THE EFFECTS OF MULCH ON STORMWATER TREATMENT AND MAINTENANCE EFFORT IN BIORETENTION SYSTEMS

Final Report

Prepared for:

Stormwater Action Monitoring and

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Executive Summary

This 2-year field study sought to evaluate mulch's role in bioretention best management practices, specifically improving water quality, slowing down runoff, improving soil moisture, and mitigating maintenance. The goal of this project was to quantify the effectiveness of mulches in bioretention systems to remove specific pollutants from stormwater, maintain hydrologic dynamics within a cell, and mitigate maintenance effort by suppressing the growth of weeds. As a result of this work, Phase I and II permittees will have a basis for mulch selection in order to maximize stormwater pollution removal and minimize maintenance effort.

Three types of mulch; nugget, medium bark, and arborist chips, were compared to a no-mulch control within bioretention cells located at Washington State University's Puyallup Research and Extension Center. With this test facility of 16 bioretention cells each of the three mulch types was replicated four times, and their performances were compared against those of four no-mulch cells. We define treatment performance as the ability of a bioretention cell to remove/sequester stormwater pollutants, store water in the form of soil moisture, and reduce runoff volume. Weeding effort and plant growth were quantified to measure planted vegetation's success over time.

The work showed that mulch was a critical aspect of preserving soil moisture in a bioretention system. Arborist chips worked the best in retaining soil moisture at the soil surface, however cells with nugget mulch retained the most storm event volume compared to other cells with and without mulch. Cells with mulch limited the export of Nitrite-Nitrate from the bioretention soil media. Mulch reduced the proliferation of weeds and reduced weeding effort by half. We also saw that shade around our bioretention cells limited plant stress.

MULCH TYPES

NUGGET

MEDIUM BARK

ARBORIST CHIPS

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1. Introduction

1.1. Introduction to the Mulch and Bioretention Study

Stormwater that flows into bioretention or rain garden systems first contacts the mulch layer, by design, before any other component in that system. The specific role of mulch in bioretention systems function has not been specifically evaluated. Mulch can prevent weeds and invasive species. Given that repeated weeding and invasive removal is a costly addition to operations and maintenance budgets for any municipality, we aim to provide information to optimize mulch choice to minimize maintenance efforts. In addition, mulch layer may provide carbon and nutrients in the bioretention soil layers and help reduce evaporation, eventually helping plant survival and growth. The incremental benefit to stormwater treatment is unknown, but this study aims to determine if the mulch layer itself affects analyte removal from stormwater in bioretention systems by increasing adsorptive surfaces for stormwater analytes such as hydrocarbons, metals, fecal coliform, or nutrients.

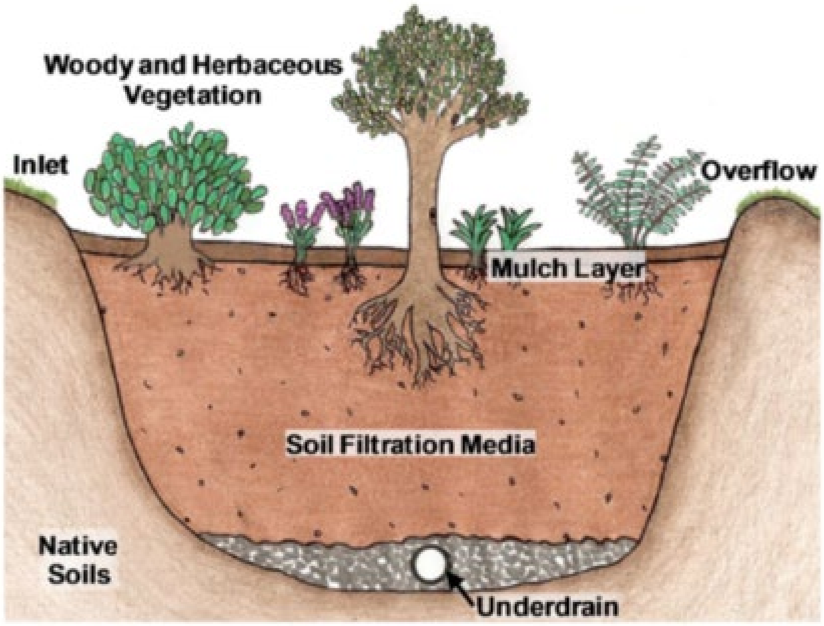

Figure 1: Schematic of a bioretention system with underdrain (from Roy-Poirier et al., 2010)

1.2. Problem Description

With the proliferation of rain gardens and bioretention systems in Western Washington designed to control and treat stormwater, there is a critical need to understand the role that mulch plays in treating stormwater and reducing maintenance effort. From a stormwater treatment perspective there are five primary aspects of mulch's role in making bioretention systems better and more cost effective:

1. Stormwater that flows into bioretention or rain garden system first contacts the mulch layer before any other component in that system, providing an opportunity for contaminant treatment potential.
2. Mulch is an easily replenishable carbon source for critical biogeochemical processes that treat stormwater pollutants. Carbon sources in the bioretention soil media (BSM) layer itself cannot be replaced without digging out the plants and BSM. However, mulch can be easily added on top. BSM is also known as *bioretention media*, *bioretention soil*, *soil filtration media* (e.g., Figure 1), and *engineered soils*.
3. Mulch is the most easily replaced component of a bioretention system if exposed to high and unexpected pollutant loading.
4. The mulch layer blocks solar radiation and wind protecting both moisture and temperature of the soil.
5. Mulch plays a critical role in preventing weeds and invasive species from outcompeting plants in a bioretention system. While this doesn't necessarily address stormwater treatment per se, there is sufficient evidence to show that weedy and unkempt bioretention systems are considered unsightly and tend to be undervalued by the public. Additionally, repeated weeding and invasive removal is a costly addition to operations and maintenance budgets for any municipality.

We believe that the roles mulch has in effective stormwater treatment and mitigation of maintenance effort needs quantification to ensure cost effective and sustainable efforts by local governments who will build and maintain the hundreds of bioretention facilities and rain gardens in Washington in the coming years.

1.3. Results of Prior Studies

Considerable recent efforts to characterize stormwater pollutant removal by various types of BSM, typically are not designed to gather information about the role of the mulch layer, if even included in the study column. Sufficient evidence exists to show that mulch plays a critical role in stormwater pollution remediation. Some of this seminal work is outlined below:

Phosphorous and Mulch - Mei, Ying, et al. (2012) in a study on five types of mulch [bark of white poplar, bark of sophora japonica, haydite, pearlite, and vermiculite] showed that short term phosphorous sorption capacity was maximum when using vermiculite.

Metals and Mulch – Davis et al. (2001) identified the importance of a mulch layer in the removal of metals from influent stormwater. They showed that there was a significant uptake of metals in the upper mulch layer, and that an inch-thick layer of mulch was sufficient to retain most the influent metals. This study was performed at a laboratory scale.

Oils, and Grease and Mulch – Hong et al. (2006) in a bench-scale infiltration study showed that a thin mulch layer was capable of trapping 80 to 95% of all oils and greases added to a synthetic stormwater influent load. Furthermore, 90% of the sorbed oils and greases biodegraded between 2 and 8 days, a biodegradation that was shown to be accompanied by increased microbial populations.

Heavy Metals, and Polycyclic Aromatic Hydrocarbons and Mulch – Ray et al. (2006) found that the sorption of heavy metals [copper, cadmium, chromium, lead, zinc] and PAHs [1,3 dichlorobenzene (DCB), naphthalene (NP), fluoranthene (FA), butylbenzylphthalate (BBP), and benzo(a)pyrene (B[a]P)] to a layer of hardwood mulch was dependent upon the pollutant species, contact time and initial concentrations. Sorption rates ranged from 20 to 100% with metals sorbing faster to the mulch than the PAHs. This study was also conducted at a laboratory bench-scale. Mulches can be effective in removing heavy metals from landscape and garden soils. Common urban contaminates such as lead and cadmium can be removed from the soil solution by mulched leaves of eucalyptus (Eucalyptus spp.), pine, poplar (Populus spp.), and arborvitae (Thuja spp.). Likewise, a mixture of compost and woodchips was found to decontaminate forest soils by complexing copper into a less toxic form (Chalker-Scott, 2007)

Microbes, Rhizosphere, and Mulch – Tiquia et al. (2002), in a field microcosm study that compared the application of several organic mulches to topsoil against a bare soil control, showed that mulch treatment significantly affected organic matter content, soil respiration, microbial biomass N, soil pH, cation-exchange capacity, and concentrations of plant nutrients. The populations of certain bacterial populations in the rhizosphere was also significantly higher in the composted plots compare to the bare soil plots.

1.4. Regulatory Requirements

The data collected from this study are intended to provide more information on the performance of the mulch layer in a typical bioretention best management practice (BMP), and associated maintenance effort. Ultimately these results will inform Ecology's stormwater guidance, specifically bioretention design (BMP T7.30, "Bioretention Cells, Swales, and Planter Boxes," of Volume V of the 2019 SWMMWW as amended in 2014).

Urban jurisdictions use Green Stormwater Infrastructure (GSI) technology, such as bioretention, in new and re-developed infrastructure in order to comply with National Pollutant Discharge Elimination System (NPDES) regulations for municipal stormwater.

1.5. Study Goals

A listing of specific study objectives was to measure the following in bioretention cells with three types of mulch against a no-mulch control:

- Quantify pollutant removal efficiencies for 7 pollutants of concern, over two wet seasons.
- Quantify stormwater fluxes in terms of inflow/outflow and soil moisture dynamics over two wet seasons.
- Quantifying maintenance effort in terms of weed removal and plant replacement over the period of study.

Anticipated study outcomes were a better understanding of what types of mulch in bioretention systems are best suited to treat stormwater, ensure plant success, and limit weeding efforts.

2. Methods

The work was carried out at Washington State University's Puyallup Research and Extension Center (Figure 2), located in the South Puget Sound Region.

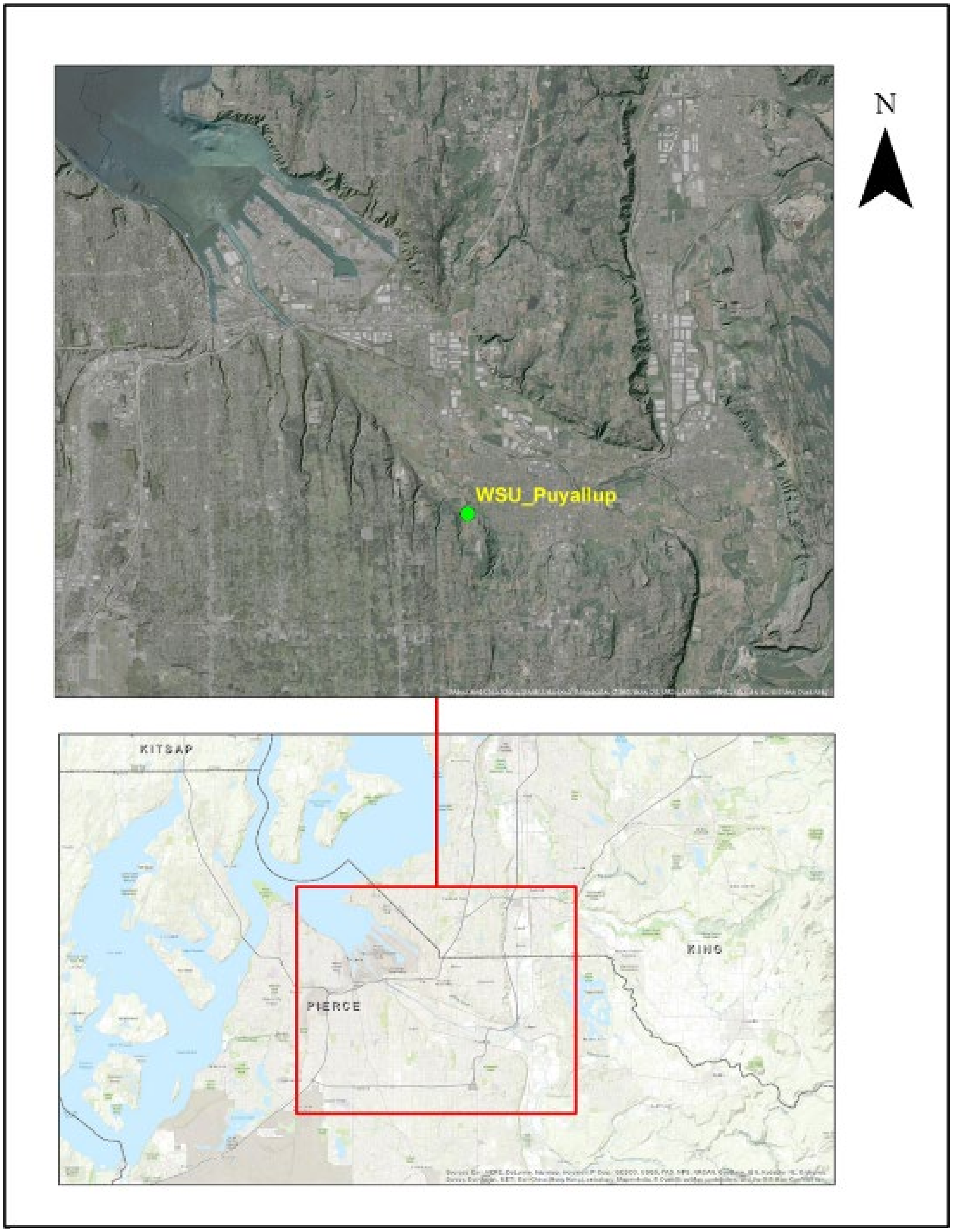

Figure 2: Location of WSU's Puyallup Research and Extension Center

Figure 3: Image showing layout of facilities at WSU's Puyallup Research and Extension Center. Stormwater captured from a drainage area (purple) will be stored in a cistern, that in turn will be used to dose 16 bioretention cells (red area

