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Effects of Rock Covering on Underlying Engineered Media in Bioretention Practices in Middle Tennessee, USA

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Abstract: Bioretention practices have become a common way to protect natural waterways in urban and suburban landscapes across the United States. However, optimal design, implementation, operation, and maintenance are still in need of study. A field survey of 52 bioretention practices was conducted in Davidson County, Tennessee, to address research questions related to operation and maintenance. A suite of site conditions were documented, such as size, signs of erosion, and dominant surface cover. Samples were collected from the surface of the engineered media layer and analyzed for organic matter content and bulk density. Vegetation was described in terms of dominant species and canopy cover. On average, the organic matter content of media under plant-based mulch cover was significantly greater than that under rock cover ($p = 0.002$). Bulk density of the surface media is strongly and inversely correlated to organic matter content; bulk density did not generally vary with bioretention area age and was highly variable within treatments. On average, the bulk density of the media under the plant-based mulch cover was significantly less than that under the rock cover. Media under the composite treatments had similar bulk density to both the plant-based mulch ($p = 0.233$) and the rock covers ($p = 0.132$). Plant canopy did not surpass 70% in practices with bulk density values above 1.55 g/cm^3. These results suggest that consideration should be made regarding the tradeoffs between utilizing rock coverings and potential for plant establishment impacts.

Keywords: *bioretention, urban water, runoff, green stormwater infrastructure, engineered media*

Urbanization plays a significant role in the loss and degradation of inland water systems in the United States (O'Driscoll et al. 2010) and across the globe (Millennium Ecosystem Assessment 2005). To combat threats posed to surface waterbodies, bioretention has been widely adopted as a form of green stormwater infrastructure (GSI) to manage the quantity and quality of urban stormwater runoff discharged to streams, creeks, rivers, and wetlands (Davis et al. 2009). Bioretention is a method of stormwater management using native plantings and soil conditioning (Coffman et al. 1994). Performance requirements for bioretention practices are commonly described in terms of capture volume, percolation and/or infiltration rates, and pollutant removal capacity. The design and operation of bioretention practices vary based on location-specific performance requirements. Functional processes at work in bioretention include hydraulic mixing, physical settling and straining, chemical adsorption and transformations, and biological uptake and conversion (Davis et al. 2009). Characteristics affecting these processes include, but are not limited to, size and contributing drainage area (Yang and Chui 2018), underlying soil characteristics (Davis et al. 2012), vegetation establishment (Muerdter et al. 2015; Dagenais et al. 2018), saturation and redox potential (Deitz and Clausen 2006), and local conditions like salting and climate (Soberg et al. 2017).

The integration of ecological, physical, chemical, and biological functions of soil, plants, and microorganisms has long been recognized

Research Implications

- Surface covering material selection in bioretention applications affects underlying media characteristics that are linked with performance.
- Organic matter content was greater under plant-based mulch covering than under rock coverings which may have implications for overall bioretention water quality function.
- Promoting vegetation health by not using rock surface coverings may result in better bioretention function.

as fundamental to bioretention function (Roy-Poirier et al. 2010). There is a growing body of knowledge shedding light on the interactions of engineered media, plants, and microbes in bioretention that impacts the physico-chemical properties of these systems (Skorobogatov et al. 2020). A study by Lucas and Greenway (2008) showed that the presence of vegetation improved nutrient removal as compared to no vegetation in bioretention mesocosms. Vijayaraghaven et al. (2021) used a bibliometric analysis to evaluate the specific role of bioretention components to outline desirable vegetation and media characteristics, and concluded that the performance of bioretention is yet to be fully optimized. There exists a need to better understand the interactions between design components and the potential impact of implementation decisions on bioretention function.

As the application of bioretention-based GSI matures, many design variations and adaptations have been deployed and evaluated at field scale in response to performance needs or operational concerns. Such adaptations include creating an internal water storage layer to enhance denitrification (Dougherty et al. 2007), nesting the practice within the footprint of a retention pond to address water quantity and quality issues and reduce overall infrastructure footprint (Chin 2017), using internal baffles to maximize mixing (Donaghue et al. 2022), using engineered media amendments like biochar and fungi to enhance pollutant removal (Mitchell et al. 2023), managing active storage with sensor-based controls (Persaud et al. 2019), and utilizing a reduced diversity or volunteer plant palette to help with vegetation maintenance while not hindering performance (Dagenais et al. 2018).

