Carbon stocks and sequestration of stormwater bioretention/biofiltration basins

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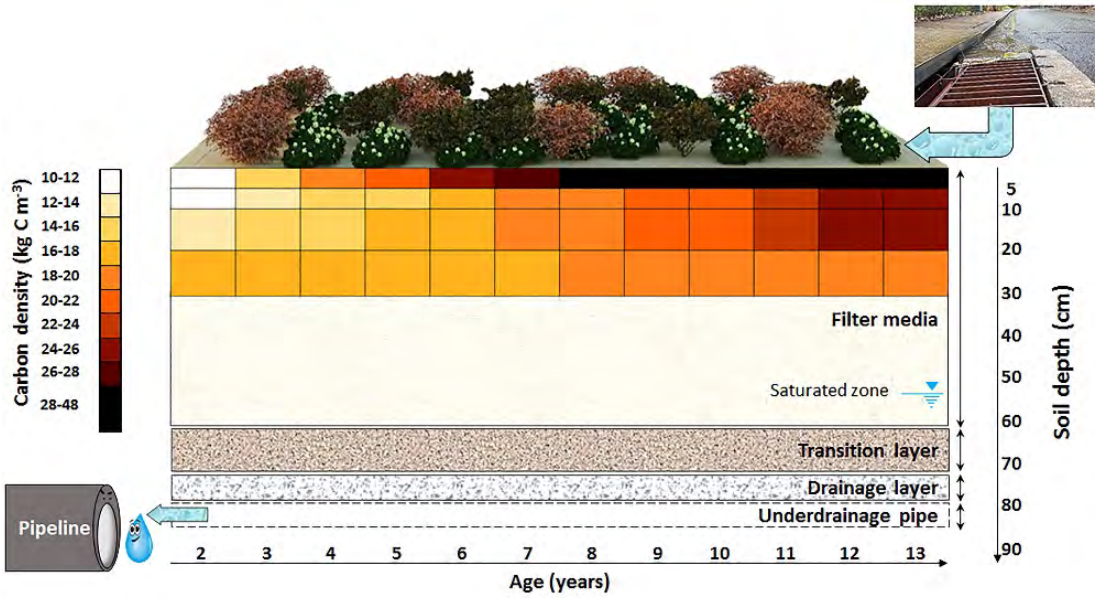
Abstract

Bioretention basins are a prominent type of vegetated stormwater infrastructure that provides various ecosystem services, such as carbon (C) sequestration. Despite the key role of organic matter in the performance of bioretention basins, there is little understanding of their C accumulation properties. Using detailed field studies, we investigated the spatial, temporal and vertical variation of C capture in the soil of 25 subtropical bioretention basins in Australia. A thirteen-year soil chronosequence was used to estimate C sequestration rate. It was observed that the bioretention basins displayed a spatially uniform depositional pattern of C in their ponding area. The mean areal C density of soil in the upper 20cm was 3.8 ± 0.3 kg C m^{-2}, from which 32% was associated with the top 5cm of soil. There was a strong influence of age on C density only throughout the first top 20cm of the soil profile with a C sequestration rate of 0.31 kg C m^{-2} yr^{-1}. Carbon quickly accumulates in the top 5cm layer while in the lower depths it accumulated at a more gradual rate. The results show that bioretention systems could be designed for the enhancement of their C sequestration potential, and amendments in their design, such as addition of a carbon source layer, are important for better managing carbon availability in the basins.

Graphic abstract



Graphic abstract: Linear accumulation of C in bioretention soil with age (x axis) and within the soil profile (y axis).

Keywords

Green infrastructure; Stormwater control measure; Ecosystem service; Carbon sequestration; Rain garden; Biofiltration basin.

1. Introduction

Worldwide, the removal of vegetation and expansion of impervious surfaces in cities are increasing the impact of urban stormwater on both humans and aquatic ecosystems. In response to the rapid urbanisation, the attention to the management of urban drainage systems has increased (Fletcher et al., 2013). Traditionally, manmade event-driven wetlands such as free water surface flow and horizontal subsurface flow systems have been used to treat urban and agricultural stormwaters (Vymazal, 2007; Vymazal et al., 1998). Free water surface flow constructed wetlands were the most popular treatment system for rain-driven events, and horizontal subsurface flow constructed wetlands were mostly used for treating combined sewer flows in Europe (Kadlec and Wallace, 2008; Vymazal, 2009; Vymazal and Kröpfelová, 2008). These treatment wetland systems therefore have been classified as structural Stormwater Best Management Practices (BMPs) where used for sustainable stormwater improvement (EPA, 1999; Kadlec and Knight, 1996).

A diverse philosophical approach such as BMP, green infrastructure (GI), low impact development (LID), stormwater control measure (SCM), sustainable urban drainage system (SUDS), and water sensitive urban design (WSUD) has been employed to describe urban drainage and stormwater management systems in different parts of the world. The terms historically originated from flood management background and shifted to ecological benefits of receiving water such as water quality and flow regime restoration (Fletcher et al., 2015). There are various stormwater treatment devices, including constructed wetlands, detention or retention facilities, bioretention basins, green roofs, rain gardens, buffer strips, swales and stormwater ponds. These systems are primarily designed for hydrological and stormwater quality purposes (Lucke and Nichols, 2015).

However, they have great potential for the provision of various environmental benefits and several ecosystem services such as air quality improvement, biodiversity and carbon (C) storage (Pandit et al., 2017; Pataki et al., 2011; Vymazal, 2011).

C storage and sequestration both within above-ground and below-ground are recognized as a strategy for climate change mitigation (Davies et al., 2011; Litynski et al., 2008). C storage and sequestration have been widely studied in agricultural lands, grasslands (Song et al., 2018), turf (Pahari et al., 2018), and aquatic sites such as natural and constructed wetlands (Craft et al., 2018; Reddy et al., 2016). Despite the accelerated attention to C storage and emissions regulation within urban areas there have been limited research studies, focused on quantifying the C storage of designed vegetated basins.

The C storage and sequestration measurement of vegetated stormwater infrastructure is limited to green roofs, vegetated swales and stormwater ponds. However, they have a significant potential in mitigating their life-time carbon footprint through C sequestration (Kavehei et al., 2018a). It is estimated that bioretention basins have a 70% C mitigation potential over a 30-year life-time (Kavehei et al., 2018a). To have a comprehensive net carbon footprint analysis of vegetated stormwater systems, greenhouse gas (GHG) emissions and C sequestration should be included in the investigation (Kavehei et al., 2018b).

