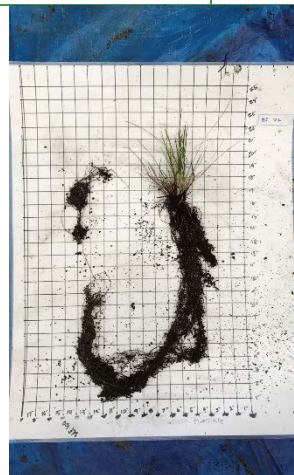
Week 27



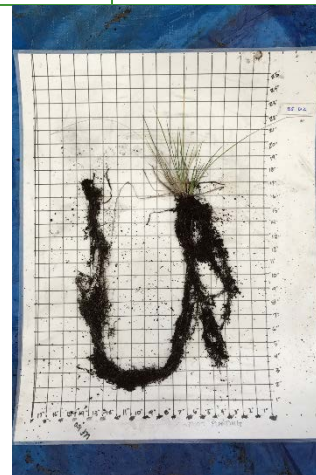
J-1



J-2



D-1



D-2

Table 14. Row B – Treatment 6.

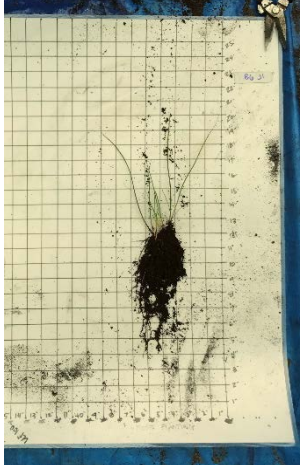
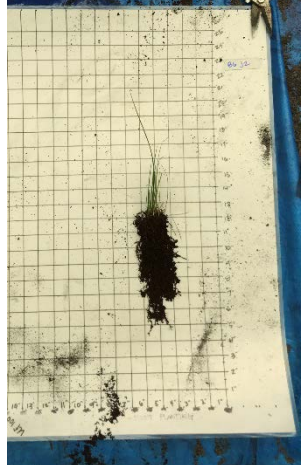
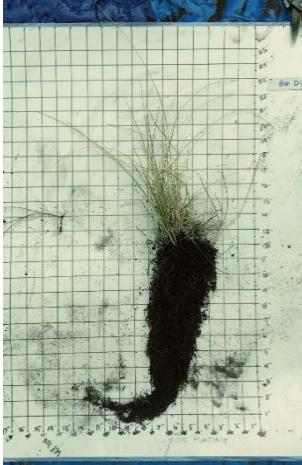
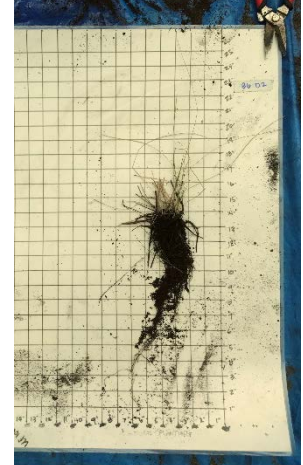
					
Treatment: 70% lava sand, 20% coco coir, 10% high-carbon wood ash Field Notes: Key: J = <i>Juncus patens</i> D = <i>Deschampsia cespitosa</i>					
					
Week 10	Week 15	Week 18	Week 21	Week 23	Week 27
					
J-1	J-2	D-1	D-2		

Table 15. Row B – Treatment 7.



Treatment:

70% state sand/volcanic sand mix*, 20% coco coir, 10% high-carbon wood ash, 2-inches of compost mulch

*50% state sand, 50% volcanic sand

Field Notes:

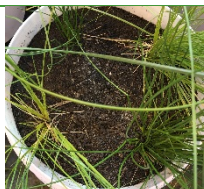
As with all compost-media blends, B7 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

Mushrooms were observed growing on 1/24/17.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 10

Week 15

Week 18

Week 21

Week 23

Week 27



J-1

J-2

D-1

D-2

Table 16. Row B – Treatment 8.