The use of a stone or river rock surface covering in place of conventional plant-based mulch is an example of a modification being implemented more commonly in Middle Tennessee and across the country. Metro Water Services Nashville-Davidson County (Metro) operates an Individual National Pollutant Discharge Elimination System (NPDES) permit to manage the separate storm sewer system (MS4) in Davidson County, Tennessee, USA, the county containing the fast-growing Nashville metropolitan area. Metro was an early adopter of green infrastructure technologies in Tennessee. Therefore, many other Tennessee MS4s look to Metro to provide a model based on the relatively long period of observation of practice performance. As the number of bioretention practices in Davidson County grew to over a thousand practices, rock surface covering was the most used surface cover in bioretention practices. The perceived advantages of rock covering over plant-based mulch include less washout during storms, ease of maintenance (less weed pressure), and preference in aesthetic appeal. However, the practice of using rock covering raises questions about the potential for impact to overall function of bioretention cells in terms of infiltrating water, filtering pollutants, and supporting the designed plant community.

In collaboration with municipal professionals at Metro, the research team conducted a field study with a goal to evaluate the impacts of rock surface covering on bioretention function. Bioretention function is the capturing, infiltrating, and filtering of pollutants from urban stormwater runoff, and porous soils and healthy vegetation are critical to these functions. Specific research questions for this study included: 1) Does surface cover affect media bulk density? 2) Does plant-based cover generate more organic matter than rock cover? 3) Does media bulk density affect plant canopy establishment? 4) What plant species are most observed? and 5) What conclusions can be drawn that may inform operation and maintenance activities to address common failures?

Methods

Study Site Selection

Davidson County, Tennessee, USA, lies in the Inner Basin ecoregion in the Cumberland River Basin in North-Central Tennessee. Fifty-two sites, out of the over one thousand practices, were selected in the operating area of Metro Water Services Nashville-Davidson County (Figure 1), capturing geographic variability throughout the service area with different surface covers (rock, organic, composite) and across a range of practice size (from 20 to 1,660 m^2) (Table 1). Practices were installed within the timeframe of 2009 to 2016, in either a commercial or residential land use setting. All practices were subject to the local requirement of using engineered media consisting of 70-85% sand, 10-30% silt plus clay, and 5-10% organic matter (by volume) (Metropolitan 2021).

Design documents were shared by Metro to the project team, describing each practice in terms of size, components, and placement in the larger development/landscape setting. These design documents were used to record pertinent design components, such as ponding depth, vegetation species (if specified), and presence of underdrain.

Field Methods

Each site was visited once during the summer of 2018 during dry weather conditions (not actively raining and no surface ponding). Measured site characteristics included size and dimension of depression, ponding depth, and thickness of mulch layer. Observations were recorded of the

