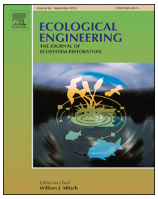
Ecological Engineering 120 (2018) 532–545

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Review

The role of plants in bioretention systems; does the science underpin current guidance?

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ARTICLE INFO

Keywords:
Stormwater
Green infrastructure
Vegetation
Functional traits
Rhizosphere
Plant diversity

ABSTRACT

Plants are essential components of bioretention systems, with bioretention design-guides around the world providing extensive advice on the role of selection of plants to maximize system performance and sustainability. Four principal hypotheses regarding the role of plants have been identified in bioretention design manuals: (i) Planted systems are more effective than unplanted systems, (ii) Plant species differ in their effectiveness, (iii) Native species are more effective than exotic ones, (iv) Diverse systems are more efficient than monocultures. This paper examines the extent to which these hypotheses are supported by the scientific literature. Comparison of planted and unplanted systems show that increased permeability and hydraulic conductivity, as well as removal of nitrogen, are the main benefits of the presence of plants in bioretention. Knowledge on their positive effect on hydrocarbons remains fragmented, although there is evidence from phytoremediation studies in other plant-based technologies. Choosing the right species makes a difference in hydraulic performance and nitrogen removal, with root traits being identified as important predictors of performance. No scientific results can support the hypothesis that native plants or diversely-planted systems offer better performance than systems planted with fewer species or with exotic species. Questions remain regarding the plant-microbe interaction in the bioretention context, the role of biomacropores in pollutant migration or the differential impact of plant choice on performance.

1. Introduction

Without appropriate mitigation strategies, impervious areas and hydraulically efficient drainage systems created as part of the process of urbanization, pollute and degrade receiving waters, leading to the 'the urban stream syndrome' (see for example Roy et al., 2009; Walsh et al., 2005). Traditionally, stormwater has been managed with a singular focus on flood mitigation (Chocat et al., 2001; Fletcher et al., 2015). However, recent decades have seen the evolution of alternative approaches, aimed at reducing the degradation of receiving waters, by restoring more natural flow regimes, reducing the concentrations and loads of pollutants, and returning a more natural site water balance.

A wide range of stormwater treatment technologies or *stormwater control measures* (SCMs) has been developed to address these objectives. Some of them are highly sophisticated engineered systems, often simultaneously designed to reduce runoff volumes, promote evapotranspiration and infiltration, and to ensure treatment or retention of pollutants (e.g. Van Roon, 2005).

One of the most promising of the SCMs is the suite of technologies commonly called *bioretention* or *biofiltration* systems (Fig. 1) (Bratières et al., 2008b). Often also called 'raingardens', swales or bioswales, they are favored not only for their demonstrated pollutant removal (City of Portland, 2014; Davis, 2007; Davis et al., 2001; Hatt et al., 2009; Hunt et al., 2008; Trowsdale and Simcock, 2011), but also for their flexible incorporation into the urban landscape (Bratières et al., 2008b; Ellis, 2013). Like many of the green infrastructure technologies, they provide a range of co-benefits including enhancement of local biodiversity (Kazemi et al., 2009), mitigation of the urban heat island effect (Coutts et al., 2012; Wadzuk et al., 2015) and benefits for human health and well-being (Church, 2015; Dill et al., 2010).

Given this wide range of benefits, it is perhaps not surprising to see the use of bioretention systems becoming increasingly popular (Bratières et al., 2008b). As in most areas of practice, professionals involved in their implementation rely heavily on local, regional or

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https://doi.org/10.1016/j.ecoleng.2018.07.007
Received 5 February 2018; Received in revised form 25 June 2018; Accepted 7 July 2018

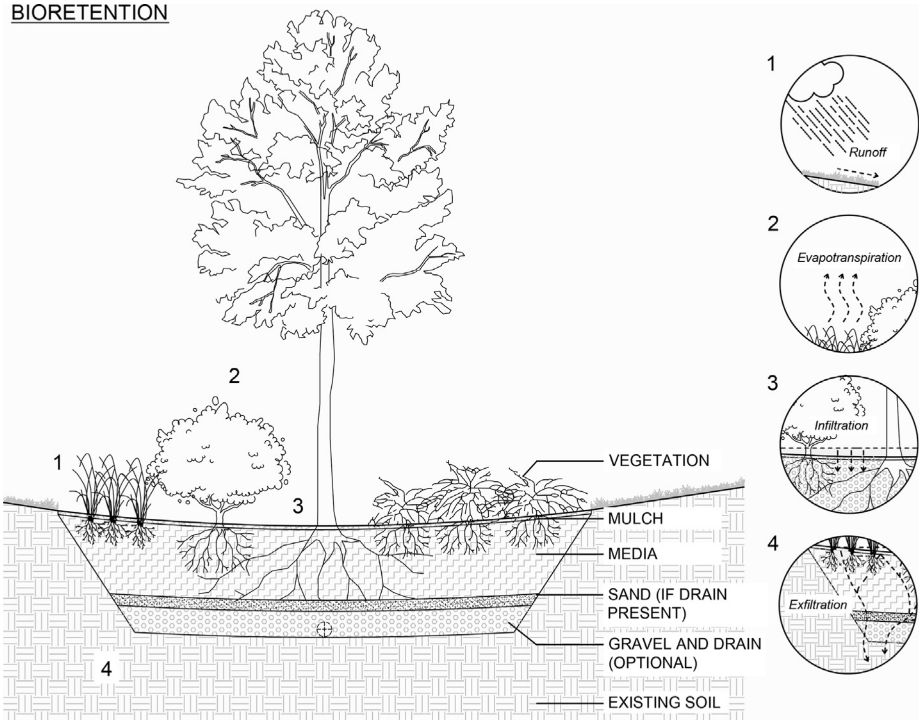

Fig. 1. Schematic representation of the structure and main water fluxes in a bioretention system.

national guidelines on the design, construction and maintenance of bioretention systems. In recent years, many such manuals have been developed (e.g. City of Portland, 2014; Minnesota Pollution Control Agency, 2014b; Philadelphia Water Department, 2014). In some regions, such manuals are even applied as standards (e.g. Hasenin et al., 2011). The recommendations provided in these manuals are thus likely to be quite influential on the design and ultimately the performance of stormwater bioretention systems around the world.

The various bioretention guidelines around the world contain many hypotheses and statements regarding the performance of bioretention systems and specifically on the influence of vegetation on this performance (Table 1). Some even provide information about the effects of the type of vegetation used eg.: “*Plants with fibrous root systems are more effective in bioretention systems than those with tap root systems*” (Water by

Table 1
Statements regarding the role of vegetation in the performance of bioretention and examples of quotations from the manuals.