Bioretention systems are depressed landscape areas vegetated with selected species and designed to receive runoff from the catchment and gradually treat it through different engineered layers of soil (Davis and McCuen, 2005). These systems use vegetation and soil ecosystems to manage stormwater close to the source of stormwater runoff (EPA, 2013). Unlike stormwater wetlands, bioretention systems are smaller size systems, designed to drain within hours and reduce stormwater volumes and peak flows which

make them a good solution to counteract the surface runoff increase associated with urban development (Roy-Poirier et al., 2010). The concept of bioretention system was developed in early 1990s by Prince George's County, in Maryland, USA (County, 1993). Globally, they are a prominent design of sustainable stormwater management systems with a great ability to improve stormwater quality, remove heavy metals and add other ecosystem services (Dagenais et al., 2018; Roy-Poirier et al., 2010).

Bioretention basins are typically designed to have a sand-based soil media with some organic matter amendments by overlaying a mulch layer which provides many pollutant removal benefits (Hunt et al., 2011). The diverse use of specific vegetation in bioretention basins and physiochemical characteristics of soil media can help to promote biological remediation of pollutants (Liu et al., 2014; McPhillips et al., 2017; Roy-Poirier et al., 2010). Various laboratory and field studies have demonstrated the pollutant removal potential of bioretention basins (LeFevre et al., 2012; Sun and Davis, 2007).

The high total biomass and extensive root system have a strong positive correlation with the nutrient and nitrogen removal of bioretention basins (Dagenais et al., 2018; Payne et al., 2018). Bioretention basins have a great performance in capturing hydrocarbons (derived from oil and grease, benzene, etc) through sorption to organic matter, biodegradation and plant uptake(LeFevre et al., 2012). The decomposition of above ground biomass from a variety of bioretention vegetations and roots along with inflow of hydrocarbons via stormwater provide C to the system. The availability of organic C, denitrifying organisms and oxygen deficient environment in soil media are required for nitrogen removal through denitrification, which is a microbial process of soil nitrate conversion to nitrogen gas (N_2O and N_2) (Waller et al., 2018). The denitrification in stormwater systems is mostly driven by C (Collins et al., 2010). Recent studies have

shown that the addition of a C source and a submerged zone (anoxic environment) at the bottom of bioretention filter media has a significant impact on nutrient, nitrogen and some metal removal and increases denitrifying bacteria activity (Blecken et al., 2009; Peterson et al., 2015; Wang et al., 2018).

Despite the importance of bioretention basins as a major type of green stormwater infrastructure and rising interest in below-ground C and global C budgets, the C storage of these urban vegetated basins has not yet been experimentally measured (Kavehei et al., 2018a). The first goal of this study is to investigate the spatial, temporal and vertical variation of C accumulation in bioretention filter media. The second goal is to quantify the average and maximum C storage and the sequestration potential of bioretention basins within a subtropical climate.

2. Materials and methods

2.1. Study Sites

Twenty-five bioretention basins, aged from 2-13 years, were sampled in the subtropical climate of the Gold Coast, south-east Queensland, Australia (Fig. 1). The average temperature of the Gold Coast ranges from 19 °C to 29°C in the warm humid summer (November – February) and 12 °C to 21°C in mild winter (June – August). The mean annual rainfall is around 1273 mm with an approximate 120-140 days of no rain per year (Commonwealth of Australia 2016a; Liu et al., 2016).

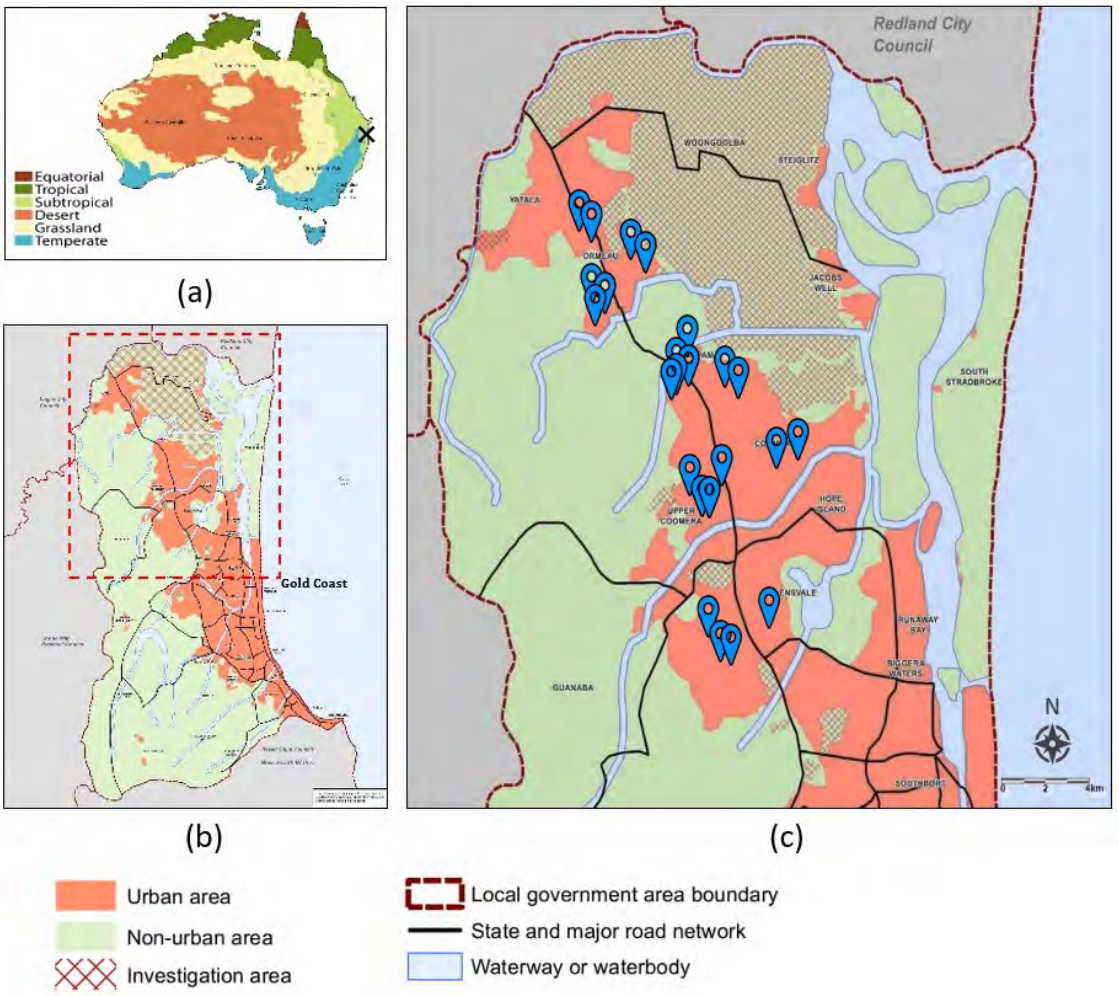


Fig. 1. Bioretention sites located in this study: (a) location on the Köppen climate classification map of Australia(Commonwealth of Australia 2016b); (b) the Gold Coast city, designated urban area(Council of the City of Gold Coast, 2018); (c) the location of the sites.

