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Green Streets Plant Coverage and Health Study

Slough 104B Project, 2020-2022

Monitoring Program

- Assessed the influence of three design variables on plant coverage and health in 53 green streets facilities. Compared coverage and health in lined vs. unlined systems and evaluated effects of two underdrain configurations and two soil blends for their potential to improve outcomes for plants.
- Assessed plants during the transition to the long-term maintenance program, when green streets are not irrigated during the summer.
- Obtained continuous soil moisture data in a small group of lined facilities to document differences by underdrain type and soil type, supplementing visual observations about plant coverage and health.

Overall Findings

- In lined facilities of all types, plant coverage decreased significantly during summer 2021. For the surviving plants, particularly in systems with the standard soil blend, there was a significant reduction in plant health. No difference was observed by underdrain type.
- In unlined systems of all types, there were minimal changes in plant metrics during the study.
- Soil moisture results were generally consistent with plant observations in lined systems. Moisture at field capacity was significantly higher in facilities with the trial blend compared with facilities with the standard soil blend. Comparison of results by underdrain was inconclusive.
- The monitoring period covered two exceptionally harsh summers, with record-breaking heat in both cases.

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Introduction

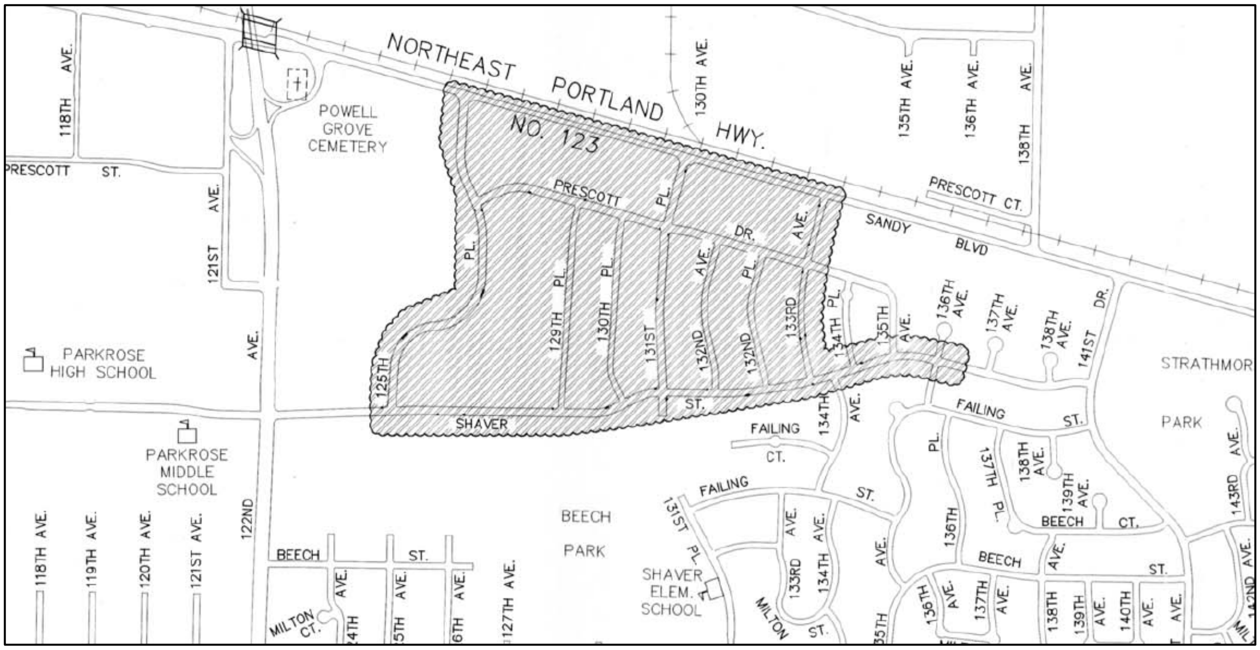
Plant health, plant mortality, and costs for replanting and maintaining green streets facilities are a primary concern for BES as it manages a portfolio of more than 2,500 facilities. Lined green streets are a particular focus given the fact that plant roots don't have access to the underlying native soil and the O&M group[1] managing Portland's green streets facilities has reported higher levels of plant mortality in lined systems. About 10% of Portland green streets are fully lined. More extreme summer conditions, along with predictions about climate change, have added to the need to understand the effectiveness of design changes with potential to improve plant health and survival during extended dry periods.

The Slough 104B project, constructed by BES in 2018, has provided a unique opportunity to compare outcomes for plants based on different design characteristics. BES constructed the 53 green streets

[1] Green Stormwater Infrastructure (GSI) O&M group

facilities to treat runoff and reduce sediment loads draining to the Columbia Slough. This report summarizes results from BES assessments of plant cover and health over time. It also includes supporting information about trends in soil moisture in a small subset of lined facilities. Water quality results and drawdown test results for the Slough 104B project are reported in separate reports.

Figure 1. Map of the Slough 104B project area



The summers of 2021 and 2022 were both extreme. Summer 2021 was the second hottest summer on record in Portland, with a heat dome over three successive days in June that broke records for daily high temperatures. It was fairly common in Portland to see scorching of the tips of south-facing vegetation as a result of the heat dome. A UCLA study of the heat dome event concluded the 2021 heat dome was a very rare event even in the context of assumptions about climate change (McKinnon & Simpson, 2022). Precipitation totaled just 0.12 inches between mid-June and mid-September at the Parkrose rain gage. Summer 2022 also was extreme: Portland recorded the hottest months of July and August on record (link), and tied its record for 100-degree days with a total of five. There was 0.58 inches of precipitation between late June and late October.

Experimental Design/Methods

General Facility Characteristics

- All of the facilities are biofilters (bioretention facilities with underdrains).
- The facilities are sized for treatment, with an average sizing ratio of approximately 1.5%.
- About half the facilities are fully lined.
- About half the facilities have a planted area of less than 100 ft^2; the largest is about 300 ft^2.
- The impervious areas draining to individual facilities range from 1,800 ft^2 to 23,000 ft^2.
- Facilities on Shaver Ave., most of which are fully lined, have somewhat higher solar exposure than most of the rest of the facilities.

Design Variables

The plans for the Slough 104B green streets facilities incorporated a randomized experimental design with four treatments within lined and unlined facility types, providing comparison of results in statistical treatments combining three different design characteristics. The design variables include whether or not the facility is fully lined, two underdrain configurations, and two soil blends. Table 1 and the following section summarize information about the three design features.

Table 1. Facility design variables

Design Feature	Version A	Version B
Liner	Fully lined – no infiltration	Unlined - infiltration
Soil Type	2010 standard blend (2010 City standard specifications)	Trial "High-fines" blend (Basis for 2023 special specification[2])
Underdrain Type	2016 standard underdrain w/ 18" soil (2016 SWMM specification)	2020 standard underdrain w/ 24" of soil (2020 SWMM specification)

Liner: Lined vs. Unlined

Facilities along higher-traffic streets, about half the total, are fully lined in compliance with the requirements for spill protection in the Columbia Slough wellhead protection area. The rest of the facilities are infiltration facilities, some of which have vertical curtain liners along the outer walls to shield utilities in the street from infiltrating runoff.

