Emerging investigator series: The Role of Vegetation in Bioretention for Stormwater Treatment in the Built Environment: Pollutant Removal, Hydrologic Function, and Ancillary Benefits

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Emerging investigator series: The Role of Vegetation in Bioretention for Stormwater Treatment in the Built Environment: Pollutant Removal, Hydrologic Function, and Ancillary Benefits

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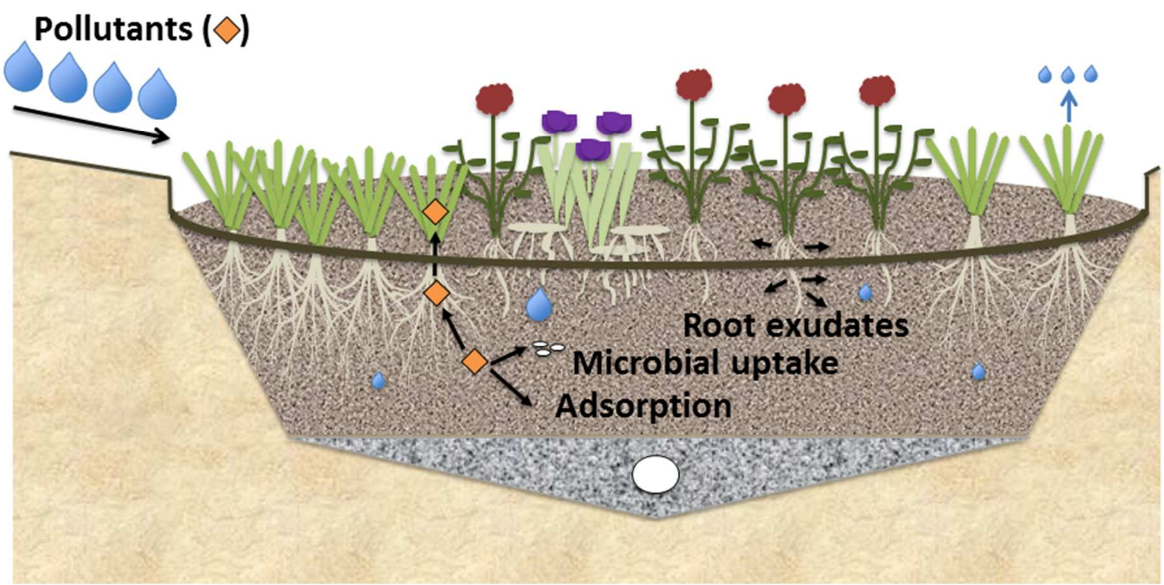

Bioretention vegetation contributes to both the hydrologic and pollutant removal functions of bioretention.

ABSTRACT

Vegetation influences both the hydrologic and pollutant-removal performance of bioretention cells for green infrastructure stormwater management in the built environment. Vegetation can intercept rainfall, lessen erosive sheetflow, ameliorate bioretention soil media clogging to maintain infiltration capacity, and decrease total stormwater volume through transpiration. Plants influence multiple pollutant removal processes, including phytoextraction, *in-planta* phytotransformation, and alteration of the rhizosphere and associated microbial community. We present the current state of knowledge of vegetative influence on pollutant-removal performance and mechanisms, including for total suspended solids, nitrogen, phosphorus, toxic metals, hydrocarbons, pathogens, and emerging contaminants in urban stormwater. Additional benefits and opportunities for vegetation in bioretention include improved aesthetics of stormwater infrastructure, lessened irrigation / fertilizer demand, provision of urban micro-habitats, thermal attenuation, public education, increased resilience for climate change adaptation, and the potential for air quality improvement as well as biomass and / or food production. We describe plant traits and species that improve pollutant removal and hydrologic function, such as plant biomass and growth rate. We identify key areas of future research need, including a focus on transferrable findings / mechanistic studies, a better understanding of root system / rhizosphere impacts, quantification of the impact of plant shoot harvesting, and further study of emerging organic contaminants and metals. We conclude that vegetation in bioretention systems produces measurable water quality and hydrologic performance benefits, but that plant processes could be substantially further researched and developed to improve stormwater systems.

WATER IMPACT STATEMENT

Stormwater runoff is a major source of pollution worldwide. Bioretention can mitigate stormwater flows and pollution. Current knowledge concerning vegetation influence on hydrologic and pollutant removal mechanisms and performance in bioretention is addressed in this review. Analysis of plant traits and specific plants that maximize bioretention function are discussed, with recommendations for further research.

1. INTRODUCTION

Stormwater runoff generated from impervious surface areas in the built environment causes substantial deleterious environmental impacts to surface water quality and disrupts the native hydrologic regime. Consequences of stormwater runoff include degraded aquatic ecosystems,[1] pollution of drinking water sources,[2] human exposure to pathogens,[3] erosion of streambanks, and economic impacts on aquatic recreation through beach closures.[4] Stormwater can accumulate and transport pollutants such as nutrients, toxic metals, oil and grease, trace organic contaminants, and pathogens into waterways.[5] A suite of strategies has emerged to mitigate stormwater pollution. Although terminology differs by location (*i.e.*, low-impact development,[6] water sensitive urban design,[7] the sponge city plan,[8] etc.), the strategies all consist of engineered stormwater management systems that are based on nature (*e.g.*, soil, plants, etc.) to treat stormwater onsite. These engineered systems are integrated into built landscapes to mitigate changes in hydrology and increased pollution caused by runoff from land development.

One technology within the framework of stormwater low-impact development is bioretention cells, sometimes called "rain gardens," "bioinfiltration," or "biofilters." Bioretention cells (Fig. 1) are engineered infiltration facilities that contain high-permeability bioretention soil media (hereafter: "media") and vegetation to maximize infiltration and remove pollutants from stormwater.[3] The surface of the media is often mulched. An underdrain is sometimes used to collect and remove water that infiltrates through the media, especially in situations when the native surrounding soils have a low infiltration rate.[9] Bioretention can aid in restoring pre-development hydrology, delaying peak flow and reducing total volume, and is being integrated into some locations for combined sewer overflow prevention.[10–12] Bioretention is also employed for pollutant removal of total suspended solids, nitrogen, phosphorus, metals, hydrocarbons, and pathogens, as well as for temperature mitigation. Bioretention is often applied as a stormwater best management practice to meet water quality requirements such as total maximum daily loads.[9] The media is an important component for all of these functions, and vegetation also plays a significant—if underappreciated—role.

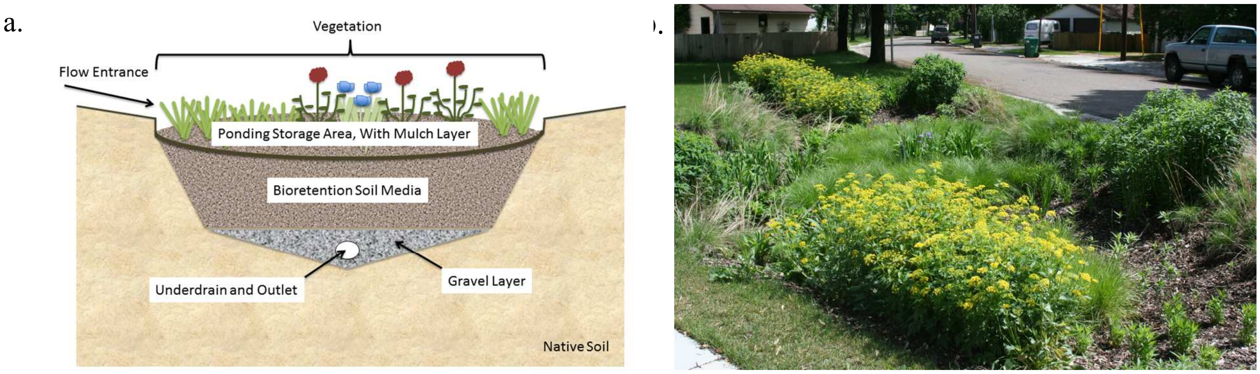

Fig. 1: Typical bioretention: a. cross-section (Image: Muerdter), b. A vegetated bioretention cell in St. Paul, Minnesota, USA (Photo: LeFevre)

Despite the importance of vegetation in bioretention design, substantial knowledge gaps exist in areas where plant processes contribute to improved stormwater outcomes. Plants are often selected only for aesthetics, survivorship, or being native to the region, with the vegetative contribution to bioretention pollutant removal and hydrology being overlooked. Because native vegetation is often used for site- and climate-specific resiliency, translating specific vegetation studies to different locations can be difficult. *Thus, an understanding of mechanisms rather than mere 'black-box results' is critical in generating transferrable research findings and knowledge.* This review examines current research findings on the role of vegetation in bioretention, makes recommendations on the role of plant processes in engineered natural treatment systems such as bioretention, provides context from current practice guidance, and suggests areas of future research need.

2. VEGETATION FUNCTIONS IN BIORETENTION

2.1 Hydrologic Processes

Vegetation contributes to bioretention hydrologic function above, at, and below the media surface, through plant interception of rainwater, surface flow regulation, water infiltration modification, and plant transpiration.

