Biofilters for urban agriculture: Metal uptake of vegetables irrigated with stormwater

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ABSTRACT

In an era where increasing urbanization is resulting in issues such as urban poverty, malnutrition and unemployment, urban agriculture is increasingly regarded as a multi-functional approach to addressing these issues. However, increasing water scarcity limits the feasibility of urban agriculture and hence alternative water sources for irrigation are required. While stormwater has the potential to be used for urban agricultural irrigation, stormwater contaminants can pose potential health risks. Thus, a column study was conducted to (1) determine whether biofilters planted with vegetable crops are capable of treating urban stormwater, and (2) identify the level of heavy metal uptake into various vegetable crops when irrigated with stormwater. The column study was conducted over nine weeks with nine vegetable species (broad beans (Vicia faba), kohlrabi (Brassica oleracea Gongylodes Group), kale (Brassica oleracea Acephala Group), lettuce (Lactuca sativa), mint (Mentha spicata), mustard spinach (Brassica juncea), radish (Raphanus sativus), spinach (Spinacia oleracea) and sweet corn (Zea mays)) irrigated with stormwater. The treatment function of the system was not compromised by the use of vegetable crops. 70% concentration reduction was achieved for Cu, Pb, Zn, Mn and Ni. The concentration of total nitrogen and total phosphorus in the effluent were reduced by up to 47% and 69%, respectively. Heavy metal accumulation was limited in the edible portions but the levels of Cd and Pb concentration exceeded the Food Standards for Australia and New Zealand and World Health Organization guideline values, deeming it unsuitable for consumption. Cultivating vegetable crops in biofilters did not affect plant growth and the biofilter’s stormwater treatment functions. However, heavy metal concentrations within plants does raise potential health concerns, requiring further studies to improve crop safety.

1. Introduction

Urban agriculture is a practice located within urban areas and involves various crops as well as the rearing of livestock (FAO, 2008). It often uses water, land and waste materials obtained from urban areas as inputs (FAO, 2008). Urban agriculture has been practiced for many centuries, with roots in the development of ancient civilizations and is currently being revived in many parts of the world in an attempt to provide direct access to food, employment opportunities, community engagement and healthier food options (Moglia, 2014). The practice of urban agriculture is constrained by increasing water scarcity which is further compounded by increasing water demands from rapid urbanization and population growth (Moglia, 2014). To reduce the pressures on potable water supplies whilst also meeting the irrigation requirements for urban agriculture, alternative water sources such as wastewater, greywater and stormwater are increasingly being advocated and utilised (Finley et al., 2009, Nnadi et al., 2015, van Lier and Huibers, 2010). However, such water sources contain pollutants such as heavy metals, organic micropollutants and pathogens which render them unsuitable for irrigation without pre-treatment (van Lier and Huibers, 2010, Tom et al., 2013). The effects of improper use of recycled water on the contamination of crops by heavy metals have been demonstrated and the potential health risks of overconsumption of such metals have also been highlighted (Tom et al., 2014). Studies on metal accumulation in the edible portions of vegetables found that metal concentrations often exceeded guideline limits (Muchuweti et al., 2006, Tom et al., 2014). For example, one laboratory-scale study on vegetable metal accumulation in a system irrigated with stormwater found that Pb concentrations in plants exceeded the guideline limits set by the Food Standards for Australia.
and New Zealand (FSANZ) (Tom et al., 2014). Attempts at classifying the metal accumulating abilities of a range of vegetables have found that leafy vegetables are generally high accumulators of heavy metals while fruiting plants and legumes contain lower metal concentrations in the edible portions (Yang et al., 2010). However, variations in metal accumulating rates also exist within vegetable species and with metal types (Tiwarl et al., 2011, Tom et al., 2014).

While some metals such as Cu, Zn and Mn are essential trace elements required for various physiological processes, other metals such as Cd, Pb and Hg are toxic to humans (WHO, 1996). In excess, these heavy metals can lead to health issues such as cancer, disruption of the endocrine system, organ and neurological damage (WHO, 1996). With most of the dietary intake of metals originating from vegetable consumption, the improper use of contaminated alternative water sources for irrigation raises serious health concerns (WHO, 1996).