Underdrain: Full Underdrain vs. Short Underdrain

- Roughly half the facilities have a full underdrain system, per the requirements of the 2016 SWMM, with an underdrain system stretching the full length and breadth of the facility. The cross section has 18 inches of imported soil sitting on 3-4 inches of fine aggregate (filter layer), underlain by 12 inches of drain rock. The underdrain pipe runs almost the full length of the facility.
- About half the facilities have a short underdrain configuration that currently is standard in green streets facilities (2020 SWMM). The slotted underdrain pipe, surrounded by fine aggregate, extends about a quarter of the length of the facility. The soil depth is 12 inches above the underdrain assembly and 24 inches across the rest of the facility.

Soil Blend: Trial ("High-fines") Soil vs. Standard Soil

- About half the facilities have a trial soil blend containing substantially more silt and clay than the standard soil blend to improve water-holding capacity for plant health. The blend contains approximately 30% topsoil by volume and has a fines content of 15-20%. A detailed description of the blend is provided in a separate report (insert reference).
- The other half of the facilities contain a soil blend meeting BES' 2010 standard specification for vegetated facilities. The blend is sandier than the trial blend, with a range of 5-15% for the fines

[2] The new specification is for facilities with underdrains or rock galleries. The standard soil blend will continue to be installed in infiltration facilities at a depth of 12 inches.

content. In some cases vendors have been able to meet this standard by mixing sand and compost without the addition of topsoil.

Design Treatments

There are 8 facility configurations denoted by a 3-letter code for the configuration in the plan set (Table 2 & 3). Each configuration is represented by 5-8 facilities.

Table 2. Treatments for lined facilities

Configuration Code	"HSL"	"HWL"	"SSL"	"SWL"
Soil Type	Trial	Trial	Standard	Standard
Underdrain Type	Full (18" soil)	Short (24" soil)	Full (18" soil)	Short (24" soil)
Lined vs. Unlined	Lined	Lined	Lined	Lined
# of Facilities	7	7	8	7

Table 3. Treatments for unlined facilities

Configuration Code	"HSU"	"HWU"	"SSU"	"SWU"
Soil Type	Trial	Trial	Standard	Standard
Underdrain Type	Full (18" soil)	Short (24" soil)	Full (18" soil)	Short (24" soil)
Lined vs. Unlined	Unlined	Unlined	Unlined	Unlined
# of Facilities	6	5	6	7

Assessment of Plant Health and Coverage

All 53 facilities received individual assessments during each site visit. The same assessment team conducted all of the assessments. The team was comprised of two people from the CRM group and one person from the GSI O&M group[3]. The assessment team applied the standard GSI O&M protocol for visual assessments of plant cover and plant health. The protocol uses a 5-level rating system to characterize plant health and coverage in vegetated stormwater facilities (Tables 5 and 6). GSI O&M has used the system for a number of years for managing green street maintenance work and reporting on the condition of green streets as part of BES' asset management system (BES, 2023).

Plant cover is assessed as the percentage of the planted surface area covered with desirable plants at the density prescribed in the planting plan[4]. The focus is on the percentage of the facility planted per the planting plan, rather than total vegetation cover, to avoid the potentially confounding influence of seasonal differences in foliage (biomass). For plant health, the rating is for the vigor of the surviving desirable plants in the facility. The rating doesn't take into account undesirable plants (e.g., weeds or volunteers) or how much of the ground surface in the facility is covered by desirable vegetation. A facility which has lost 50% of its cover due to plant mortality can nonetheless receive a high rating for plant health.

[3] Green Stormwater Infrastructure Operations and Maintenance team.

[4] For rushes and sedges, which spread and fill in the spaces between the original plants over time, the assessments of cover gradually shift to estimating total area covered rather than the number of plants.

As discussed in the section on data analysis, in both cases the plant assessment data is categorical rather than numeric. Note that for plant cover the ranges aren't consistent (e.g., the range in plant cover represented by a "2" is different than for a "4"). For plant health, the ratings are estimates of vigor and for consistency it was important the same team of individuals completed the assessments.

Table 4. Rating system for plant cover

Rating	Percent Cover										
	0	10	20	30	40	50	60	70	80	90	100
1										■	
2									■	■	
3						■	■	■			
4				■	■	■					
5	■	■	■								

Table 5. Rating system for plant health

Rating	Health (Vigor)
1	Excellent vigor
2	Average vigor
3	Fair vigor
4	Poor vigor
5	Dead or nearly dead

Assessment of Plant Biomass Browning

The original monitoring workplan didn't include assessments of browning, but the quick progression of browning in lined facilities during summer 2021 was a clear indicator of moisture stress and prompted additional site visits. Staff first noticed browning in July in a group of lined facilities along Shaver Avenue and returned to assess browning in all 53 facilities in late August and again in late September. Plant mortality rates were confirmed the following April during the regular assessment of plant health and coverage; it was clear at that point in time which plants had survived as surviving plants sprouted.

Staff estimated the level of browning as a percentage of the total visible biomass in each facility. Plants weren't individually assessed and no distinction was made about the spatial distribution of browning within each facility or within the plant structure (e.g. browning concentrated in plant tips).

Assessment of Soil Moisture

BES collected continuous soil moisture data in a small group of lined facilities to support visual observations about plant health and coverage. It is a working hypothesis that seasonal moisture stress is the largest single factor contributing to poor plant health and mortality in fully-lined green street facilities. Plants in fully-lined systems don't have access to moisture (or nutrients) in native soils and rely solely on the moisture stored in the imported soil blend. The monitoring was an opportunity to understand how quickly wilting-point conditions develop during dry periods, and to assess differences in results by underdrain type and by soil type.

Staff monitored soil moisture in two phases between Fall 2020 and Winter 2022. In both phases, staff equipped six lined green street facilities with continuous soil moisture data loggers to compare soil moisture averages between three facilities with one design variable and three facilities with the alternative design variable. There were three Stevens soil moisture sensors[5] in each facility, one near the middle and at each end of the facility. The sensors were positioned 7-8 inches below grade, collecting data from the root zone. The loggers recorded data at 15-minute intervals. The two phases are described below.

- Phase 1. Comparison by underdrain type, fall 2020 to winter 2021. Data was collected from three lined facilities with the standard underdrain and three lined facilities with the short underdrain system while holding the soil type constant – all six facilities had the trial soil blend.

- Phase 2. Comparison by soil type, spring 2022 to winter 2022. Data was collected from three facilities with the standard soil and three facilities with the trial soil blend while holding the underdrain type constant – all six facilities had the short underdrain.

Detailed descriptions and results for BES' analysis of the Phase 1 and Phase 2 soil moisture data are documented in separate reports (reference).