2.1.1 Plant Interception. Above-ground portions of vegetation intercept and store rainwater, or channel rainwater to the ground along stems.[13,14] Interception reduces both the total volume of stormwater runoff and erosive forces by protecting the soil surface from direct rainfall.[15] Interception storage can be substantial; for example, the average per-tree interception of 20 tree species was the equivalent of a 0.86 mm storm.[16]

Field studies of interception storage in bioretention are lacking in the literature. Nevertheless, the amount of rainfall intercepted by vegetation can be estimated from various models[17] and previous studies of particular plant species. Plant species create different amounts of interception based on attributes such as surface area and leaf smoothness.[14] For example, generally conifers store more water on plant surfaces than broadleaf trees.[16,18] Seasonality also greatly impacts interception by deciduous plant species.

2.1.2 Surface Flow. The capability for vegetation to slow overland flow and reduce erosion has been quantified in other settings, but has yet to be quantified in bioretention.[19–21] The impact on overland flow can vary greatly between vegetation types. For example, the Manning's Roughness Coefficient value[13] for "woods with dense underbrush" (0.80) is >five-fold the value for "short grass" (0.15). Slowing surface flow with vegetation presence can decrease erosion, preventing the movement of bioretention mulch and media that otherwise would be scoured off of the inlet area of the cell and redistributed to other parts of the bioretention cell. Mulch is important for the removal of metals and hydrocarbons, thus an evenly distributed layer of mulch throughout the bioretention cell is desired.[9]

2.1.3 Stormwater Infiltration. Media clogging due to sediment influx is the main cause of failure in bioretention.[22] In a clogged system, partially treated or untreated water can pond for longer than desired, permitting mosquito development. Clogging can also cause water to overflow the bioretention cell, bypassing treatment and creating flooding.[23] Many bioretention design manuals specify a maximum allowable ponding time, for example*,* 48 hours.[24]

The roots of bioretention vegetation create macropores and root channels that enhance media hydraulic conductivity and prevent clogging. Specifically, more extensive, thick roots and vigorous vegetation growth rates increase infiltration over time and are recommended for clogging prevention. For example, under low flow rates, a shrub (*Buxus sinica*) facilitated faster bioretention infiltration than turf grass, which has a shallow root system.[25] Similarly, *Melaleuca ericafolia*, a thick-rooted Australian native shrub/tree, increased hydraulic conductivity (155 mm hr^{-1} to 295 mm hr^{-1} after 56 weeks) in bioretention columns over time.[26] Hydraulic conductivity decreased in unplanted controls and treatments with other vegetation. Vegetation growth during the study period was not reported; thus the causation of differential hydraulic conductivity by plant roots must be presumed from treatment design. A field study in Australia, however, did document a correlation between vigorous vegetation growth and significant increases in infiltration.[27] Larger root biomass also correlated to greater increases in infiltration than smaller root biomass in Oregon, USA.[28] Similarly, a field study in France found two to four-times higher hydraulic conductivity in parts of an infiltration basin with actively growing plants vis-à-vis bare areas or vegetated areas during seasons of plant rest.[29] Thus, seasonality and the extent of growth of a root network over time can impact infiltration rates. It should be noted that in all of these studies hydraulic conductivity measurements were not decoupled from the impact of evaporation and transpiration.

The ratio of root depth to media depth should be considered in the bioretention design process. Root depth will vary depending on plant species, climate (typically deeper roots are found in dry climates), and the presence of an internal water storage layer in the bioretention design (which creates a saturated layer, discouraging root growth).[30] Deeper root systems facilitate enhanced water infiltration into the media through root channels and macropores. Very aggressively growing roots may be able to penetrate and clog a bioretention underdrain. Additionally, denser plantings with increased infiltration and roots that reach the bottom of the mesocosm have been linked with lessened nitrate removal from stormwater, in comparison with less-dense plantings,[31] presumably due to the formation of preferential flow paths. Thus, less-effective pollution removal performance may sometimes be a tradeoff of the increased infiltration and clogging prevention created through root density. The depth of the mature plant root system should be considered in the initial design, not just the root depth of the initial planted material. Measurements of root depth in bioretention research include an average longest root of 29.1 cm for three forb species in Maryland, USA bioretention[32] and the majority of roots for two Australian species, a sedge and a woody species, to be above 63 cm.[26] Media depth will vary depending on available space, budget, and climate. Deeper media maximizes outflow volume reduction,[9] and thus will be preferable in climates that receive high-volume precipitation events, whether those events are frequent (*e.g.*, temperate or tropical climates) or infrequent (*e.g.*, arid).

2.1.4 Transpiration. Transpiration is the process by which water is taken up by the plant roots, transported through the plant tissue, and evaporated from leaf surfaces. Transpiration of water by vegetation helps maximize the volume of stormwater treated by the bioretention cell by decreasing the total water exported to the underdrain / surrounding soil. Lessening total water export may also lower the transport of soluble pollutants out of bioretention cells. Evapotranspiration, a more inclusive term than transpiration, consists of abiotic evaporation as well as transpiration. In seasonal climates, evapotranspiration can vary substantially throughout the year as the weather changes.[33] Work on evapotranspiration in bioretention is growing (*e.g.*, references[34–36]), although vegetation differences are not examined in most studies. Bioretention vegetation type was linked to varying evaporation rates in one Wisconsin, USA study.[37] Vegetation differences caused four-fold evapotranspiration variation. The shrub treatment had the highest average evapotranspiration rate (9.2 mm day^{-1}), which was not significantly different than the prairie treatment (7.9 mm day^{-1}). The turfgrass treatment evapotranspiration averaged 5.9 mm day^{-1}, and the bare soil control averaged 2.1 mm day^{-1}. Although transpiration and evaporation were not explicitly decoupled in this study, higher transpiration in the shrub and prairie treatments than the turfgrass evapotranspiration is also likely.

Transpiration data alone, decoupled from evapotranspiration, is very limited in bioretention. In one study in Utah, total annual transpiration by bioretention cell vegetation was 7% (=5,600 liters) of the inflow volume during the growing season.[38] Different plant species can transpire at widely varying rates (*e.g.*, 3–25 Mg/yr among five tree species),[39] depleting soil moisture and thus regenerating the hydrologic storage capacity of the media between events. For example, prior to storm events, bioretention mesocosms planted with prairie and shrub vegetation had significantly lower soil volumetric water content at depths of 0–0.15 and 0.30–0.45 m compared to turfgrass.[40] Specific studies of tree evapotranspiration and transpiration rates in bioretention are needed in addition to forb, grass, and shrub data. As reviewed in Berland et al.[14], tree evapotranspiration rates in urban forests can have high in inter- and intraspecies variation, but can be substantial (*e.g.*, ~2.5×10^4 kg yr^{-1} for *Gleditsia triacanthos*, honeylocust).[39] The effect of planting density on transpiration should also be considered. In a non-bioretention pot study, densely planted trees transpired at lower rates than those planted farther apart.[41]

Crop coefficients, developed in agriculture to predict evapotranspiration rates, could be a useful tool in bioretention modeling, while recognizing the different conditions between agriculture and bioretention.[42] The rate of plant transpiration could be estimated from the evapotranspiration rate, using the ratio of transpiration to evapotranspiration for the specific plant (*e.g.*, reference [43]). Crop coefficient evapotranspiration calculations also account for water stress. When plants are water-stressed, *i.e.*, ≤2x the wilting point, transpiration rates are substantially lowered.[44] Water stress on the vegetation in bioretention cells between precipitation events will occur in many climates, because the media is designed to drain rapidly. Saturated zones, a continually damp area of the media created by upturned underdrain elbows, can provide a source of water for vegetation between natural rainfall events to minimize water stress.

2.2 Stormwater Quality Benefits

Multiple plant-related mechanisms impact pollutant removal in bioretention. After a brief introduction to the mechanisms (Figure 2), the plant impacts on pollutant processing are discussed in the context of specific pollutants. Typical stormwater concentrations and sources of pollutants are available in the literature and other sources (*e.g.*, references[45–47]). Design choices for specific sites should consider the pollutants of highest concern for that location.