The interactive map of the sites' locations can be accessed via the link below.

https://goo.gl/maps/YgpS1eNjAoL2

The twenty-five bioretention basins were selected for this study according to the following criteria; design purpose, land use type, surface area, vegetation coverage,

vegetation types, accessibility and the age of the sites. All selected sites had been designed for nutrient processing purposes within the urban areas and have more than 100 m^2 of ponding area. The vegetation coverage of the sites was estimated via aerial drone images to ensure coverage of more than 30%. The plant diversity was observed to be mostly limited to three core plant species of bioretention basins: *Carex appressa, Ficinia nodosa* and *Lomandra longifolia.*

The chronosequence method, a "space-for-time" concept, was used to study the long-term dynamics of soil development and C accumulation in bioretention soil media. The sites' ages were obtained from Gold Coast City Council asset database and were compared and amended using Google Earth historical imagery. The first plantation date, after the site construction, was considered as the starting time of the sites' operation. The sites were then classified into four age classes: Class I: (1-3 years), Class II: (4-6 years), Class III: (7-9 years) and Class IV: (≥10 years). The first three age classes each contain seven sites, and the oldest age class includes four sites.

A detailed overview of the temporal changes in the design characteristics of bioretention basins in the region of study is displayed in Table 1. The applied standards for the sites construction shows a volumetric C level of 5% for the soil media at the time of construction. In addition, soil amendments such as use of fertilizer, mulch and compost are an applied maintenance to ensure adequate soil moisture and plant health. It has been also recommended that a 5 to 7.5 cm mulching layer should overlay on the topsoil before planting or replanting of the basins. All the selected basins were designed to have underdrainage pipes and are regulated by the Gold Coast City Council. It is assumed that similar operation and maintenance activities were employed through the long-term performance of the sites. However, the authors note that the results of this study are

limited by the lack of supporting data regarding the applied maintenance and C amendments to soil media and the detailed design of the drainage profile which includes whether the sites were designed with a saturated zone, sealed with an impermeable liner or a permeable liner to allows water infiltration to surrounding soil.

Table 1. An overview of the changes in the design characteristics of bioretention basins over time in Australia.

Layers & key design parameters		**2006**	**2010**	**2014**
Extended detention depth (mm)		<300	200–400	<300
Mulch layer	Depth (mm)	50-75	50-75	50-75
Vegetation layer	Species (No. per basin)	NA	5	6
	Plant coverage (%)	70–80	80	90
Filter media	Depth (mm; Min)	600–1000; Min:300	600–1000; Min:400	500–1000; Min:400
	C level (volumetric %)	>5	>5	>5
	Texture	Sandy loam	Loamy sand	Loamy sand
	Hydraulic conductivity (mm/hour)	50–200	100–500	100–300
Transition Layer	Depth (mm)	>100	100–200	>100
	Texture	Coarse sand	Coarse sand	Coarse sand
Drainage Layer	Saturated zone	NA	Applicable	Applicable
	Texture	Coarse sand/Fine gravel	Fine gravel	Fine gravel

2.2. Experimental Design

At each basin, three sampling locations of Central, Intermediate and Batter zones were set along a transect, from a central point in a basin to the corner of the basin where the slopes start (called the Batter zone). Each transect was kept far enough from the inlet to avoid the impact of rapid flush of water into the basin and where possible, perpendicular to the inflow water (Fig. 2b). At each sampling point, the samples were retrieved at a

point between plants and in four depths: 0-5cm, 5-10 cm, 10-20 cm and 20-30 cm (Fig. 2a). A total of 284 samples were collected from 25 sites, (12 soil cores in each site), from November to December 2017. In a few cases, the sampling of the last depth of 20 to 30cm was not successful as the soil did not retain in the auger or the soil was not deep enough (two cases at the batter zone).

Fig. 2. Horizontal and vertical sampling stratification (a) three sampling locations along a transect, (b) soil profile sampling depth.

2.3. Sample collection, chemical and physical analysis

A 40 mm diameter stainless steel open-auger was used to sample undisturbed soil cores. The cores were divided into two depth intervals of 5cm (0-5cm and 5-10cm) and 10cm (10-20cm and 20-30cm). Samples were removed and stored in plastic bags. The samples were oven-dried at 60˚C for 72 hours, and subsamples homogenised by grinding to < 250 µm. Samples were analyzed for total C (%C) with an elemental analyser isotope ratio mass spectrometer (EA-IRMS, Serco System, Griffith University). Each core was independently processed and analyzed for chemical analysis. 10% of the samples were tested for the percentage of inorganic C by adding a 10% solution of Hydrochloric acid

(HCL). No reaction was observed in any of the samples, and thus, due to the absence of carbonates, the percentage of total C was assumed equal to organic C (Bouchard et al., 2013; Merriman et al., 2017).

Samples of a known volume were then oven-dried at 105˚C over 24 hours, weighed and used to measure bulk density from the dry weight of each sample. The soil texture of the sites was determined in four soil profile depths using a method for soil particle-size determination (Kettler et al., 2001). Briefly, a 15g fine soil sample was mixed with a 45ml aqueous solution of sodium hexametaphosphate (HMP) to accomplish soil-particle dispersion. The samples were mechanically shaken for 3 hours and afterwards sieved through a 0.053 mm sieve to measure the sand fraction. The silt and clay solution settled undisturbed for a sedimentation period of 4 hours. The suspended clay fraction was then decanted, and the percentage of sand and silt was calculated from the oven-dried weight and the original weight of the samples. Following this, the soil PH was measured of 1:5 soil:water suspension following NSW standard Australia (Department of Sustainable Natural Resources, 2003).