Monitoring Schedule

Table 4 shows the schedule of monitoring activities. Staff completed standard plant health assessments every 3-6 months over roughly two years during the study. In August and September 2021 there were additional site visits to document progressive browning during the extreme conditions that summer. Soil moisture monitoring occurred in two phases beginning with Phase I in the second half of 2020. Table 6 includes irrigation to show the transition from summer irrigation (summer of 2020) to summers without irrigation (2021). In 2022 the 6 facilities with soil moisture sensors were but back on a regular watering regime to obtain data for more drying periods).

Table 6. Schedule of monitoring activities

	2020				2021				2022			
Monitoring Activity	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**
Plant C&H	X	X	X	X	X	X	X		X		X	
Plant Browning						X	X					
Soil Moisture			UD	UD	UD	UD	UD	UD	S	S	S	S
Irrigation	53 facilities				None				6 Facilities w/moisture sensors			

"UD" = Comparing soil moisture results by underdrain type.
"S" = Comparing soil moisture by soil type.

Results and Analysis

Plant Coverage and Health

BES staff completed the data analysis. The ratings for plant coverage and health were treated as non-numeric values (categories). Log-linear (Poisson regression) models were applied to identify interactions

[5] Stevens Water Monitoring Systems Inc. HydraProbe Soil moisture sensors, purchased in 2019.

between different factors influencing plant metrics. The graphs allow for visual observations about the distribution of the data (e.g., changes in plant coverage over time).

Analysis was performed to evaluate the effects on plant heath over time of the underdrain system, the soil blend, and whether the facility is lined or unlined. The statistical analysis comparing the influence of the two underdrain systems was inconclusive: underdrain type did not significantly affect plant health or coverage in any of the facilities. Results by underdrain type therefore aren't included in Table 7 or the graphical distributions for plant health and cover (Figures 2-5). Also note that plant health results for the six facilities irrigated in 2022 were removed from the plant health analysis since the results would have skewed the data.

For plant cover in lined facilities, the statistical analysis showed a significant relationship between liner, plant cover, and time for the data from 2021 (Table 7) and soil, liner, and plant cover in 2022 (Table 7). Generally, facilities without a liner and with the trial soil blend had better plant cover. These statistical results are similar to those for plant health with the exception that in 2022 soil type had a significant influence on plant coverage when combined with liner type, with facilities with a liner and the standard blend having the worst outcomes for plant coverage. The graphical distributions for plant cover in lined facilities in 2021 showed a significant negative trend with more than half of the lined facilities in both categories receiving ratings of "4" or "5". In contrast with trends for plant health, ratings for plant cover in lined facilities improved only marginally, if at all, in 2022. In September 2022 more than two thirds of lined facilities with the standard blend had ratings of "4" or "5" for plant cover; the distribution of ratings was somewhat better for lined facilities with the trial soil blend.

For plant cover in unlined facilities, Figures 4 and 5 don't provide any discernable evidence of trends by soil type or by year. A consistently high percentage of facilities with average or excellent plant health ratings of "1" and "2" with sporadic, single instances of ratings of "4" or "5".

For plant health in lined facilities, the statistical analysis shows a significant relationship between liner, plant health, and time for the data in 2021 and between liner and plant health for the data in 2022 (Table 7). Generally, facilities with liners have much worse outcomes for plant health than those without. Comparing the graphical distributions of plant health data in all lined facilities between June and September 2021 (Figure 2) shows a dramatic change in plant health. In June no lined facilities had plant health ratings of "4" or "5" and by September a large percentage of lined facilities had ratings of "4"or "5". The apparent shift was more pronounced for lined facilities with the standard soil blend: by September 2021 all of the facilities with the standard soil blend had ratings of "4" or "5" while among facilities with the trial soil blend a few facilities had ratings higher than "4" or "5". In April 2022, when staff could confirm which plants had survived based on new growth, the distributions for lined facilities in both categories had improved somewhat since September 2021. The improvement in the distribution of ratings for facilities with the trial soil blend were greater than for facilities with the standard blend; in April 2022 more than half the group with the standard soil blend still had ratings of "4" or "5" while the ratings had improved for the those with the trial blend. The distribution of ratings improved slightly for both categories between April and September 2022.

For plant health in unlined facilities, Figures 2 and 3 show a slight negative shift in the distribution of ratings during the summer of 2021. Just one unlined facility had a rating of "4" or "5" in September 2021. In 2022 there was a modest improvement in the distributions, with more than a third of the unlined facilities receiving a rating of “1” for plant health in September 2022. There was no discernable difference in the distributions by soil type.

Table 7. Results of statistical analysis using log-linear models

Type	Year	Interaction	p-value
Plant Cover	2021	Liner:Cover:Time	1.77E-05
Plant Cover	2022	Liner:Cover:Soil	6.95E-03
Plant Health	2021	Liner:Health:Time	7.08E-06
Plant Health	2022	Liner:Health	2.31E-08

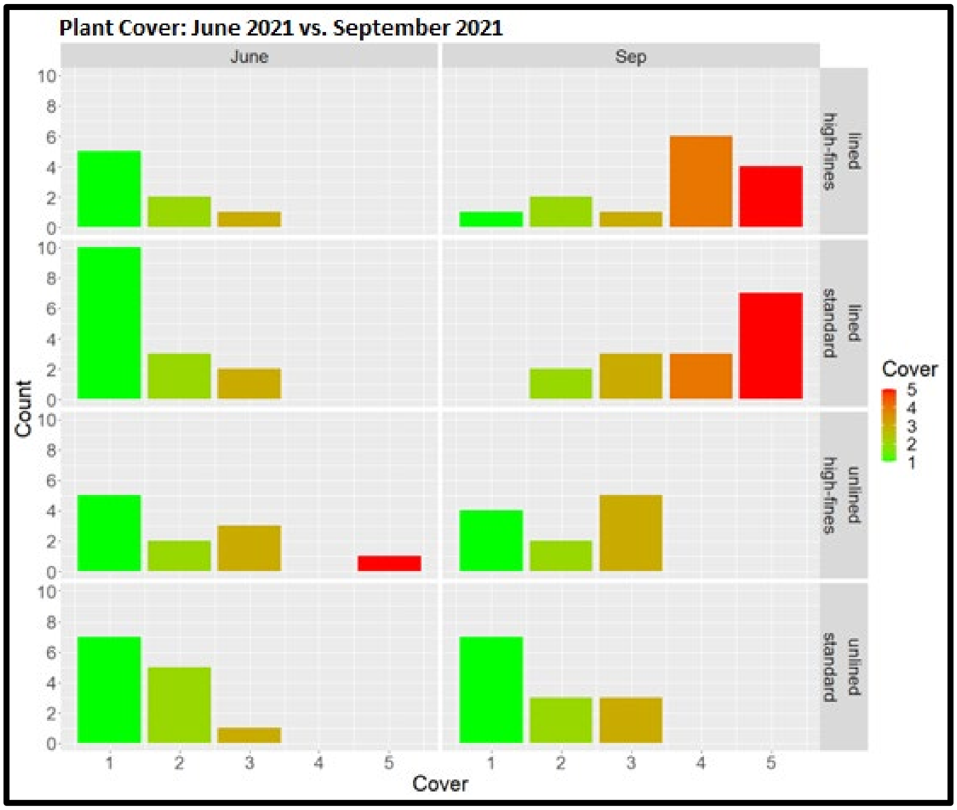


Figure 2. Distribution of plant cover scores between facilities with different soil types and liner types over two sampling periods in 2021.