Three types of mulch shown on page 2 were compared to a no-mulch control within 16 bioretention cells (Figure 3). Each of the three mulch types was replicated four times, and their performances were compared against those of four no-mulch control cells. (Figure 4). All statistical testing involved checking data for normality first and then choosing appropriate parametric or non-parametric tests.

2.1. Flow control and treatment

We defined treatment performance as the ability of a bioretention cell to remove/sequester stormwater pollutants, store water in the form of soil moisture, and reduce runoff volume. Stormwater runoff was collected from 72,084 ft^2 of impervious surface on the WSU Puyallup facility and stored in a common dosing cistern. Artificially dosed storm events comprising specific stormwater pollutants were added to the dosing water and applied to the 16 test cells over 6 dosing events or artificial storms.

Six artificial storm events were conducted between March 2020 and September 2021. These events are listed chronologically in Table 1. Storm events varied by magnitude, but all occurred over 6 hours. Storms comprised a sequence of 9 pulsed events, with each pulse

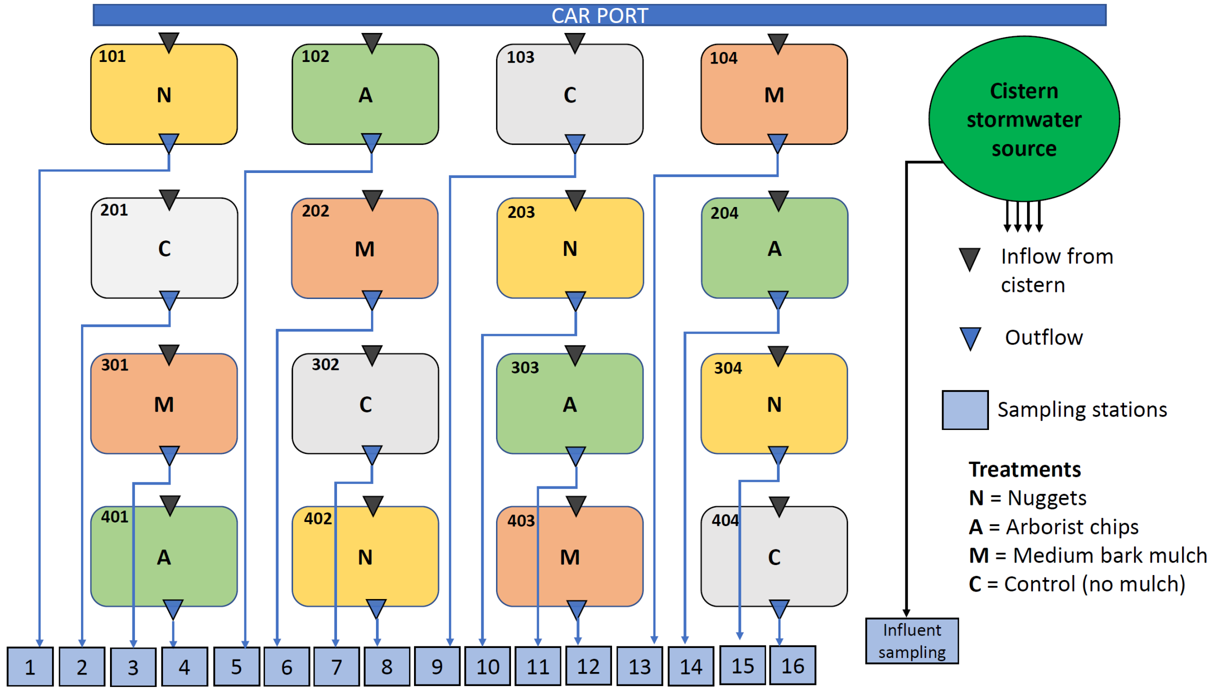

Figure 4: Layout of bioretention cells and mulch treatments applied

taking 20 minutes and each pulse separated from the next pulsing event by 20 minutes of no pumping. Intermittent pumping of dosed water from the cistern ensured similar delivery times and consistent loading to cells at varied (hydraulic) distances from the cistern. The magnitude of each pulse gradually increased and then decreased, with the middle pulse (5th pulse) corresponding to the highest pumped flow rate. Ultimately, the total volume of dosed water pumped out of the cistern for the 1.0-inch storm was five times more than the 0.2-inch storm. More details are available in the QAPP – Table 8.2 and Figure 7.

Table 1: Storm event dates, magnitude, and potential issues.

Storm date	**Storm size (inches)**	**Noteworthy issues**
3/11/2020	0.2	Charging event before synthetic storm impacted volume calculations. All data from this storm were used except storm volumes
5/18/2020	0.8	
8/3/2020	0.4	
1/26/2021	1.0	
6/10/2021	0.6	
9/22/2021	0.5	

2.1.1. Measuring hydrology

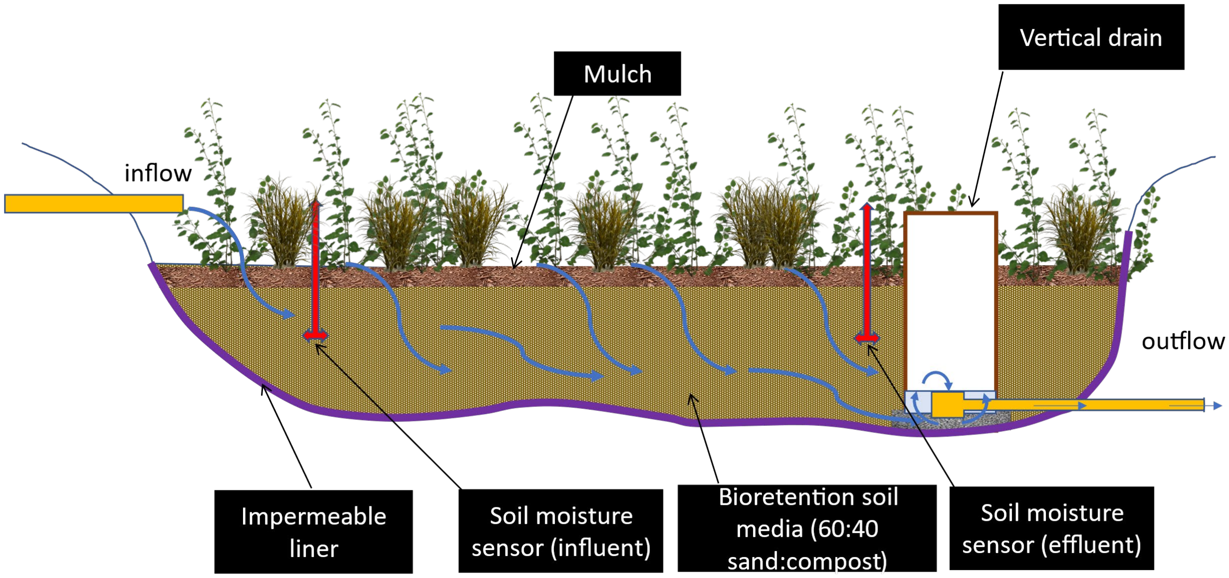

Figure 5: A cross-section of an individual cell showing the configuration of inflow, outflow, and soil moisture sensors

Inflow and outflow volumes were used to characterize how mulch affects water retention in each cell. Soil moisture levels in the bioretention media were measured at two locations in each cell at a depth of 30 cm below the mulch surface – one close to the stormwater inlet into the cell, the second close to the effluent outlet below grade (Figure 5).

We compared average daily soil moisture, peak outflow rates (per artificial storm), and total outflow volume (per artificial storm) from bioretention cells with a mulch type, compared to bioretention cells without mulch.

2.1.2. Measuring water quality

All the cells were dosed with a synthetic blend of stormwater during 6 artificially generated storm events. Artificial stormwater was applied to each cell with a network of pumps and pipes, using water that has been dosed artificially with 7 common analytes.

We tested for the following parameters for each storm dosing event in the influent and effluent from the bioretention cells.

1. Nitrate – Nitrite (target influent value: 0.3 mg/L)
2. Total phosphorous (target influent value: 0.3 mg/L)
3. Dissolved copper (target influent value: 0.1 mg/L)
4. Dissolved zinc (target influent value: 0.1 mg/L)
5. Total Petroleum Hydrocarbon (target influent value: TPH 15 mg/L)

TPH was analyzed as Diesel Range Organics (TPH-DRO) and Motor Oil Range Organics (TPH-MOR). These two analytes were chosen based on the dosing protocol listed in the QAPP where diesel and used motor oil were added to the influent.

6. Total Suspended Solids (target influent value: 150 mg/L)
7. Dissolved Organic Carbon (measured only in effluent)

Pollutant removal efficiencies were quantified by measuring inflow volume, outflow volume, influent concentrations based on flow-weighted samples collected at the influent sampling station (Figure 4), and effluent concentrations based on flow-weighted sampling at the 16 bioretention cell outlets. For each storm, flow-weighted aliquots were composited into one composite storm sample at every one of the 17 sampling stations.

We calculated median pollutant removal efficiencies across all storms grouped by analyte and mulch type. Pollutant removal efficiency or the reduction (%) in pollutant concentration during each storm (ΔC) was calculated as:

$$\Delta C = 100 \times \frac{(C_{in} - C_{out})}{C_{in}}$$

Where:

C_{in} = Flow-weighted influent pollutant concentration
C_{out} = Flow-weighted effluent pollutant concentration

Testing for statistical significance between median pollutant removal values by mulch treatment was performed with the non-parametric Kruskal-Wallis test at the $a = 0.05$ level of significance.

2.2. Plant health and weeding effort

Each of the 16 bioretention cells was planted with the same plant palette, totaling 55 plants per cell. There were two types of woody-plants, *Mahonia aquifolium* 'Compacta' (Oregon grape) and *Physocarpus opulifolius* 'Tiny Wine' (ninebark). In addition, there were four types of ornamental grass-like species-- *Carex testacea*, *Juncus ensifolius*, *Iris tenax*, and *Pennisetum a*. 'Burgundy Bunny'.

The plants were planted in November 2018, and due to funding delays, data collection only began in February 2020, ending in September 2021. We found that the black plastic lining the cells radiated much heat. Concerned that mass mortality of plants due to heat stress would impact the study, a decision to irrigate during the summer, was made. The plants were irrigated the summers of 2019, 2020, and 2021. Irrigation occurred using a timed sprinkler system.

November 2018

September 2019 – data collection began in Feb 2020

December 2020

September 2021 – data collection ended in Sept 2021

Figure 6: Images of plant growth in one cell through the study - clockwise from top left

It should be noted that arborist chips did need to be replenished at midway point (1 year) of the study. The arborist chips decomposed, and the mulch layer was no longer providing adequate coverage.