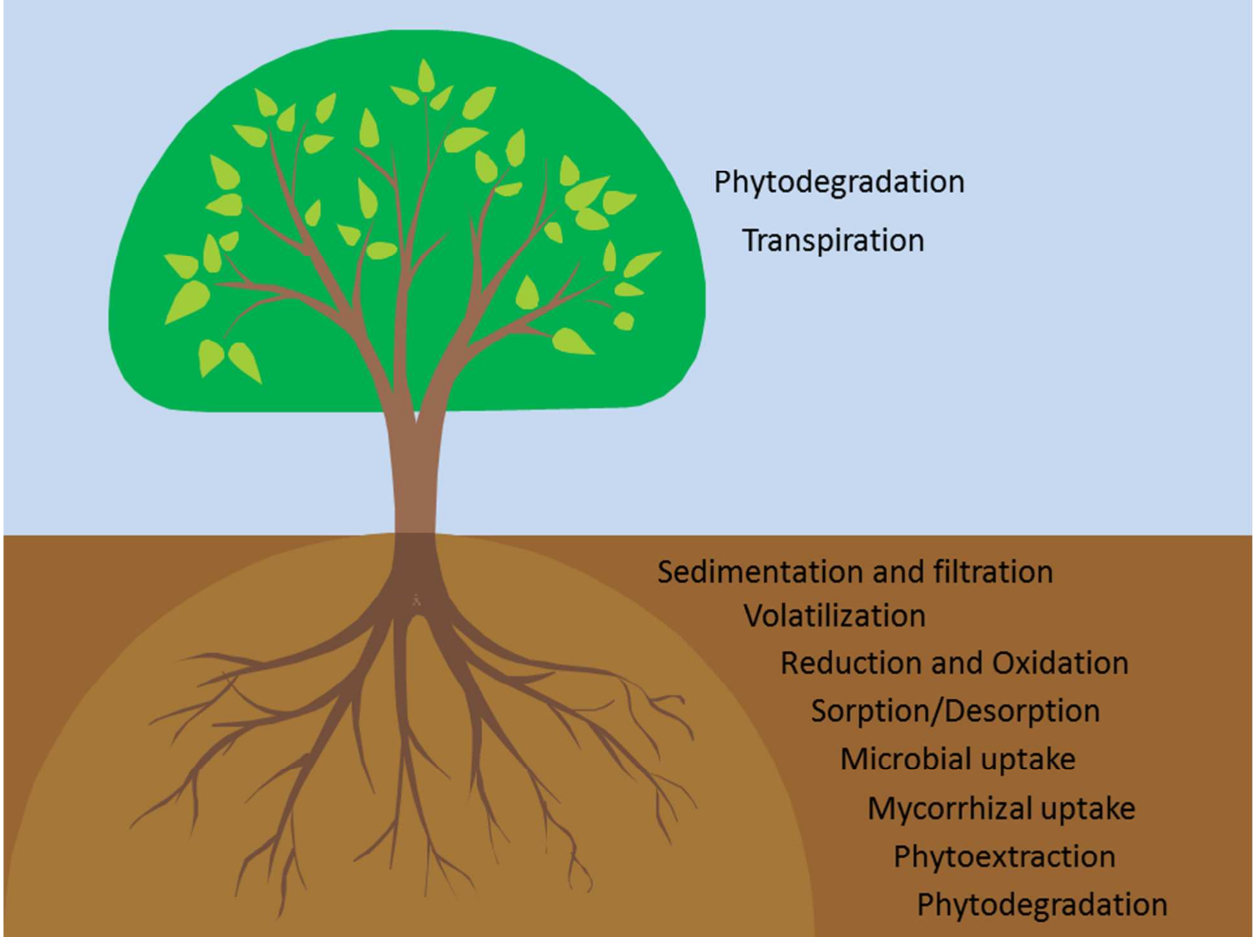

Fig. 2: Pollutant removal mechanisms that can occur in vegetated bioretention systems. (Illustration: Wong).

2.2.1 Mechanisms of Plant-Related Bioretention Pollution Removal

2.2.1.1 Phytoextraction and Phytodegradation Mechanisms. Phytoextraction is the process of direct pollutant uptake from soil and its translocation into plant tissues, either above or below ground.[48] Phytoextraction moves the pollutant into the plant tissue without chemical modification, for example, the uptake of lead into plant shoots and roots from contaminated soil. The lead remains in the same form as in the soil, *i.e.*, it is not mineralized or altered to a different form. Phytoextraction can be an advantage when metals of commercial value are taken up into plants because the metals can be removed from the plant tissue and recovered.[48] After phytoextraction, pollutants are often transported to the plant vacuole for sequestration and to prevent harm to active plant metabolic processes.[49] Phytoextraction depends on a number of factors such as temperature, plant phenology (*i.e.*, seasonality), and media components.[50] In contrast to phytoextraction, phytodegradation chemically alters the pollutant, ideally lowering of pollutant toxicity. For example, some pollutants form conjugates with sugars or amino acids after entering plant tissue, and can thus escape detection by methods that only measure the parent pollutant and not the conjugated form.[51–54]

2.2.1.2 Rhizosphere Mechanisms. The rhizosphere, *i.e.*, the zone adjacent to and influenced by plant roots, has very distinct abiotic and biotic characteristics from the surrounding soil, thus impacting pollutant fate.[55] These characteristics include redox conditions, pH, and the microbial community. For example, field bioretention studies show higher bacterial abundance in planted bioretention cell areas than unplanted,[56,57] and higher bacterial abundance in areas with deeply rooted plants vis-à-vis turfgrass.[56]

Multiple factors contribute to the rhizosphere effect, notably oxygen introduction from plant roots[58] and root exudates. Soil oxygen levels impact redox conditions. For example, aerobic conditions in soil oxidize ferrous iron and increase the P sorption capacity.[59] Oxygen levels also impact rhizosphere microbial community structure and function; for example, creating significantly greater aerobic nitrifying bacterial populations in the rhizosphere than the bulk soil during plant growth seasons.[60] In addition to oxygen, root exudates influence the rhizosphere microbial community. Root exudates are a complex mixture of sugars, organic acids, and secondary plant metabolite compounds that are released through plant roots. Simple carbohydrates in exudates, which can represent 30% of a plant's net fixed carbon,[61] stimulate microbial growth in the rhizosphere and can increase cometabolic pollutant degradation. In bioretention, runoff supplemented with dissolved organic carbon increased microbial populations and degradation of trace organic contaminants such as atrazine and fipronil.[62] Thus, carbohydrates in root exudates may perform a similar function.

2.2.2 Impact of Plant-Related Mechanisms on Specific Bioretention Pollutants

2.2.2.1 Total Suspended Solids (TSS). TSS removal rates in bioretention are typically high.[9] The main mechanisms of total suspended solids (TSS) removal in bioretention are settling / sedimentation and filtration by the mulch and media.[9] High (>80%) TSS removal has been documented in unvegetated bioretention systems.[63] Nevertheless, improved TSS removal in field bioretention cells after planting (vis-à-vis unvegetated bioretention cells) is attributed to media stabilization and vegetation presence minimizing mulch and media movement in the bioretention cell.[64] Vegetation may contribute to maximizing sedimentation by slowing stormwater flow, which allows more even distribution of solids throughout the bioretention cell.[9] Long-term, vegetation's main function in bioretention TSS removal is to prevent media clogging by TSS deposition in the mulch and media. This is accomplished by root growth maintenance of stormwater infiltration rates.[26–29]

An additional benefit of TSS capture is the concurrent removal of many other particle-associated pollutants, including several metals, P, and hydrophobic organic contaminants such as PCBs and dioxins.[65–67] Thus, stormwater regulations on total suspended solids levels simultaneously control other pollutants.

2.2.2.2 Nitrogen. Reported nitrogen removal rates in bioretention cells vary widely (from net export to 99% removal[21]), with plant presence usually facilitating increased nitrogen uptake compared to unplanted conditions. Multiple studies document higher total nitrogen (TN) removal[59,68–72] total dissolved N (TDN),[37,70] ammonium (NH_4^+) removal,[70] and nitrate (NO_3^-) /

NO_x (NO_3^- + NO_2^-) removal,[68,70,73–75] in planted bioretention compared to unplanted systems. Even with salt-containing influent (present in cold climates where deicing salt is used), vegetation presence improves TN, TDN, and NO_x removal in bioretention.[76] In some cases, plant presence and/or type did not yield significant N impacts.[70,71,74,75,77,78] The lack of difference in these cases is likely due to inherent variation among plant species and/or the non-plant components of the studies (*e.g.*, media type, saturation conditions). Significant differences have been documented among vegetation types for the removal efficacy of TN and/or TDN,[70,73,75–77,79] nitrate or NO_x,[68,73–76] ammonium,[70,75,76] and dissolved organic nitrogen.[75] Indeed, plant selection can represent the difference between N export and N removal.[37,73] The strongest performing plant species for N removal are listed in Table 2.

Nitrogen-processing mechanisms in bioretention influenced by plants can be organized into biological mechanisms and hydrological mechanisms. All of these mechanisms can potentially be influenced by plant age.[1] Reported literature values may be lower than would occur in well-established bioretention sites, because many studies are conducted immediately after planting. Further research in this area is warranted.