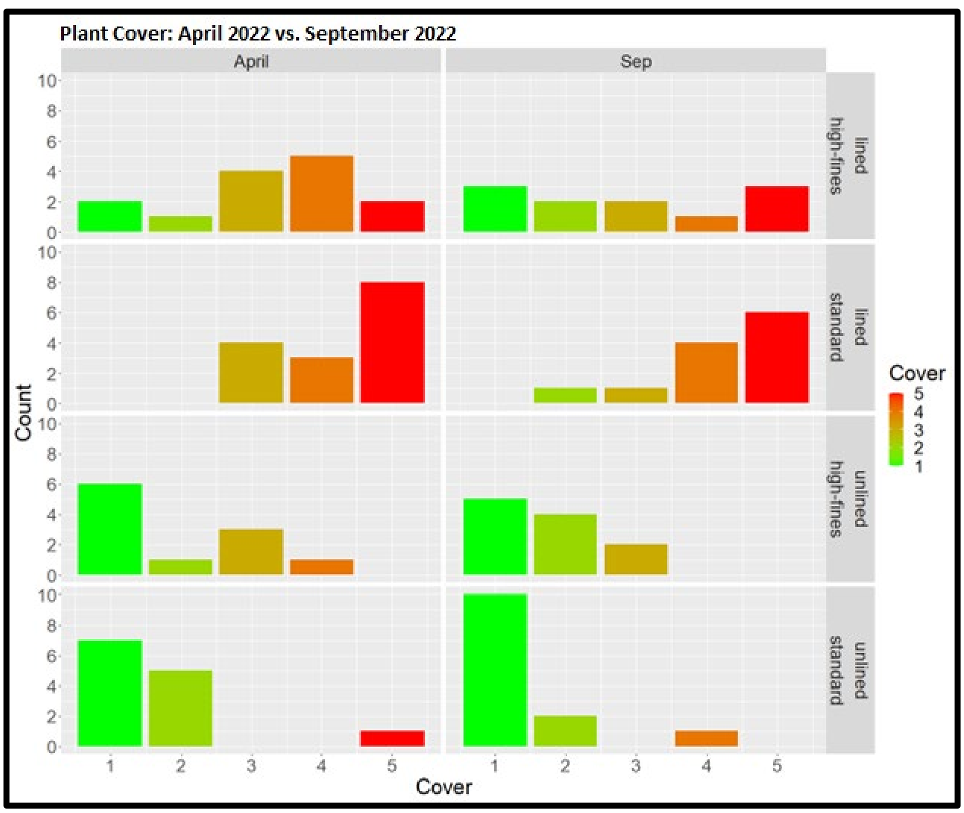


Figure 3. Distribution of plant cover scores between facilities with different soil types and liner types over two sampling periods in 2022.

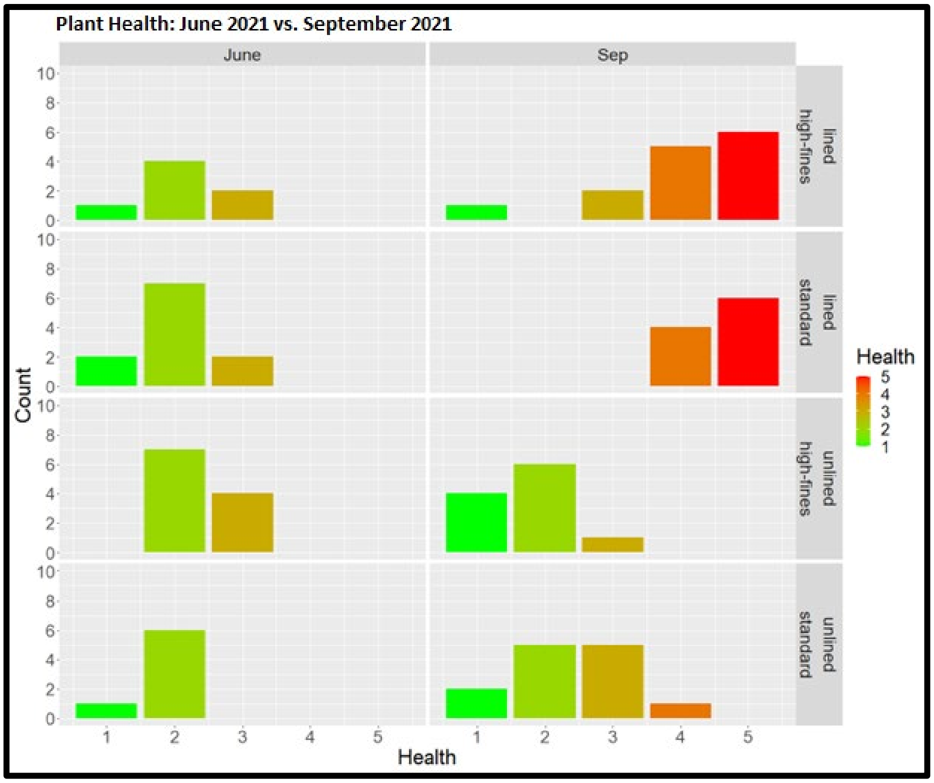


Figure 4.
Distribution of plant health scores between facilities with different soil types and liner types over two sampling periods in 2021.

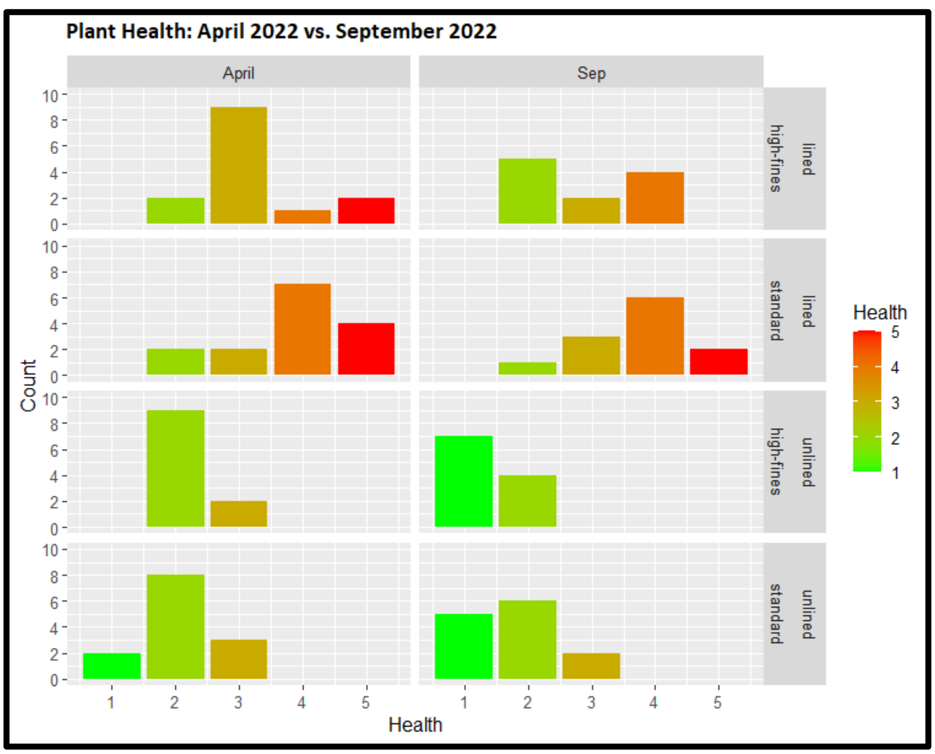


Figure 5.
Distribution of plant health scores between facilities with different soil types and liner types over two sampling periods in 2022.