Plant success was measured by monitoring plant health and mortality every month. We also monitored plants for damage not associated with treatment (e.g., herbivore damage and other environmental factors). In addition, we measured the success of plant establishment by measuring the total spread of the above-ground parts. We also noted whether growth was so vigorous that the cell could become a monoculture of that species.

Specific plant health metrics measured were:

1. Plant height, base circumference, crown circumference
2. Plant vigor – rating from 1 to 5. A rating value of 1 suggests the plant is in good health; a rating of 3 and beyond suggests the onset of stress. A stress rating value of 5 suggests 76%-100% damage.
3. Dormancy counts – noticeably dormant plants were counted.

Mulch's effect on mitigating weeds was measured through monthly logging of person-hours needed to remove weeds or plants not planted in the cells. We also logged weed types, the number of individuals, and weed weights.

Specific weed metrics measured were:

1. Total hours spent weeding each bioretention cell over the study were logged
2. The number of weed plants and weed types (species type and whether they were perennial, annual, or woody) were noted.
3. In 2021, weeds that were removed were also dried and weighed.

3. Results & Discussion

It should be noted that all our results show water quality and quantity treatment of the whole bioretention system, not just the mulch layer, but because of the study design we separate the findings from the no-mulch controls and interpolate findings unique to the mulch cover.

3.1. Soil Moisture

Each bioretention cell was instrumented with a soil moisture sensor 30 cm below the cell surface at both inflow and outflow locations. The control cells' soil moisture was consistently the lowest at both inflow and outflow locations. However, there is a clear separation of soil moisture values at the outflow locations amongst the three mulch treatments – cells with arborist chips having the highest soil moisture values, and medium bark, the lowest of the three mulch types tested. Soil moisture values measured over the study period are shown for the inflow locations in Figure 7 and the outflow locations in Figure 8.

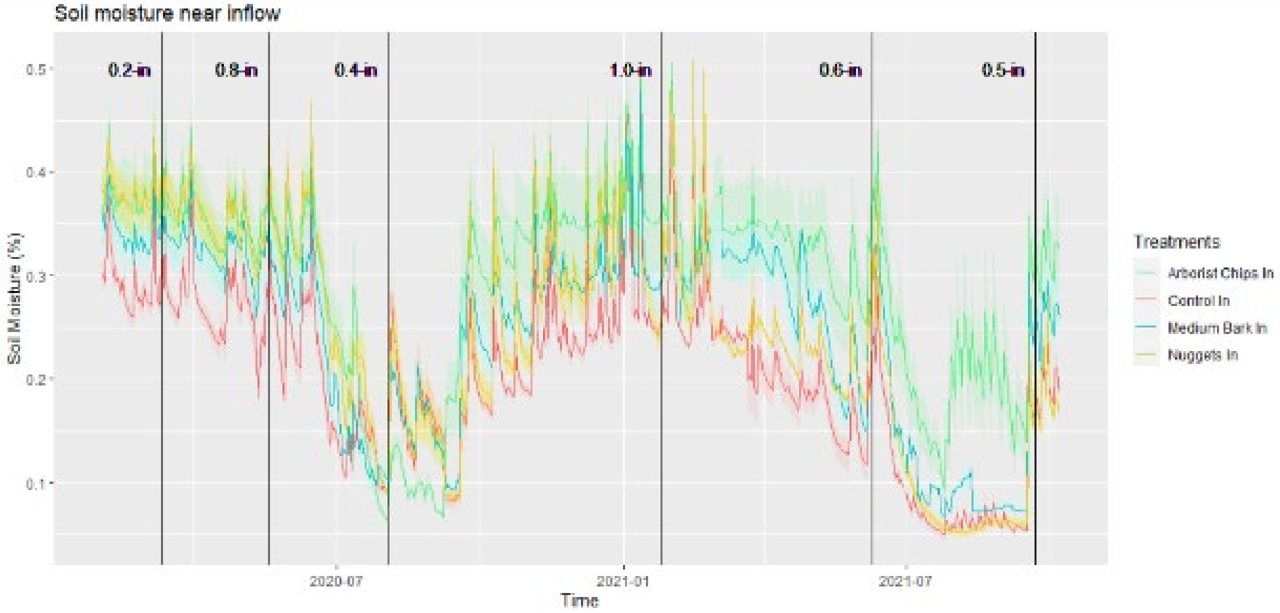

Figure 7: Average soil moisture values by mulch type measured at inflow locations.

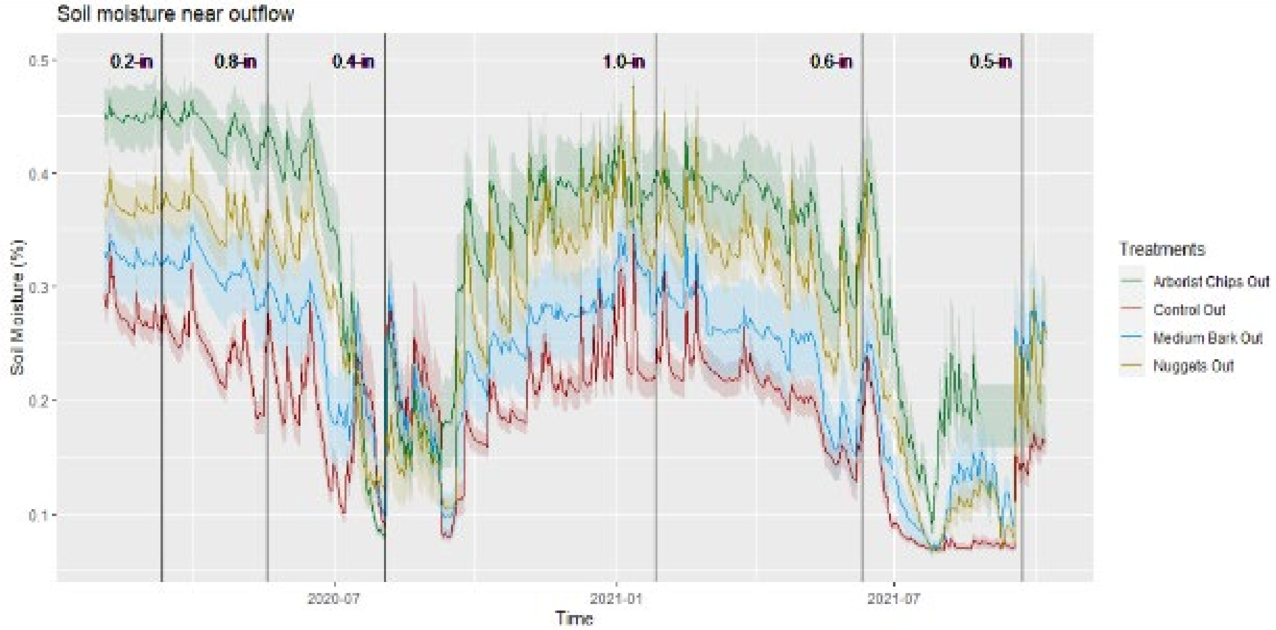

Figure 8: Average soil moisture values by mulch type measured at outflow locations.

3.2. Bioretention Hydrology

Six artificial storm events were studied, with storm events ranging from 0.2 inches to 1.0 inches. Average outflow volumes associated with the 1.0-inch storm for each of the three mulch treatments and controls cells are presented in Figure 9. To assess the role of mulch in water control we calculate the outflow volume as a fraction of the volume of stormwater pumped into each bioretention cell.

Peak outflow rates expressed as a fraction of the peak flow rate of stormwater pumped into each bioretention cell ranged from 27.5% (Controls, 0.4-inch storm) to 63.6% (Medium Bark, 0.2-inch storm) – these are presented in Figure 10. Outflow peak flow rate fractions averaged by treatment and across 6 events were: 49.1% (Arborist Chips), 47.8% (Control), 49.4% (Medium bark), and 54.5% (Nuggets). Statistical testing of these peak flow rate fractions revealed that none of the treatments were significantly different from each other

The outflow volume fraction ranged from 41.5% (Nuggets, 0.4-inch storm) to 92.7% (Controls, 0.8-inch storm) – these are presented in Figure 10 by storm event. Overall, the average (5 events) outflow volume fractions by treatment were: 83.6% (Arborist Chips), 81.8% (Control), 76.4% (Medium bark), and 64.2% (Nuggets). Statistical testing of these volume fractions was performed using parametric statistics because the volume fraction data were normally distributed. Testing by ANOVA and paired t-testing showed that stormwater outflow volumes from cells with Nuggets were significantly less than all other cells ($p<0.05$) over the 5 storms considered (0.4, 0.5, 0.6, 0.8, and 1.0-inch storms)

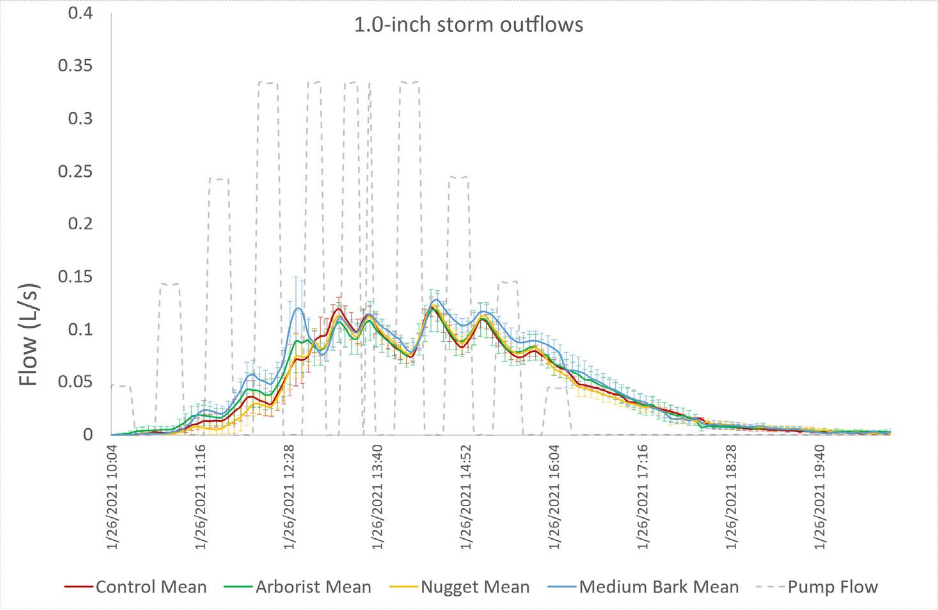

Figure 9: Example of hydrograph for one storm event (1.0-inch storm). Each line represents an outflow rate from the cells averaged by mulch type.