Treatment:

70% volcanic sand, 30% compost, p-layer*

*medium sand, 5% activated alumina, 5% iron aggregate

Field Notes:

As with all compost-media blends, B8 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

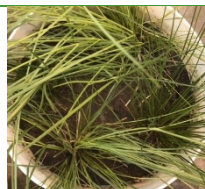
Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 10



Week 15



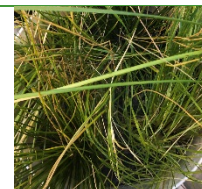
Week 18



Week 21



Week 23



Week 27



J-1



J-2

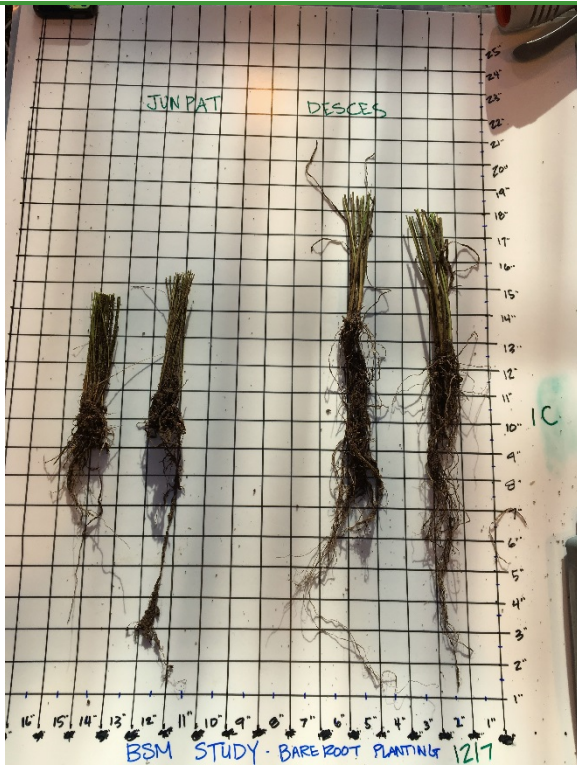


D-1



D-2

Table 17. Row C – Treatment 1.



Treatment:

60% Ecology sand, 40% Cedar Grove compost

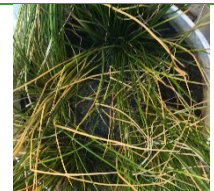
Field Notes:

As with all compost-media blends, C1 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 4

Week 10

Week 15

Week 19

Week 23

Week 27



J-1

J-2

D-1

D-2

Table 18. Row C – Treatment 2.



Treatment:

70% volcanic sand, 20% coco coir, 10% high-carbon wood ash

Field Notes:

Key:

J = *Juncus patens*

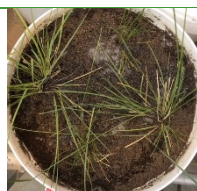
D = *Deschampsia cespitosa*



Week 4



Week 10



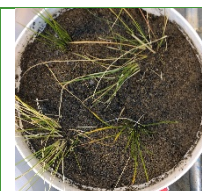
Week 15



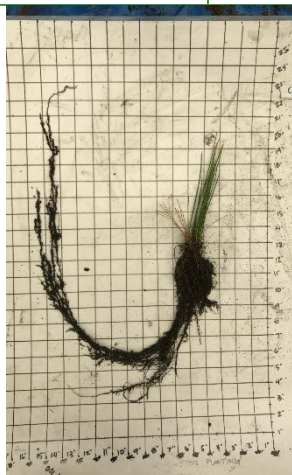
Week 19



Week 23



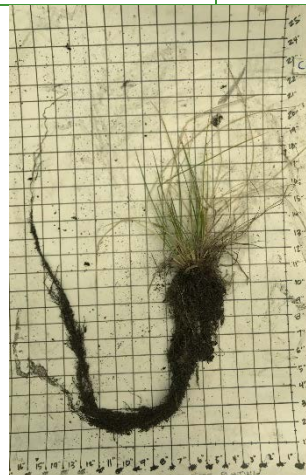
Week 27



J-1



J-2



D-1



D-2

Table 19. Row C – Treatment 3.



Treatment:

50% state sand/volcanic sand*, 40% coco coir, 10% high-carbon wood ash

*75% state sand, 25% volcanic sand

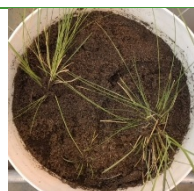
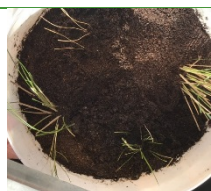
Field Notes:

One *J. patens* found deceased on 1/10/17.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 4