The C density was calculated from the percentage of the C and the bulk density. The C density of soil accounts for potential changes in soil (Bouchard et al., 2013; Merriman et al., 2017). The areal C density (kg C m^{-2}) of soil cores was determined through the following equation as a function of the computed total percentage of C, bulk density and soil sample depth.

$$\text{Areal C density (kg C m}^{-2}) = \rho \ * \ D \ * \ \%C \qquad (1)$$

where $\%C$ is the percentage total C (kg C kg^{-1} of soil), ρ is the bulk density (kg m^{-3}), and D is soil depth (m).

A subset of six bioretention basins was selected for the hydraulic conductivity test using the in-situ method for bioretention basins, described by Hatt and Le Coustumer (2008). The basins of different ages and C level were selected to investigate the impact of hydraulic conductivity on soil C accumulation. For the bioretention sites with a less than 1000 m^2 surface area, the test was performed at five monitoring points, spatially distributed. An extra point was added for every additional 200 m^2. A 10 cm diameter PVC cylinder was placed on the soil with no surface covering and inserted 5 cm into the soil. The cylinder was filled with water to a depth of 5 cm above the soil surface and with the use of a measuring cylinder, the level of water maintained. The time interval and volume required to maintain the water level at the 5 cm pressure head was recorded until the infiltration rate was steady. Next, the cylinder was filled to a depth of 15 cm and the time interval and volume required to maintain the water level was recorded again. The hydraulic conductivity was then calculated based on the following equations.

$$\mathrm{k(h)} = k_{fs} e^{\alpha \mathrm{h}} \qquad (2)$$

where K is the hydraulic conductivity, α is a soil pore structure parameter, and h is the negative pressure head.

$$k_{fs} = \frac{G}{a}\left(\frac{Q_2 - Q_1}{H_2 - H_1}\right) \qquad (3)$$

where a is the cylinder radius, H_1 and H_2 are the first (5 cm) and second (15 cm) pressure heads, respectively, Q_1 and Q_2 are the steady flows for the first and second pressure heads, respectively.

$$G = 0.316\frac{d}{a} + 0.184 \qquad (4)$$

where d is the depth of insertion of the cylinder and a is the cylinder radius.

2.4. Statistical Analysis

One-way analysis of variance (ANOVA) was used to test the differences among C in the soil and soil pH, soil density, soil moisture and horizontal sampling locations within sites (Central, Intermediate and Batter zones) Due to the insignificant difference among C stocks within each site, the three values were considered replicates for each site. The variation of C and soil depths and age classes were also tested with Analysis of Variance. Tukey's honest significant difference (HSD) test was used within the ANOVA when identification between the driving data set was required.

Regression analysis was used to assess changes of C, hydraulic conductivity and soil texture (% Clay + Silt) with the ages of the sites. The areal C density was accumulated in depth to represent the top 20cm of soil in each sampling location. Then the areal C density of the top 20cm of soil was tested independently for each bioretention site as an average of the three replicates. The influence of potential factors: the actual site age, hydraulic conductivity and % Clay+Silt content on the C accumulation rate was modelled with linear regression to estimate the C sequestration rate and maximum C density. The statistical significance of the regression relationship was determined by ANOVA. A segmented regression hypothesis was tested and the Pearson correlation factor of predicted and observed values showed no significant change between the segmented ($r(25) = 0.674$, $p < 0.0003$) and linear model ($r(25) = 0.665$, $p < 0.0003$). Normality and homogeneity of variance were assessed using residual plot analyses, histograms and Shapiro-Wilk test. To comply with normality and homogeneity assumptions, when required, variables were log transformed. Significance was set at $\alpha = 0.05$. All statistical tests were analysed with SPSS statistical program (v24, IBM, New York, USA) and presented as mean ± standard errors.

3. Results and discussion

3.1. Design and soil physical characteristics

Table 2 illustrates the physical characteristics of the studied sites with the mean values and standard error. The soil filter media were mostly Sandy Loam or Loamy Sand with an acidic nature which is in accordance with the bioretention's design recommendation of 5.5 to 7.5 pH range (Water by Design, 2014). The soil pH, density and moisture are presented in the appendix (Fig. A.1 and A.2). The soil pH, density and moisture did not vary significantly between the Central, Intermediate and Batter Zones ($p= 0.79$, 0.915 and 0.257 respectively). The influence of soil depths on the soil moisture and pH was not significant; however, the top 5cm of soil had slightly higher values. Conversely, the bulk density increased significantly with depth from 1.0 ± 0 g cm^{-3} at the top layer to 1.5 ± 0.1 g cm^{-3} at the depth of 30cm ($F_{(2,68)}$ = 14.246, $p < 0.0001$). However, its statistical significance drops between the 20 cm and 30 cm soil density ($p=0.186 > 0.05$).

Table 2. Characteristics of bioretention basins in subtropical Australia to an accumulated depth of 20 cm (mean ± standard error).

Age Classes	**Age** (year)	**Ponding Area** (m^2)	**Bulk Density** (g cm^{-3})	**pH**	**Soil Texture**		**Soil classification**
					% Silt	**% Clay**	
Class I	2	361	1.0 ± 0.1	5.6 ± 0.1	3.9 ± 2.2	2.5 ± 1.4	Sand
	2	409	1.4 ± 0.1	6.0 ± 0.3	5.6 ± 0.3	6.1 ± 3.1	Sand
	3	952	1.0 ± 0.1	5 ± 0.1	10.0 ± 3.5	1.2 ± 1.1	Sand
	3	464	1.1 ± 0.0	5.4 ± 0.1	4.1 ± 0.1	12.0 ± 3.8	Loamy Sand
	3	217	1.0 ± 0.0	4.8 ± 0.1	14.0 ± 4.5	3.4 ± 2.5	Loamy Sand
	3	686	1.1 ± 0.0	5.4 ± 0.2	7.2 ± 3.2	8.5 ± 4.1	Loamy Sand
	3	771	1.4 ± 0.1	6.3 ± 0.0	5.3 ± 1.7	8.3 ± 2.8	Loamy Sand
Class II	4	489	0.9 ± 0.1	6.0 ± 0.0	30.6 ± 11.1	3.7 ± 2.8	Sandy loam
	4	1156	1.4 ± 0.1	5.0 ± 0.2	27.3 ± 3.2	34.0 ± 4.4	Clay loam
	5	722	1.2 ± 0.1	5.2 ± 0.1	5.7 ± 1.2	6.7 ± 2.3	Loamy Sand
	5	1223	1.5 ± 0.1	5.6 ± 0.2	29.8 ± 7.5	22.8 ± 13.2	Loam
	5	1101	1.1 ± 0.1	5.9 ± 0.0	9.8 ± 1.9	8.2 ± 6.1	Loamy Sand