Categories of frequent statements	Examples of quotations	Explanations
Vegetation is essential for the functioning of bioretentions	“Vegetation is a vital component of the environmental and hydrologic function of LID practices. Plants are effective in slowing and soaking up runoff and treating pollution through various natural processes” (Toronto and Region Conservation Authority & Credit Valley Conservation Authority, 2010, p. 5)	“The beneficial functions plants perform in the landscape are varied and complex, and range from providing habitat for beneficial microbes to physically inhibiting the flow of stormwater. The ability of plants to intercept and hold rainwater and to decrease water flow with stalks, stems, branches and foliage is one of the better recognized functions of vegetation, but there are many others” (Shaw & Schmidt, 2003, p. 1)
Vegetation maintains soil porosity and contributes to the removal of TSS, nutrients, metals and organics, more specifically hydrocarbons	“Plants in bioretention systems have been shown to improve dissolved nutrient removal, improve hydrocarbon removal and aid TSS sequestration”, (Minnesota Pollution Control Agency, 2014a) “…the vegetation in bioretention gardens uses the nutrients found in stormwater as it grows. Plants also take up metals, organics and other pollutants to be used by the plant, stored as a by-product in specialised cells, or transformed through enzymatic action by plant cells” (Malcolm & Lewis, 2008, p. 4)	“High plant surface area and soil organics” are associated with the “biological microbial decomposition” of “BOD, COD, petroleum hydrocarbons, synthetic organics, pathogens», «Plant uptake and metabolism» and «high plant activity (and) surface area» are linked to “N, P (and) metals uptake and metabolism” and finally “plant excretions” to the “natural die-off of pathogens” (Auckland Regional Council, 2003, pp. 4–10) “Root growth and decay provides micro-pathways for water infiltration and oxygen movement and limit the potential for the filter media to become clogged” (Water by Design, 2014, p. 87) “The nutrient removal efficiency of biofiltration systems is related to the root structure and density of the plants within the system” (Payne et al., 2015, p. Appendix K) “Denitrification requires organic matter as a carbon source, which is supplied by decaying root matter and mulch” (Minnesota Pollution Control Agency, 2016a)
Phosphorus removal is mainly or exclusively due to the media, not to the vegetation	“Principal mechanisms for phosphorus (P) removal in bioretention are the filtration of particulate-bound P and chemical sorption of dissolved P” (Minnesota Pollution Control Agency, 2016b)	

Design, 2014, p. 86). The question therefore arises as to whether the recommendations in bioretention guidelines are based on well-founded scientific findings. In related technologies such as constructed wetlands, studies have shown the essential role that vegetation and vegetation selection play (Gagnon et al., 2012; Vymazal, 2011).

The aim of this article is to test the extent to which hypotheses and assumptions concerning the role and choice of vegetation contained in many of the recognised bioretention guidelines are supported by the scientific literature. We focus here only on vegetation (rather than, for example, the specification of filter media or drainage layout), because this topic, while complex and of primary importance, remains poorly understood in the context of bioretention systems (Payne et al., 2013). We identified recommendations or statements pertaining to plants in manuals on bioretention (Annex A) and summarized these recommendations into four general hypotheses:

A. Planted systems are more effective than unplanted systems.
B. Plants species differ in their effectiveness.
C. Native species are more effective than exotic ones
D. Diverse systems are more efficient than monocultures.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoleng.2018.07.007.

These hypotheses are not independent from each other (for example, hypotheses B, C and D suppose that hypothesis A is true). Furthermore, the validity of these hypotheses depends on the performance objectives considered (for example, hypotheses A may be true for nitrogen removal but not for increased soil porosity). In our evaluation, we considered effectiveness of bioretention systems in terms of hydraulic and hydrologic properties, and in terms of pollutant removal (Table 1). In assessing the degree to which current recommendations included in bioretention manuals reflect the state of current scientific understanding, we also identify knowledge gaps and needs for future research.

2. Hypothesis A: Planted systems are more effective than non-planted

2.1. What the manuals say

We can hardly imagine a bioretention system, or "raingarden", without vegetation. Yet, on a purely functional basis, the question of the beneficial contribution of plants in hydraulic or pollutant removal is not trivial. Even without plants, the functions of a bioretention system will be, at least partially, fulfilled by the passage of the water through the soil media. Purely physical and chemical processes such as filtration, adsorption and precipitation will contribute to pollutant removal. Biofilm on the soil media and bacteria in the water will be responsible for several catabolic reactions such as nitrification, oxidation, fermentation, etc. Media porosity allows for infiltration, temporary storage and then exfiltration through the subsoil, all of which act to attenuate peak flows (Davis et al., 2012). Yet, not surprisingly, stormwater management manuals generally put forward the benefits of using vegetation in bioretention. Some manuals underline the role played by vegetation in meeting distinct hydraulic, hydrologic and treatment goals. For example, Water by Design (2014) states (p. 16) that "*Vegetation takes up nutrients, supports biological growth (critical for stormwater treatment), maintains and enhances the porosity of soil, and continuously breaks up the surface of the filter media to help to prevent surface clogging*" (see Table 1 for other quotations). According to these guidelines, vegetation maintains soil porosity and contributes to the removal of TSS, nutrients, metals and organics. The manuals may provide a theoretical explanation for the role of vegetation or they may give indications of the vegetation traits (root structure, growth rates, plant size, tolerance to bioretention conditions) that are linked to various functions of the bioretention. For example, Payne et al. (2015) note the role of root structure and density in determining pollutant removal efficiency (Table 1). However, most manuals recognize that phosphorus removal occurs mainly through adsorption to the media, with little contribution by the vegetation.

2.2. Theoretical background: Where the statement originates from

Plants may be considered as true ecosystem engineers: they pump water through plant transpiration, trap sediments, uptake nutrients, release oxygen and organic compounds from their roots, offer substrate for bacterial growth, etc. Through these characteristics, they positively contribute to many of the functions of bioretention systems (Table 1). In terms of system hydraulics, the growth, senescence, death and subsequent degradation of plant roots create pores that help maintain soil porosity, thus increasing the overall infiltration rate of the soil (Gonzalez-Merchan et al., 2012; Le Coustumer et al., 2012). This can improve the hydrologic performance of a bioretention system by reducing the amount of bypass or overflow, and by maximising the amount of infiltration-flow (water which infiltrates through the filter media and then to underlying soils and groundwater) or filtration-flow (water which flows through the filter media and is then collected by an underdrain). However, roots may also result in the creation of macropores which lead to preferential flow paths, in turn reducing the treatment effectiveness and resulting in migration of pollutants. Such behaviour has been observed in agricultural contexts (Beven and Germann, 1982; Gärdenäs et al., 2006) and on green roofs (Zhang et al., 2018).

Pollutant removal in bioretention systems involves several physical, chemical and biological processes, and depending on the pollutant involved, plants may play a direct or indirect role in water treatment. Plant uptake directly removes nutrients and metals such as nitrogen and phosphorus from the water. Plants also show varying degree of uptake of certain metals and metalloids, and some plant species are even considered hyperaccumulators for their high capacity to absorb and concentrate certain metals in their shoots and leaves. Harvesting the aboveground portion of the plants may remove permanently the nutrients and pollutants stored in plant tissue (Ali et al., 2013). However, in theory, a large part of the water treatment in the bioretention is the direct result of microbial processes rather than plant uptake: mineralization of organic molecules, nitrification-denitrification, etc. By releasing oxygen and exudates in the rhizosphere, plants may play an important indirect role in water treatment by providing favourable conditions for bacterial activity. For example, the rhizosphere creates ideal conditions for the coupled nitrification-denitrification, through the creation of adjacent pockets of oxygenated and deoxygenated soils (Payne et al., 2013).

Hydrocarbons tend to sorb to soil or root surfaces or be incorporated into organic material (Hutchinson et al., 2003). Given the high molecular weights and sorption potential, low solubility and hydrophobic properties of most hydrocarbons (PAH in particular), plant uptake, while possible, is not expected in great quantities (Hutchinson et al., 2003; Kamath et al., 2004; Shahsavari et al., 2015; Surridge et al., 2009). The most important mechanism of hydrocarbon removal is through soil microbial degradation (Kamath et al., 2004). However, plants may play an indirect but important role in hydrocarbon degradation by releasing oxygen and root exudates, thus promoting microbial growth and activity in the rhizosphere (Chaudhry et al., 2005; Kamath et al., 2004).