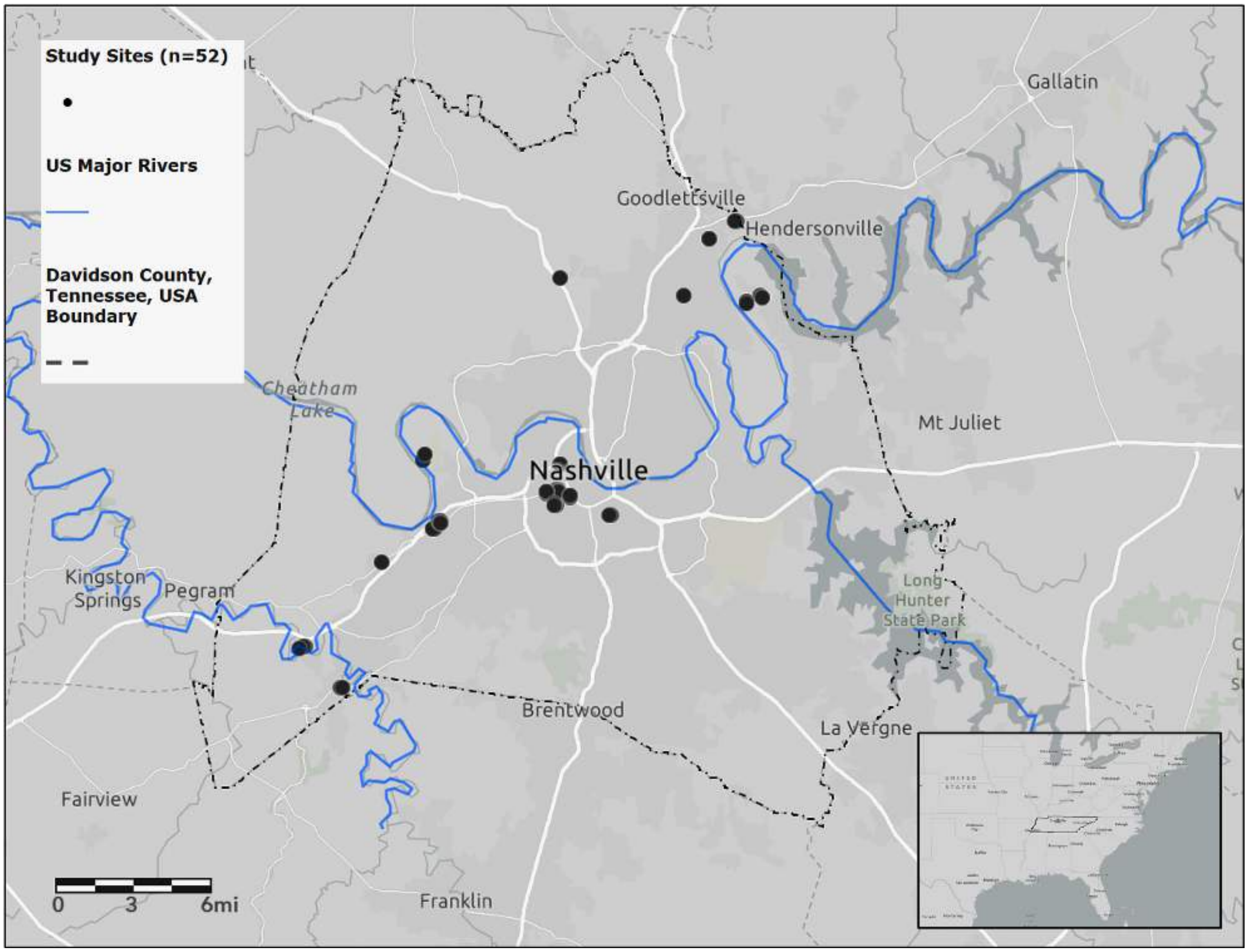

Figure 1. Map of study sites (n = 52) in Davidson County, Tennessee, USA. Note that some sites were co-located as separate bioretention cells at the same general location.

Table 1. Study site information including location, age, and pertinent characteristics.