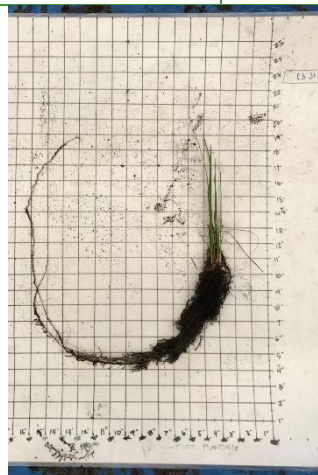
Week 10

Week 15

Week 19

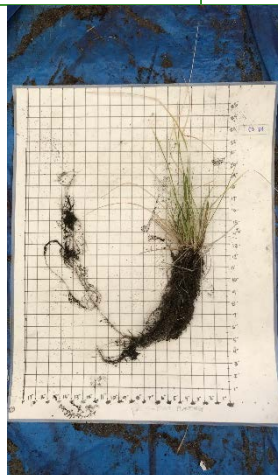
Week 23

Week 27

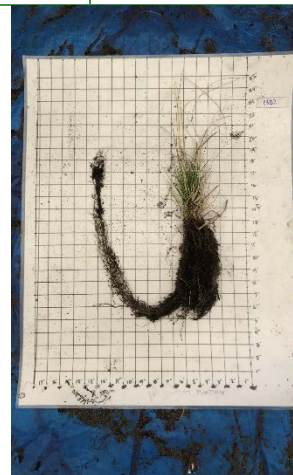


J-1

Deceased

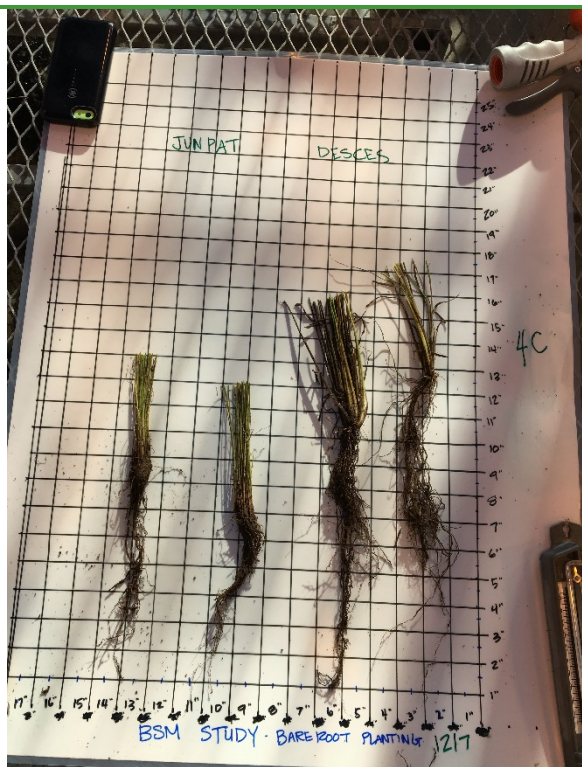


D-1



D-2

Table 20. Row C – Treatment 4.



Treatment:

70% state sand/volcanic sand*, 20% coco coir, 10% high-carbon wood ash

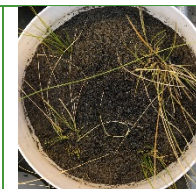
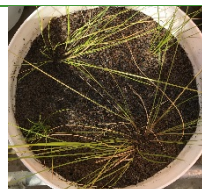
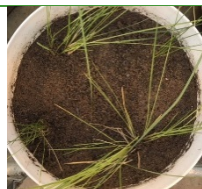
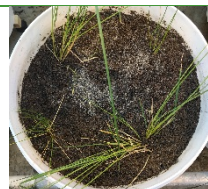
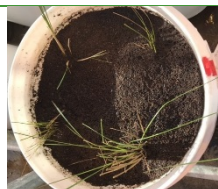
*75% state sand, 25% volcanic sand

Field Notes:

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 4

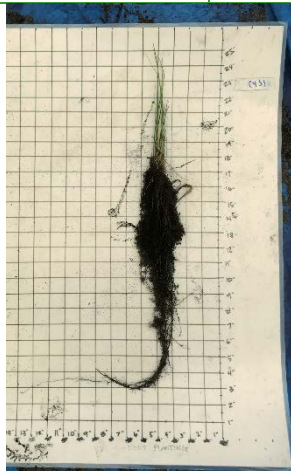
Week 10

Week 15

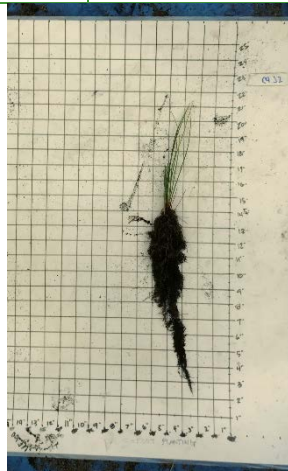
Week 19

Week 23

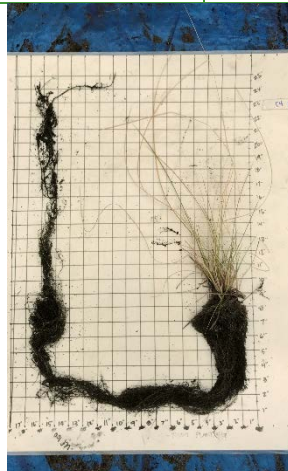
Week 27



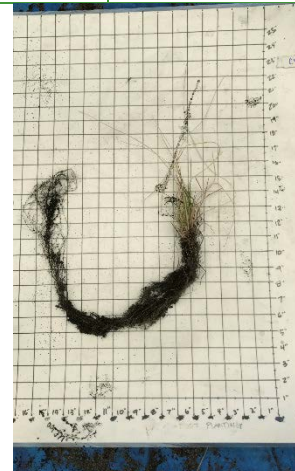
J-1



J-2



D-1



D-2

Table 21. Row C – Treatment 5.

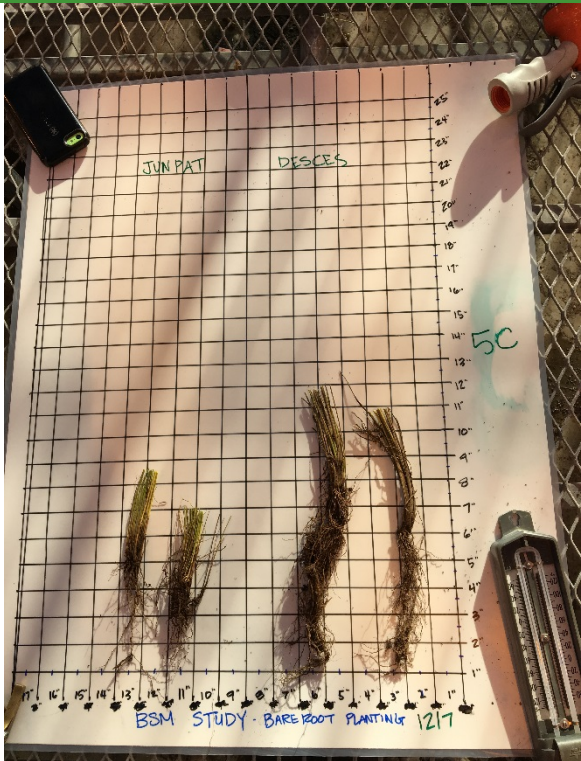
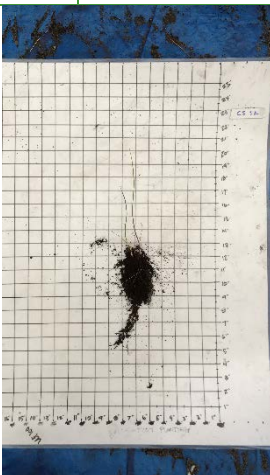
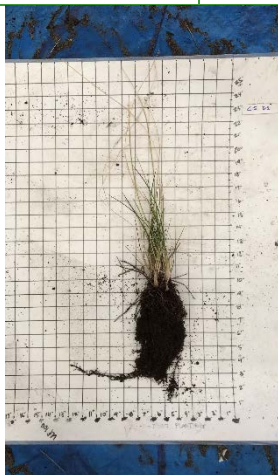
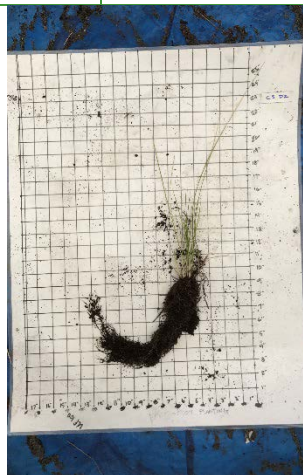
							Treatment: 50% lava sand, 40% coco coir, 10% high-carbon wood ash Field Notes: Key: J = <i>Juncus patens</i> D = <i>Deschampsia cespitosa</i>
							
Week 4	Week 10	Week 15	Week 19	Week 23	Week 27		
							
J-1	J-2	D-1	D-2				

Table 22. Row C – Treatment 6.