Biological mechanisms include the direct plant uptake of N and the rhizosphere influence on the media microbial community. First, direct plant uptake will occur because N is essential for plant growth.[80] Plants are typically 2–5% N by dry weight.[81] Therefore, bioretention plants will assimilate N from the media and stormwater. NO_3^- and NH_4^+ are the two major forms of N taken up by plants.[81–83] As an anion, NO_3^- is water-soluble and plant-accessible. NH_4^+ can be captured in the soil via sorption or ion exchange and subsequently assimilated by plants. Some plant species can also take up organic N compounds,[84–86] which is relevant in bioretention because organic N is typically a component of incoming stormwater. Ideal plants for bioretention should have high water-use efficiency, *i.e.*, a high conversion of available water to biomass, which includes N. Water-use efficiency can vary between plant species, e.g., between ~16 mg N (L H_2O)$^{-1}$ and 93 mg N (L H_2O)$^{-1}$ in a study of eight plant species,[87] and as a plant ages.[88]

The second biological mechanism of plant influence on N removal in bioretention is rhizosphere interactions with the media microbial community. Ammonium can be nitrified to nitrite by *Nitrosomonas* spp. bacteria and nitrite can be nitrified to nitrate by *Nitrobacter* spp. bacteria.[89] Nitrate can be easily leached from bioretention. Due to nitrification, bioretention effluent concentrations can be higher than the input nitrate concentration.[21,68,90–93] Plants can affect this export though both direct nitrate uptake[91] and the influence of the rhizosphere on microbial nitrification and denitrification. In a study of microbes present in media, higher levels of four nitrification and denitrification genes occurred in the media samples of densely or moderately vegetated cores than from areas with minimal or moderate vegetation, suggesting greater biotransformation capacity.[57] An additional potential impact on bioretention nitrogen cycling is the microbial production of nitrous oxide and methane, both greenhouse gases. One study reported[94] that although nitrous oxide emissions were affected by plant root structure, the total amount of incoming nitrogen being converted to greenhouse gases was small (<1.5% of the incoming nitrogen load). Thus, the emission of greenhouse gases from properly functioning bioretention cells should be minimal.

Without design and maintenance management, plant presence in bioretention can facilitate N export due to plant nutritional needs and senescing biomass. Organic matter is usually included in media to stimulate plant growth, often in the form of compost. Compost, however, contributes to N export via leaching, particularly immediately after installation.[95] A minimal amount of compost should therefore be used in order to minimize nutrient export while providing for plant growth. Another consequence of plant presence is the reintroduction of N from decomposing, senesced plant biomass. This biomass can contribute organic N, which can be mineralized into NO_3^- and leach out of the bioretention cell.[92] Shoot harvesting and removal from the bioretention cell permanently removes this N from the bioretention system.

Lastly, hydraulic factors, including the presence of a bioretention saturated zone and overall hydraulic conductivity, impact N removal and the plants in bioretention. The use of saturation zones in bioretention continues to be investigated to promote microbial denitrification and attenuate plant water stress, but the exact impact on plant survival has not been quantified. Saturated zones enhanced the plant removal of multiple N species in some studies[70] but not in others.[1] This variation appears to depend on both the individual plant species used and the media/study configurations varying between studies. The second hydraulic-related mechanism is the influence of root architecture on hydraulic conductivity. Plants with more extensive root systems are speculated to be the most effective at promoting N removal. For example, in a study in Texas,[68] Big Muhly grass (*Muhlenbergia lindheimeri*), a large bunch grass with a root depth of ~460 mm in the mesocosms, removed significantly more NO_x than Buffalograss 609 (*Buchloe dactyloides*), a turf grass with roots only in the top ~100 mm of the media. Similarly, a *Carex* sp. with a dense root architecture and many fine root hairs was the most successful out of five tested plant species at NO_x and TN removal in an Australian column study.[73] Nevertheless, excessive hydraulic conductivity promoted by high root density and roots reaching the bottom of the media may provide insufficient contact time for maximum removal of nitrate.[31] Therefore, an extensive root network that does not penetrate to the bottom of the media appears to be the most favorable architecture for N removal.

2.2.2.3 Phosphorus. Phosphorus removal rates in bioretention cells vary widely, ranging from removal to net export.[96] Although P removal can be high (*e.g.*, 81%)[73] without plants,[71] plant presence can create increased P uptake vis-à-vis unplanted treatments, especially for dissolved P, which plants uptake directly.[59,69,73,77] For example, in a study with an influent concentration of 2.5–3.5 mg TP L^{-1}, >80% of which was dissolved, plant storage in *Carex appressa* was the dominant (64% on average) P sink in the system, illustrating the importance of vegetation in treating dissolved P.[97] P removal can differ with vegetation type, in addition to the influence of P type.[73,74,77] For example, in an Australian mesocosm study,[75] only one of twenty tested plant species removed significantly more TP than the unplanted control. In contrast, all but one tested species removed more total dissolved P than the unplanted control. Other studies report minimal or no significant difference in P removal among different plant speices.[1,31,68,78] These results are likely due to plants that are inherently similar in their P uptake abilities, and/or low dissolved P concentrations in the influent. Of note for United States bioretention is that the majority of previous studies on P and plant uptake occurred outside of the United States, with several species that do not have American counterparts of the same genus.

The main mechanisms of P removal in bioretention are media sorption (dissolved P), plant/fungal uptake (dissolved P) and mulch/media filtration (particulate P).[96,97] Phosphorus processing mechanisms in bioretention influenced by plants include direct plant and mychorrizal uptake, plant alteration of media, and the introduction of P back to the bioretention cell from senesced plant biomass. Plants directly assimilate P for normal physiological functioning (ATP production, nucleic acids, and phospholipids).[98] Plants take up dissolved inorganic orthophosphate ($H_2PO_4^-$ or HPO_4^{2-}), and thus are expected to have a larger impact on phosphate than particulate-associated P. The phosphorus fraction in plant tissue can vary widely depending on species, but is typically 0.2–0.5% P by dry weight[81,99]–an order of magnitude less than the N content. Nevertheless, plants can concentrate P, with xylem sap P levels 100 to 1,000 times in the soil.[81] Plants with associated mychorrhizal fungi may assimilate P more rapidly; in one study, 75% of applied TP was removed from the liquid medium within two hours of application by mychorrizal-innoculated pine (*Pinus sylvestris)* plants, vis-à-vis >8 hours for non-mychorrizal control pine plants.[100] Additionally, mycorrhizae can store excess P for future plant use.[101] In a field study, plant-mycorrhizal associations were found in 4 out of 11 dominant bioretention plant species from nine bioretention sites.[102] Further work is needed to quantify the impacts that such mycorrhizal colonization has on bioretention pollutant removal dynamics.

Plants can also influence P in bioretention by altering media infiltration. The gradient created by root removal of P from the soil solution encourages desorption of P from the soil or particulate matter. Plant roots also facilitate oxidization of the media's ferrous iron, increasing media P sorption ability.[59] Between storm events, vegetation appears to help temporarily retain PO_4-P, especially in media with the greatest sorption capacity, through a not fully elucidated mechanism.[59] As a negative impact on P removal, P can also leach from compost/other organic matter included in the media to support plant growth.[95,103] Thus, as with N, minimal OM (or OM with very low P content) should be incorporated if phosphorus removal is critical, and the plant palette adjusted accordingly. As with N, dead vegetative biomass can also contribute P back to the bioretention cell upon decomposition. P concentration in stormwater has been correlated to the amount of tree canopy over streets, which introduces dead biomass to the stormwater.[104] This challenge can be avoided in bioretention through vegetation shoot harvesting.

2.2.2.4 Metals. Metal removal from stormwater influent in bioretention is typically high. The most common metals in stormwater are copper, zinc, and lead, although other metals can be present.[105] Metals vary in their intrinsic properties and thus in their bioretention behavior.

In a planted 'bioretention box' in Norway, overall mass reduction rates were 90% for zinc, 82% for lead, and 72% for copper.[106] Removal can be high in nonvegetated bioretention: in both planted and unplanted treatments in a greenhouse study,[107] >92% of input metals were removed in the upper 27 cm of soil, with the majority of metal removal occurring in the mulch.[93] Nevertheless, removal of zinc, copper, and mercury improved after planting in one study of field bioretention cells,[64] and vegetation type can be a significant factor in iron, aluminum, and chromium removal from stormwater in bioretention mesocosms.[108]

Although the majority of metal removal in bioretention is attributed to non-vegetative mechanisms such as filtration and adsorption, plants can facilitate enhanced removal through direct plant uptake including hyperaccumulation, rhizosphere impacts, and metal sorption/desorption and complexation with the organic matter used to support plant growth. Plants can directly take up metals such as zinc, copper, manganese, and nickel for micronutrients.[109] Other metals taken up by plants have unclear direct biological functions, such as cadmium, lead and mercury.[109] In bioretention studies, direct uptake into plant tissue has been documented for zinc,[106] copper, lead,[93,107,110] and cadmium.[110] Measured plant tissue metal concentrations in one study ranged from 0.5–3.3%.[110] In another study, plant uptake of Cu, Zn, and Pb accounted for 2–7% of the influent concentrations.[106] Plant uptake of metals provides a route for permanent metal removal via plant harvesting.

Effective vegetation metal removal performance in bioretention has been attributed to root architecture, plant age, and leaf area. *Melaleuca ericifolia* was significantly less effective than other plant species in iron, aluminum, and chromium removal, which is hypothesized to be from preferential flow paths created by thick *Melaleuca* roots.[108] Metal uptake varied with time for all species in the *Melaleuca study*, indicating changes in conditions as plants grow and media conditions evolve.[108] Mn removal has been correlated with greater root soil depth and leaf area.[111] The tested plant species from the existing literature that facilitate metals removal are listed in Table 2. Additional plant species should be tested for their metal uptake capabilities in bioretention.