Site ID	Latitude	Longitude	Sizes (m^2)	Year Built	Surface Cover
DG-1	36.11724	86.92367	367.1	2013	Composite
HC-2,3,4	36.13586	86.88746	89.7, 51.1, 166.9	2013	Composite
MN-1,6	36.15779	86.79991	84.4, 67.7	2010	Composite
SC-2,3	36.15662	86.80822	67.4, 65.6	2014	Composite
VD-1,3	36.14927	86.80086	259.4, 20.8	2014	Composite
AT-1,2,3	36.30008	86.69405	154.6, 62.1, 135.8	2014	Plant-based
BB-1,2	36.17526	86.89431	59.3, 119.4	2013	Plant-based
CB-1	36.17833	86.89227	141.2	2015	Plant-based
FW-1,2,3	36.26817	86.65768	1659.7, 933.4, 416.8	2014	Plant-based
HG-5	36.14013	86.88145	661.7	2009	Plant-based
MC-1,2	36.30956	86.67380	238.6, 665.8	2014	Plant-based
MC-2	36.31052	86.67556	665.8	2014	Plant-based
MN-2,3,4,5	36.15779	86.80014	92.6, 50.5, 46.1, 39.5	2010	Plant-based
MTA-1	36.27754	86.79753	159.4	2012	Plant-based
OH-1,2	36.26435	86.66808	136.8, 182.1	2012	Plant-based
RB-1,2,3	36.06929	86.97597	53.4, 53.1, 46.5	2013	Plant-based
SC-1,4,5	36.15675	86.80824	129.0, 254.7, 78.8	2014	Plant-based
SS-1,2	36.17236	86.79832	6.8, 6.8	2014	Plant-based
TA-1,2	36.14425	86.76282	62.7, 131.5	2016	Plant-based
VD-4	36.15015	86.80161	132.6	2014	Plant-based
AZ-1	36.26775	86.71164	122.9	2011	Rock
BM-1,2,3	36.15428	86.79139	162.0, 245.1, 255.5	2011	Rock
HC-1	36.13602	86.88670	50.4	2013	Rock
HG-1,2,3	36.14008	86.88361	109.4, 155.7, 45.8	2009	Rock
HG-4	36.13953	86.88208	64.1	2009	Rock
VD-2	36.14943	86.80173	201.8	2014	Rock
ZX-1,2	36.04577	86.95139	67.8, 31.6	2014	Rock

presence of fine sediment deposition, signs of erosion, shape of depression, vegetation health and abundance, and the presence of design components (e.g., forebay). Vegetation was documented with photographs of dominant plant species as well as a representative plant canopy cover photograph, using a mobile phone camera. Individual plant photographs were stored in a cloud location, shared with local plant experts (the Davidson County Master Gardeners), identified as accurately as possible, and compared to design documents (if available) for accuracy. Volunteer plants or weeds were not identified. Visual assessment of plant health was recorded. Canopy cover (%) was determined using the Canopeo (Oklahoma State University, Stillwater, OK) mobile application, which quantifies the proportion of an image with green pigment. It should be noted that this method did not allow for differentiation between plant species nor between designed plant community and volunteer vegetation.

Samples of the engineered media (n = 3) were collected for evaluating bulk density and organic matter content. Surface cover was removed to expose the top of the engineered soil layer. A bulk density hammer was used to push a 0.305 m long, 2.45 cm diameter acrylic core into the profile, extracted, and then capped with paraffin and foil. Samples were transported back to the laboratory in Knoxville, Tennessee, for analysis.

Laboratory Methods

Engineered media samples were dried for three days and mass measured to the nearest 0.00 g. Bulk density was determined as the mass of the dried media per volume of the sample (g/cm^3). Dried samples were then analyzed for organic matter content using the loss on ignition method. Samples were ignited at 400 degrees C for two hours, set to cool in a desiccator, and the mass determined. Organic matter content (%) was calculated by taking the difference in the masses of the dried sample and the ignited samples, dividing by the dry sample mass and multiplying by 100.

Statistical Methods

There were 52 independent sites used in the study. Sites were delineated into three categories based on surface cover: rock, plant-based, and composite. To be included in the rock category, at least 75% of the area of the practice needed to be covered in rock. Rock armoring in the inlet and outlet areas for energy dissipation was common, and not considered a factor for categorization. The plant-based category was assigned when mulch or plants covered the entire surface area (excluding energy dissipation areas). The composite category was assigned to the remainder of sites, where there was a mix of both plant-based and rock covering.

The Student t test (unequal variances) was used to evaluate the potential differences in media characteristics between the three surface cover categories (rock, plant-based, and composite). An alpha value of 0.05 was selected to show significance. Linear regression was used to determine if there was a relationship between media characteristics of bulk density and organic matter content, as well as between those characteristics and canopy cover.