Treatment:

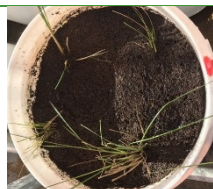
70% lava sand, 20% coco coir, 10% high-carbon wood ash

Field Notes:

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



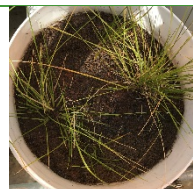
Week 4



Week 10



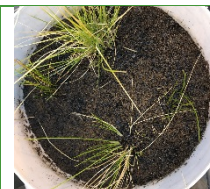
Week 15



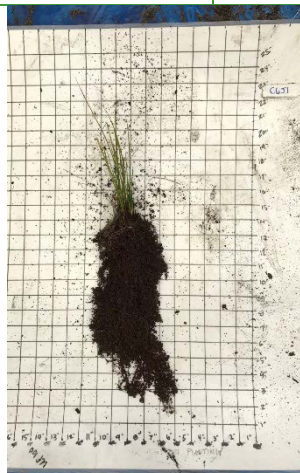
Week 19



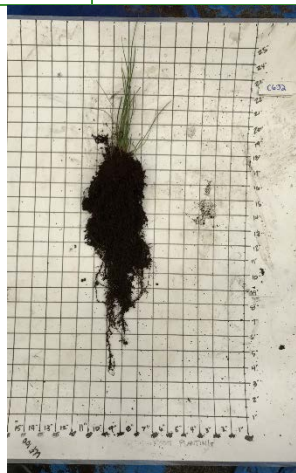
Week 23



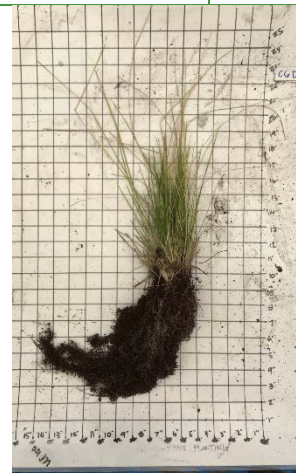
Week 27



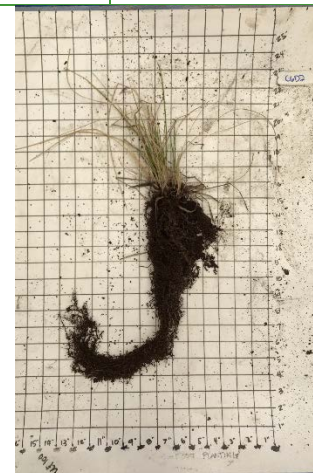
J-1



J-2



D-1



D-2

Table 23. Row C – Treatment 7.



Treatment:

70% state sand/volcanic sand mix*, 20% coco coir, 10% high-carbon wood ash, 2-inches of compost mulch

*50% state sand, 50% volcanic sand

Field Notes:

As with all compost-media blends, C7 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

Mushrooms were observed growing on 1/24/17.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 4

Week 10

Week 15

Week 19

Week 23

Week 27



J-1



J-2

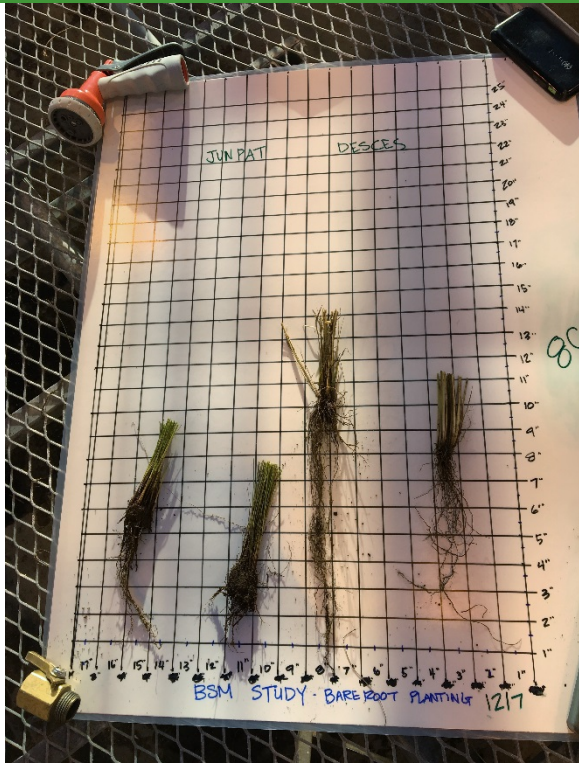


D-1



D-2

Table 24. Row C – Treatment 8.