Browning Observations

Figures 6 and 7 show the distribution of browning results for late August 2021 and a month later in September 2021. In late August more than half the lined facilities had browning percentages greater than 50% and almost all of the facilities with browning percentages under 50% contained the trial soil blend. Browning was reported in just one unlined facility. These observations are supported by the results from the one-way ANOVA test used for the statistical analysis: the analysis indicates a significant difference in percent browning between lined and unlined facilities, with a p-value of 4.37×10^{-15}.

The distribution of results for September 2021 shows a very high percentage of the lined systems had browning rates of 75% or more, while browning in unlined facilities increased but generally was well under 50%. The statistical test again confirmed a significant difference in results based on whether or not the system was lined, with a p-value of 1.51×10^{-15}.

These results suggest the trial soil blend helped delay the onset of severe browning in some lined facilities, but that by late September, after 14 weeks without rain, outcomes for plants were similar for all lined facilities – the plants were severely stressed and damaged in almost all of them. In lined facilities with the standard soil blend the visits didn't capture the progression of browning: by late August it was already severe.

These browning observations indicate unlined green streets, even those with full underdrain systems and the standard soil blend, were resistant to browning through August and showed only moderate browning by the end of September.

Figure 6. Plot showing plant browning observations by facility type in August 2021

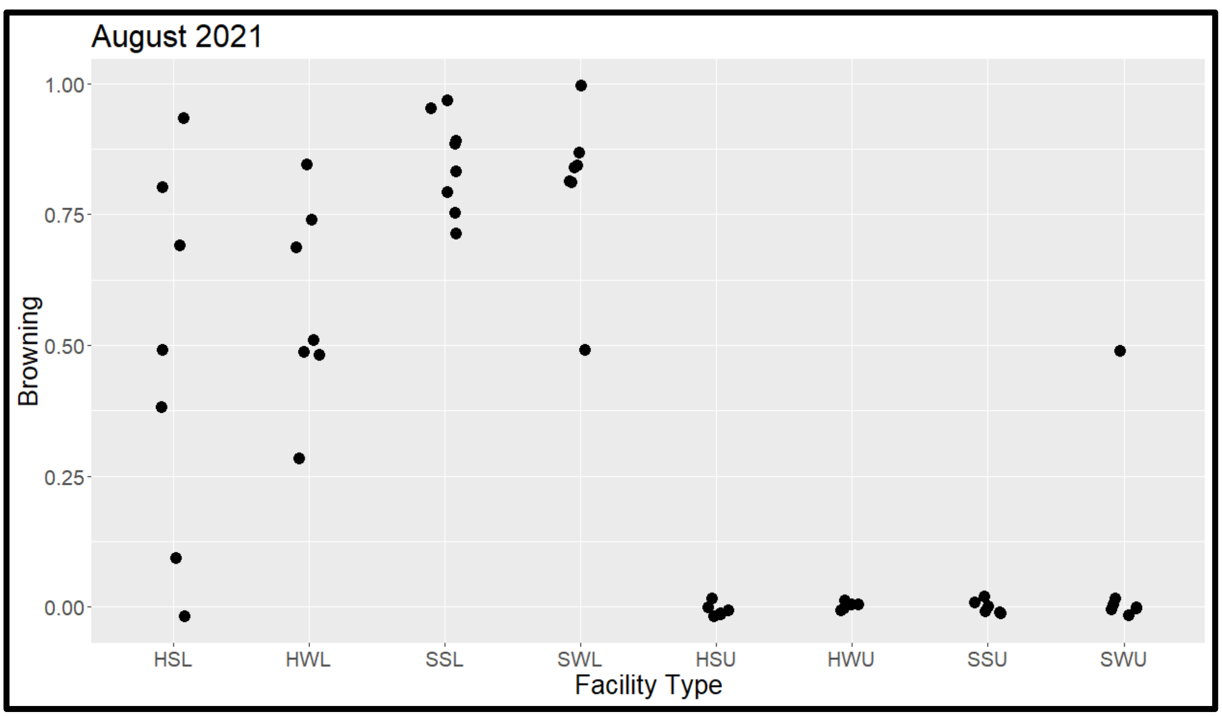
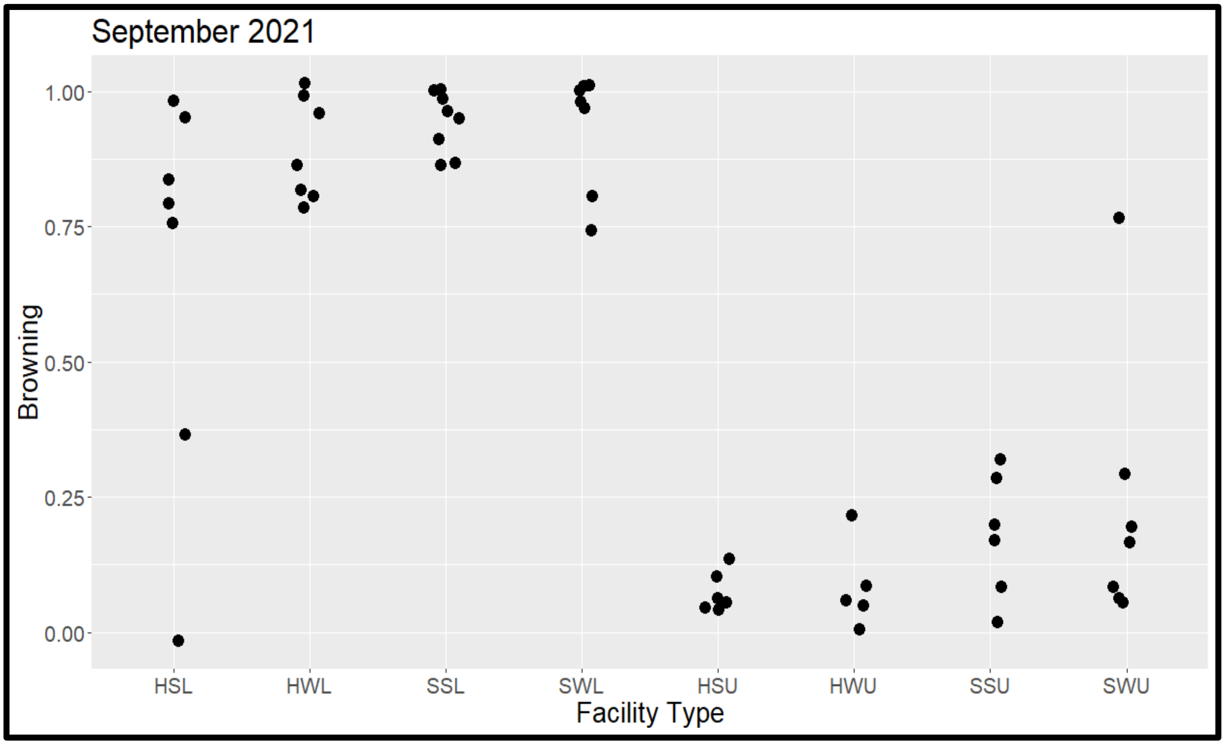