	6	2594	1.3 ± 0.0	5.3 ± 0.1	26.5 ± 0.6	27.4 ± 0.8	Sandy Clay Loam
	6	274	1.3 ± 0.1	5.3 ± 0.1	35.8 ± 2.7	17.9 ± 1.1	Loam
	7	908	1.3 ± 0.1	6.8 ± 0.2	6.3 ± 2.3	5.5 ± 1.4	Sand
Class III	8	2646	1.5 ± 0.1	7.4 ± 0.3	6.9 ± 1.4	21.3 ± 2.5	Sandy Clay Loam
	8	790	1.4 ± 0.1	6.2 ± 0.1	15.1 ± 3.5	8.4 ± 1.2	Sandy Loam
	8	875	1.4 ± 0.1	6.8 ± 0.3	18.7 ± 1.3	15.1 ± 0.8	Sandy Loam
	9	420	1.7 ± 0.1	6.6 ± 0.1	11.0 ± 1.4	11.6 ± 1.0	Sandy Loam
	9	387	1.4 ± 0.1	5.6 ± 0.1	15.3 ± 3.8	3.6 ± 0.6	Loamy Sand
	9	233	1.6 ± 0.1		7.1 ± 2.2	9.5 ± 2.2	Loamy Sand
Class IV	10	2158	1.3 ± 0.1	5.7 ± 0.2	18.0 ± 6.5	13.5 ± 0.3	Sandy Loam
	11	303	1.1 ± 0.0	5.9 ± 0.1	3.0 ± 2.3	0.4 ± 0.4	Sand
	13	403	1.1 ± 0.1	5.3 ± 0.1	16.3 ± 2.2	14.2 ± 4.4	Sandy Loam
	13	308	1.2 ± 0.1	5.7 ± 0.0	33.4 ± 2.1	10.9 ± 5.4	Sandy Loam

3.2. Spatial variation of C

The mean areal C density (± standard error) for 20 cm of depth at the Central, Intermediate and Batter zones in bioretention basins was 4.2 ± 0.4 kg C m^{-2}, 4.0 ± 0.4 kg C m^{-2} and 3.8 ± 0 kg C m^{-2} respectively (Fig. 3a). Bioretention basins are designed to receive runoff from catchments and gradually treat it through filter media. The Central zone in a bioretention basin is more likely to be inundated than the Batter zone as the latter is only inundated after heavy rainfall events. This would suggest that the spatial accumulation patterns of C would vary across a basin. However, there was no statistical significance between the C accumulation and sampling zones within the sites ($F_{(2,64)} = 0.286$, $p = 0.752 > 0.05$), which demonstrates that the spatial accumulation of C is uniform across the studied basins. The results verified that the vegetated Batter zone is as important as the other zones in the design of bioretention systems from a C storage point of view. However, the unvarying plant density between the studied sites might be a reason for the uniform accumulation of C. Afterward, in this study, the values of the three sampling points were considered as three replicates representing each site.

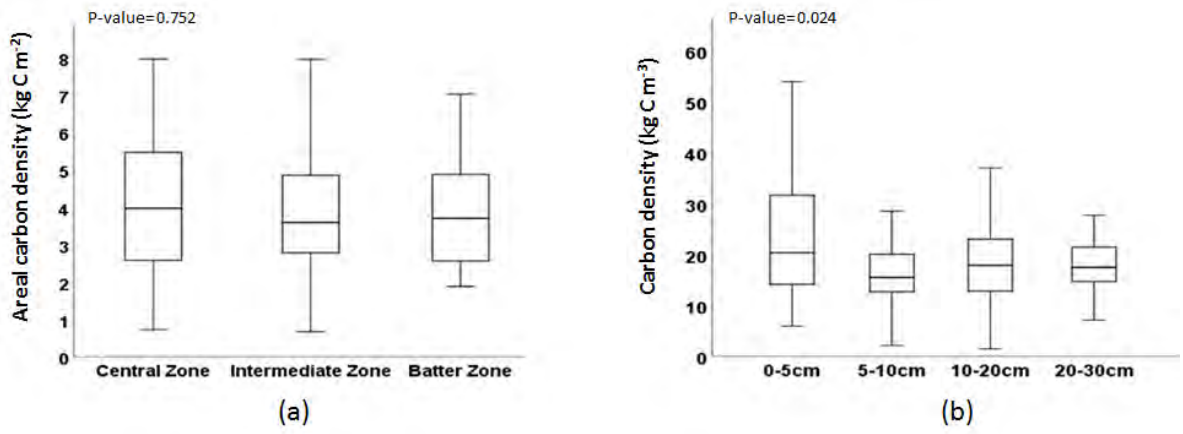


Fig. 3. Bioretention basins, subtropical Australia: (a) Mean areal C density of the Central, Intermediate and Batter zones; and (b) mean C density across four different soil depths. The top 5cm of soil had significantly higher C density than the lower depths.

3.3 Vertical variation of C

The mean C density (± standard error) of all bioretention sites for the four depths of 0-5cm, 5-10cm, 10-20cm and 20-30cm was 25.7 ± 3.2 kg C m^{-3}, 17.2 ± 1.7 kg C m^{-3}, 18.0 ± 1.7 kg C m^{-3} and 17.9 ± 1.8 kg C m^{-3} respectively (Fig. 3b). The C in the top 5cm of soil was significantly higher than at the lower depths ($F_{(3,92)}$ = 3.291, p =0.024). However, the variation of C between the 5-10cm soil and deeper depths was insignificant (p=0.993 and 0.996 respectively).

The availability of organic matter in the form of a C source is a requirement for the denitrification process which is supplied by above-ground biomass production and decay of root matters (Water by Design, 2014). The results from C storage of all bioretention basins together, identified that the top 5cm layer accumulates more than 32% of the C within the top 20cm of soil. The relatively high C stocks of the top soil layer are associated with lower soil density. The subsequent degradation of above-ground biomass in the form

of organic matter amendments by overlaying a mulch layer and the death of bioretention plants form pores that increase porosity and density of soil. The abundance of C in the top 5cm soil layer shows that above-ground biomass production and C amendments to the soil are the significant sources of C into bioretention systems.