Treatment:

70% volcanic sand, 30% compost, p-layer*

*medium sand, 5% activated alumina, 5% iron aggregate

Field Notes:

As with all compost-media blends, C8 had a higher occurrence of bugs (flies, snails, spiders) than other treatments.

A recruited Douglas fir (*Pseudotsuga menziesii*) was first observed 1/17/17 and grew throughout the study.

Key:

J = *Juncus patens*

D = *Deschampsia cespitosa*



Week 4

Week 10

Week 15

Week 19

Week 23

Week 27



J-1

J-2

D-1

D-2

APPENDIX G

Plant Biomass Data and Summary Statistics

Table G-1. Plant Biomass Data and Summary Statistics.

Treatment	Species	Root/Stems	Average	Min	Max
60sand/40comp	Deschampsia	Roots	41.90	7.88	123.44
60sand/40comp	Deschampsia	Stems	44.77	21.27	75.38
60sand/40comp	Juncus	Roots	62.71	3.21	135.22
60sand/40comp	Juncus	Stems	33.63	3.87	75.76
60sand/40comp	Total Roots and Stems	Total Roots and Stems	45.75	3.21	135.22
70vs/20cp/10ash	Deschampsia	Roots	5.54	2.29	10.37
70vs/20cp/10ash	Deschampsia	Stems	4.90	2.51	11.46
70vs/20cp/10ash	Juncus	Roots	3.69	1.25	6.21
70vs/20cp/10ash	Juncus	Stems	1.58	0.79	2.28
70vs/20cp/10ash	Total Roots and Stems	Total Roots and Stems	3.93	0.79	11.46
50ss-vs/40cp/10ash	Deschampsia	Roots	3.43	2.35	4.95
50ss-vs/40cp/10ash	Deschampsia	Stems	3.76	2.52	5.88
50ss-vs/40cp/10ash	Juncus	Roots	3.23	1.43	7.25
50ss-vs/40cp/10ash	Juncus	Stems	0.84	0.63	1.07
50ss-vs/40cp/10ash	Total Roots and Stems	Total Roots and Stems	2.89	0.63	7.25
70ss-vs/20cp/10ash	Deschampsia	Roots	2.66	1.08	6.86
70ss-vs/20cp/10ash	Deschampsia	Stems	2.78	1.18	3.81
70ss-vs/20cp/10ash	Juncus	Roots	3.02	1.78	4.76
70ss-vs/20cp/10ash	Juncus	Stems	0.95	0.55	1.32
70ss-vs/20cp/10ash	Total Roots and Stems	Total Roots and Stems	2.39	0.55	6.86
50ls/40cp/10ash	Deschampsia	Roots	3.93	0.66	6.23
50ls/40cp/10ash	Deschampsia	Stems	1.95	0.70	2.71
50ls/40cp/10ash	Juncus	Roots	1.54	0.76	3.11
50ls/40cp/10ash	Juncus	Stems	0.51	0.19	0.75
50ls/40cp/10ash	Total Roots and Stems	Total Roots and Stems	1.98	0.19	6.23
70ls/20cp/10ash	Deschampsia	Roots	7.23	1.24	19.22
70ls/20cp/10ash	Deschampsia	Stems	4.65	1.24	11.25
70ls/20cp/10ash	Juncus	Roots	4.57	1.17	8.78
70ls/20cp/10ash	Juncus	Stems	1.34	0.29	2.98
70ls/20cp/10ash	Total Roots and Stems	Total Roots and Stems	4.58	0.29	19.22
70ss-vs/20cp/10ash/compmulch	Deschampsia	Roots	35.25	5.64	66.16
70ss-vs/20cp/10ash/compmulch	Deschampsia	Stems	20.76	4.98	37.86
70ss-vs/20cp/10ash/compmulch	Juncus	Roots	62.98	17.63	137.82
70ss-vs/20cp/10ash/compmulch	Juncus	Stems	17.15	4.88	26.95
70ss-vs/20cp/10ash/compmulch	Total Roots and Stems	Total Roots and Stems	34.03	4.88	137.82
70vs/30comp/p-layer	Deschampsia	Roots	72.17	8.96	166.72
70vs/30comp/p-layer	Deschampsia	Stems	43.89	32.65	58.53
70vs/30comp/p-layer	Juncus	Roots	87.18	46.43	162.44
70vs/30comp/p-layer	Juncus	Stems	30.42	14.60	53.65
70vs/30comp/p-layer	Total Roots and Stems	Total Roots and Stems	58.41	8.96	166.72