Stormwater runoff flows on surfaces which may be contaminated with faeces. Consequently, stormwater transports human pathogens such as enteric viruses (e.g. Hepatitis E), bacteria (e.g. *Campylobacter* spp., *Salmonella* spp., *Eschericia coli* O: 157.H7), and protozoa (e.g. *Cryptosporidium parvum* and *Giardia duodenalis*) (Ferguson et al., 2003). The fate of such pathogens in the environment depends on environmental conditions such as moisture, pH, temperature, sunlight and the presence of competing predating bacteria (Bitton, 2005; Engström

Table 2
Qualitative summary of effect of plants on bioretention performance based on scientific studies. Role of plants: negligible (0), minor (+), important (+ +), crucial (+ + +), minor to negative (+ −), more studies needed (?).

Bioretention system functions	Possible mechanisms for beneficial contribution of plants	Empirical evidence from experimental studies	Qualitative role of plants on performance
Hydraulics	Transpiration	Small size of bioretention, small leaf area relative to the catchment area No transpiration studies just ET. No unvegetated control. Deduction from other studies Difficulty of measuring transpiration	+
	Permeability/porosity Growth, senescence, death and subsequent degradation of plant roots create pores which help maintain soil porosity	Macropore development by plant roots. More studies needed to support the statement that vegetation helps maintain permeability in bioretention	+ +
Sediment filtration	Aerial parts reduce velocity of runoff and promote sedimentation of suspended solids	No effect of plants according to empirical studies	0
Nitrogen removal	Removal through plant uptake. The rhizosphere offers ideal conditions for nitrification-denitrification, through the creation of adjacent pockets of oxygenated and deoxygenated soils	Unvegetated bioretention may in fact lead to net nitrogen export almost all nitrate removed by biotic assimilation	+ + +
Phosphorus removal	Removal through plant uptake	Possible positive rhizosphere effect for well-established plant communities in unsaturated soil. Otherwise no effect	+
Metals removal	Removal through plant uptake	Removal very high due to soil and mulch. Plant uptake low (e.g. 0,5%–14% of total retention of metals). Alteration of soil properties by plants (lower pH, more soluble OM) can increase metals in effluent	+ −
Pathogens removal	Reduction soil moisture Stimulation of competition and predation by other microorganisms and biofilms	Contradictory results from different studies. If permeability is increased, retention time and hence pathogen removal are reduced. Aging of a planted system could have an impact on the infiltration rate and the development of the microbial community	?
Organics (hydrocarbons) removal	Removal through plant uptake (possible but limited) Rhizosphere creates conditions that promote bacterial degradation of hydrocarbons	No effect or indirect effect through increase of microbial activity in the rhizosphere	?

et al., 2013; Nasser, 2016; Stevik et al., 2004). Plants in bioretention systems may have a dual effect on the removal of pathogens. On the one hand, plants can augment their removal by reducing soil moisture, producing root exudates and favouring growth of other microorganisms and biofilms that can enhance straining, competition and predation (Engström et al., 2013; Mendes et al., 2013). On the other hand, plants may negatively affect removal through the production of protective organic matter, and through shading (Wu et al., 2016).

2.3. What is the scientific evidence supporting the hypothesis?

The obvious approach to measure the contribution of plants to the various functions of bioretention systems is to compare planted and unplanted systems. However, very few experimental studies have included unplanted controls. Thus, much of what we know of the effect of plants on bioretention performance comes from indirect evidence, as described below. (See Table 2 for Qualitative summary of effect of plants on bioretention performance based on scientific studies).

2.3.1. Hydraulics (permeability, preferential flow path, infiltration rate, etc)

Studies on the impact of vegetation on the water balance of bioretention systems are relatively rare. While this might seem surprising, it testifies perhaps in part of the difficulty of measuring evapotranspiration in bioretention systems, requiring specialised flux chambers (Hamel et al., 2014) in the field or specialised lysimeters in laboratory applications (Denich and Bradford, 2010). It also likely reflects the relatively small size of bioretention systems relative to their catchment (Bratières et al., 2008b), meaning that the leaf area is very small relative to the inflow. For example, Hamel et al. (2011) measured the water balance of an infiltration-based bioretention system in clay soils, considering not only the evapotranspiration in the bioretention system itself, but also the surrounding soils. Over a year, they observed that evapotranspiration contributed to less than 10% of the total water balance. Similarly, the lysimeter-based analysis of Denich and Bradford (2010) showed ET rates in an established bioretention system of around 3–8 mm/day. For a bioretention system making up 2% of its impervious catchment area, this is equivalent to 0.06–0.16 mm/day over the entire catchment area. Even for a system making up 10% of its catchment area, the ET loss would only be 0.3–0.8 mm/day. Li et al. (2009), however, observed ET losses of around 19% of inflow, suggesting that vegetated bioretention systems could make significant contributions to restoring pre-development ET, with the limiting factor being their relatively small surface area. In another lysimeter study, bioretention ET was found to equal 3.1 mm/day for a freely draining system and 6 mm/day for a system with an internal water store at the base (Wadzuk et al., 2015), similar to the results of Denich and Bradford (2010). Unfortunately, none of these studies used a non-vegetated control, allowing the evaporation component to be separated from transpiration, but the dominance of transpiration in the evapotranspiration flux can be deduced from studies in similar vegetation types (e.g. Liu et al., 2008; Sadras, 2006)

Several studies have demonstrated an influence of vegetation on the evolution of permeability over time in stormwater bioretention systems. For example, Lucas and Greenway (2008a,b) found that vegetated bioretention columns had greater infiltration rates than unvegetated systems. Pham et al. (2012) conducted a similar study, but found less clear results, with vegetated columns in some cases having a lower infiltration rate in the first 18 months after column establishment. However, these results should probably be interpreted with caution, given that the columns were particularly small (100 mm diameter), which may have artificially influenced root development and distribution, or suffered from edge effects (Lang et al., 1993).

Field studies thus perhaps provide the most reliable evidence for the influence of vegetation on bioretention infiltration performance. Two recent studies compared adjacent planted and unplanted areas in infiltration systems (Gonzalez-Merchan et al., 2012) and bioretention systems (Virahsawmy et al., 2013), both showing higher infiltration rates in planted areas. In an earlier study, Lewis et al. (2008) measured infiltration rate in a bioretention system over an 18 month period, observing a rapid decrease as the system became compacted by hydraulic loading and solicited by fine sediment. However, they then observed a significant increase in infiltration performance towards the original value, a phenomenon they attributed to macropore development by plant roots.

Overall it would appear that empirical evidence supports the theory that vegetation increases or maintains bioretention system permeability, although this is an area that requires further research. Similarly, the potential for plant-created macropores to create preferential flow paths, leading to pollutant migration, has not been adequately studied in the bioretention context.

2.3.2. *Sediments*

Vegetation can influence sedimentation through two mechanisms. Firstly, the previously-described increase in roughness decreases flow velocities, increasing time for sedimentation of particles to the soil surface. Such behaviour is widely observed in vegetated swales (Barrett et al., 1998; Deletic and Fletcher, 2004) as well as in wastewater and stormwater treatment wetlands (Wong et al., 2000). While vegetation may thus play a role in sedimentation within the ponding zone, it is less likely that the presence of vegetation will have a major effect on removal of sediment through the filter media. Sediments will likely be removed through simple filtration within the filter media, as occurs in simple unvegetated sand filters for example (Siriwardene et al., 2007).

Broadly most studies show what theory would suggest; removal of sediment through bioretention filter media does not vary significantly between vegetated and unvegetated configurations. The bioretention studies that specifically address this question have all found consistent performance regardless of the presence of vegetation. No influence of vegetation type was found in studies conducted by Bratières et al. (2008b), Ellerton et al. (2012) and Read et al. (2008). It can thus be assumed with confidence that sediment removal performance of bioretention systems will typically be high, regardless of the presence of vegetation.