Using stormwater in urban agriculture has significant potential for it reduces the need for potable water for irrigation, while also mitigating the impacts of high stormwater runoff on receiving waterways. However, urban stormwater is known to contain pollutants such as heavy metals (Tom et al., 2013). Treatment of stormwater is often done using Water Sensitive Urban Design (WSUD) technologies (Payne et al., 2015) and one commonly used WSUD technology is biofilters which consists of media and vegetation, but can also include submerged zones to improve its treatment efficiency (Payne et al., 2015). The purpose of this system is to allow stormwater infiltration and retention for the removal of pollutants via a range of biological, chemical and physical processes (Payne et al., 2015, Read et al., 2008). An example of this is the removal of nitrogen from incoming stormwater where the removal is a combination of chemical processes such as nitrification and denitrification of dissolved nitrogen, physical straining of particulate nitrogen by the filter media and plant uptake of essential nitrogen (Payne et al., 2015, 2014). The potential of combining food production with a stormwater treatment system increases the multi-functionality of biofilters by reducing pressures on potable water while increasing the sustainability of food production methods, in addition to stormwater treatment.

Two major classes of pollutants entering biofilters are nutrients and heavy metals. While there are other pollutants present in stormwater, studies to date have focused on these two (Marla and Kim, 2016, Zhang et al., 2011). Their removal from stormwater by biofiltration is dependent on vegetation selection and filter media properties. Vegetation has been shown to be an essential component of biofilter systems for the removal of pollutants, particularly total nitrogen (TN) (Payne et al., 2014, Zhang et al., 2011). The role of plants in pollutant removal can be in the form of direct uptake of pollutants or by affecting soil conditions that controls the rate of breakdown of pollutants by microbes (Ali et al., 2011, Waaun and Okeireen, 2011, Sobiru et al., 2017). However, the effectiveness is dependent on plant traits such as root length, depth of penetration in the biofiltration and mass (Payne et al., 2014, Read et al., 2009). While plants such as Carex appressa (tall sedge) and Juncus spp (rushes) are known to be the most effective plant species for pollutant removal in biofilters, studies on the use of vegetable crops in biofilters are few (Payne et al., 2014). Therefore, the feasibility of using vegetables in place of typical biofilter plants in biofilters and its effects on stormwater treatment requires further understanding.

Biofilters have been shown to have high heavy metal removal efficiency, largely driven by mechanical straining, with up to 98% removal of Pb and Zn (Read et al., 2008, Blechen et al., 2009b). However, once the metals are filtered out, it is largely unknown if the metals are retained within the filter media or subsequently taken up by vegetation.

While there are numerous studies on hyperaccumulators and heavy metal accumulation in vegetables grown on contaminated soils or irrigated with wastewater, studies on metal uptake by plants in stormwater biofilters are few. Read et al. (2008) showed that a negligible amount of metal is taken up by the vegetation with most of the metals retained in the filter media. However, when considering metal concentration in vegetables for consumption, strict guidelines exist and even small amounts of metals in vegetables can pose a risk to human health.

The aim of this study was to (1) determine whether biofilters planted with vegetable crops are capable of treating all key stormwater pollutants in urban stormwater and (2) identify the level of heavy metal uptake by specific vegetable crops when irrigated with stormwater. The objectives were to quantify metal accumulation in three types of vegetables – leafy, leguminous and root – cultivated in biofilters and irrigated with stormwater to assess the potential for using biofilters in urban agriculture.

2. Methods

2.1. Column set up

A laboratory-scale column study was conducted over nine weeks using five replicates of nine vegetable species and one non-vegetated control. A laboratory-scale study with a period of nine weeks was chosen to allow the testing of heavy metal uptake in fast growing plants and identify the water treatment function of the biofilter within the early stages of operation. The vegetable species used were broad beans (Vicia faba), kohlrabi (Brassica oleracea Gongylodes Group), kale (Brassica oleracea Acephala Group), lettuce (Lactuca sativa), mint (Mentha spicata), mustard spinach (Brassica juncea), radish (Raphanus sativus), spinach (Spinacia oleracea) and sweet corn (Zea mays). These vegetable species were chosen based on their short growing time, root depth and their varied ability to remove nitrogen, phosphorus and heavy metals from the soil. The set-up of the columns is shown in Fig. 1.