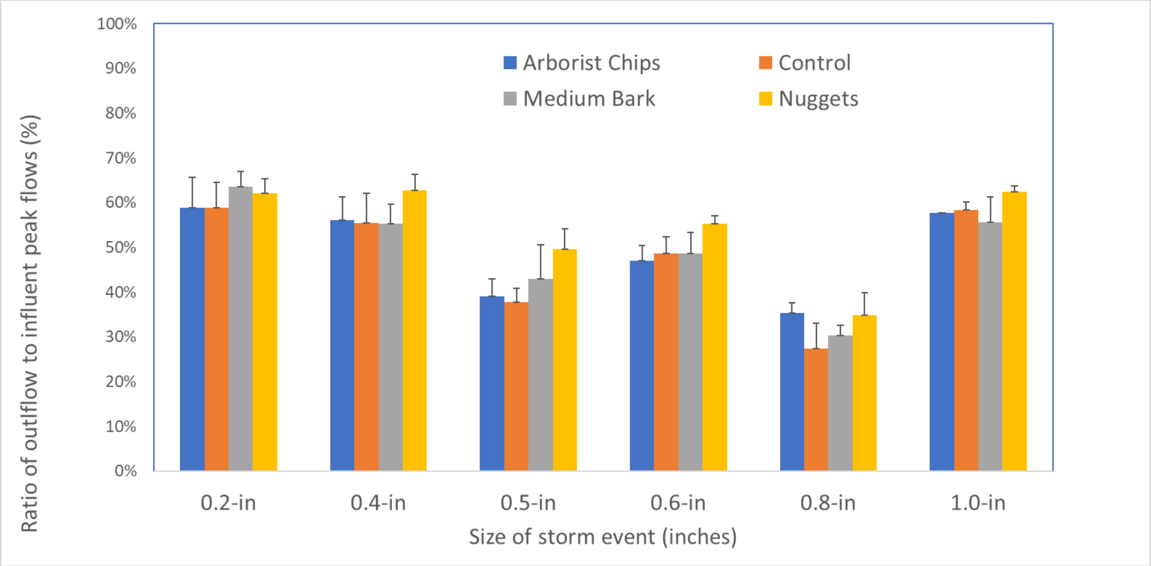

Figure 10: Peak outflow for all storm events, averaged by mulch treatment, and presented as a fraction (%) of peak inflow

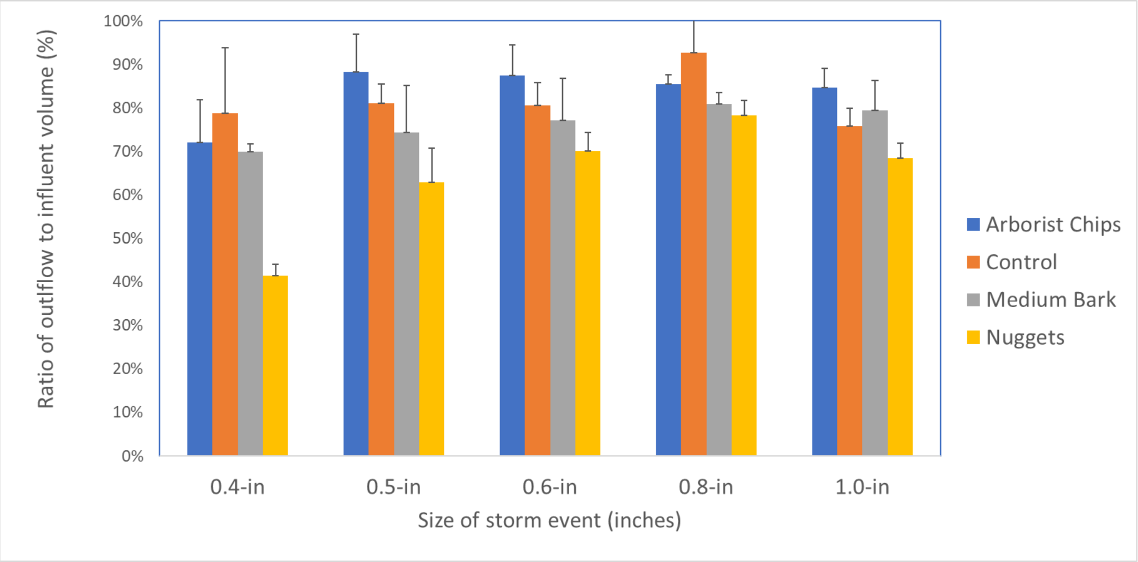

Figure 11: Average outflow storm volumes observed, presented as a fraction (%) of inflow, for five storm event and four mulch treatments (grouped by storm)

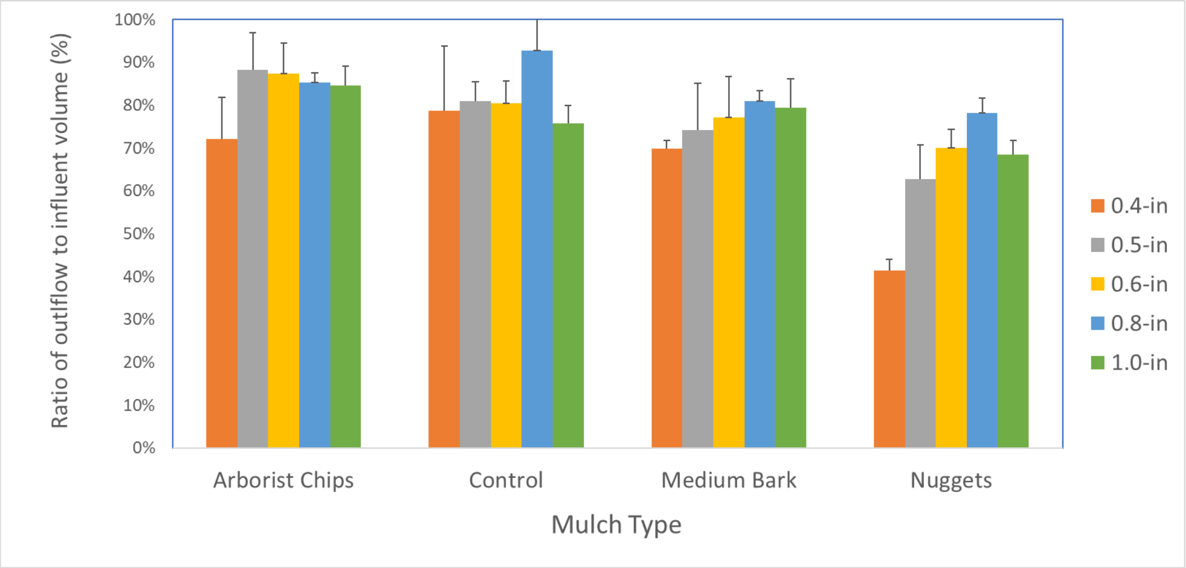

Figure 12: Average outflow storm volumes observed, presented as a fraction (%) of inflow, for five storm event and four mulch treatments (grouped by mulch treatment)

3.3. Pollutant Removal Efficiencies

Pollutant removal efficiencies were evaluated for a suite of 7 analytes from six storm events. From a general perspective, no individual mulch type outperformed any other mulch type. Additionally, we could not distinguish the difference in pollutant removals between mulched and un-mulched (control) cells except for Nitrite-Nitrate. For Nitrite-Nitrate, cells with mulch exported significantly lower concentrations of Nitrite-Nitrate compared to controls. For every other analyte, the pollutant removal capacity of mulch alone was likely too small to be distinguished through our research methods compared with bioretention media alone.

Influent dosing concentrations were meant to be consistent across all storm events; however, this was harder to control than we expected. Hence, influent concentrations varied across storm events – influent concentrations are plotted in Figures 13 to 16. In addition, boxplots representing pollutant removal efficiencies by analyte are also presented in Figures 13 to 16.

Per Washington state Technology Assessment Protocol – Ecology (TAPE) protocol for assessing emerging stormwater treatment technology, there are specific performance goals that need to be met, many of those goals have prescribed influent ranges:

1. **Basic Treatment:** 80 percent removal of total suspended solids for an influent concentration range of 100 mg/L to 200 mg/L.
    a. For influent concentration less than 100 mg/L the effluent goal is 20 mg/L total suspended solids.
2. **Enhanced Treatment:** 30 percent removal of dissolved copper for influent concentration range of 0.005 mg/L to 0.02 mg/L

    AND

    60 percent removal of dissolved zinc for influent concentration range of 0.02 mg/L to 0.30 mg/L
3. **Phosphorous Treatment:** 50 percent total phosphorus removal for an influent concentration range of 0.1 to 0.5 mg/L as well as achieving basic treatment.

These criteria were compared against the results we observed.

3.3.1. Conventionals

Our influent TSS concentrations ranged from 43 mg/L to 244 mg/L, which is a wider range than that prescribed by TAPE (100 mg/L to 200 mg/L). However, every effluent sample was at or below the stricter 20mg/L criterion – suggesting that our systems conformed to the Basic Treatment performance goal.

Generally, removals were above 80% for all samples, except for 6 (of 93 total) that were associated with the 0.4-inch storm. Those values ranged from 70 to79% removal. However, overall median values across all storms were above 90%. For those samples between the TAPE prescribed influent range, TSS was consistently removed across all storm events, while DOC was consistently exported. Median values for TSS removal across all storm events ranged from 94.0% (arborist chips) to 96.2% (medium bark). There were no significant differences in TSS removal between control and mulched bioretention cells or between mulch types.

Dissolved organic carbon (DOC) was not dosed to the influent; influent concentrations plotted in Figure 13 reflect ambient DOC of stormwater used in the study. Negative removal rates in Figure 13 (bottom-right panel) imply that effluent DOC concentrations were higher than influent, suggesting DOC export from all bioretention cells across all treatments and storm events. Median DOC export ranged from -163.6% (arborist chips) to -189.6% (medium bark). There were no significant differences in DOC export between control and mulched bioretention cells. We should note that DOC is not a contaminant of concern and its presence in bioretention effluent is a critical part of the treatment of other stormwater contaminants such as toxic metals.

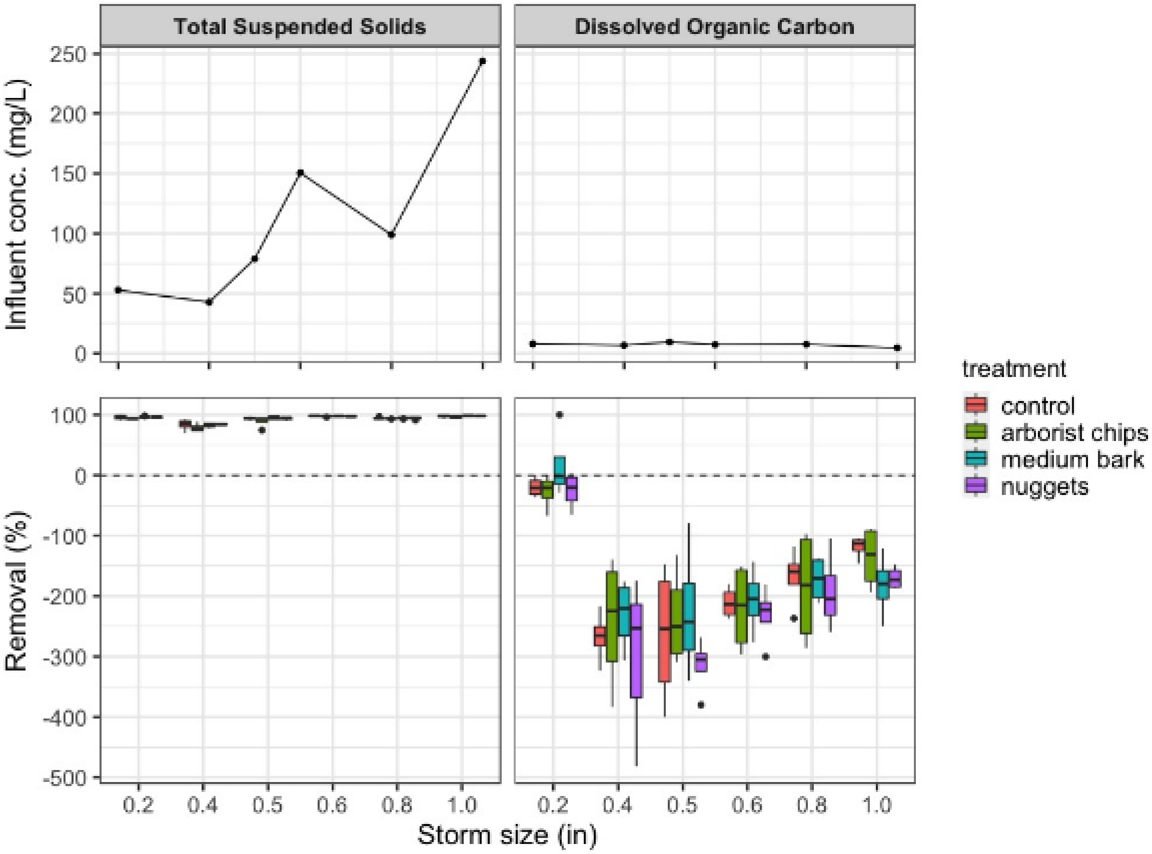

Figure 13: Influent concentrations (upper panels) for TSS and DOC, and pollutant removal rates across all six storms (lower panels.)

3.3.2. Metals

Our influent dissolved copper concentrations ranged from 0.006 mg/L to 0.040 mg/L. Of the samples that were between the prescribed TAPE influent range (0.005 mg/L to 0.02 mg/L), we did not see 30% removal for any of the treatments based on medians value per treatment across all the storms, meaning that our system failed the Enhanced Treatment performance goal. Removals for the subset of samples within the TAPE specified influent range varied from 20.5% to 28.5% removal.