2.3.3. *Nitrogen*

In urban runoff, only a small proportion of nitrogen is in particulate form, with Taylor et al. (2005) finding that around 75–85% of nitrogen was in dissolved forms. This means that, except for adsorption, nitrogen removal will depend significantly on biological processes. These include decomposition (mineralisation) of organic nitrogen, reduction of ammonia to nitrite and then to nitrate (via nitrification), denitrification of nitrate (and subsequent release to the atmosphere as gas), and assimilation of nitrate by microbial and plant biomass (Payne et al., 2013). The question of the long-term fate of nitrogen in bioretention systems remains important, given the likely senescence and subsequent degradation of organic matter. Permanent losses of nitrogen from bioretention systems will depend on denitrification (which in turn depends on the presence of nitrate, created by nitrification).

There is a wide range of studies which demonstrate the importance of vegetation for nitrogen removal in bioretention systems, either direct or indirect. For example, many studies show that unvegetated bioretention configurations can result not only in poor nitrogen removal performance, but may in fact lead to net nitrogen export (Bratières et al., 2008a; Hatt et al., 2007a,b; Henderson et al., 2007). In exploring the role of vegetation and associated microorganisms, Payne et al. (2014) used a labelled $^{15}NO_3^-$ isotope to trace the fate of influent nitrogen in bioretention columns. Interestingly, at “typical” stormwater concentrations and with low organic matter substrate, they showed that the vast majority (89–99%) of the labelled nitrate was removed by biotic assimilation (i.e. assimilation by “plants, bacteria fungi and other microbes” (Payne et al., 2014, p. 2), with only 0–3% being removed by denitrification, thus seemingly disproving the previously-assumed dominant role of denitrification (Zinger et al., 2013), which in part derives from studies conducted using bioretention media without vegetation (Kim et al., 2003). Many studies have been conducted in various environments (wetland, agricultural fields etc.) to investigate the mechanisms of nitrogen removal. Bioretention systems themselves are distinct from these previously studied environments, as they are characterized by alternate cycles of wetting and drying, by variable as well as low nutrient and pollutant inputs, and by the use of plants that can withstand these conditions. All these factors can have an effect on the fate of nitrogen in these systems. The removal of nitrate might also be temporary, since once assimilated, the nitrogen contained in plants can be released again upon senescence (Lee et al., 2009). Consequently, despite the advances made by Payne et al. (2014), more studies are needed to elucidate the exact mechanisms responsible for nitrogen removal (biotic assimilation vs denitrification) in bioretention systems, especially in field conditions, as column studies might exaggerate the role of plants due to their high root-to-media ratio (Freckleton et al., 2009; Passioura, 2006).

2.3.4. *Phosphorus*

Phosphorus occurs in runoff as soluble or insoluble complexes, and in both organic or inorganic forms (see Roy-Poirier et al. (2010) for an overview of phosphorus forms and cycle in bioretention systems). Because phosphorus interacts strongly with soil particles, it is assumed that retention in bioretention systems occurs mostly through passive sedimentation and adsorption to the substrate. Thus, one common approach to increase phosphorus removal is by incorporating material with high phosphorus sorption capacity (lightweight aggregates, blast furnace, media rich in calcite or ferric oxyhydroxide, etc.). However, phosphorus storage through precipitation and sorption decreases over time as substrate saturation occurs. Phosphorus in its dissolved forms (mostly dissolved phosphates) is also taken up by plants and incorporated in the biomass, and later is released as the plant material decomposes. Harvesting of this plant material may remove phosphorus from the system. Kadlec and Scott (2008) report that the aboveground harvestable amount of phosphorus of standing crops is quite constant, typically ranging from 1 to 5 g P/m^2. Assuming one harvesting per year, this gives an estimation of the total possible amount of phosphorus that could be removed. This amount could be compared to phosphorus input in order to evaluate what fraction of phosphorus may effectively be removed through harvesting, and if it is worth to do so. Nevertheless, harvesting plants to increase phosphorus removal in water or soil has sparked much interest since then (Roy, 2017).

Measures of biofilter performance in total phosphorus removal have been reported as ranging from moderate to good, but the specific contribution of plants has rarely been measured. For example, using biofilter mesocosms planted with *Carex rostrata*, Blecken et al. (2010) obtained phosphorus removal above 90%, but as the input phosphorus was largely particulate, the authors surmised that most of the removal was due to physical processes such as sedimentation and filtration as the main modes of retention. A few experiments have compared phosphorus removal in planted and unplanted biofilters columns to evaluate the contribution of plants (e.g. Zhang et al., 2011), finding no difference in phosphorus removal between planted and unplanted. Lucas and Greenway (2008a,b) found greater phosphorus retention in planted bioretention mesocosms that was not explained by simple phosphorus uptake. They concluded that the soil rhizosphere in well-established plant communities may facilitate sorption capability in unsaturated soil, but that minimal positive effect of vegetation is expected in soil saturated with phosphorus.

2.3.5. *Metals*

Metals in runoff are strongly associated with total suspended solids. Only a very low percentage of metals, as low as 3%, remain in the liquid phase (Djukić et al., 2016). TSS sedimentation and filtration are therefore expected to be the main removal process for metals in bioretention, rather than plant uptake.

Removal of heavy metals by bioretention is generally excellent, more than 95% both in column pilot studies and some field studies (Blecken et al. 2009; Hatt et al., 2009). Lower removal of copper, lead, or zinc (43%–70%; std 11%–42%) was nevertheless found in some field studies (Davis et al., 2003; Hatt et al., 2008; Li et al., 2011). Cu removal in particular is very variable; from high to even negative (Bratières et al., 2008a; Hatt et al., 2008; Li and Davis, 2008; Li et al., 2011; Trowsdale and Simcock, 2011). The export of copper from the bioretention could be due to slow-release fungicides in the potting mix or used on plants in the nursery» or from contaminated sediments. Very low copper concentrations in the inflow as well as complexation with soluble organic matter can exacerbated this phenomenon (Li and Davis, 2008; Trowsdale and Simcock, 2011).

Studies conclude that metal pollutants are mainly retained by soil and mulch, the latter being the most efficient on a per weight basis, but in some cases plants can act as hyper-accumulators, making a significant contribution to metal retention (Davis et al., 2001; Muthanna et al., 2007a,b; Sun and Davis, 2007). Besides accumulating metals in their tissue, plants could also have an impact on the immobilization of metal in the substrate by their effect on soil conditions and microbial populations. Comparison of metal removal by planted and unplanted systems takes these phenomenon into account. However, Read et al. (2008) found no difference between vegetated and unvegetated pots for mean removal of Al, Cr, Cu, Pb and Zn, in a trial including 20 Australian species. Bratières et al. (2008a) found no effect of vegetation on Pb, Zn, Cu in an experiment with a subset of the species studied by Read et al. (2008) and Zhang et al. (2013) found no difference in metal removal between planted and unplanted treatment with and without a submerged zone with three other species. In another study, high temperature or the presence of de-icing salt altered the metal removal capacity of bioretention systems, while the presence of a submerged zone improved it. The interaction between the plant effect and these factors on metal removal have not been specifically investigated (Soberg et al., 2014).

2.3.6. Pathogens

Vegetation in bioretention systems can have a multiple effect on the removal of pathogens, through the creation of preferential flow pathways (macropores and cracks), the production of protective organic matter, and through shading. It can augment their removal by reducing soil moisture, by favouring the growth of other microorganisms and biofilms which can enhance straining, competition and predation (Bitton, 2005; Engström et al., 2013; Nasser, 2016; Stevik et al., 2004).