Metal hyperaccumulating plants provide the possibility of high metal uptake, but are relatively untested in bioretention.[10,50] Hyperaccumulators can assimilate an extremely high concentration of metals (more than 100 times those found in non-hyperaccumulating plants) into their tissues without the phytotoxic effects experienced by non-hyperaccumulators under the same conditions.[112] Hyperaccumulators have been identified for As, Cd, Co, Cu, Mn, Ni, Pb, Sb, Se, Tl, and Zn.[112] Hyperaccumulators could be beneficial when designing a bioretention system for an area with known high concentrations of heavy metals. A *Thlaspi* species, a known zinc hyperaccumualtor, was planted in bioretention in Maryland but none survived more than a few weeks after planting.[10] We are not aware of any other documented uses of hyperaccumulators in bioretention. Hyperaccumulating plants often have small biomass that accumulates slowly with shallow roots.[113,114] Therefore, for the overall removal of the maximum mass of metals, the use of plants that accumulate metals at less than hyperaccumulating levels but that have substantially more biomass may be more effective. Further work is needed on both hyperaccumulating and metal-accumulating plants with high biomass that can survive in bioretention and contribute to metal removal. With both non-hyperaccumulating and (especially with) hyperaccumulating plants, the presence of metals in the plant biomass can be a concern for animal consumption as well as for eventual return to the media if no biomass harvesting occurs. A bioretention pot study[110] determined that Zn, Cu, and Pb levels in non-hyperaccumulating bioretention plants did not exceed the toxic levels recommended for livestock forage, but Cd concentration did. Wildlife exposure from bioretention metal ingestion warrants further investigation. Disposal of the plants can also become a financial burden if the plant shoots qualify as hazardous waste.[109]

Vegetation also alters the microbial and chemical composition of the rhizosphere whereby metals are mobilized for plant uptake or adsorption onto the media.[115] Organic acids in plant root exudates can affect the retention and mineralization of metals in the rhizosphere, e.g. increasing the available Zn fraction.[115] Additionally, acidification occurs when the plant or microbes take up ammonium and release H^+, and can influence metal speciation by altering the surface charge of soil particles or facilitating metal redox reactions.[115,116] A decrease in pH causes a decrease in metal adsorption.[89] The stimulation or suppression of certain microbes in the rhizosphere by plant influence can also affect metal behavior. Metals adsorb to microbes, and secreted microbial metabolites can complex metals.[116]

Finally, vegetation can indirectly impact metal removal in bioretention via organic matter (typically compost) added to the media for plant growth. Compost can leach copper, lasting for several years of simulated rainfall in one study.[95] Nevertheless, the presence of organic matter in general in the media can also provide a benefit to metals removal by increasing the sorption of metals to the media via complexation.[9] For example, increased copper retention was found with the addition of wood chips and pea straw to the media.[117]

2.2.2.5 Hydrocarbons. Although hydrocarbon removal rates are generally high in bioretention, vegetated systems remove more total petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAH) than soil alone.[118] In bioretention specifically, both column and field studies have found consistent oil and grease removal of greater than 96%.[20] In a Maryland field bioretention study, PAH event mean concentration reductions of 31–99% were documented.[119] In Minnesota, planted columns removed 93% of the naphthalene versus 78% for the unplanted columns, suggesting that vegetation played an important role in removal.[120] Furthermore, the two plant species tested had different masses of naphthalene taken up into their plant tissue. Beyond uptake, both plant species generated lower naphthalene export (7% for vegetated columns) than the unplanted column (22%).

Hydrocarbons in stormwater are predominantly removed via sorption to and filtration by bioretention mulch and media, but plant removal mechanisms also impact hydrocarbon fate, especially for lower molecular weight PAHs. Abiotic filtration is an important process because 74–90% of hydrocarbons are associated with particles.[121] Therefore, a simple layer of mulch was able to sorb and filter 80-95% of input toluene, naphthalene, and used motor oil in a bench-scale bioretention study.[121] Approximately 90% of the motor oil was biodegraded within eight days. In a different study of planted bioretention columns, labeled naphthalene tracing demonstrated sorption to the media was the dominant fate, removing 56–73% of the added naphthalene.[120] Hydrocarbons on the top of the mulch are also exposed to solar radiation, which can facilitate photodegradation.[122] Finally, biochar has also shown promise for PAH removal from water in non-bioretention settings,[123] and may be a useful amendment in bioretention.

Plant removal processes of hydrocarbons in bioretention include direct plant uptake, influence on the rhizosphere microbial community, the introduction of additional organic matter to the media, and the prevention of photodegradation through plant shading of the mulch/media. In isotope-labeled bioretention columns, direct plant uptake accounted for 2.5% (for clover)–23% (for grass) of naphthalene removal.[120] The difference in incorporation into plant biomass is likely attributable to several factors, including the extensive root structure of the grass. For both species, the majority of the naphthalene in the plant tissue was present in the shoots, indicating translocation from the roots after uptake, and the possible efficacy of plant shoot harvesting for permanent removal.

Plants also influence the rhizosphere microbial community that degrades hydrocarbons. Hydrocarbons that have been trapped in the media through sedimentation and filtration can be degraded by indigenous microbial petroleum hydrocarbon degraders.[56,120] Evidence for the role of vegetation in supporting these microbial communities is mixed. In a column study without vegetation, microbial degradation process removed 90% of the trapped material (naphthalene, toluene, and dissolved motor oil).[121] In a column study with vegetation and no-vegetation controls, complete microbial mineralization (12–18% of total removal) was not different between the treatments.[120] Nevertheless, the grass columns had significantly more microbial naphthalene dioxygenase functional genes present than the clover or unplanted columns.[120] When soil samples collected from the columns at the end of the study were used as inoculum in batch biodegradation experiments, samples from vegetated columns resulted in significantly faster kinetics. Similarly, in a field study, greater numbers of two bacterial genes that aid in hydrocarbon breakdown were found in Minnesota bioretention field sites with deeply-rooted vegetation than those sites with grass only or mulch only (non-vegetated).[56] This suggests that more complex vegetation better supports a bacterial population that can degrade hydrocarbons, potentially leading to increased removal efficiencies. Root exudates can improve PAH transformation by altering the bioavailability of PAHs, allowing bacteria to access and breakdown these pollutants.[124]

An additional plant mechanism related to hydrocarbon fate is the introduction of organic matter to the media for plant growth. The presence of organic matter in the media increases the sorption of hydrocarbons, especially for higher molecular weight PAHs with log K_{ow} values of

>4, which are less easily biodegraded than low molecular weight PAHs.[9,125] Thus, the contribution of organic matter from decaying bioretention cell vegetation may enhance oil and grease removal in bioretention, and if present in sufficient quantity, may even make introduced mulch unncessary.[121] Finally, plants can negatively impact the mineralization of hydrocarbons filtered or sorbed to the mulch and media by blocking sunlight, thus blocking photodegradation.

2.2.2.6 Pathogens. As with metals and hydrocarbons, pathogens can be removed in bioretention at a high level by the media alone, although vegetation can significantly influence pathogen removal by altering infiltration rates. It should be noted that removal, *i.e.*, fewer pathogens in effluent than influent stormwater, does not automatically constitute deactivation of the pathogens. The impacts of other vegetation mechanisms on pathogen removal rates remain untested. Pathogens, often measured as fecal coliform or *E. coli* levels but also including protozoa and viruses, can be introduced from incoming stormwater, wildlife or pet waste, leaking sewers, etc. In one study, unvegetated columns produced a mean removal of *E. coli* of 72%, which increased to 97% or greater between six and 18 months (the end of the study).[126] In another study, vegetation type had a significant effect on *E. coli* removal through the vegetation's impact on infiltration rates.[127] Greater *E. coli* removal occurred with plants that produced low infiltration rates. Nevertheless, another study reported *E. coli* removal of >90% in all treatments, planted and unplanted.[68] Fecal coliform rates varied more widely, from 56 to 99.9% removal, with media type having more of an impact on removal rate than plant presence or plant species.[68]

Plant-related pathogen removal mechanisms in bioretention include both documented influences, such as root structure, and untested (in bioretention) influences, as explained in detail herein. Root structures that facilitate slower infiltration rates are correlated with greater pathogen removal.[127,128] A substantial driver of pathogen removal in bioretention cells is the presumed result of physical filtration of the pathogens in the media. For example, in a meta-analysis, the presence or absence of shrubs explained 10% of the total variance in fecal indicator bacteria (FIB) removal rates, due to the shrubs' influence on infiltration rates.[128] Better FIB (including *E. coli*) removal occurred with plant species associated with lower infiltration rates that allow for more physical filtration. Other studies noted the presence of vegetation influenced the *E. coli* removal rate in dry conditions,[127,129] including a significant correlation between vegetation type and infiltration rate.[127] In contrast to FIB and *E. coli*, there was no correlation between bioretention vegetation and the removal efficiency of protozoa and viruses.[129] These results could be due to the decrease in soil moisture content from greater evapotranspiration in vegetated sites, the macropores and preferential flow paths created by the roots, and/or the variation in size and inherent biology between FIB and *E. coli* vis-à-vis protozoa and viruses.[130]