The Shapiro-Wilk test was used to test the normality of the bulk density and organic matter content. For all coverage types, the bulk density and organic matter content are normally distributed at the 95% level of confidence. For the plant-based mulch cover and the composite cover, both bulk density and organic matter content are normally distributed at the 95% level of confidence; whereas, these properties are normally distributed at the 90% level of confidence for the rock cover. Therefore, all statistical tests and regressions were performed without data transformation.

Results

Media Characterization

Bulk density, organic matter, and canopy cover are reported in Table 2. On average, the organic matter content of media under plant-based mulch cover was significantly greater than that under rock cover (Table 2; $p = 0.002$). The media under the composite material has an organic matter content that was not different to that under the plant-based mulch ($p = 0.370$). The organic matter content of media under rock and composite materials was not different ($p = 0.099$). In general, the age of the bioretention areas did not significantly influence organic matter content within surface treatments, primarily due to the high variability in the

Table 2. Average bulk density (BD), organic matter (OM), vegetation cover (VC), and surface cover at each field site. NA – not applicable, no data collected for that site characteristic.

Site ID	BD (g/cm^3)	OM (%)	Surface Cover	VC (%)	Site ID	BD (g/cm^3)	OM (%)	Surface Cover	VC (%)
DG-1	0.89	14.4	Composite	50.9	MN-3	1.38	11.9	Plant-based	45.8
HC-2	1.54	3.9	Composite	71.1	MN-4	1.36	11.5	Plant-based	82.8
HC-3	1.54	4.8	Composite	52.6	MN-5	1.26	10.2	Plant-based	62.4
HC-4	1.58	5.5	Composite	59.1	MTA-1	1.15	12.9	Plant-based	69.4
MN-1	1.57	6.5	Composite	34.2	OH-1	1.69	3.1	Plant-based	55.2
MN-6	1.51	9.9	Composite	43.5	OH-2	1.74	2.1	Plant-based	35.1
SC-2	1.37	8.5	Composite	41.3	RB-1	1.01	11.6	Plant-based	97.0
SC-3	1.36	6.2	Composite	65.4	RB-2	0.86	11.8	Plant-based	99.3
VD-1	0.80	15.9	Composite	95.8	RB-3	0.89	15.9	Plant-based	98.7
VD-3	1.02	17.3	Composite	99.4	SC-1	1.36	7.7	Plant-based	31.1
AT-1	1.08	12.5	Plant-based	54.3	SC-4	1.41	6.9	Plant-based	90.3
AT-2	1.03	12.4	Plant-based	47.5	SC-5	1.34	6.2	Plant-based	44.1
AT-3	0.94	13.0	Plant-based	2.0	SS-1	0.97	NA	Plant-based	48.9
BB-1	1.44	5.4	Plant-based	83.1	SS-2	1.26	16.3	Plant-based	41.9
BB-2	1.46	5.1	Plant-based	91.9	TA-1	1.40	8.0	Plant-based	39.2
CB-1	1.10	13.8	Plant-based	69.5	TA-2	1.24	9.5	Plant-based	95.0
FW-1	0.84	12.5	Plant-based	94.0	VD-4	0.93	16.1	Plant-based	95.7
FW-2	0.93	15.9	Plant-based	71.0	AZ-1	1.61	1.7	Rock	36.6
FW-3	0.90	15.1	Plant-based	77.8	BM-1	1.59	4.8	Rock	27.2
HG-5	1.10	13.1	Plant-based	81.9	BM-2	1.69	4.5	Rock	31.1
MC-1	0.87	12.2	Plant-based	72.6	BM-3	1.69	5.7	Rock	35.2
MC-2	0.89	15.9	Plant-based	34.5	HC-1	1.40	4.4	Rock	53.2
MN-2	1.55	7.4	Plant-based	36.8	HG-1	1.74	4.9	Rock	60.6

measured values (Figure 2). The bulk density of the engineered media was strongly and inversely correlated to organic matter content (Figure 3). Similar to the organic matter content, bulk density did not generally vary with bioretention area age (Figure 4) and was highly variable within treatments. On average, the bulk density of the media under the plant-based mulch cover was significantly less than that under the rock cover ($p < 0.001$). The media under the composite treatments had similar bulk density to both the plant-based mulch ($p = 0.233$) and the rock covers ($p = 0.132$).