Our influent dissolved zinc concentrations ranged from 0.129 mg/L to 0.290 mg/ which is within the range (0.02 mg/L to 0.30 mg/L) per TAPE protocols for influent dissolved zinc concentrations. Median values for dissolved zinc were above 94% for all treatments, across all storms.

For dissolved copper and dissolved zinc, cells with mulch and without mulch (control) were not significantly different in terms of pollutant removal efficiency. No mulch type performed significantly better than another. Both metals were consistently removed across

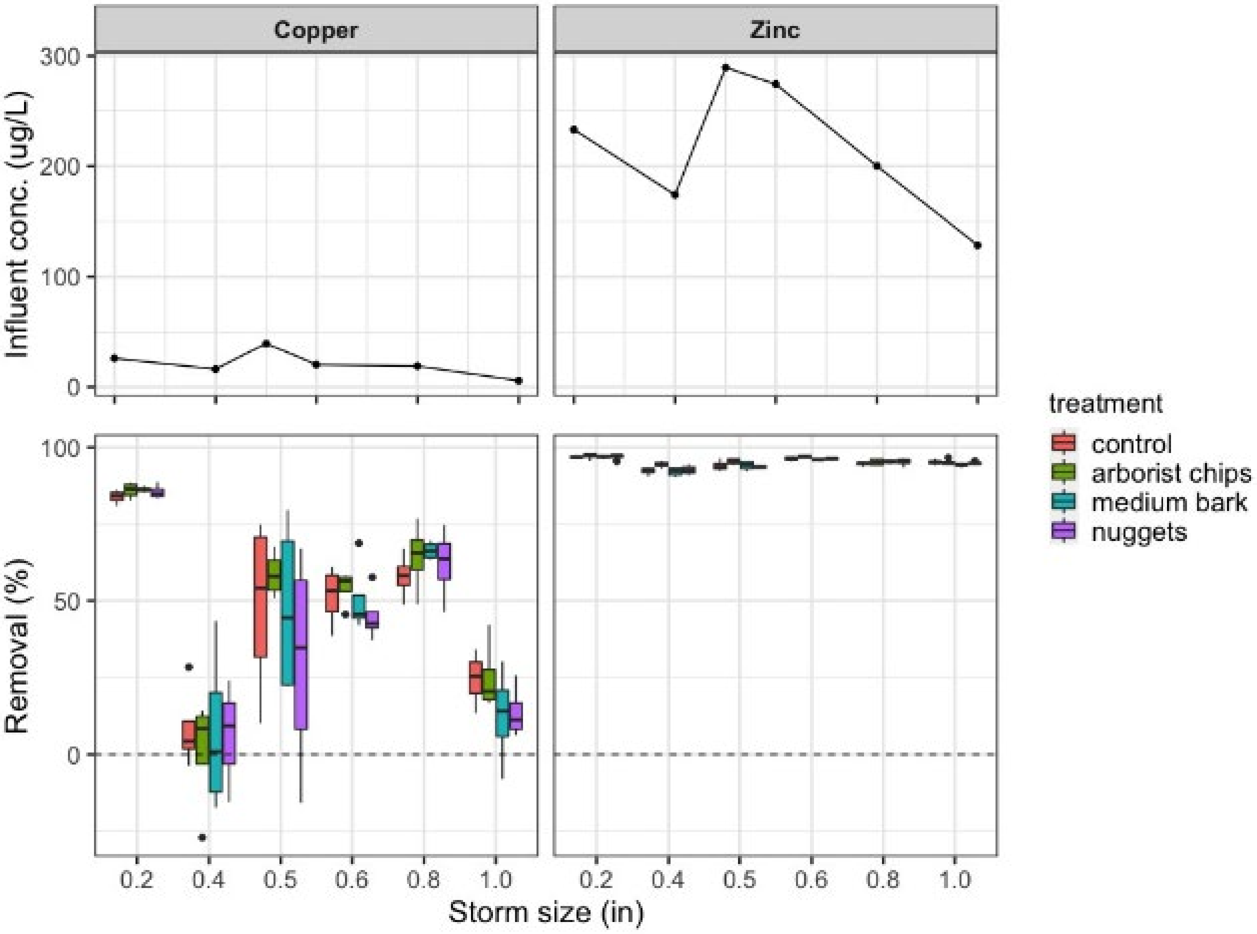

Figure 14: Influent concentrations (upper panels) for Dissolved copper and Dissolved zinc, and pollutant removal rates across all six storms (lower panels.)

all storm events except the 0.4-inch storm when some Dissolved copper export was measured. Median Dissolved copper removals across all storms ranged from 42.5% (nuggets) to 55.0% (arborist chips). The best removal rates were observed for the smallest storm event (0.2-inch); however, there was no correlation between storm size and removal performance. Median Dissolved zinc removals across all storm events was consistently between 95% and 96 % for the three mulch types and controls.

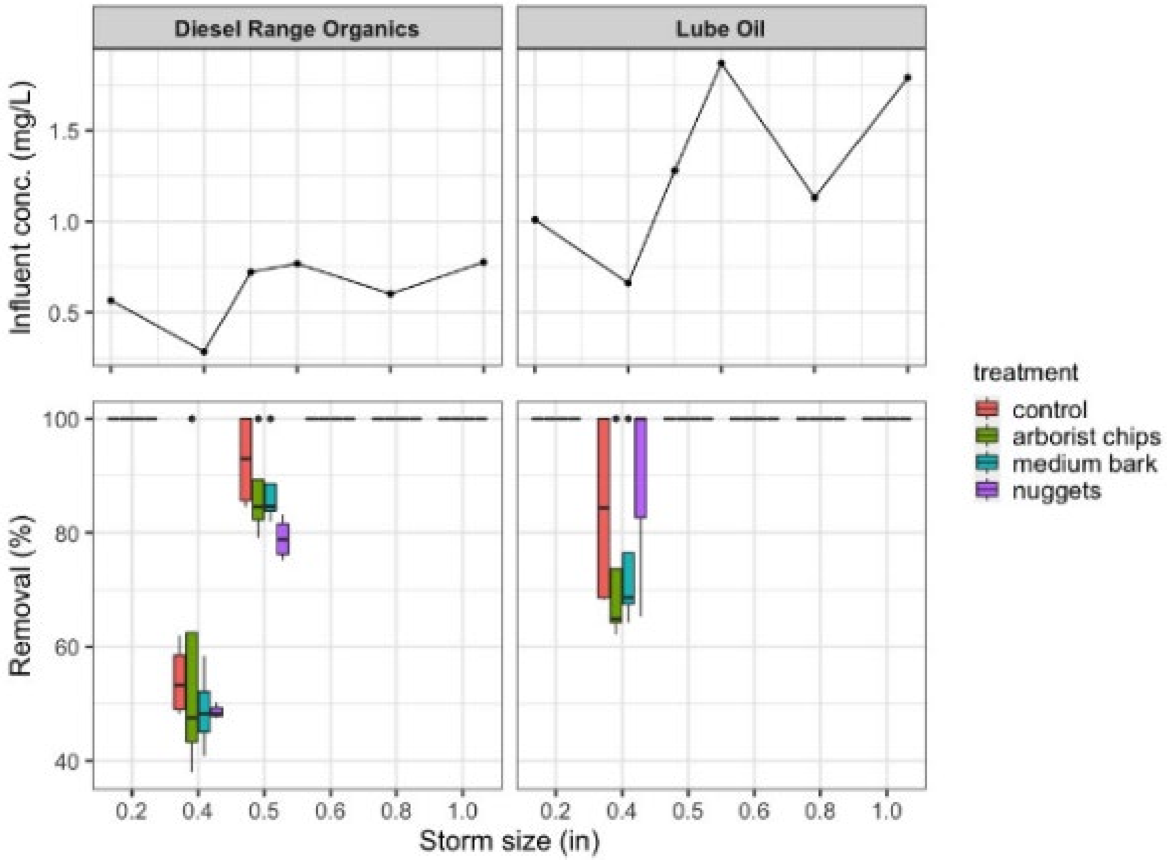

Figure 15: Influent concentrations (upper panels) for Diesel Range Organics and Lube oil, and pollutant removal rates across all six storms (lower panels.)

3.3.3. Hydrocarbons

For Diesel Range Organics (DRO) and Lube oil, cells with mulch and without mulch (control) were not significantly different in terms of pollutant removal efficiency. No mulch type performed significantly better than another. Both hydrocarbons were consistently removed across all storm events, with median removal rates across all storms being 100% for both. Except for two storm events (0.4 and 0.5-inch storms) for DRO and one storm event (0.4-inch storm) for Lube oil, effluent concentrations were all below detection limits. Lower removal performance for these two storms is shown in Figure 15.

3.3.4. Nutrients

Generally, we observed that Nitrate-Nitrite (N-N) and Total phosphorous (TP) effluent concentrations were higher in the outflows than the inflow concentrations - implying nutrient export from the cells. Only the 0.5-inch event showed some N-N removals, but those were only in cells with mulch; the control cells continued export of N-N. Statistical analyses of N-N export rates showed that cells with mulch exported significantly less N-N (Kruskal-Wallis chi-squared = 12.55, df = 3, p-value = 0.006) compared to the cells without mulch (control). Median export of N-N from control cells across all storms was 117.5%. For cells with mulch, cells with nugget mulch exported -30.1% TP, while the least export was observed from cells with medium bark (-12.6%).

For most storm events, TP concentrations in the effluent were above influent concentrations; however, some removal was seen in the 0.6-inch and 1.0-inch storms. Median TP export values across all storms ranged from -42.7% (medium bark) to -92.2% for nuggets.

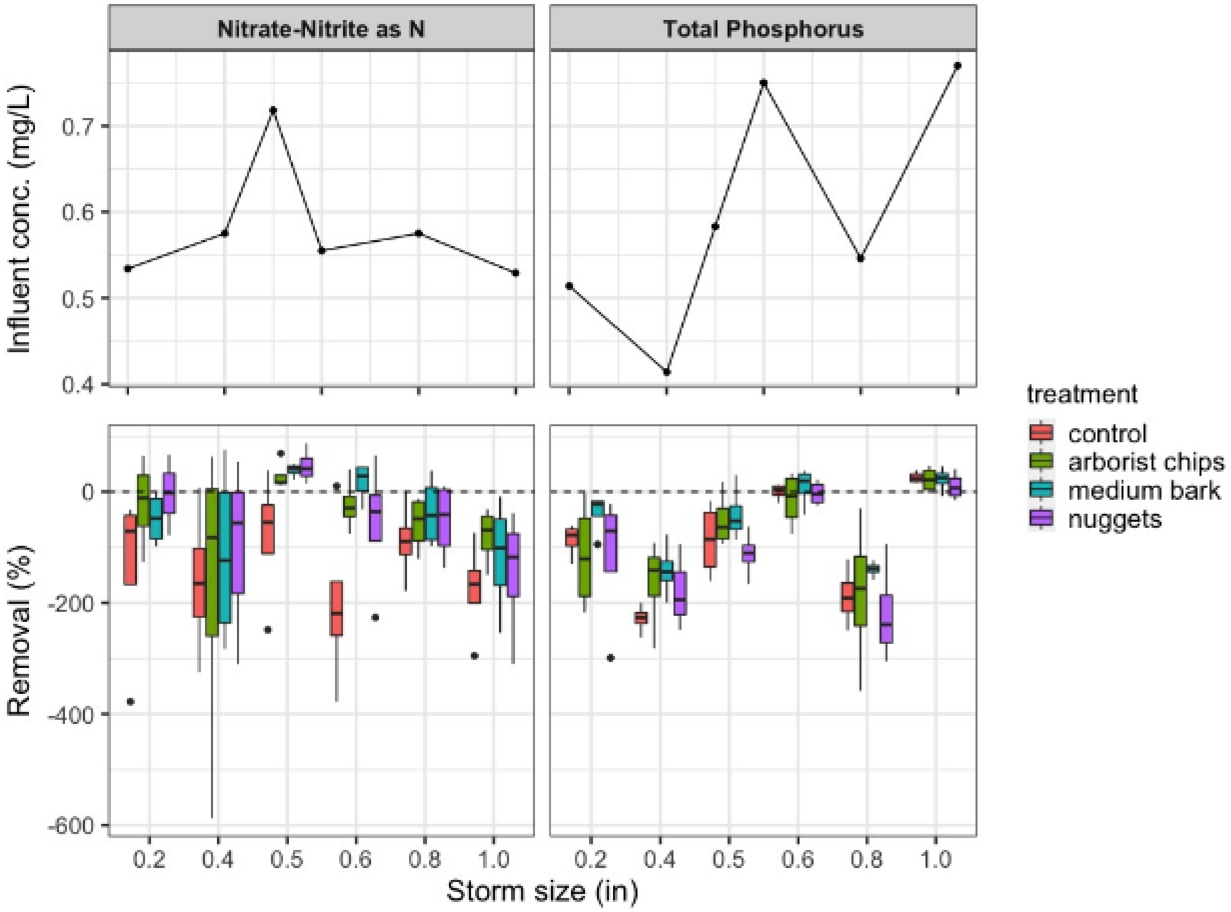

Figure 16: Influent concentrations (upper panels) for Nitrate-Nitrite and Total phosphorous, and pollutant removal rates across all six storms (lower panels.)