When comparing nine different BMPs (dry detention pond, wet pond, wetlands, bioretention and proprietary devices), Hathaway et al. (2009) found that bioretention and wetlands were the more promising BMPs for the removal of fecal coliforms and Escherichia coli. Chandrasena et al. (2011) reviewed studies on the removal of *E. coli* by bioretention systems, observing a very high level of variability and conflicting results between studies.

One study concluded that vegetation had no effect on the removal of *Clostridium perfringens*, *E. coli* and F-RNA coliphages (Li et al., 2012). However, that study used a species that was effective at nutrient uptake in one study (Read et al., 2008), but performed poorly at *E. coli* removal in another study (Chandrasena et al., 2014). Kim et al. (2012) did find distinctly a better performance of soil-only columns in *Clostridium perfringens* removal, compared to vegetated columns, which they attributed to the greater retention time in the unplanted columns. Indeed, the growth of roots and its effect on the soil media can influence the retention (Chandrasena et al., 2014) and the development of the microbial community as well as the survival of the pathogen (Engström et al., 2013). For example, *E. coli* survival was negatively affected by root exudates as well as flower, leaf and seed extract of *Leptospermum continentale* in a study recently published by Chandrasena et al. (2017).

2.3.7. Hydrocarbons

Experiments on hydrocarbon removal in biofilters are few, but all report very high treatment performance. For example, (DiBlasi et al., 2009) monitored polycyclic aromatic hydrocarbons (PAH) in a bioretention cell receiving drainage from asphalt parking lots and roads, and found that most PAH were transported and accumulated in the top few centimeters of the soil media. No measure of plant uptake was conducted.

Degradation of polyaromatic hydrocarbon has been shown to be higher under planted than unplanted system (Aprill and Sims, 1990; Siciliano et al., 2003), but we found only indirect evidence of the role of plants in promoting hydrocarbon removal in bioretention systems. In fact, a study by McIntyre et al. (2014) failed to find any additional effect on the removal of PAH in columns planted with *Carex flacca* compared to unplanted systems (95%). However, the authors acknowledged the fact that the plants were not fully developed at the time of the experiment which could have influenced the results. In another experiment, runoff treated by planted columns reduced the concentration of metabolites from naphthalene and penanthrene in Coho salmon larva compared to soil only columns. Otherwise there was no significant difference between planted and unplanted controls, partly because the soil only treatment already showed very high removal, in part due to their very low infiltration rate (0.058 mm/s). These results should be put into perspective considering that here is a very abundant scientific literature on phytoremediation of soils contaminated with hydrocarbons. In this field there is ample evidence and a large consensus on the positive role of plants in promoting microbial degradation (see reviews by Chaudhry et al. (2005) and Collins (2007)).

Verdict

There is growing and convincing evidence that vegetation (i.e. plants and their associated microorganisms) do play a positive role for several – but not all – performance objectives of bioretention systems. They particularly contribute to nitrogen removal, as well as directly supporting bioretention system permeability. Plants may contribute to some phosphorus removal if regularly harvested, but it will be low compared to other removal mechanisms. While in principle plants may contribute to removal of metals by uptake with an appropriate species selection, they do not play a significant role under normal circumstances. Plants do not have any effect on TSS removal, but may influence pathogen removal (either positively or negatively).

For some bioretention functions, the positive role of plants remains to be determined. The potential for plant-created macropores to create preferential flow paths, leading to pollutant migration, has not been adequately studied in the bioretention context. The effect of plants on the removal of organic pollutants in bioretention is still open to debate, with further research needed.

Importantly, more full-scale studies are needed, since column studies alone cannot be used with certainty to understand the role of plants.

3. Hypothesis B: Plants species differ in their effectiveness

3.1. What the manuals say

It goes without saying that this hypothesis (and those following) will likely hold only for the bioretention functions where hypothesis A (that plants have an effect) holds. Most manuals do not relate the choice of plants to specific performance objectives, but some manuals insist that plants differ in their effectiveness. For examples, the most recent version of the South East Queensland *Bioretention Technical Design Guidelines* (Water by Design, 2014) gives indications of the vegetation traits (root structure, growth rates, plant size, tolerance to bioretention conditions) that are linked to general effectiveness or to more specific bioretention functions. For example, it is noted that fibrous-rooted plants will be more effective and that a mixture of plants with deep and shallow root systems ensures the removal of pollutants at various depths. Fast- and slow-growing plants are also desirable, because fast-growing plants rapidly cover the media, absorb nutrients and replenish substrate organic matter while slow-growing plants are valuable in the long term because of their usually larger size and larger root system which ensures their long-term absorption and retention potential. Payne et al. (2015) provide tables of plant traits associated with specific bioretention functions, advocating the use of plants with extensive root system for efficient removal of nutrient, metals and pathogens. The authors are even more specific in their requirements for nitrogen removal: "high total root length, root surface area, root mass, root:shoot ratio and proportion of fine roots" (p. 88). Designers should also be looking for plants with high transpiration rates to reduce volumes, and for plants with thick roots and sturdy stems to maintain porosity, according to these authors.

In the *Vegetation Guidelines for Stormwater Biofilters* (Oversby et al., 2014) the use of sedges and rushes is advocated, because they can absorb nutrients in excess of their needs. Moreover, their aerial parts can enhance TSS removal if planted densely. These plants and some grasses also have greater roots surfaces for microorganisms to colonize. The authors insist that "*the removal of nitrogen is the function that most requires the correct selection of plant species*" (Oversby et al., 2014, p. 9).

3.2. Theoretical background: Where the statement originates from

We will consider the role of plant type on hydraulics and hydrology, nitrogen, pathogens and organic compounds. We will not address the effect of plant species on the removal of TSS, phosphorus, and metals, given the findings in Hypothesis A that the influence of plants in these aspects is relatively small.

As mentioned earlier, the contribution to evapotranspiration including rainfall interception, will vary substantially with the height and density of the vegetation (Van Dijk and Bruijnzeel, 2001) and its transpiration rates (Farrell et al., 2012). Aerial traits (e.g. height of plants, stem density and stiffness) and root morphology (e.g. density, diameter of roots) have an impact on runoff velocity and its infiltration rate in soil (Blanco and Rattan, 2010; De Baets et al., 2009; Martinez and McDowell, 2016; Yu et al., 2016).

It is likely, given the dependence of nitrogen retention and removal on biological processes, that bioretention nitrogen retention performance will vary significantly with the morphological and physiological traits of plants (and their associations with microbes and fungi). For example, legumes and non-legume plants are known to be associated with bacteria that can fix nitrogen from the atmosphere to meet their nitrogen needs. They can even increase the nitrogen content of soil (Santi et al., 2013; Vitousek et al., 2013). Mycorrhizal fungal associations, which occur with some species, may augment nitrogen uptake performance (Belan and Nenn, 2010). The relative importance of plant and microbial uptake of nitrogen in other environments such as treatment wetlands remains unclear, with differing results between studies (Payne et al., 2013). Regardless, it is likely that the rate of biomass accumulation in a bioretention system will influence its ability to take up nitrogen, thus suggesting that faster-growing plants are likely to be most effective. Maintenance of this growth rate over the long-term may require removal of accumulated biomass via harvesting.