Vegetation

Canopy cover (%) varied widely between sites, from 16 to 99% among practices that contained living plants (Table 3). Two sites did not have any living plants. There was no significant relationship between canopy cover and any other variable.

Plants that were documented as present and healthy are listed in Table 4. The most observed herbaceous plants were common rush (*Juncus effusus*), black-eyed susan (*Rudbeckia fulgida*), and rose mallow (*Hibiscus lasiocarpos)*. The most observed shrubs were Virginia sweetspire (*Itea virginica*), summersweet (*Clethra alnifolia*), and inkberry holly (*Ilex glabra*). The most observed small tree was the sweetbay magnolia (*Magnolia virginiana*).

Discussion

This study evaluated the relationships between bioretention practice components of surface cover type, engineered media, and vegetated canopy cover. The strong inverse correlation between media bulk density and organic matter content supports conventional soil science knowledge about the same relationship in soil (Saini 1966). Since it has been shown that high organic matter in maturing bioretention cells has a positive relationship with trace metals measured in bioretention media (Costello et al. 2020), there are implications of surface cover selections on water quality treatment potential.

Significant differences in media bulk density between the rock covering and plant-based covering sites suggest that surface cover material influences

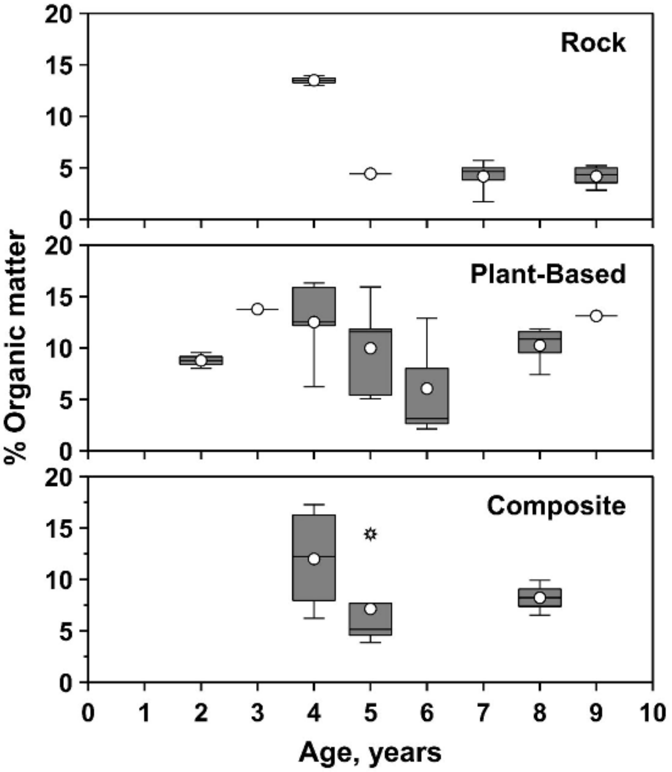

Figure 2. The organic matter content of soil media as a function of surface cover type and age.

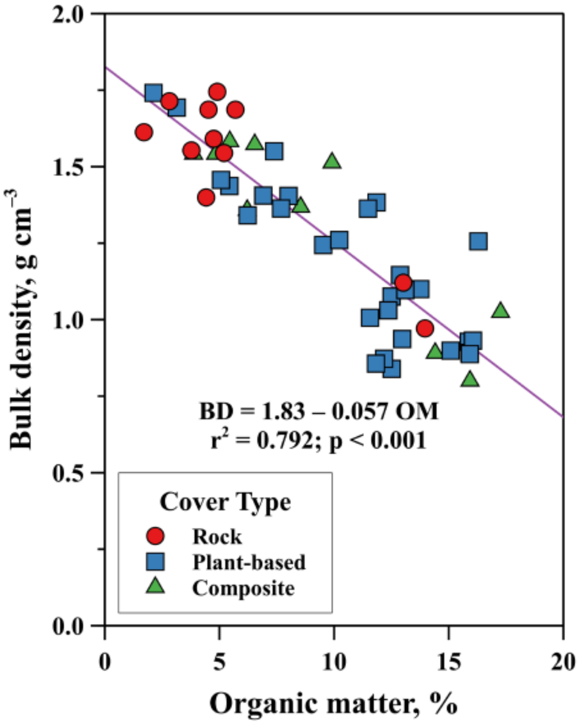

Figure 3. The relationship between bulk density and organic matter content of soil media as a function of surface cover type.