3.4 Vertical and temporal variation of C

The mean C density (± standard error) of 20cm soil increases by the site's age classes: 12.2 ± 2.1 kg C /m^3 for the youngest age class, Class I; 19.7 ± 1.9 kg C /m^3, Class II; 22.3 ± 3.4 kg C /m^3, Class III; and 29.0 ± 4 kg C /m^3 for Class IV. The relationship between age classes and C accumulation is highly significant ($F_{(3,67)} = 9.158$, $p = <0.0001$). Fig. 4a illustrates the variation of C storage within four different age classes and across four different soil depths. The C content of the top 5cm of soil increases significantly with time, from 11.6 ± 1.3 kg C /m^3 for the youngest class (I) to 43.0 ± 8.4 kg C /m^3 for the oldest class (IV) ($F_{(3,27.8)} = 17.385$, $p = <.0001$). Although the C density level drops in the second depth (5-10cm), compared to the surface soil, the positive correlation between the C accumulation and time remains statistically significant ($F_{(3,67)} = 4.693$, $p = <0.005$). The influence of age class on the accumulation of C in a deeper soil depth, 10-20cm, continues to be significant although to a lesser extent ($F_{(3,65)} = 3.197$, $p = <0.03$). The results of C stocks at the depth of 20-30cm does not show any relationship with age of the sites ($F_{(3,48)} = 0.548$, $p = 0.652 > 0.05$). It can be inferred that within the 13 years of operation, C accumulates in bioretention basins; however, it requires longer time for C to accumulate below 20cm of filter media.

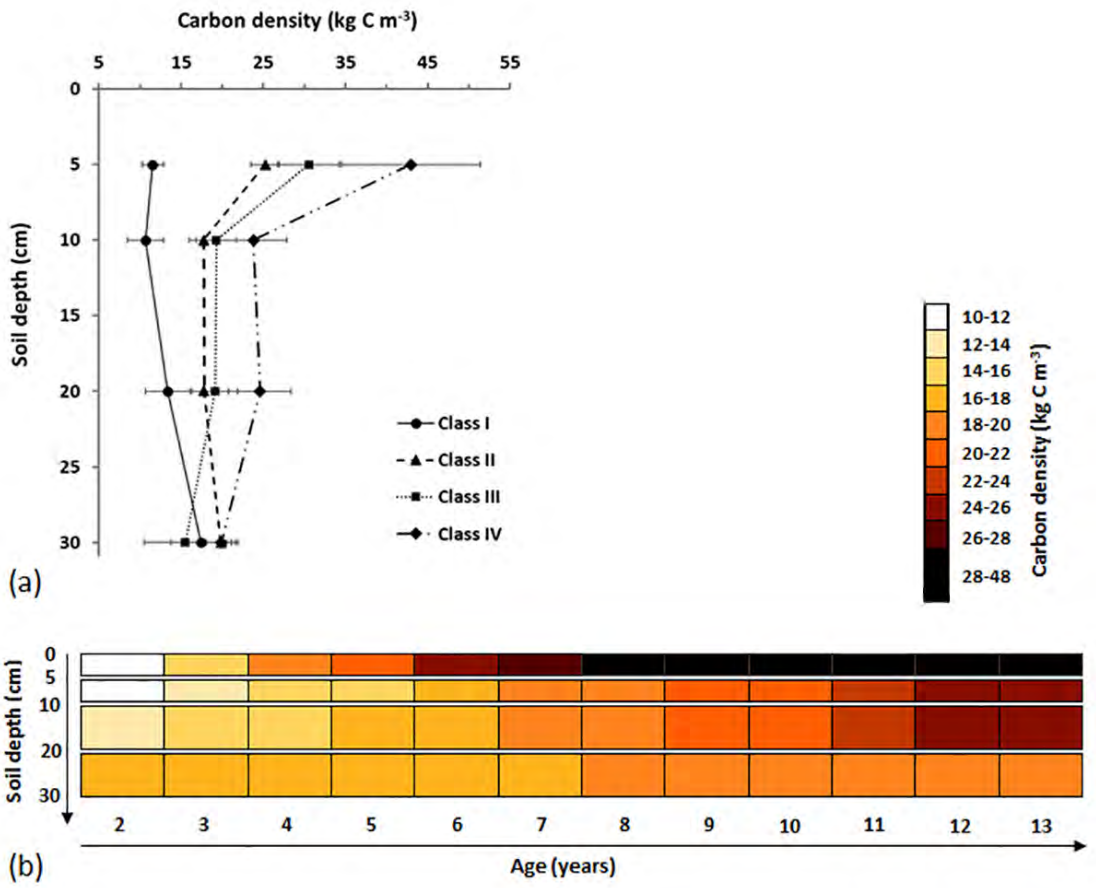


Fig. 4. Bioretention basins: (a) Mean C density of four age classes across four soil depths; and (b) Proposed model of C accumulation in a depth profile of filter media in subtropical Australia.

Bioretention basins are constructed sites with a supplied Sandy substrate mix. The results within this study can represent the initial phases of C dynamics in a relatively young basin. Fig. 4b depicts the linear accumulation rate of C in different soil depths, across the ages of the bioretention sites. As the sites get older, C accumulates in deeper soil. At very young ages, the amount of C in the top layers is less than in deeper layers, which demonstrates the initial availability of C in the supplied substrate mix at the time of the site's construction. C quickly accumulates in the top 5cm layer due to the abundance of

above-ground biomass, while the layers within the 5-20cm depth accumulate at a more gradual rate. It takes only 6 years for the top 5cm layer to accumulate an approximate C density of 25 kg C /m^3, whereas in the 5-20cm layer the same amount accumulates over 13 years (Fig. 4b). This indicates that C accumulation in these lower layers is due to the percolation of C from the top layers.

In general, plant production and biomass allocation are the driving factors of the vertical distribution of C in soil (Jobbágy and Jackson, 2001), and the deeper the soil, the more likely it is that older C is stored (Jobbágy and Jackson, 2001; Wang et al., 2016). A meta-analysis study on 112 natural sites (grassland, forest and cropland), across different climate zones has displayed that the dynamics of C in the 0-30cm soil layer are seven times faster than in the 30-100cm layer (Balesdent et al., 2018). In a global estimate, the 0-30cm soil layer accounts for 81% of the new C which has been incorporated into the first meter of soil over the recent 50 years. The percentage of the C that has been transferred from the atmosphere to soil decreases by depth from 52 % at 0-10cm to 19 % at 10-20cm and less than 10% at 20-30 cm of soil (Balesdent et al., 2018).