Figure 7. Plot showing plant browning observations by facility type in September 2021



Soil Moisture

Figure 8 is a graph of facility moisture averages for the group of Phase 1 facilities over summer 2021, which was the first summer the facilities weren't irrigated since their construction in 2018. All six of the facilities are lined, contain the trial soil blend and are split evenly by underdrain type (three and three). The moisture content in all six facilities was below 15% by the last week of July and continued to decline slowly until the first rains in mid-September[6]. BES doesn't have plant- and soil-specific reference values for the soil moisture at the onset of wilting point conditions as the soil dries. However, research suggests many plants are stressed at a sustained moisture content of <15% and visual assessments of the plants in this study suggest plants in lined facilities were very stressed by the end of August.

Figure 9 is a graph of Phase 2 facility averages over the summer of 2022, when the study compared results in lined facilities by soil type. All of the facilities had the short underdrain. The six facilities were irrigated on a regular basis, on average every ten days, to obtain data for multiple "events". After observing plant health and soil moisture results for the summer of 2021, the monitoring team concluded it would be much more informative to irrigate the six test facilities rather than continuing with the long-term management program (which doesn't include irrigation). Note the data from one of the facilities with the trial soil blend is missing starting in July due to equipment problems.

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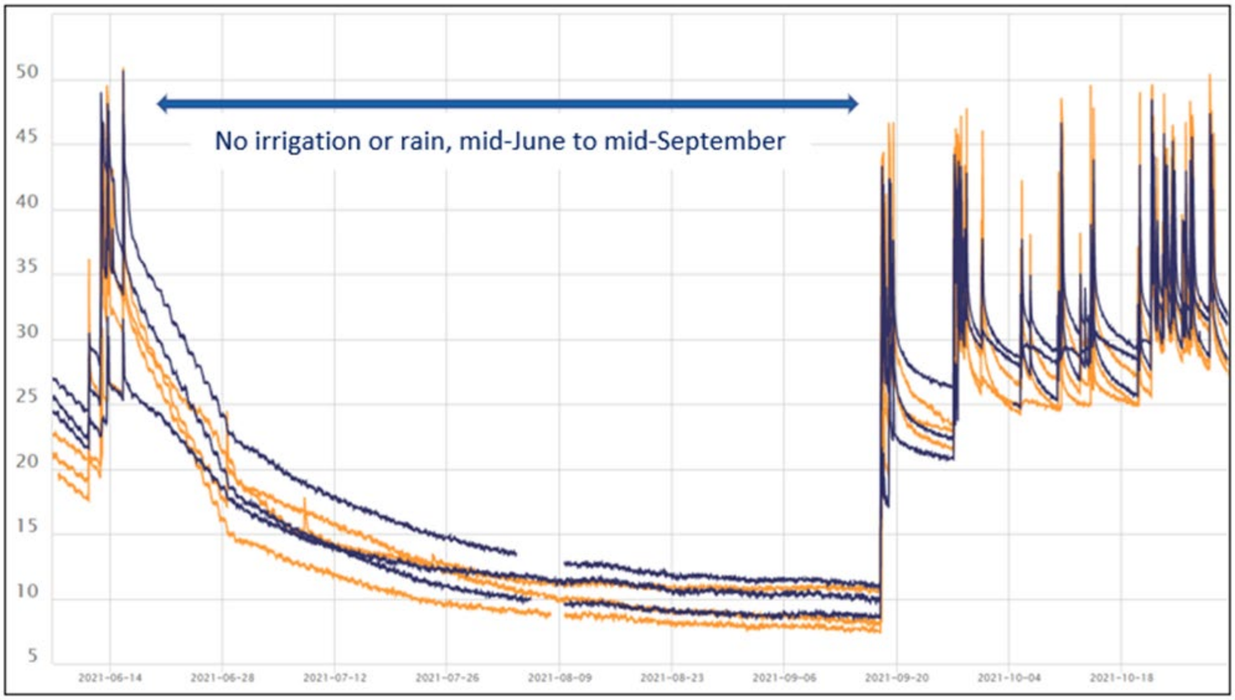
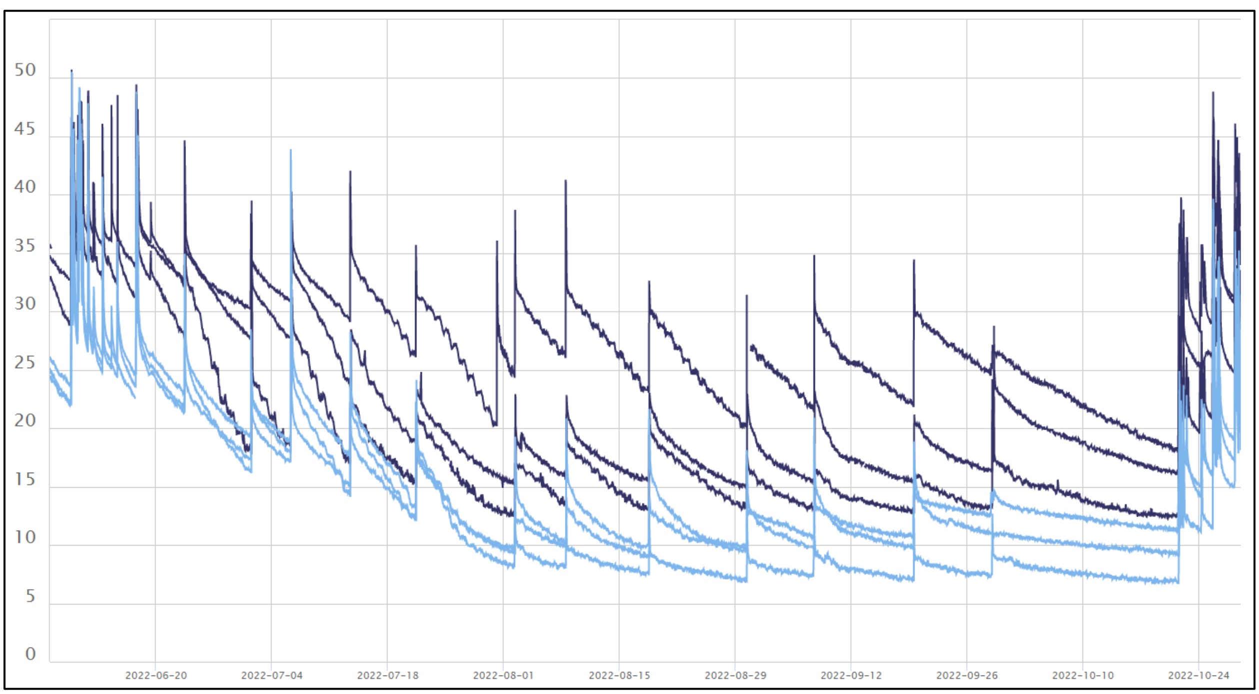
[6] The summer of 2021 was extreme, with temperatures reaching 116F during a heat dome in late June. It was the second-hottest summer on record for Portland.