3.4. Plant Health

Throughout the 18-month plant study, there was a decline in the health of all plants, as evidenced by the number of plants showing vigor ratings of 5 (Figure 17), indicating high stress in the plants. There were no discernable differences amongst mulch treatment types.

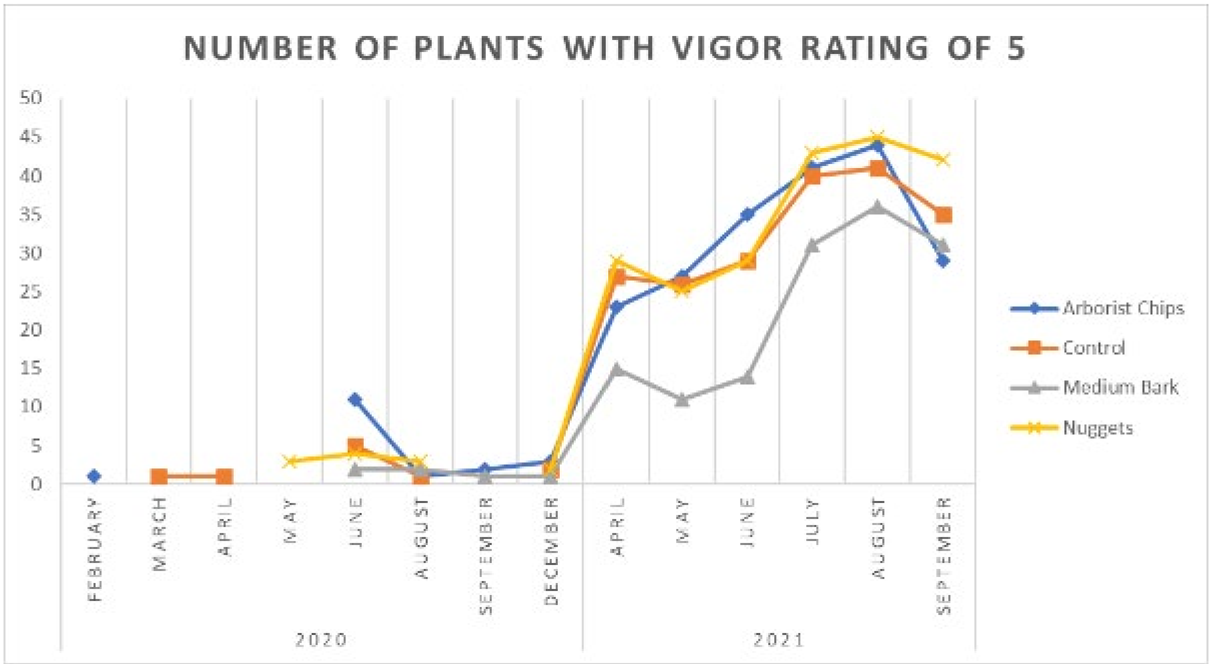

Figure 17: Monthly counts of individual plants exhibiting a vigor rating of 5 - 75% to 100% damage.

3.4.1. Ornamental Grass Species

Plant growth and vigor data associated with the four ornamental grass species were consistent across mulch treatment types and are not reported in this memo. However, it was noted that all the species of ornamental grasses did not do well by the end of the study, with many individual plants showing evidence of stress. Measurements of plant dormancy for three of the four ornamental grass species show increased dormancy throughout the study. Dormancy counts for Pennisetum were omitted because those data were not recorded accurately. The highest number of plants that appeared to be dormant were those in the control cells.

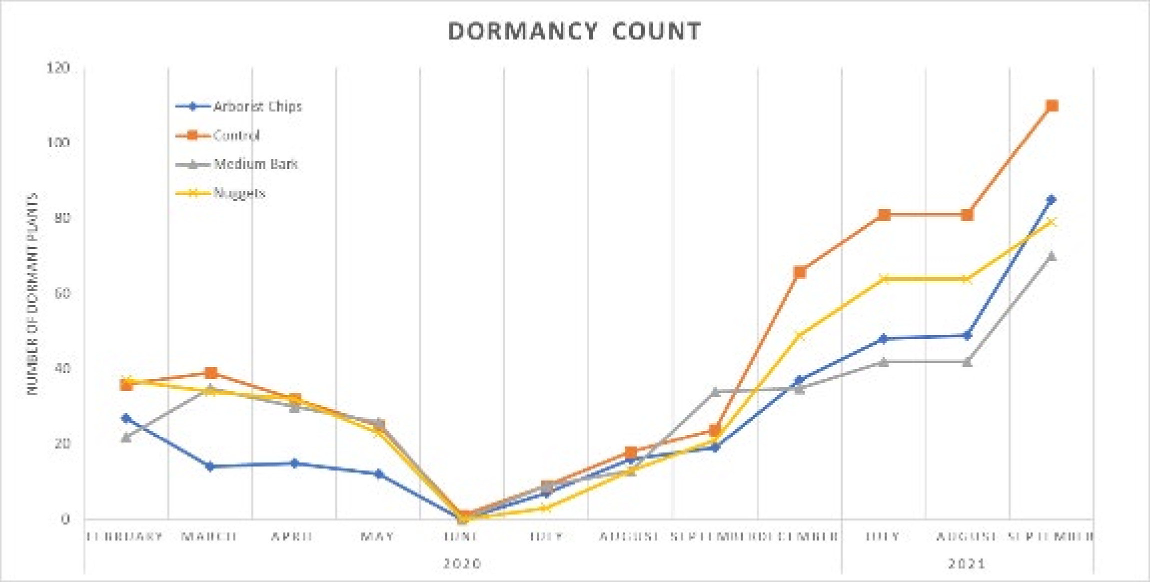

Figure 18: Monthly counts of three types of ornamental grasses that appeared dormant

3.4.2. Woody Shrubs

The ninebark took over most of the cells dominating coverage quickly and shading the other plants. In July 2021, ninebark plants were pruned across all cells (Figure 19). It was determined that the ninebark was putting out runners (Figure 20), a process that was likely facilitated by the mulch.


07/07/2021

Figure 19: Ninebark plants quickly took over the system and had to be pruned in July 2021. The image on the left is of one cell pre-pruning, and the image on the right shows the same cell post-pruning.

Figure 20: Horizontal spread of ninebark plants was traced to basal runners that were being put out

The evidence of basal runners and lateral spread of ninebark is evidenced in Figure 20 above, where cells that contained mulch saw ninebark plants with base circumferences that increased over the study. In contrast, the control cells without mulch saw minor changes in the ninebark base circumferences. Similarly, base circumferences of Oregon grape at the end of the study were highest in the arborist chips and medium bark mulched cells (Figure 23) – Oregon grape spread also attributed to basal runners.

3.4.3. Species survival

A tally of the survival of species at the end of the study is summarized below:

1. Ninebark and Oregon grape:100% survival
2. Carex: 25% survival
3. Pennisetum: 64% survival
4. Iris and Juncus: Undetermined because plants merged together over the study. Juncus primarily went dormant in July, and Iris in September.

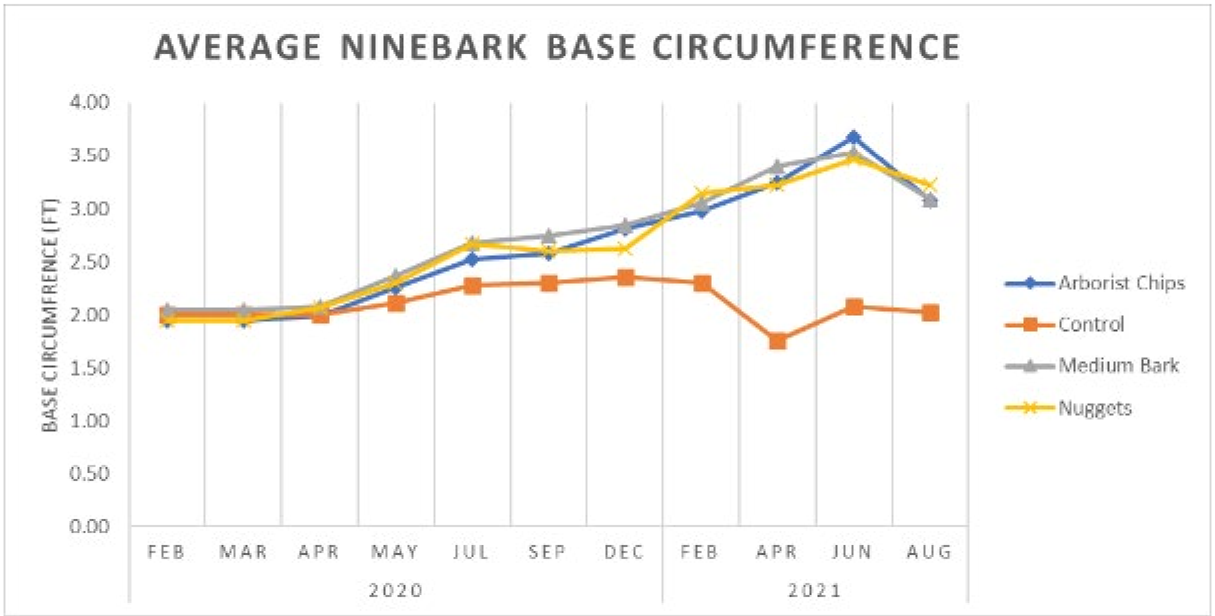

Figure 1: Average ninebark base circumferences throughout the study

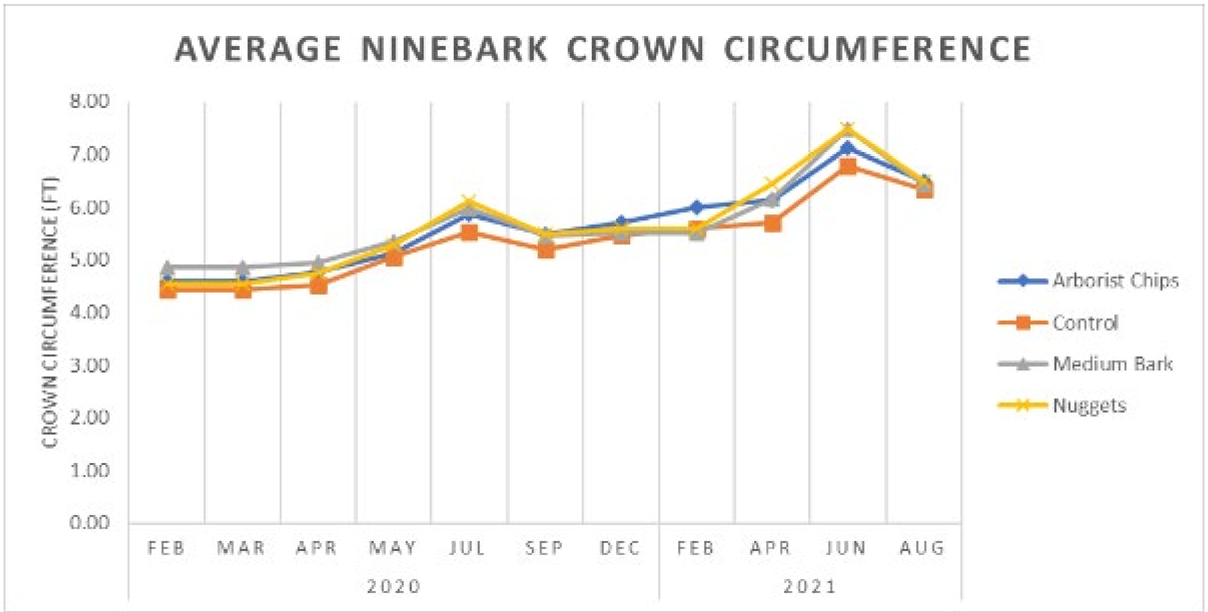

Figure 22: Average ninebark crown circumferences throughout the study. The two peaks and dips are pre and post-pruning measurements. Pruning took place in the summers of 2020 & 2021