3.5 C Accumulating factors and sequestration rate

The mean areal C density of bioretention basins ranged from 0.7 ± 0 kg C m^{-2} to 7.1 ± 0.1 kg C m^{-2} for the accumulated depth of 20cm. The C stocks in bioretention filter media display a highly significant relationship with the site age ($F_{(1,23)}$ = 18.235, p = <0.0003). A linear model predicted a C storage of 5.9 kg C m^{-2} at the age of 13 years (95% confidence interval of 2.9–8.9 kg C m^{-2}). Fig. 5 illustrates the mean C density of each bioretention basin and the regression prediction. The hydraulic conductivity shows significant correlation with soil texture ($F_{(1,5)}$ = 6.80, p =0.048 < 0.05). However, a linear regression model shows an insignificant relationship between C accumulation with both

the hydraulic conductivity and %Clay+Silt in 20 cm of soil ($F_{(1,5)}$ = 2.20, p =0.198 > 0.05 and $F_{(1,23)}$ = 3.588, p =0.07 > 0.05). In addition, the combination of both site age and %Clay+Silt was modelled against the C accumulation, which revealed an insignificant influence of soil texture on areal C density (p =0.08 > 0.05). Finally, the linear model demonstrates a C sequestration rate of 0.31 kg C m^{-2} yr^{-1} (95% confidence interval of 0.16–0.46 kg C m^{-2} per year) of which 44% (adjusted R square) of the C density could be explained by this prediction. The equation predicted C accumulation = 1.871 + 0.309 x (Site age).

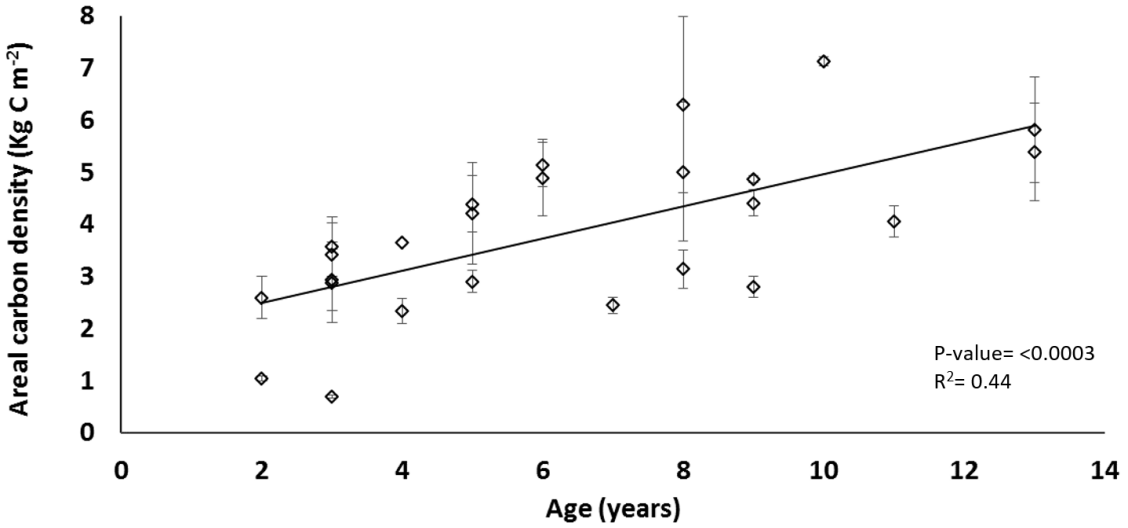


Fig. 5. Mean areal C density of studied bioretention sites and the regression prediction, accumulated depth of 20cm.

Age is the most influencing factor on accumulation of C in bioretention basins, in this study, and also in vegetated swales (Bouchard et al., 2013) and wet retention ponds under different climate zones (Merriman et al., 2017). No relationship was found between C stocks and soil texture in bioretention basins, which is supported with the findings for stormwater ponds in the humid tropical climate of Singapore and the subtropical climate

of the USA (Merriman et al., 2017). However, soil texture is a main influencing factor in C storage in the drier subarctic environment of Sweden. It has been determined that the relationship between C accumulation and soil texture is less when annual precipitation and temperature are higher, which is consistent with the subtropical climate of our study (Merriman et al., 2017).

The bioretention sites did not show any evidence of C saturation with age within 13 years of operation. Although, the results show a slight change in the rate of C accumulation for sites older than 8 years, the C saturation age of bioretention could not be distinguished. The variation in results of older sites might be due to more disturbance caused by major maintenance or by more experience of soil erosion through bypass from the system. Bouchard et al. (2013), found a saturation age of 21.5 years for the vegetated roadside swales as a green stormwater infrastructure, while Merriman et al. 2017 could not uncover the saturation age of stormwater ponds. They projected that saturation age would be more than 26 years. Overall, this indicates that more data is required for older bioretention sites to further investigation of the C saturation age.

Bioretention basins in south-east Queensland, Australia have C sequestration rate of 0.31 kg C m^{-2} yr^{-1} which is half of the estimated value by Moore and Hunt (2013) (0.63 kg C m^{-2} yr^{-1}), based on tree sequestration rates. The measured sequestration rate of bioretention is comparable to the averaged measured rate of 0.4 ± 0.17 kg C m^{-2} yr^{-1} for a wide range of green roofs (Kavehei et al., 2018a). On the other hand, the C sequestration rates of other similar basins that control and manage stormwater such as the vegetated swales and stormwater ponds shows lower rates of 0.1 kg C m^{-2} yr^{-1} (Bouchard et al., 2013) and 0.08 kg C m^{-2} yr^{-1} (Merriman et al., 2017), respectively. However, Merriman et al. 2017 demonstrated a higher accumulation rate of 0.14 kg C m^{-2} yr^{-1} for stormwater

ponds in the humid tropical climate of the Singapore, arguing that high annual rainfall and long growing season can facilitate more plant production and subsequent C storage in the soil. Table 3 presents an overview of the areal C density and sequestration rate of green stormwater infrastructure in different climate types.

Table 3. Comparison of C sequestration rate and C density of vegetated stormwater infrastructure.