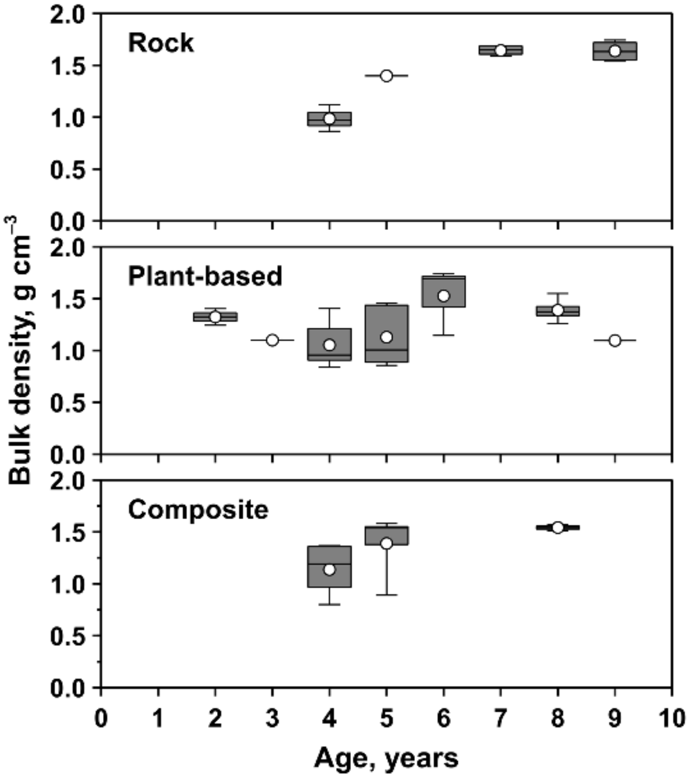

Figure 4. The bulk density of soil media as a function of surface cover type and age.

Table 3. The organic matter content and bulk density of surface media under various mulch cover types.†

Cover Type	Organic Matter Content %	Bulk Density g cm^{-3}
Plant-based (n = 20)	10.89 ± 4.02 a	1.19 ± 0.26 a
Rock (n = 12)	5.89 ± 3.93 b	1.51 ± 0.25 b
Composite (n = 10)	9.29 ± 4.90 ab	1.32 ± 0.30 ab

†Means ± standard deviations over all ages as a function of cover type. Mean followed by the same letter in the same column are not significantly different at the 95% confidence level.

Table 4. List of plants identified as present and healthy in bioretention study sites in Davidson County, TN, USA.

Common Name	Scientific Name
Ostrich Fern	*Matteuccia struthiopteris*
Switch Grass	*Panicum virgatum*
Common Rush	*Juncus effusus*
River Oats	*Chasmanthium latifolium*
Joe Pye Weed	*Eutrochium purpureum*
Butterflyweed	*Asclepias tuberosa*
Black-eyed Susan	*Rudbeckia fulgida*
American Alumroot	*Heuchera americana*
New England Aster	*Symphyotrichum novae-angliae*
Rose Mallow	*Hibiscus lasiocarpos*
Gray Dogwood	*Cornus racemosa*
Beautyberry	*Callicarpa americana*
Witch Hazel	*Hamamelis virginiana*
Smooth Hydrangea	*Hydrangea arborescens*
Inkberry Holly	*Ilex glabra*
Virginia Sweetspire	*Itea virginica*
Buttonbush	*Cephalanthus occidentalis*
Oakleaf Hydrangea	*Hydrangea quercifolia*
Summersweet	*Clethra alnifolia*
Sweetbay Magnolia	*Magnolia virginiana*