Vegetation is presumed to influence pathogen presence and removal through the hosting of wildlife, light screening, root exudate antimicrobial compounds, and the alteration of microbial grazers, but these mechanisms are poorly illuminated for bioretention. Vegetation, through its provision of habitat or food such as berries or browse, can attract wildlife and introduce pathogens through direct defecation in the bioretention cell.[9] Thus far, studies on animal use of bioretention are limited to insect populations, which exhibit greater biodiversity in bioretention than lawn-type greenspace,[131–133] and neglect warm-blooded animals. Secondly, UV light kills pathogens, as is widely used in wastewater treatment plants.[134] Naturally occurring sunlight therefore has the potential to kill pathogens on the surface of bioretention cells, but dense vegetation in bioretention may hinder UV light exposure.[9,135] Nevertheless, no experimental data correlating light exposure in bioretention and pathogen die off have been generated, and this remains an area for future study. Additionally, plant root exudates can contain antimicrobial compounds,[136] which can influence rhizosphere microbes. This impact is untested in bioretention. Lastly, the community of microbial predators of pathogens in the media is likely influenced by vegetation. In unvegetated columns, indigenous protozoa in the media grew logistically, with an ~10-fold increase in total number between fresh columns and ≥13-month-old columns, and may have played a role in the increase of *E. coli* removal over time, through predation.[126] The contribution of vegetation to the microbial ecology of the media, and bioretention plant-related pathogen removal generally, is an area of research that requires further study.

2.2.2.7 Emerging contaminants. Emerging contaminants are those chemicals found in the aquatic environment that are not regulated, and/or those that have become of concern in recent years.[137] Emerging contaminants may include, but are not limited to, disinfection byproducts, new-market pesticides/biocides, pharmaceuticals and personal care products, and endocrine-disruptors. Soluble emerging contaminants are susceptible to plant uptake,[52] though knowledge of this interaction in bioretention is very limited. In one study, after the equivalent of ~1.3 years of runoff applied, planted bioretention columns demonstrated >75% removal of diuron, >50% removal of methylbenzotriazole, oryzalin, and tris(3-chloro-ethyl)phosphate (TCPP), and poor removal of atrazine, simazine, and prometon.[138] Further removal for all contaminants occurred when the same bioretention systems were amended with biochar or granular activated carbon. Biochar was the most effective of the two amendments, maintaining >99% removal of all contaminants during the experiment. Additional work on the synergy between vegetation and black carbon, as well as the mechanisms of vegetation's impact on removal of these emerging contaminants, is warranted. Previous hydroponic plant uptake studies report that the relatively polar emerging contaminant benzotriazole (anticorrosive) and mercaptobenzothiazole (tire rubber vulcanizer) are rapidly assimilated by *Arabidopsis* plants and metabolized, in some cases with the metabolite being released from the plant.[52,139] These metabolites were also documented in food crops,[53] but have not yet been documented in bioretention plants. Another class of emerging contaminants of particular interest in bioretention is polar neonicotinoid pesticides. Neonicotinoids are of concern because of their ubiquity as the most widely used insecticides in the world[140] including in urban applications, their harmful impacts on non-target insect species, and their translocation within plants.

2.3 Ancillary Benefits of Vegetation in Bioretention

2.3.1 Aesthetics. Plants can increase the aesthetics of bioretention, especially compared to traditional “grey” infrastructure, translating to increased property values. The Maryland Stormwater Design Manual[141] states that, “Aesthetics and visual characteristics should be a prime consideration” for stormwater best management practices. The 2007 Prince George’s County Bioretention Manual describes how designers can increase “real estate values up to 20 percent by using aesthetically pleasing landscaping,”[142] suggesting diverse, visually pleasing bioretention vegetation rather than only turf grass. In addition to inherent plant aesthetics, vegetation may also cover visually unappealing sediment deposits,[106] and/or provide a ‘green screen’ between pedestrian and car traffic.[116]

A critical attribute of aesthetics is plant survivorship. Plants must be able to tolerate the extremes in moisture that result from occasional inundation during / immediately following storms coupled with extended dry periods due to media with high hydraulic conductivity. For example, the measured infiltration rate in a Maryland, USA, bioretention cell[32] results in water moving through the root zone in 21 minutes. Vegetation must be able to take up water during this short window and then survive during the antecedent dry period before the next precipitation event. Additionally, plants must be able to withstand any other geographic-specific stressors on plant survivorship, such as salt runoff from winter deicing operations. Vegetation must also match the desired aesthetic of the bioretention cell and surrounding area under the planned maintenance regime to maximize aesthetic value.[143] Especially in arid regions, dead/dormant vegetation can still provide aesthetic appeal that may be acceptable to the general public. Nevertheless, green plants and flowers are typically desired, especially in regions where this is the norm.[144]

2.3.2 Lessened irrigation and fertilization demands. Bioretention can decrease the need for supplemental irrigation and fertilization compared to 'traditional' landscaping choices. Because the drainage area is typically many times the area of the bioretention cell (approximately 20 times,[19] although a hydraulic loading ratio of up to 49 times has been suggested as a maximum[73]), bioretention receives a much greater quantity of stormwater and thus more stormwater nutrients than landscaping receiving only areal rainfall. Therefore, plants may be able to grow in bioretention that would not survive outside of bioretention. Nevertheless, the selected bioretention must be able to withstand the other contaminants that become concentrated in bioretention, such as metals and salt, and the rapid infiltration of water followed by dry conditions. If plants are selected that can withstand those challenges, then the influx of nutrients and water into bioretention is presumed to lessen the need for traditional fertilization and irrigation compared to a non-bioretention landscape.

2.3.3 Provision of urban 'micro' habitats. Bioretention vegetation can provide small animal habitat in urban areas. For example, a significant difference in invertebrate biodiversity between bioretention and lawn-type greenspace has been measured, with an average of 22 invertebrate species in bioretention compared to five species in lawn-type greenspace.[131,133] In this study, the highest biodiversity occurred in sites with a greater depth of leaf/plant litter, the highest number of plant taxa, and a greater quantity of mid-stratum (*i.e.*, not trees or groundcover) vegetation. Thus, bioretention cells with complex and varied vegetation have the potential to provide more invertebrate habitat than bioretention cells with only one low-growing plant species. Habitat provision, including for pollinators, is expected to be maximized when native plants are used.[145,146] Additionally, soil invertebrates and earthworms have been found in media, especially near the media surface.[147] Their presence is expected to contribute to soil development as the bioretention cell ages, especially with the contribution of root exudates and plant biomass (if the biomass is not removed after its senesce as part of bioretention cell maintenance). Further study of wildlife usage of bioretention would help quantify the ecosystem services that bioretention provides.

A possible concern for the provision of animal habitat is the use (on plants purchased for bioretention) of chemicals that maybe harmful to wildlife. For example, neonicotinoid pesticides are the mostly widely used insecticides worldwide,[140] and their inadvertent negative impacts on honeybees have received considerable attention. Neonicotinoids are used in nursery plants sold to the general public[148] (although in decreasing amounts due to negative publicity), and thus plants purchased for use in bioretention may contain neonicotinoids, providing an exposure route for pollinators in bioretention cells.

2.3.4 Food and/or Biomass Production. Plants in bioretention vegetation could be used as food crops. Global agricultural fertilizer use is projected to exceed 200 million metric tons in 2018, a 25 percent increase from 2008.[149] Fertilizer production often requires energy intensive processes, such as mining or the Haber-Bosch process for ammonia fixation.[150] In contrast, nutrient collection from stormwater is integral to bioretention without requiring additional energy input. Vegetables (beet, onion, spinach, tomato, broad bean) were grown in Australian bioretention, with yields generally similar to traditional vegetable gardens.[151] Sub-irrigation was used to reduce vegetable contact with potential stormwater contaminants, but further work is needed to examine the uptake of contaminants, including metals, into food crops grown in bioretention. This work could be informed by previous studies on the use of reclaimed water in agriculture, *e.g.*, references [53,152].

Bioretention could be used to grow crops for electricity production through biomass combustion. Switchgrass (*Panicum virgatum*) has been successfully grown in bioretention.[110,153] The energy for transportation to and from a bioretention cell is often expended as part of bioretention maintenance, which may include plant harvesting. Assuming such maintenance would occur regardless of plant type, then the net energy production of switchgrass grown in a bioretention cell could be approximately 1.9 x 10^6 kJ (527 kW-h) per year (calculations shown in ESI). This is 59% of the average 2016 monthly energy consumption of a U.S. home.[154] A case-by-case analysis will be needed, including consideration of any air pollution generated, but switchgrass growth and harvesting could be energy-generating if a biomass power plant is nearby. Biomass harvesting must not compact the media with heavy equipment that would negatively impact hydraulic conductivity.