The importance of plant traits in determining nitrogen uptake has been demonstrated in a range of situations (Szota et al., 2015; Wedin and Tilman, 1990; Zhang et al., 2010), reinforcing the need to select appropriate species in bioretention systems. For example, fine, dense root systems are known to be effective in nutrient uptake (Payne et al., 2013). Payne et al. (2013) suggest that while rapid-growing plants will initially provide the best nitrogen removal (due to their greater nutrient uptake, transpiration rate and greater facilitation of microbial N transformations), it will be important to incorporate some larger woody species will help in reducing biomass turnover, thus favouring long-term retention.

The removal of pathogens from soil or water is dependent on a great number of environmental factors. Plant genotype and soil type in particular shape the microbial community of the rhizosphere and consequently can affect the fate of pathogens in the soil and soil solution (Mendes et al., 2013; Philippot et al., 2013). Plant species also affect permeability and consequently movement of pathogens in soils and the time allowed for pathogens degradation processes to occur.

Plants species have a different impact on organic pollutant degradation processes, but the factors that explain that difference are not well understood. These include the ability to provide oxygen to deeper soil layers through arenchyma tissues, the nature, quantity and timing of root exudation as well as the size of the root system which provides these exudates. These factors influence the composition of the microbial rhizosphere community as well as the ability of that community to perform the degradation of petroleum compounds (Chaudhry et al., 2005; Martin et al., 2014)

3.3. What is the scientific (empirical) evidence supporting the statements contained in the guidelines?

The influence of vegetation on the evolution of permeability over time in stormwater bioretention systems is well established. Plant root systems help to maintain hydraulic conductivity and to reduce clogging (Le Coustumer et al., 2012). Plants species with greater root mass density and root diameter, tree species in particular, are most suitable for this function (Goh et al., 2017; Le Coustumer et al., 2012).

Plant species also differ in their influence on nutrient retention. Read et al. (2008) for example found effluent N concentration to vary by a factor of up to three, consistent with the large differences between species found by Bratières et al. (2008a). In a follow-up study, Read et al. (2010) demonstrated that plant traits such as root length, root depth, root mass and plant growth rate were the principal morphological traits driving nitrogen removal performance. However, Pham et al. (2012) tested 22 species, classifying them into "lawn grass", "grass", "sedges", "rushes", "shrubs" (and "unplanted), finding that the differences between these plant types were relatively small. In part, this was due to the variability within each group, but they also hypothesised that it was due to the choice of filter media, with a low-N substrate being used. Given that substrate is a known driver of N removal in bioretention systems (Davis et al., 2006), it is not surprising to observe an interaction between vegetation type and substrate; while a wide range of species may be effective at removing nitrogen in a low N substrate like in the experiment described above, they may not be capable of compensating for a substrate which is inherently high in organic matter and thus potentially provides a source of N in the bioretention leachate.

Kim et al. (2012) found that plant species differed significantly in the removal of *E. coli* when they compared several species and unvegetated controls. Chandrasena et al. (2014) found that the lowest effluent *E. coli* concentration was achieved with two shrubs and a lawn grass amongst seven species of Australian lawn grass, grass, sedges and shrubs. The authors suggested that this was due to: 1. direct effect of plants species in the rhizosphere (competition, predation, antimicrobial root exudates), 2. indirect effect of the plant on the infiltration rate as was mentioned previously. Plant roots can create preferential flow paths either directly by the formation of macropores or indirectly by drying more rapidly the soil leading to the formation of cracks (Chandrasena et al., 2012, 2014; Rusciano and Obropta, 2007). More recent studies have shown that the microbial activity of the root or seed

Table 3
Qualitative summary of effect of plant traits or species on bioretention performance based on scientific studies.

Performance	Traits of importance	Explanation/comments
Hydraulics	Thick roots	Higher Ks with trees than with shrub, sedge and grass species. Thicker roots were capable of creating significant macropores, thus maintaining permeability
Nitrogen	Root length, root depth, root mass and plant growth rate	Notable difference between species with certain plant traits, not between plant types such as "lawn grass", "grass", "sedges", "rushes", "shrubs". Possible interaction between plant species and substrate
Phosphorus	No traits identified	Effect of vegetation is considered negligible
Metals	No traits identified yet. May vary between metals. Partitioning between root and shoot varies	Effect of vegetation is considered negligible
Pathogens	Traits linked to soil permeability/detention time and composition and functioning of rhizosphere community	1. direct effect of plants species in the rhizosphere (competition, predation, antimicrobial root exudates), 2. indirect effect of the plant on the infiltration rate as was mentioned previously. Shrub more performant in one study

exudates differ between species associated with sustainable stormwater treatment (Chandrasena et al., 2017; Shirdashtzadeh et al., 2017) which is a promising new area of study.

The only published information on the difference between plants regarding petroleum product degradation in bioretention is a field survey of 58 raingardens and 4 upland sites as control. In that study, LeFevre et al. (2012a,b) showed that copies of microbial functional genes encoding for enzymes used in the degradation of petroleum hydrocarbons were more abundant in raingardens planted with deeply-rooted plants than in those containing turf grasses or mulch.

Finally, it is important to note that the performance of one species can varies from excellent to poor depending on the function studied. For example, *Carex appressa*, a species with excellent nitrogen removal, performed poorly at *E. coli* removal when compared with other species in one study (Chandrasena et al., 2014). (See Table 3 for summary of effect of plant traits or species)

Verdict

Scientific studies indicate that certain plant species improve bioretention performance more than others, but this varies between the functions, meaning that trade-offs are likely required.

Important

Plant with thick roots help maintain soil permeability.

Plant species selection is highly important for nitrogen removal. There are strong indications that root length, root depth, root mass and plant growth rate are important morphological traits driving nitrogen removal.

Plant species vary in their removal of *E. coli* and other pathogens. Plants with a larger root system can augment the detention time of the stormwater in the bioretention, which helps the removal of pathogens.

Negligible

Removal of TSS is not determined by plant species or certain plant traits.

Since the removal of phosphorus is not determined by vegetation, existing differences in removal between plant species are not important.

Removal of metals in bioretention can differ significantly between plant species. However, overall, vegetation has generally a negligible effect on the removal of metals.

More studies are needed

To confirm the plants traits that are drivers of hydraulic performance, nitrogen and pathogen removal by studying more species from different families under different experiment and field conditions and climatic regimes.

To test the capacity of high biomass producing species to remove greater quantities of metals from stormwater in bioretention (ex: *Salix* spp. or *Populus* spp.).

To determine the impact of plant traits or species on the degradation of petroleum products in bioretention soils.

Finally, more research should be done on trees. They have received much less attention than other plant forms although they are widely planted in bioretention systems.

4. Hypothesis C: Using native vegetation ensures a better performance of the system

4.1. What the manuals-technical books say about it

The term native is diversely defined depending on the guidelines or manual. Native plants can be vaguely described as having historically been present in a given area. More precise local definitions are used: "native species are those that lived in Missouri before Europeans explored and settled in America and brought many common, but non-native species, with them" (Metropolitan St. Louis Sewer District (MSD), 2012, pp. 4–5).

The argument that native plants are more desirable than introduced species is regularly put forward by proponents of native vegetation both in the literature destined to the amateur gardener (Wilson, n.d.) and in publications from professional associations (American Society of Landscape Architects, 2016). Most manuals on bioretention systems also advocate the use of native over exotic plant species. The most common arguments in promoting native plant species are not about performance *per se* but rather about a greater inherent biodiversity or heritage value, and about avoiding risks of introducing exotic species that could become invasive. For example, the Maryland Stormwater Design Manual (Center for Watershed Protection, & Maryland Department of the Environment, 2009) states "*Native plants should be preferred because of their aesthetic qualities and ability to contribute to establishing a unique sense of place (especially when featuring plants native to the area)*" and "*Introduced species can often escape cultivation and begin reproducing in the wild. This is significant ecologically because many introduced species out-compete indigenous species and begin to replace them in the wild*".