Figure 8. Summer 2021, comparison of facility soil moisture by underdrain type*



* Orange data = full underdrain; blue = short underdrain. All facilities have trial ("high-fines") soil blend.

Figure 9. Summer 2022, comparison of facility soil moisture by soil type*



*Dark blue data = trial soil blend; light blue data = standard soil blend

Comparing figures 8 and 9, average summer soil moisture for the three facilities with the short underdrain and the trial soil blend, which were monitored in both phases, improved significantly in 2022 when the systems were irrigated. In Figure 9, average moisture in the group of facilities with the standard soil blend is lower than the average for the group containing the trial soil blend during the summer irrigation period. Averages for the facilities with the standard soil blend are consistently below 15% after the beginning of July, even with regular watering; the results suggest irrigation had limited effectiveness hydrating the systems. It's interesting to note the stair-step downward trend in soil moisture levels between waterings early in the summer when moisture levels were higher and presumably the soil absorbed water more easily than later in the summer when moisture levels were much lower. Comparing results from the two summers, it appears irrigation in June was successful at slowing, but not stopping, the decline in moisture levels.

The data for facilities with the trial soil blend shows a similar downward trend during the beginning of the summer, with fairly consistent results later in the summer. Average moisture for the facilities with the trial blend are somewhat higher through the summer compared with moisture levels in the systems with the standard blend. Just one of the three facilities with the trial soil blend has a moisture content which dips under 15% fairly regularly.

There is research documenting the hydrophobic nature of dry soils, particularly sandy soils containing a significant organics. There is evidence that coarse-grained soils containing organics are particularly difficult to hydrate at low moisture levels unless there's a small percentage of clay in the blend. (Hunt and Gilkes, 1992). This could explain the downward trend in moisture holding capacity of both soils throughout the summer and the inability of the standard blend to rehydrate during irrigation events.

The statistical analysis of moisture results incorporated soil moisture averages by facility. Staff identified drying events in the facility average for each data logger, which were defined as the period between field capacity and the next occurrence of saturation. Field capacity was defined as the data point 24 hours after a peak in soil moisture values. Generalized Additive Models[7] (GAM) were applied to the drying events, including an intercept and smooth term for each soil type. The intercept term represented the starting point for each soil type, while the smooth term indicated the drying rate, similar to the slope term in a linear regression.

Results from phase one indicated that facilities with the short underdrain had approximately 1.3% higher soil moisture than facilities with full underdrains at field capacity (Figure 7). Overlapping confidence intervals indicate the difference in soil moisture between underdrain types may not be statistically significant. There was effectively no difference in the drying trend between the two underdrain types.

[7] A Generalized Additive Model is a nonparametric regression model describing the relationship between a response variable and a set of predictor variables. The model is more flexible than a standard linear model and allows the use of a standard ANOVA table.

Figure 10. Predicted soil moisture drying trends with 95% confidence intervals for the full ("standard") and short ("Seattle") underdrain types

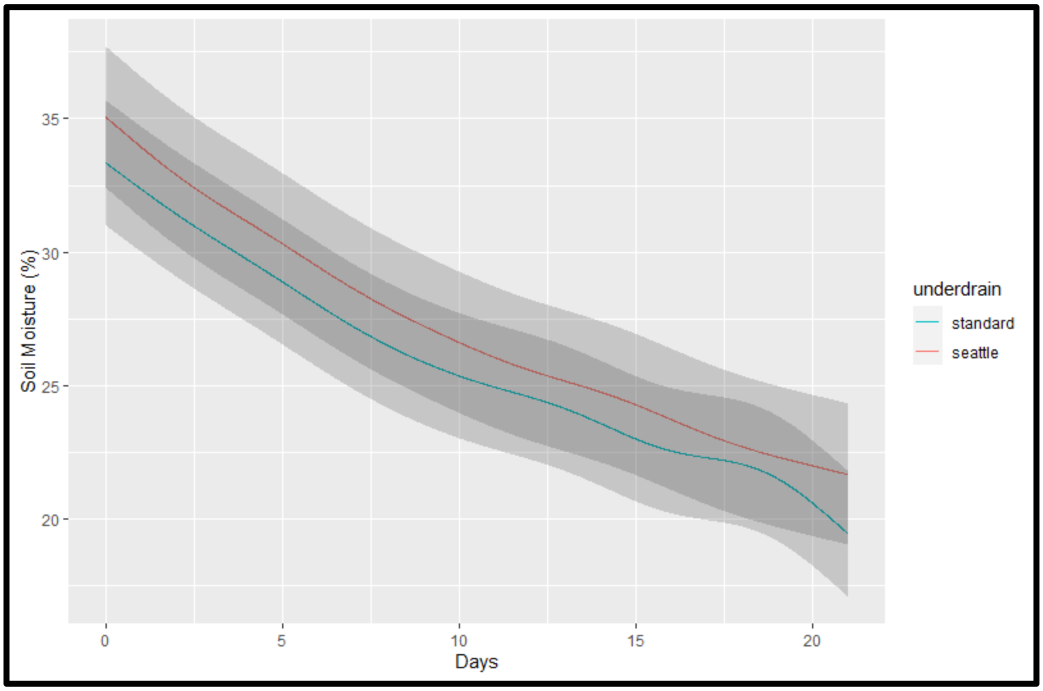
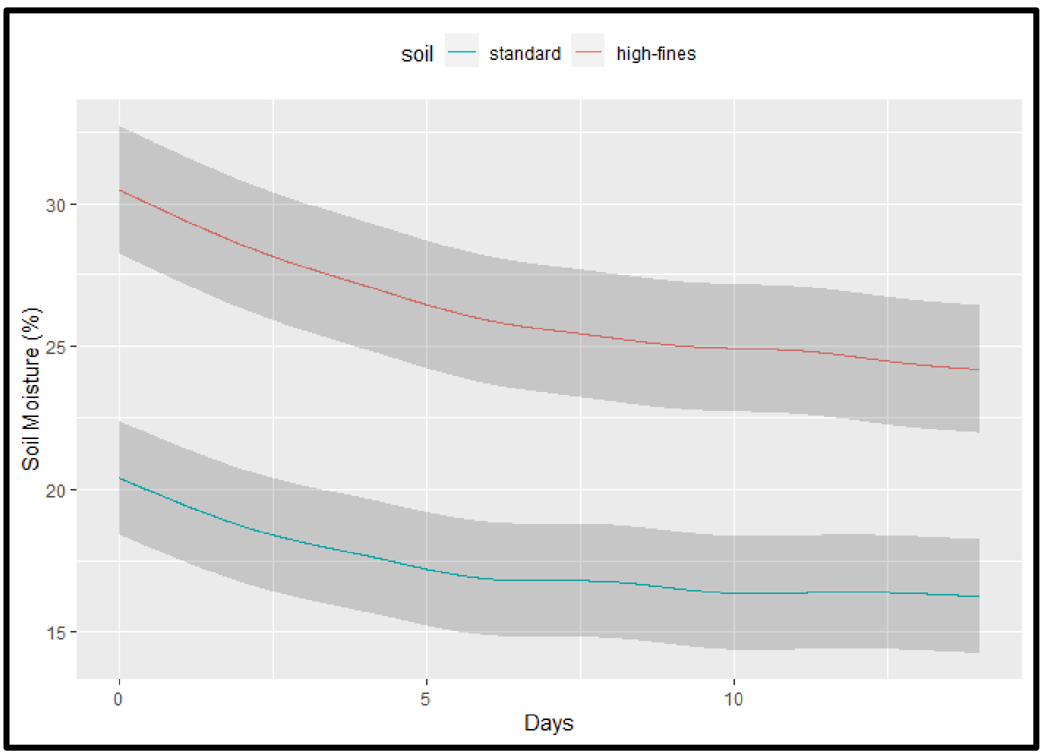