2.3.5 Additional Benefits.

- *Thermal Attenuation.* Vegetation shades the bioretention surface, which can contribute to the thermal attenuation of the stormwater. Such thermal attenuation of stormwater in bioretention has been documented,[155] and is important for temperature-sensitive aquatic species such as trout, which may live in the receiving natural waters (lakes, streams, etc.)

of unattenuated stormwater and/or bioretention effluent. For this reason, vegetation that produces a near 100% canopy cover has been recommended for bioretention.[9] A tradeoff is that shading can increase pathogen survival at the surface of the media by blocking UV light.

- *Public Education*. Bioretention can provide important public education of water quantity and quality if signage or other communication is used (*e.g.*, Figure 3). Vegetation can provide an entry-point for this education, by drawing more positive attention to the facility that an unvegetated bioretention cell.

A University of Maryland Sustainability Fund Project

Guilford Run Bioretention Facility

RUNNING A CLEAN GARDEN: Bioretention facilities are also known as rain gardens. This facility filters runoff water before it flows into the local creek of Guilford Run, which feeds into the Anacostia Watershed. The Maryland Sustainability Engineering (MSE) students brought this facility to life.

HOW IT WORKS:
Storm water runoff from Parking Lot 1 washes into the garden facility, eventually exiting as filtered water through the underdrain pipe.

Because of the slope of the site, MSE designed the facility to have two tiers, or two garden cells at different heights. It maximizes the filtering capacity to accept runoff from 3.5 acres of land.

ABOUT MSE:
MSE is comprised of students who peered into their own community and identified the need for strong partnerships and creative engineering in order to solve pressing local problems, such as improving the health of the Anacostia watershed.

To remove pollutants, the water is filtered through absorption, microbial action and sedimentation

Stormwater runoff carries chemicals from vehicles and potentially harmful bacteria from humans and animals

terps leave small footprints
This sign uses reclaimed aluminium from the Maryland State Highway Administration.

Fig. 3: Example of onsite educational signage at a bioretention facility at the University of Maryland. (Photo: Muerdter.)

- *Climate Change Adaptation.* Bioretention has been proposed and is being implemented as a tool to help offset the hydrologic effects of climate change in urban areas.[156,157] Vegetation can increase the hydrologic resilience of stormwater infrastructure, as described herein. Bioretention plant selection should also consider possible climate change impacts on plant health.

- *Air Quality Improvement.* Vegetation has the potential to improve air quality. For example, one study demonstrated that planted biofilters can remove gaseous toluene at a significantly higher rate than unplanted biofilters.[158] Additional studies of other gas phase pollutants in bioretention conditions are needed in order to understand the contribution of vegetation to improving urban air quality via vegetation in bioretention.

3. DESIRABLE PLANTS AND PLANT TRAITS FOR BIORETENTION DESIGN

Plant type and species should be chosen with prioritized pollutant/hydrology goals in mind. Due to environmental and geographic restrictions, not all plants can be used in every location. Plant traits (Table 1) are characteristics that are more widely applicable than recommendations for specific species. Table 2 presents specific plants that are effective for a given pollutant/hydrology goal in bioretention. Additionally, we aggregate multiple bioretention design resources that provide region-specific plant recommendations (ESI).

Table 1 Plant traits that benefit pollutant removal and hydrologic performance.

Plant Trait	**Effect on Bioretention Performance**(Reference)
Plant mass	Higher plant biomass decreases nutrient effluent concentration and increases transpiration.[68,75]
Growth rate	A rapid growth rate (*e.g.*, > 10 mg g^{-1} day^{-1} relative growth rate) decreases nutrient effluent concentrations, especially when coupled with the root characteristics listed below.[74,111]
Root lipid content	High root lipid content (*e.g.*, >~0.6%) increases PAH uptake.[159](Not yet tested in bioretention)
Root length	Long roots and a large total root length of a root system (*e.g.*, ~1,000 m)[111] decreases nutrient effluent

	concentration, although roots that reach the bottom of the media may increase nutrient effluent concentration.[31]
Root mass/thickness[31,111]	Large total root mass and dense fine root patterns (*e.g.*, >40% dense roots)[111] decreases nutrient effluent concentration (although note caveat about root length above).[31] Thicker roots increase hydraulic conductivity.
High-nutrient tolerance[75]	Plants that are adapted to high-nutrient conditions will be more likely to increase nutrient removal.[75]
High water-use efficiency	Plants with efficient water use [*e.g.*, > 78 mg N (L H_2O)$^{-1}$ for tropical trees] will decrease nutrient effluent concentration.[87] (Not yet tested in bioretention)
Adaptation to bioretention microenvironment (bowl, slope, etc.) conditions[160]	Plants should be matched to water and media conditions in the different areas of the cell. This will increase plant survival, and therefore increase the potential for increased pollutant removal.[160]
Salt tolerance	For areas with road deicing salt use during winter, or other sources of salt, salt tolerance should be high.[161]
High pollutant uptake per monetary investment in plant material[162]	The cost efficiency of bioretention pollutant removal can be maximized by choosing plants that have high pollutant uptake but low purchase cost.[162]

Table 2 Summary of recommended plant traits or species to maximize pollutant removal and hydrologic performance in bioretention cells

Pollutant/ Hydrologic Behavior	**Recommended Plant Trait or Plant Species**[Reference]	**Proposed Mechanisms**	**Comments**
Aluminum	*Carex appressa*[108]	Not specified	
Cadmium	High biomass[110]	Direct uptake	
Chromium	*Carex appressa*[108]	Not specified	
Clogging	Thicker roots,[26,68] vigorous vegetation growth[27] *Melaleuca ericifolia*,[26] *Muhlenbergia lindheimeri*[68]	Macropores from thicker roots, roots shrink and expand due to weather conditions, coarse roots have slower turnover rate and grow to deeper soil depths.	Fine roots did not maintain permeability, caused clumps.
Copper	*Carex microptera*[107], *Carex praegracilis,*[107] *Correa alba,*[75] Creeping Juniper,[93] *Ficinia nodosa,*[75] *Kentucky-31*,[110] *Panicum virgatum,*[110] *Phragmites australis*[107]	Direct plant uptake	
E. coli	Plants that create low infiltration rates[127] *Leptospermum continentale*,[127] *Melaleuca incana*[127], *Palmetto buffalo*[127]	Low infiltration rate, perhaps direct uptake or rhizosphere processes	
Transpiration	High biomass[68]	Direct plant uptake	
Hydrocarbons: PAH: naphthalene	*Carex hystricina*,[124] *Dalea purpurea,*[124] *Spartina pectinate*[124]	Plant root exudates can abiotically enhance desorption of naphthalene	
Hydrocarbons: PAHs: phenanthrene and pyrene	*Helianthus annuus,*[163] *Zea mays*[163]	Direct plant uptake	Not yet tested in bioretention.
Iron	*Carex appressa*[108]	Not specified	
Lead	*Carex microptera,*[107] *Carex praegracilis,*[107] Creeping Juniper[93]	Direct plant uptake	
Manganese	Large leaf area,[111] maximized root soil depth,[111] *Carex appressa,*[75] *Melaleuca ericifolia*[75]	Not specified	

TN	High plant mass, long roots, high root mass, large root soil depth, extensive root systems, dense fine root architecture, high number of microscopic root hairs, arbuscular mycorrhizal fungi, rapid growth Prairie vegetation community,[37] *Agapanthus praecox*,[74] *Amelanchier utahensis*,[71] *Artemisia cana*,[71] *Banksia integrifolia*,[69] *Betula nigra*,[162] *Betula nigra* Dura-Heat,[162] *Bouteloua gracilis*,[71] *Buchloe dactyloides*,[68] *Callistemon pachyphyllus*,[69] *Carex appressa*,[73,75] *Carex microptera*,[77] *Carex praegracilis*,[77] *Carpobrotus edulis*,[74] *Carpobrotus glaucenses*,[69] *Cercocarpus ledifolius*,[71] *Cercocarpus montanus*,[71] *Dactylis glomerata*,[71] *Dianella brevipedunculata*,[69] *Elegia tectorum*,[74] *E. purpureum subsp. maculatum* Gateway,[162] *Ficinia nodosa*,[74,75] *Goodenia ovata*,[75] *Helianthus angustfolius*,[162] *Juncus amabilis*,[75] *Juncus effusus*,[31,71] *Juncus flavidus*,[75] *Medicago sativa*,[71] *Melaleuca ericifolia*,[73] *Muhlenbergia lindheimeri*,[68] *Panicum virgatum* Shenandoah,[162] *Pennisetum alopecuriodes*,[69] *Pennisetum clandestinum*,[74] *Phragmites* sp.,[71] *Phragmites australis*,[77] *Poaceae* family,[160] *Rhododendron indicum* L.,[164] *Salix exigua*,[71] *Schizachyrium scoparium*,[71] *Sorghastrum nutans*,[71] *Stenotaphrum secundatum*,[74] *Typha* sp.,[71] *Typha capensis*,[74] *Zantedeschia aethiopica*[74] Avoid: *Carex praegracilis*,[77] *Poa pratensis*,[37] *Scirpus acutus*,[77] *Scirpus validus*,[77] specified shrub community[37]	Direct plant uptake, microbial uptake, fungal uptake, increased infiltration	