It is also often believed that native plants would grow better and need less maintenance because they are more adapted to the local environment: "*Because they have evolved to live here naturally, indigenous plants are best suited for our local climate. This translates into greater survivorship when planted and less replacement and maintenance during the life of a stormwater management facility.*" (Center for Watershed Protection, & Maryland Department of the Environment, 2009). Being better adapted could then be translated into a greater performance of the bioretention: "*Regionally native plants are typically best suited to the variable conditions found in rain gardens. In addition, their rooting depth, habit and growth cycle are conducive to enhancing soil drainage and water percolation and storage as the garden matures.*" (Rodie et al., 2007, p. 1). In their much used "Plants for Stormwater Design", Shaw and Schmidt

(2003, pp. 1–2) state that native plants "*are recommended exclusively due to their hardiness and wide variety of function they provide*".

4.2. Theoretical background: Where the statement originates from

The underlying argument supporting a possible greater overall performance of native plants comes from the fact they have evolved under their current habitat and climatic conditions for thousands to millions of years, giving them an obvious advantage in general adaptation over newly introduced plant species. Yet, the very widespread existence of invasive species and so-called weeds reminds us that at least some exotic plants can be very well adapted to a foreign environment. A possible reason for their success is that exotic species may escape natural enemies from their native range and/or experience lower attack from natural enemies in their new range relative to native species (the so-called "Enemy release hypothesis"; Keane and Crawley, 2002). Another possible cause of success is that some exotic species are often favored by increased nutrient availability and altered disturbance regimes associated with human activities (Daehler, 2003). The environment in which bioretention systems are implemented generally differs considerably from the conditions prevailing in the native natural environments in terms of hydrology, soils, neighboring vegetation, animals and biogeochemistry (Pickett et al., 2011). Combined, it is not certain that native plants will necessarily better contribute to bioretention goals than comparable exotic species that are relatively well adapted to the local climatic conditions.

4.3. What is the scientific (empirical) evidence supporting the statements contained in the guidelines

We found no convincing empirical evidence that native plants provide a more efficient bioretention compared to exotic species. Among the abundant literature on bioretention, few studies compare the deliberate use of native plants or native communities with alternatives (Gautam and Greenway, 2014; Houdeshel et al., 2015; Kim et al., 2012; LeFevre et al., 2012a; Li et al., 2011; Lucas and Greenway, 2008a; Muthanna et al., 2007b; Read et al., 2008; Zhang et al., 2013). Some of these studies compare the performances of systems planted with a mixture of natives to those of unplanted systems. In these cases, no conclusion can be drawn regarding the effectiveness of native compared to non-native vegetation because the latter was not included in the experimental design (Lucas and Greenway, 2008b; Muthanna et al., 2007b; Zinger et al., 2013). In the remaining studies, the relative performances of native compared to non-native communities or species are either the same (e.g. LeFevre et al., 2012b) or worse (e.g. Houdeshel et al., 2015) than non-natives depending on the study. The fact that the species or community was native or not was not considered to be an explanatory factor of their performance. Instead, the authors hypothesized that the better performance of a species or a community was due to a better adaptation to the specific growing conditions of the bioretention or to the possession of specific functional traits (growth rate, biomass, rooting depth, type of rooting system) (Houdeshel et al., 2015; LeFevre et al., 2012a; Li et al., 2011; Lucas and Greenway, 2008a).

There is considerable debate for and against the "appropriateness" of native or exotic vegetation in a particular context, but many authors claim that the principle of precaution (against the risks of introducing an exotic invasive plant species), the intrinsic value of biodiversity and their contribution to sense of place might in fact be the strongest argument for the use of native plants (Gould, 1998; Kendle and Rose, 2000). The importance of using native species for reasons other than efficiency alone (i.e survival and lower maintenance requirements, habitat provision, non-invasiveness, aesthetics) has also been promoted for other phytotechnologies such as green roofs (Butler et al., 2012; MacIvor and Lundholm, 2011) and treatment wetlands (Rodríguez and Brisson, 2015).

Verdict

> Contrary to what is commonly stated in bioretention design guides, there is no clear indication that native plants provide higher efficiency than exotic plants in bioretention systems, nor is clear evidence of why it should be so. Using native plants may better contribute to local diversity, although exotic plants may also yield benefits for biodiversity. The contribution to sense of place is also a strong argument for the use of native plants. Thus, native plants should be used when possible, and more experimental screening should be concentrated on native plants. However, suitable exotic plants should not be discarded, as their use may be preferable in some situations, such as under more stressful conditions, where no local plants do well. Of course, as is often stated, species suspected or known to be invasive should never be used in bioretention systems.

5. Hypothesis D: Diverse systems are more efficient than monocultures

5.1. What the manuals-technical books say

Most manuals or technical books advise planting bioretention systems with several species to provide higher habitat quality and aesthetic appeal. However, the most often-cited advantage of plant diversity refers to its ability to respond to both spatial and temporal variability in environmental conditions such as water availability. For example, the Toronto and Region Conservation Authority & Credit Valley Conservation Authority (2010, p. 13) in their LID Landscape Design Guide state that: "*Recent climate data indicates that both very wet summers and periods of drought have occurred in southern Ontario. This underscores the need to plant adaptive, diverse plants that can excel under the range of moisture conditions that can be expected in urban settings*." The Australian biofilter guidelines (Payne et al., 2015, p. 93) provides similar advice: "*Vegetating a biofilter with a range of species increases the robustness… it allows species to "self-select"*. Similar statements are made in the Vegetation Guidelines for Stormwater Biofilters in the South-West of Western Australia (Monash University Water for Liveability Centre, 2014) and the Bioretention Technical Design Guidelines (Water by Design, 2014) of Southeast Queensland.

Independent of changing environmental conditions, plants may also differ in phenology, from plants having their peak of activity early in the growing season to others that are more active toward the end. Thus, in the *Bioretention Manual* from the Prince George's County, Maryland, (2007, p. 90), it is proposed that: "*A minimum of three species of trees and three species of shrubs should be selected to ensure diversity. This will … ensure a more constant rate of evapotranspiration and nutrient and pollutant uptake throughout the growing season*".

5.2. Theoretical background: Where the statement originates from

The stated goal of having a species mixture for complementarity in environmental conditions or for seasonal complementarity is to ensure a constant plant cover or plant activity: at least one species will be present (or active) at a given time and place, which may, in turn, have a direct effect on efficiency for mechanisms where the presence of plants has a positive role. As such, this possible benefit of diversity is in essence an extension of Hypothesis A: Planted systems are more effective than non-planted. A more fundamental question is whether there is a direct role of plant diversity on system efficiency. In many ecosystems, a positive relation between species diversity and ecological services or processes, such as nutrient cycling, has been documented (Cardinale et al., 2012). This effect may be attributed to a complementary exploitation of ecosystem resources between species ("complementarity effect"). Such complementarity may occur because different plants may exploit different location in the soil (shallow vs deeper root systems) or because they have different requirements and ability to acquire different nutrients. A positive effect of diversity may also be the result of a higher probability of having highly productive species ("selection effect" or "sampling effect") or due to mechanisms of facilitation between species ("facilitation effect") (Bruno et al., 2003; Loreau et al., 2001). It is increasingly considered that it is not the number of species *per se* that is important, but rather their "functional" diversity (Díaz and Cabido, 2001; Violle et al., 2007). Functional diversity refers to the number of different plant functional types or traits in the ecosystems. Thus, given a specific number of species, a system with species with different traits should result in a greater complementarity (and possibly greater ecological services) than a system with similar species.