Figure 11. Predicted soil moisture drying curves with 95% confidence intervals for facilities with standard (blue) and high-fines soil (red)



Results from phase two indicated that facilities with the high-fines soil had approximately 9.5% higher soil moisture than facilities with standard soil at field capacity (Figure 8). An ANOVA test was performed on the two soil types and showed that the high-fines soil type is significantly different ($p < 0.001$) than the standard soil type for both the intercept and smooth terms. There were differences in the slope of the two drying curves, with the high-fines curve being slightly steeper. Given the substantially higher soil moisture at field capacity for the high-fines soil blend, it makes sense moisture losses to evapotranspiration and the relative drying rate would be faster for that blend. It's important to note that even with the faster drying rate the high-fines blend had a higher moisture content at the end of the drying period than the moisture content for the standard blend at the beginning of the drying period. The effect of this large difference in soil moisture likely means the slightly steeper drying curve for the high-fines blend is inconsequential when comparing results for plant health.

Conclusions

The Slough 104B project provided a unique opportunity to assess changes in plant coverage and health influenced by combinations of three different design characteristics. The large number of facilities allowed for a relatively robust experimental design with four treatments each for lined and unlined facilities. The facilities were constructed at roughly the same time, as part of the same project, providing consistency as far as construction practices and materials. All of the facilities were part of the same irrigation program during their first two summers (2019 and 2020) and just prior to their first summer without irrigation in 2021 plant health and coverage were consistently high in all of the treatments.

The primary finding of this study was that during the summer of 2021, a summer with historic temperature extremes and the first summer without irrigation for the facilities, all categories of lined facilities had significant plant mortality and reductions in health among the surviving plants. The trial soil blend produced a statistically-significant improvement in outcomes for plants in lined facilities, and the analysis of soil moisture data in 2022 confirms substantially higher water retention at field capacity in systems with the trial soil blend compared with systems containing the standard blend. While lined facilities with the trial soil blend browned more slowly during summer 2021, and overall outcomes for plants were better in those systems, soil moisture data shows the plants in systems with the trial blend were subject to wilting-point conditions for about six weeks that summer. For lined systems, the duration of the extreme conditions was clearly outside the range of resilience for plants for all categories, which makes sense in terms of how much water lined systems can store before such an extended dry period with extreme temperatures.

Plant health improved somewhat in lined systems of all types in 2022, with slightly more improvement among systems with the trial soil blend than for those with the standard soil blend. In contrast, there was no discernable improvement in the distribution of ratings for plant cover over time. In September 2022 the plant cover ratings for more than two thirds of the lined facilities were "4" or "5", with somewhat better outcomes for lined facilities with the trial soil blend.

Results for unlined systems indicate they were much more resilient in the extreme conditions of both summers. For plant cover, there was no discernable trend overall or by soil or underdrain type. There was a relatively minor reduction in plant health in 2021 in all unlined systems and a very slight improvement in 2022. There was no difference in results for unlined systems based on underdrain or soil type. Comparing these results with those for lined systems, it appears root access to the native soil is the most important factor determining outcomes for plants during extended extreme summer conditions. The results also suggest plant roots are able to access the native soil in systems with large underdrain systems where the imported soil blend sits on 12" of aggregate.

Moisture results during irrigation in summer 2022 provide information about the effectiveness of the irrigation program during a second summer of extreme hot temperatures. Irrigation clearly increased average soil moisture in facilities with the trial soil blend compared with results from summer 2021 when the same facilities weren't irrigated. But the data indicates the irrigation program wasn't effective enough to keep soil moisture in all three facilities above the reference wilting point moisture level (15%) all of the time. For the three facilities containing the standard soil blend, average moisture was less than 15% most of the time over approximately two months. These results may reflect hydrophobicity in summer conditions, and perhaps bypass along gaps between the dried soils and the walls, more than an inadequacy of the irrigation effort. As shown in Figure 9, multiple fall rain events are sometimes required to raise soil moisture levels significantly from their summer lows.

It's hard to gage the representativeness of the results given the extreme conditions of summer 2021 and 2022, but the study provides a valuable snapshot of the vulnerability of lined systems in extreme summer conditions. Consistent with previous observations concerning plant health for lined systems, the few Slough 104B facilities with significant shade had much better ratings for coverage and plant health. Future studies should research methods for quantifying solar exposure/shade as a factor influencing outcomes for plants. In addition, it would be valuable to compare results by plant type. For instance, juncus and carex species both had significant browning during the summer of 2021 but juncus appeared to have a much better survival rate.

Outcomes and Design Changes

BES has made several changes to standard green street designs during the last few years as a result of designing, implementing, and monitoring the Slough 104B project. The shortened underdrain was made standard for all new green streets in the 2020 SWMM. Although there wasn't a demonstrable impact on plant health in the subject study of Slough 104B results, the shortened underdrain configuration is advantageous because it's simpler to construct and the increased total volume of imported soil should improve overall water holding capacity, especially in lined facilities. There have been two associated changes to soil standards for vegetated facilities. In 2019 BES updated the specification for the standard soil blend to improve the accuracy and consistency of particle gradation tests, particularly in the measurement of the proportion of fines in the mix. The second change is the addition in 2023 of a second soil blend for facilities with underdrains and rock galleries. The blend is based on the Slough 104B trial blend, contains more silt and clay than the standard blend, and should provide adequate infiltration along with better outcomes for plants (based on the results from the Slough 10B study).

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