TP	Large root mass, long roots, extensive root systems, many root hairs *Agapanthus praecox,*[74] *Banksia integrifolia,*[69] *Betula nigra,*[162] *Betula nigra* Dura-Heat,[162] *Buchloe dactyloides*,[68] *Callistemon pachyphyllus,*[69] *Carex appressa,*[75] *Carex microptera,*[77] *Carex praegracilis,*[77] *Carpobrotus edulis,*[74] *Carpobrotus glaucenses,*[69] *Dianella brevipedunculata,*[69] *Eutrochium purpureum* subsp. *maculatum* Á. Löve & D. Löve Gateway,[162] *Helianthus angustfolius,*[162] *Muhlenbergia lindheimeri*,[68] *Panicum virgatum* Shenandoah,[162] *Pennisetum alopecuroides,*[69] *Pennisetum clandestinum,*[74] *Phragmites australis,*[74,77] *Rhododendron indicum,*[164] *Stenotaphrum secundatum,*[74] *Typha capensis,*[74] *Zantedeschia aethiopica*[74]	Direct plant uptake, microbial immobilization (increased by plant presence), increased infiltration	Media pH should also be considered, for its effect on the sorption of P onto media
PCBs	*Helianthus annuus,*[163] *Zea mays*[163]	Direct plant uptake	Not yet tested in bioretention. Highest concentrations were in plant roots, not shoots.
Zinc	*Bromus ciliates,*[110] *Carex microptera,*[107] *Carex praegracilis,*[107] Creeping Juniper,[93] *Kentucky-31*,[110] *Panicum virgatum,*[110] *Vinca minor*[106]	Direct plant uptake	

Generally, plants with high above-ground biomass and thick, extensive roots are recommended to improve pollutant removal, increase transpiration, and prevent media clogging. High-biomass plants generally (but not always) maximize the mass of contaminants assimilated into plant biomass. Even if uptake rates are less than small plants, the overall greater biomass may result in greater removal. Roots that are thick and penetrate a large proportion of the media but do not reach the bottom of the bioretention cell are recommended to improve pollutant removal, increase stormwater-media contact, increase transpiration, and prevent clogging. Roots that do not penetrate to the bottom of the media are recommended to avoid preferential flow paths to the bottom of the bioretention cell, which may lessen pollutant removal performance.[31] Thick roots improve hydraulic conductivity.[26] Bulbous roots may lead to preferential flow paths and erosion, but research to confirm this assertion in bioretention is needed.[160] Root depths and shapes vary widely between species: for example, roots of native North American prairie plants are typically orders of magnitude deeper than turfgrass such as Kentucky bluegrass.[165] In one study, prairie plants were the only treatment to produce positive nitrogen removal efficiency.[37] Turfgrass, shrub, and bare soil treatments had negative nitrogen removal efficiencies. Different plants also alter media hydraulic performance, with prairie plants producing less total drainage out of bioretention than other plants or bare soil,[37] and shrub and prairie treatments having less soil moisture between storms at their rooting depth than the turfgrass treatment and no-plant control.[28]

Bioretention plants should have high nutrient uptake capacity to maximize pollution control benefits. Nutrient uptake may be achieved through high N and P fraction in biomass and/or high total biomass. Many native plants do not exert a high nutrient demand; for example, some plants have evolved in low-nutrient soils rather than the higher-nutrient conditions in bioretention.[75]

Those plants may struggle with growth in bioretention and contribute less efficiently to nutrient uptake than plants adapted to high-nutrient conditions.

Vegetation maintenance is an important consideration for maximizing biomass and therefore nutrient removal. For example, experimental cutting regimes of *Juncus effusus* (recommended for bioretention) in non-bioretention conditions in Norway found that cutting back to 1 cm of remaining stubble resulted in significantly less regrowth than leaving 5 cm of stubble.[166] Regrowth also varied with the time of cutting.

Bioretention plants should also be suited to the microenvironment of the particular section of the bioretention cell. For example, the bottom surface of the bioretention cell, rather than the sloping sides of the bioretention cell ponding area, will receive the most stormwater. Additionally, locations close to the inlet will receive the fastest-moving stormwater. Therefore, the plants at the bottom of the bioretention cell that are closest to the inlet need to be the most tolerant of high flows and frequent inundation. Finally, local conditions should be taken into account, e.g., salt-tolerant plants in cold weather climates where deicing salt is employed.

4. CONCLUSIONS

4.1 Bioretention Vegetation Role in Bioretention

The role of bioretention in vegetation is significant and complex. Plant processes in stormwater management green infrastructure have received considerably more research attention in recent years than previously, but important research gaps remain. From a hydrologic perspective, vegetation can decrease erosion of the bioretention cell surface, enhance infiltration of water into the media, prevent media clogging over time, and transpire water out of the bioretention cell. Thick roots and vigorous vegetation growth are recommended for clogging prevention. Rooting depth and planting density are important parameters, with hydrologic impact, that require further study. Vegetation impacts stormwater quality through a variety of mechanisms, including phytoextraction, phytotransformation, and rhizosphere processes. In terms of specific pollutants, vegetation does not have a large impact on TSS removal. Vegetation typically has a significant impact on nitrogen removal, with important variations between plant species. Phosphorus removal appears less impacted by plant selection than nitrogen, but plants with high P uptake/media influence capacity can significantly affect P removal. The majority of metal and hydrocarbon removal is attributed to non-plant mechanisms, though both pollutants have been found in bioretention plant tissue biomass, and plants can alter the abiotic and microbial removal mechanisms in the rhizosphere through root exudates. Pathogen removal is similar, with influence on infiltration rate as the main documented plant-related influence. The removal of some emerging contaminants has been documented in bioretention, but further work on the role of vegetation in this removal is needed.

Bioretention vegetation has benefits beyond hydraulic and pollutant removal processes. Plants make important contributions to bioretention aesthetics, can lessen irrigation and fertilization demands, provide animal habitat, produce food and/or biomass, create thermal attenuation of stormwater, enable public education, and contribute to climate change adaptation. Plants should be chosen with specific pollutant priorities in mind based on of specific plants / plant traits that have demonstrated improvement to bioretention (Tables 1 and 2). Most generally, plants with high above-ground biomass and thick, extensive roots are recommended to improve pollutant removal, increase transpiration, and prevent media clogging. Bioretention plants should have high nutrient uptake capacity to maximize pollution control benefits, and be suited to the part of the bioretention cell in which they are planted.

4.2 Future Research Areas

Based on the above findings, the authors propose several research needs for future work, as described below.

- A greater emphasis on the transferable basis for research findings. Focus research on transferable processes that provide a mechanistic understanding of pollutant removal processes and hydrology, not just "black box, in-out" findings. A deeper understanding of plant traits that can transcend regional boundaries/plant ranges, *e.g.*, those listed in Table 1, to allow for the wider application of research results. Additionally, the impact of bioretention age on vegetation performance, especially on bioretention of >2 years, requires study. Mesocosm studies are generally conducted in less than two years; field conditions after two years are expected to deviate from these results.
- Better understanding of below-ground, plant-facilitated pollutant removal mechanisms. Specifically:
    - Greater elucidation of the interaction of plant roots, and particularly root exudates, with the media and microbial community. For example, root exudates may provide a sustainable carbon source for denitrification.
    - Further work on how plant density and root depth impact contaminant removal. Experiments should examine differential pollutant removal in systems of varied rooting depths (*i.e.*, those that reach the bottom of the media and those that do not) and plant densities.
    - The role of mycorrhizae in facilitating pollutant removal. Mycorrhizal inoculations have the potential to greatly improve bioretention function, especially for nutrients and organic contaminants, and have been understudied.

- Plant shoot harvesting: quantification of the permanent removal of plant-assimilated pollutants from bioretention and the effect on post-harvest plant growth. If harvesting will occur, the feasibility of biomass crops should be investigated.
- In addition to continuing work on nutrients and other more well-studied pollutants, the impact of bioretention vegetation on other stormwater pollutants:
    - *Emerging contaminants*, particularly polar pollutants that can be assimilated into plant tissues and present the greatest risk to groundwater during infiltration. Given the potential for recycled water use in bioretention,[97,167] and the increasing quantities of trace organic contaminants in treated and environmental waters, plant interactions with emerging contaminants demands investigation. The potential synergy between vegetation and black carbon or other novel geomedia in this area should be studied.
    - *Metals*. Additional tests of metal hyperaccumulators and high-biomass metal accumulating plants in bioretention conditions to find plant species that can maximize metal removal. Also, further study is warranted on the ultimate fate and impacts to wildlife that consume the plant tissue.

Vegetation plays an important role in bioretention functioning. Studies thus far have developed the understanding of many of these roles, but continued work on vegetation function will further illuminate plant processes to fully maximize bioretention hydrologic and pollutant removal performance.

ELECTRONIC SUPPLEMENTARY INFORMATION (ESI). Table of representative vegetation bioretention design resources, biomass energy production calculation assumptions.

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