Given the growing evidence of the positive effect of species or functional diversity on ecological processes in natural systems, it is currently assumed that combining different plant species may also improve efficiencies of constructed vegetated systems such as green roofs (Lundholm et al., 2010), soil phytoremediation (Hechmi et al., 2014; Wei and Pan, 2010) or constructed wetlands (Fraser et al., 2004; Picard et al., 2005; Zhang et al., 2010; Zhu et al., 2010). It is reasonable to assume this may also apply to bioretention systems since bioretentions comprise a variety of microenvironments in terms of soil moisture, pollutant concentrations, etc. (Johnson and Hunt, 2016; Tedoldi et al., 2017).

5.3. *What is the scientific (empirical) evidence supporting the statements contained in the guidelines?*

We found almost no empirical testing of the benefits of species diversity in bioretention performance. The one published study we found compared the efficiency of bioretention system and species diversity or functional diversity using an experimental approach, Ellerton et al. (2012) demonstrated higher levels of nutrient retention in systems planted with a mix of *Lomandra longifolia* and *Carex appressa*, compared with systems planted with either species alone. Despite the lack of bioretention-specific studies, we may learn from such studies realized in closely related application in phytotechnology, and especially from constructed treatment wetlands, where many studies have been conducted.

Different plant species may have differential oxygen root transport capacity, root suitability for microorganism colonisation, affinity and uptake potential for nutrients and organic compounds, as well as patterns of seasonal growth, all of which might improve removal efficiency in wetlands (Allen et al., 2002; Liang et al., 2011; Sheoran, 2006; Zhang et al., 2010). Several experimental studies have compared the efficiency of systems planted with different species richness. Picard et al. (2005) found no effect of diversity on biomass production, nitrogen or phosphorus removal. Others, such as Zhu et al. (2010) and Menon and Holland (2013) observed a positive effect of plant diversity on removal of some pollutants. This ambiguity characterises the literature, with effects being positive, negative or neutral, depending both on the species mix and the pollutant of interest. Therefore, despite what appears to be a net advantage of species mixtures, at least based on theoretical grounds, it remains to be seen under what conditions this advantage may be measurable (Cardinale et al., 2011; Liang et al., 2011).

While experimental studies in constructed wetlands may inspire or bring information regarding bioretention systems, one has to keep in mind the differences between the two applications. Compared to bioretention systems, constructed wetlands are usually always inundated to some extent and they are also highly nutrient-rich (depending on the nature of the wastewater). The influence of plant diversity may therefore not have the same influence as in bioretention systems, where the wet-dry nature will impact plant and microbial processes (Payne et al., 2013). It is also increasingly recognized that the benefits of diversity may be better realized using a multifunctionality approach, i.e. when several ecosystem functions are considered simultaneously, rather than in isolation (Gamfeldt et al., 2008). Similarly, the effect of diversity should be investigated using a such an approach, to fully evaluate the benefits of mixtures compares to monocultures in engineered systems (Lundholm, 2015).

Verdict

> While theory would suggest that a bioretention system planted with a diverse mix of species will be more resilient and outperform one planted as a monoculture, there is a lack of empirical evidence to confirm this. There is a strong need for experiments comparing systems of different plant richness, not only to determine if there is a measurable benefit to biodiversity, but also to determine the best combination of plants based for example on their functional traits. Until then, we believe that the lack of evidence in bioretention application should not discourage the use of diversely planted bioretention systems. There are several other benefits to plant diversity, including aesthetic value (and thus social acceptance), contribution to local biodiversity, and possibly greater resistance to disturbance.

6. Conclusion and perspectives

The evidence from both direct bioretention studies and studies from associated fields supports the widely-claimed important role of plants in bioretention systems. It is important to recognize, however, that their importance varies depending on the aspect of performance being considered. Plant water use, for example, will influence the moisture regime in the substrate and thus the runoff retention and will strongly influence removal of nitrogen. On the other hand, for bioretention processes that rely entirely on physical processes (e.g. removal of TSS) or chemical adsorption (e.g. removal of dissolved phosphorus), the presence or plants will be less important.

Empirical evidence from the literature also supports the hypothesis that bioretention performance is influenced by the choice of plant species, driven primarily by the influence of functional traits such as root characteristic and growth rate. Nutrient removal seems to be most influenced by these characteristics, with further research needed to understand how the removal of pollutants such as pathogens or hydrocarbons is influenced by plant characteristics. Hydrologic performance (runoff retention, annual water balance) has been demonstrated to be a function of plant functional traits in other phytotechnologies such as green roofs (Farrell et al., 2012) and is a priority for bioretention reseach.

Despite many bioretention design guides arguing for the use of native species, there is no clear empirical evidence to support this advice, if bioretention hydrologic and treatment performance are considered alone. There are of course arguments for considering other factors such as local biodiversity, social acceptance, landscape amenity and microclimate amelioration in plant selection. It is clear that diversity (polycultures rather than monocultures) bestows a higher level of resilience and adaptability in bioretention systems. This is an important consideration, given the strong temporal and spatial variations in substrate moisture content which characterize bioretention systems.

Recent years have seen a major international effort to understand the role of plants in bioretention systems. This research is beginning to produce empirically-based vegetation selection advice, such as the framework developed by Payne et al. (2018). There is, however, further research required. In particular, the complexity of plant influences on pathogen retention and transport through bioretention substrate is very poorly understood, such that predictive tools for pathogen removal are far from being realized. Further research is also required to understand to what extent plants may have conflicting influence among the aspects of biotention performance. For example, increases in substrate permeability created by root-induced macropores could potentially lead to short-circuits and thus migration of soluble pollutants through the media layer. This behaviour has been extensively studied in other fields such as agriculture, but is essentially untested in bioretention systems, despite their likely vulnerability, given their relatively shallow substrate depths. Similarly, several of the empirical findings in bioretention systems must be considered with caution, given that they frequently come from short-duration laboratory studies. An example is the observation that relative growth rate is a good predictor of nutrient retention; it is not yet known whether such a relationship will still hold in mature bioretention systems, where the vegetation is in an equilibrium between growth, senescence and degradation.

Further research into the role of vegetation in bioretention systems will require input not only from researchers with plant expertise, but also those who understand the importance of microbial processes, given their strong interactions with plants (Payne et al., 2013). In fact, more insight is needed from soil and plant microbial ecology, to fully expand our understanding of the complex plant-microorganism-soil bioretention ecosystem. This *terra incognita* of bioretention research holds great promise for improving the performance of bioretention, particularly considering the recent advances in the beneficial use of microbiota in related areas such as agriculture (Philippot et al., 2013) and phytoremediation (Thijs et al., 2017). Experimental research on the role of plants should include both the realistic conditions of full size systems, and smaller closed experimental units (such as columns), which have limitations (edge effects, unrealistic root density), but also well-known advantages (replication, control over treatments, etc.) (Freckleton et al., 2009; Passioura, 2006). Lastly, plant-bioretention research needs to expand to encompass a broader range of regions and climates; observations from studies in one climate may not hold in another.

Acknowledgements

The authors would like to express their gratitude to the University of Melbourne for providing a Dyason Fellowship to Danielle Dagenais to visit the Melbourne School of Land and Environment and the Faculty of Architecture, Building and Planning as well as to Ouranos, a consortium on regional climatology and adaptation to climate change, for providing the funding for the production of this article. They would also like to thank Émilie Langlois-Patterson for drawing the graphical abstract and the figure.

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