Stormwater basins	**C sequestration** (kg C m^{-2} yr^{-1})	**Soil depth** (cm)	**C density** (kg C m^{-3})	**Climate**	**Basins media**	**Vegetation**	**Ref.**
Vegetated swale	0.1	20	15.3	Subhumid, subtropical climate, USA	Felsic and crystalline soils and lower coastal plain	Mostly grass	(Bouchard et al., 2013)
Stormwater pond	0.08	10	5.0-12.2	Subhumid, subtropical climate, USA	Three hydrological zones (deep, shallow and temporary inundation)	Grasses, sedges, and emergent macrophytes	(Moore and Hunt, 2012)
	0.08	10	5.0-12.2	Subhumid, subtropical climate, USA	Three hydrological zones (deep, shallow and temporary inundation)	Littoral shelf and emergent macrophytes	(Merriman et al., 2017)
	0.08	10	15.5-22.8	Subarctic climates, Sweden			
	0.14	10	13.4	Humid tropical climate, Singapore			
Bioretention basins	0.31	20	19.2	Subtropical climate, Australia	Three zones (Central, Intermediate and Batter zones)	Carex appressa, Ficinia nodosa and Lomandra longifolia	This study

A large scale survey of more than 100 south-east Australian wetlands displayed the C sequestration rates of 0.25 kg C m^{-2} yr^{-1} for permanent open freshwater sites and 0.08 kg C m^{-2} yr^{-1} for shallow freshwater marshes (Carnell et al., 2018). Although the sequestration rate of bioretention basins is higher than in natural wetlands, the level of C stocks in wetlands is more than 2 times higher than in bioretention basins. This demonstrates that the basins with high C density are likely to accumulate C at a lower

rate (Grover et al., 2012; Lewis et al., 2018). Accordingly, higher values of sequestration rates correspond to young systems, while mature systems have lower rates of accumulation (Alongi et al., 2004; Howe et al., 2009).

3.6 Design implications for C accumulation in bioretention basins

A review of international design guidelines of bioretention systems shows a variety of soil media recommendations and applied sizing methods, while the system structure (bioretention layers) remain fairly consistent (Roy-Poirier et al., 2010). The details of bioretention soil media recommendations vary between the guidelines internationally (McPhillips et al., 2017). The first bioretention guideline in Maryland (in 1993) recommended a soil media with 20% organic materials (Davis et al., 2009). The recommendation for additions of organic matter to topsoil vary internationally from 3-5% in North Carolina, USA, more than 5% in Australia and up to 60% in Delaware, USA (Davis et al., 2009; Water by Design, 2014). It has been determined that the least organic matter additions with high C:N ratio and P content should be considered to reduce the likelihood of nutrients leaching (McPhillips et al., 2017). Important though the nutrient management is, the poor quality of construction and long-term maintenance can highly influence the primary performance of a bioretention basin in infiltration of stormwater (Blecken et al., 2017; Roy-Poirier et al., 2010).

A major development in the system design was the implementation of a saturated zone which was introduced by Kim et al. (2003) and was included in the Australian guidelines since 2010. The changes in the design characteristics of bioretention basin in Australia have shown in Table 1. The designed saturated zone is intended to maintain soil moisture for vegetation growth and promote denitrification, while providing a high hydraulic conductivity of 100-500 mm/hour. However, the older bioretention basin designs, with

no saturation zone, were designed to have a lower hydraulic conductivity (50-200 mm/hour) to maintain adequate soil moisture for plants. The hydraulic conductivity and soil texture as the main design characteristics have shown an insignificant relationship with both age and C accumulation in bioretention basins. The changes in the design guidelines over time might have some influence on the results observed for accumulation of C. However, the evidence of this study shows that age is the dominant variable rather than other design parameters. In addition, the C accumulation assessment of bioretention basins demonstrated an unvarying C storage over the whole ponding area. This suggests that the vegetated Batter zone as a transforming edge of the sites is also a great source of C, and special attention should be given to planting in these areas.

Denitrification is assumed to be an important part of the nitrogen removal process in bioretention basins. However, to have a higher effective denitrification a combination of anoxic zone and organic C source has been introduced to enhance the nitrogen removal (Blecken et al., 2009; Kim et al., 2003; Zinger et al., 2007). Denitrification requires organic C and longer contact time with anaerobic conditions (Collins et al., 2010). A saturated zone is included in the design of bioretention basins to increase denitrifying bacterial activity by providing an anoxic zone (Blecken et al., 2009). However, a saturated zone at the bottom of a basin will be effective if sufficient organic C is provided at that soil depth (Chen et al., 2013). The saturation is designed to occur at the bottom of the filter media, lower than 40cm from the soil surface, where soil is mostly sand with low levels of organic matters. The results from this study show that the soil below 20cm in depth does not naturally get supplied by above-ground biomass C over 13 years of operation. However, this is the region where anaerobic conditions are most likely to occur. Thus, an addition of a C source layer in the deeper filter media is strongly

recommended. Decreasing the hydraulic conductivity of the filter media and increasing the saturation level in the soil depth could also be investigated, to improve the bioretention performance.

The analysis of C accumulation in soil media allowed us to have an estimation of soil C sequestration in bioretention basins. Moreover, above-ground biomass production from different vegetation types have a potential in accumulation of C which can be targeted in further studies to generate an understanding of above-ground and below-ground C interchange in bioretention basins. From the perspective of carbon footprint, the processes of denitrification, nitrification, methanogenesis, soil saturation and above and below ground C stocks are all associated with the production of GHGs such as CO_2, CH_4 and N_2O (McPhillips and Walter, 2015). Further research is recommended to generate a holistic net carbon footprint of bioretention basins, to optimize the design parameters for above and below ground C storage while minimizing the GHGs fluxes.

4. Conclusion

This study investigated the spatial, temporal and vertical variation of C accumulation in bioretention soil in the subtropical climate condition of East Australia and sought to quantify the average and maximum C storage and the sequestration potential of these basins. Bioretention basins have shown to have uniform spatial accumulation of C across their ponding area. 32% of the C is stored in the top 5cm of soil. C quickly accumulates in the top 5cm of soil, while the lower depths accumulate at a more gradual rate. The results identified that the accumulation of C with time is limited to the top 20 cm of soil during 13 years of site operation. We recommend C amendments to the soil media for future designs of the bioretention basins to provide adequate C at the lower depths where anaerobic conditions are most likely to occur. The bioretention basins show a C

sequestration rate of 0.31 kg C m-2 yr-1, and it is estimated that their C saturation age is more than 13 years. The C stocks analysis allowed us to develop an understanding of above-ground and below-ground C interchange in bioretention basins and their potential in sequestering C.

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