the underlying media, which has implications for the overall function of the practice. These findings suggest that rock surface covering used instead of plant-based mulch may adversely affect the function of bioretention systems in terms of storing and infiltrating stormwater runoff. There are also implications for mixing and associated treatment efficiencies of these practices. Studies have shown infiltration rates of bioretention cells to not diminish with age up to ten years (Spraakman and Drake 2021). However, the literature is more varied when examining bioretention function related to water quality treatment over time. Although the media sampled had various ages (from 2 to 9 years), the influence of age on the media characteristics, such as the accumulation of organic matter, was not evaluated. While it is evident that both organic matter and bulk density vary as a function of age under rock cover (and only under rock cover) (Figures 2 and 4), conclusions cannot be drawn about the influence of time (age). This would require the continuous sampling of the sites, beginning with installation. The measurements were all from different areas, and the initial conditions of each bioretention area were unknown.

The results also raise questions about the effect of surface covering selection and vegetation. Healthy vegetation aids in the physical, chemical, and biological processes needed for a fully functioning bioretention system (Muertder et al. 2018). Plant roots maintain soil structure and create macropores that enable fluid transport (Angers and Caron 1998), but the role of root-induced effects on media properties needs further investigation (Skorobogatov et al. 2020). Vegetation absorbs and dissipates energy, and the biomass aids in microbial processes. Plants directly uptake potential pollutants (e.g., nutrients and trace metals) (Mehmood et al. 2021). Vegetation also plays a significant role in the water budget and associated nutrient budgets in bioretention practices (Nocco et al. 2016). The plant community supports local wildlife (Kazemi et al. 2011), along with additional ecosystem services that provide co-benefits to humans. To this end, it is important to facilitate the establishment and maturation of a healthy plant community in bioretention practices to fully realize maximum functionality.

Compacted soil conditions may inhibit plant establishment. A soil bulk density of 1.6 g/cm^3 may adversely affect plant rooting capacity in sandy loam (Daddow and Warrington 1983). Media bulk density above this threshold was measured in more rock covered applications (6) than plant-based mulch covered applications (2). Though the canopy cover data varied widely, there are two implications based on the relationships between canopy cover and media characteristics. There was no canopy cover greater than 75% (performance criteria) (Metropolitan 2021) observed at sites where the media bulk density was greater than 1.55 g/cm^3, nor at locations with organic matter less than 5%. While rock is considered a permanent cover (as opposed to temporary cover like straw or some established seed), many performance requirements reference permanent vegetated cover to be greater than 80%. These findings show that more research is needed to evaluate the effect of rock coverings on meeting vegetation-focused performance requirements in bioretention applications.

There are other possible reasons for the differences in bulk density, organic matter, and vegetation characteristics observed in this study. The original hydrologic design may affect circumstances that influence the condition of media and vegetation. Installation practices, plant selection, and ongoing maintenance activities may also play a role in the observed conditions. Other interactions between the practice and adjacent topography, underlying soil, geology, and other site-specific conditions may also lead to differences in measured characteristics.

The plant species observed to be healthy and thriving in the studied bioretention practices (Table 4) may be favorable replacements where other selections have failed, or during bioretention renovations. This list is suitable for use in the Davidson County area but may also be useful for practitioners throughout the same ecoregion(s) depending on native status and site conditions. It is advised to check the native status of the species before specifying for a design or planting and give preference to those native to the region in which the application is to be installed.

Conclusion

This study found that organic matter content of bioretention media under plant-based mulch cover was significantly greater than that under rock cover. The bulk density of media was strongly and inversely correlated to organic matter content, and on average, was significantly less where plant-based cover was used rather than rock cover. These findings have implications for design and long-term maintenance. A functional goal of full plant canopy cover may help maintain soil structure, porosity, and infiltration capacity as well as support healthy vegetation. This functional goal will create a system that naturally replenishes media organic matter as part of the seasonal vegetation cycle, creating a more self-sustaining practice than one that utilizes dredged or quarried stone.

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