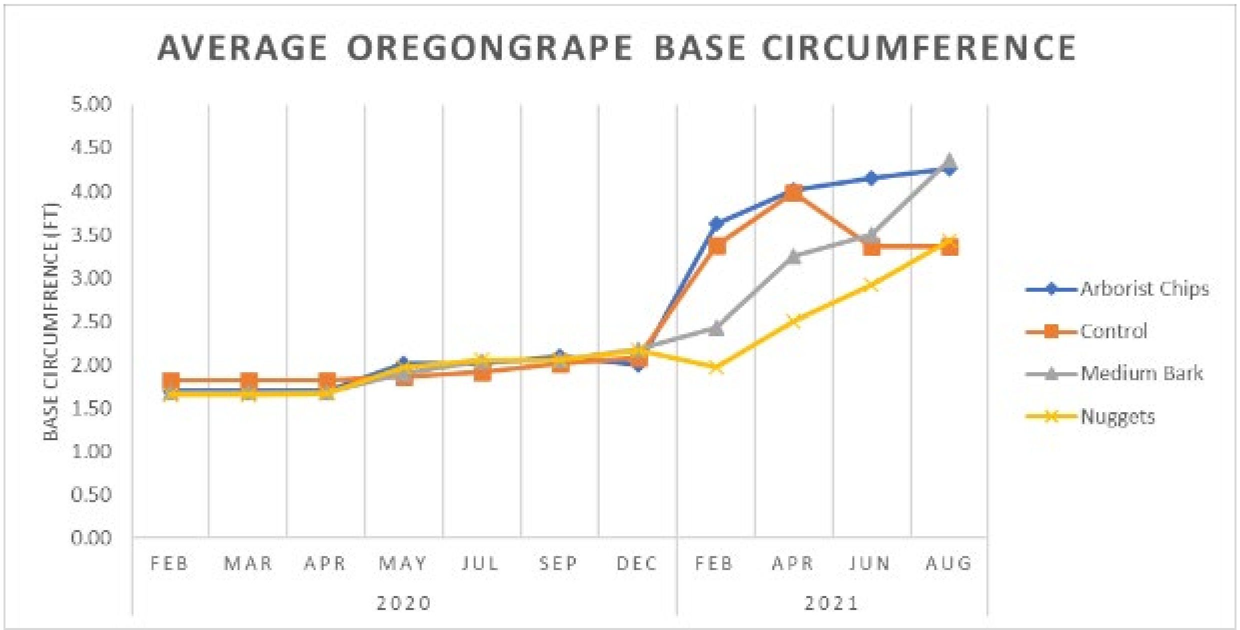

Figure 23: Average Oregon grape base circumferences throughout the study

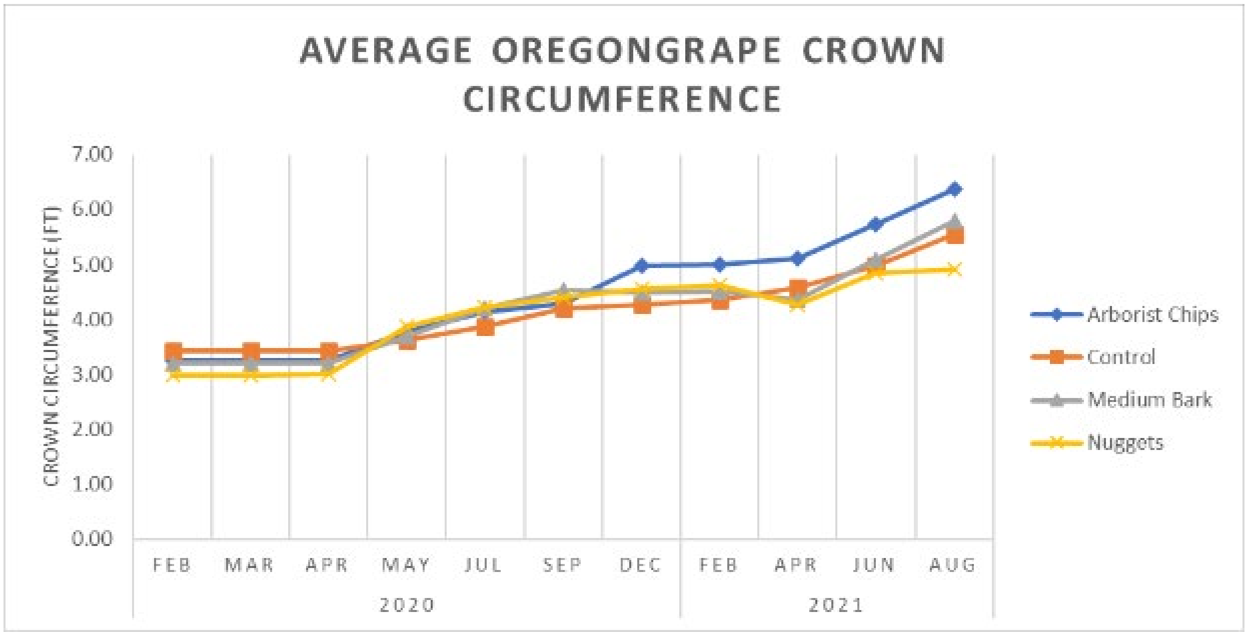

Figure 24: Average Oregon grape crown circumferences throughout the study.

3.5. Weeding Effort

Measurements of weeding effort showed a clear effect of mulch's role in minimizing weed proliferation. The total time it took to remove weeds from cells over the course of the study ranged from approximately 30 hours for the 4 cells with nugget bark, to almost 68 hours for the four cells with no mulch control cells (Figure 25).

When the average area occupied by cells of a specific mulch type was accounted for, we calculated the total effort throughout the study (20 months). Then, an average weeding effort per year (12 months) per unit area of a cell was calculated from that. These data are presented in Table 2, showing that cells with nugget bark yielded the lowest weeding effort, a value that was 59% less than the controls – cells with no mulch. Using arborist chips cut weeding down by 51% while using medium bark reduced weeding effort by 45%.

Temporal changes in weeding effort suggest expectedly that most of the weeding effort occurred in the late spring, summer, and early fall, with the control cells taking a significant fraction of the weeding effort (Figure 26). Cells with mulch in them did not show significant peaks in weeding effort. The majority of weeds were of the annual variety (Figure 27).

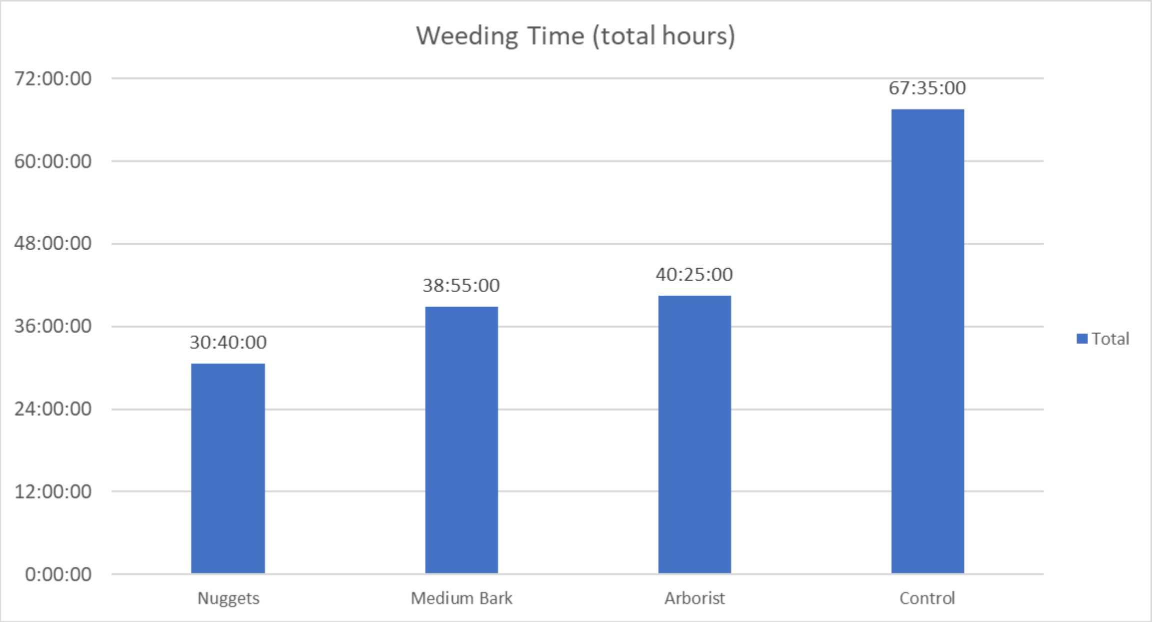

Figure 25: Total time taken to weed all 16 cells throughout the study

Table 2: Average weeding time per unit area and per year, grouped by the type of mulch used.

	Ave. days per cell over 20 months	Ave. hours per cell over 20 months	Ave. area weeded (sq. ft) per cell	Effort per cell (minutes/sq. ft. / yr)	Percent less than controls
Control	0.7	16.9	104.3	5.8	0%
Medium Bark	0.4	9.7	109.4	3.2	45%
Arborist	0.4	10.1	126.2	2.9	51%
Nuggets	0.3	7.7	114.3	2.4	59%

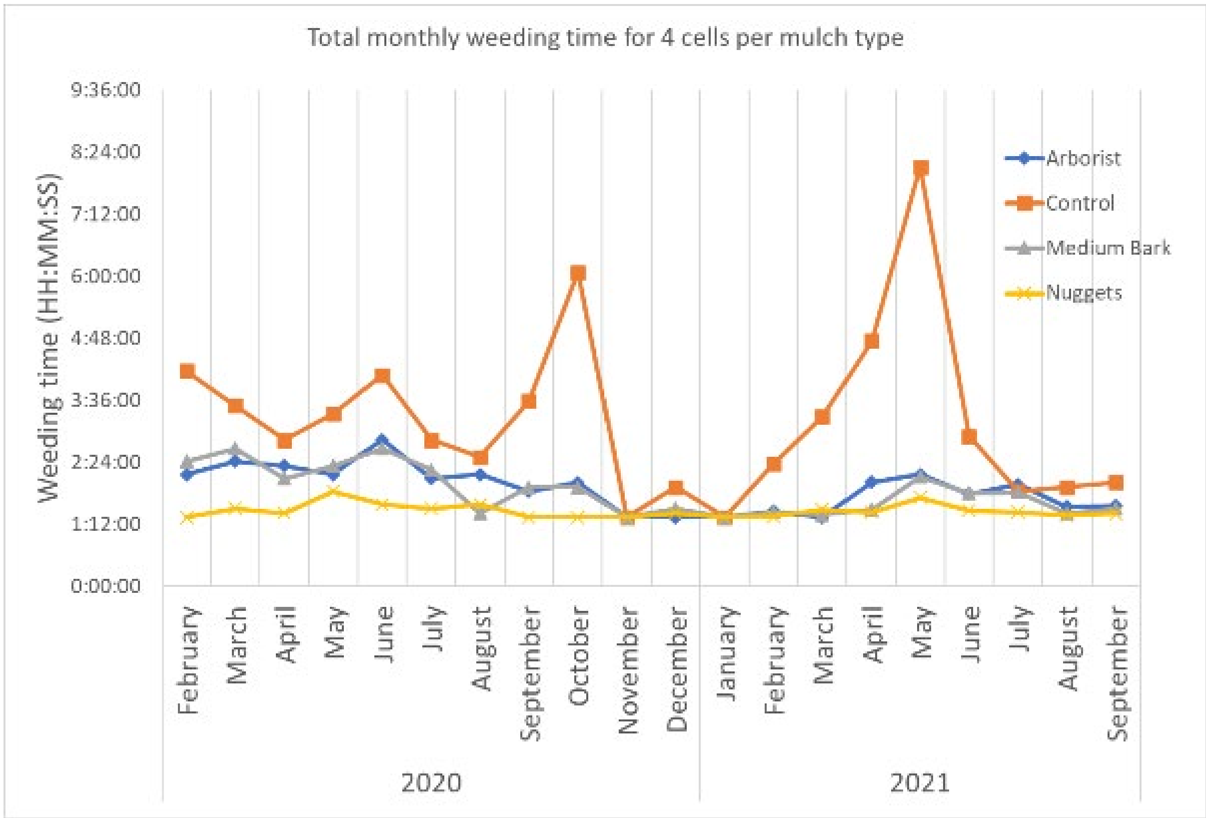

Figure 26: Weeding times by mulch type over the 20-month study

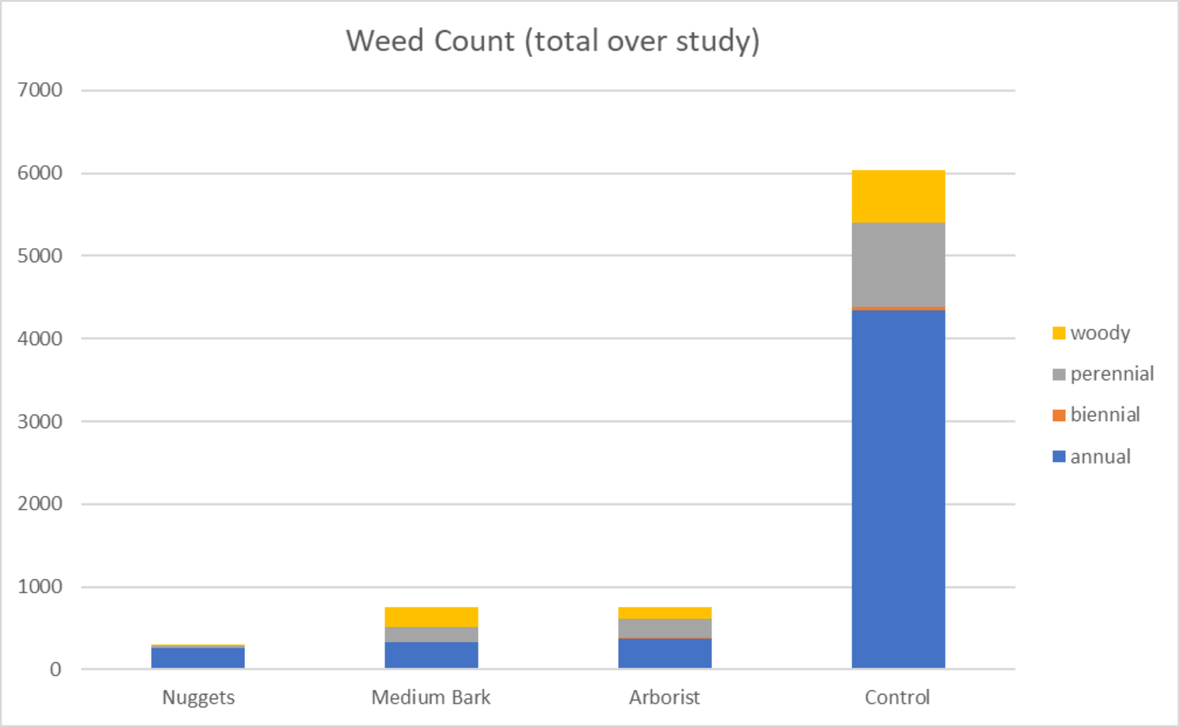

Figure 27: Weed counts classified by growth cycle

4. Conclusions (Key Findings)

1. Storm outflow volumes in cells with Nugget mulch were significantly lower than outflow volumes from all other cells. Nugget mulch was therefore the most effective mulch at retaining water and had significantly lower of storm outflow volume.
2. Generally, there was about a 50% reduction in peak outflow rates when compared to peak inflow rates pumped into the cells. There were no significant differences in peak storm outflow rates in comparisons between controls and mulch treatments.
3. Mulch plays a critical role in preserving soil moisture in bioretention cells.
4. Of the three types of mulches examined, arborist chips had the greatest ability to maintain soil moisture. However, the arborist chips were the only mulch replenished during the study. Replenishment occurred at the midway point of the study – after 1 year.
5. A cumulative probability distributions of average soil moisture over the study shows the clear separation between cells with arborist chips and control cells. For example, in Figure 26 below, at the influent location (Panel A), arborist cells are below 30% soil moisture 35% of the time, while control cells are below 30% soil moisture almost 90% of the time. At the effluent location (Panel B), arborist cells are below 30% soil

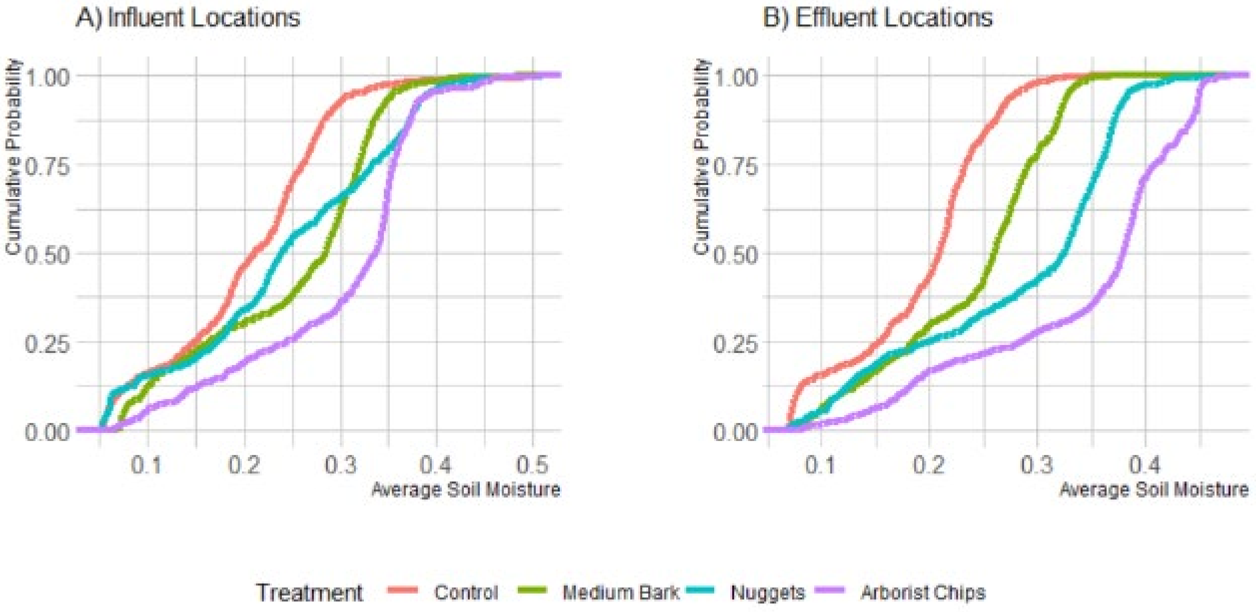

Figure 28: Cumulative Probability distributions of average soil moisture at the influent (A) and effluent (B) positions

moisture 25% of the time, while control cells are below 30% soil moisture almost 97% of the time.

6. While all bioretention cells exported Nitrite-Nitrate (N-N) and Total Phosphorus, the N-N concentrations in bioretention effluent were significantly lower in the presence of mulch compared to the no-mulch controls.
7. Mulch is a critical component in reducing the weeding effort. Our data show a doubling of weeding time needed when no mulch was used.
8. All three mulches suppressed weed growth, and though not significant, nugget bark performed marginally better than medium bark and arborist chips.
9. We recommend using ninebark sparingly in western Washington bioretention cells and rain gardens because of their ability to put out basal runners and take over the system, therefore requiring more maintenance effort. Of the 112 ninebark planted, approximately 99 of them had a spread of greater than 4 feet before we pruned them back.
10. Sun/shade plays a significant role in plant stress/survival in bioretention cells. Plants growing in bioretention cells closest to shade had the lowest cumulative vigor ratings (most healthy) compared to plants without shade (see Figure 29).
11. Be cognizant of the sources of weeds in a bioretention cell. We believe that principal sources of weeds are from plants growing in the vicinity of the bioretention cells, from the plants being planted in the cells, and possibly some weeds being transported with the mulch.
    a. The dominant weed in our cells was *Cardamine hirsuta* (shotweed).
    b. The next two species of weeds in terms of abundance were Douglas spirea and black cottonwood. Those weeds most likely came from plants near our study site.
    c. Based on observational information, we suspect some weed seeds came in on plants planted in the cells, even though they were planted as bare-roots.

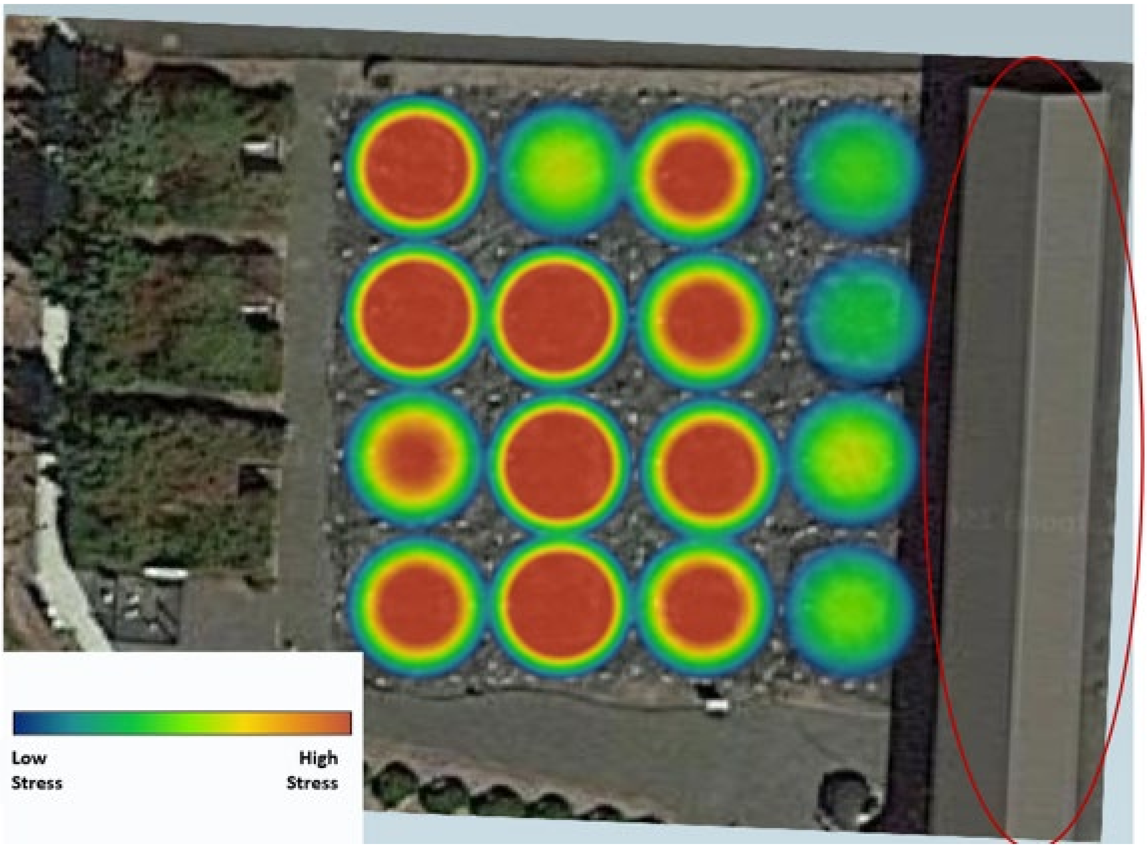

Figure 29: Cumulative vigor ratings over the 20 months showed that bioretention cells closest to shade (carport in red oval) experienced the least overall stress

5. References

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6. Appendices

Please see data repository files associated with this project for all the data that were used to produce this report.