The composition of the ameliorated fine sand filter media followed Australian biofilter design guidelines (Payne et al., 2015). A 150 mm deep submerged zone was included, to promote denitrification and provide a permanent water source (Payne et al., 2014, 2015). The porosity of the submerged zone was estimated to be 0.5; this was determined by measuring the volume of water required to saturate a known filter media volume (Eq. (1)). This value of porosity was then used to calculate the remaining water in the submerged zone (Eq. (2)).

\[ P_t = V_p / V_t \]

Eq. (1) Calculation for measuring porosity of the submerged zone, where \( P_t \) = porosity, \( V_p \) = pore volume and \( V_t \) = total volume.

The vegetables were grown from seed, which were purchased from Bunnings Warehouse Australia, in the columns and were progressively thinned to provide enough growing space, as recommended by the seed suppliers. Thinning dates varied with plant species but ranged from 2 to 6 weeks after planting. The study was conducted under growing lights that were switched on for 12h each day in a laboratory with an average air temperature of 18.7 °C throughout the study period.

2.2. Stormwater preparation and dosing

An inoculant mixture containing 1.9 L of semi-synthetic stormwater, 10 mL of fresh milk and 0.25 g of rhizobium bacteria (Innoculant type F obtained online from Eden Seeds, Queensland, Australia) was made on the first day of the experiment. The inoculation of legume seeds with rhizobium bacteria ensures that root nodules involved in nitrogen fixing are formed. All seeds were inoculated to prevent any potential bias that might arise. The semi-synthetic stormwater was prepared weekly using mains water, sediment collected from a local stormwater pond that was sieved (1 mm mesh size), and additional, laboratory-grade chemicals to achieve typical total suspended solids (TSS), nutrient and metal concentrations found in stormwater as determined by Duncan (1999) and Taylor et al. (2005) (Table 1). The slurry, chemicals and metals were mixed in a tank for 15 min prior to dosing to ensure even mixing. Each column was dosed with 40 mL of the inoculant mixture for the first
Table 1
Average inflow metal, total suspended solids and nutrient concentrations over two sampling rounds and comparison to targeted inflow concentration based on Duncan (1999) and Taylor et al. (2005).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Target concentration (mg/L)</th>
<th>Mean throughout the experiment (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium (Cd)</td>
<td>0.0045</td>
<td>0.0030</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>0.025</td>
<td>0.015</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>0.050</td>
<td>0.31</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.23</td>
<td>0.21</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>0.031</td>
<td>0.024</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>Total suspended solids (TSS)</td>
<td>150</td>
<td>70</td>
</tr>
<tr>
<td>Total nitrogen (TN)</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Total phosphorus (TP)</td>
<td>0.35</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.3. Water sampling

Inflow and outflow water samples were collected twice throughout the experiment (on the 40th and 63rd day). Water samples were analysed for TSS, TN, total phosphorus (TP) and seven heavy metals (Cr, Cu, Ni, Pb, Zn, Mn and Cd). Water quality samples were analysed by NATA (National Association of Testing Authorities, Australia) accredited laboratories using standard methods and quality control procedures (APHA/AWWA/WEF, 2005a,b). Metal analysis of water samples were conducted with Inductively Coupled Plasma Mass Spectrometry (ICP-MS) on nitric acid (HNO₃) digested samples (APHA/AWWA/WEF, 1998). Infiltration test was conducted by maintaining constant head with a known volume of water (165 mL—volume of pouring bottle) after the column has been pre-wet with 0.75 mL of stormwater to fill the ponding zone and the time taken to infiltrate is the estimated infiltration rate. The remaining submerged zone (SZ) volume prior to dosing was calculated as according to Eq. (2).

\[
\text{Proportion of remaining}\text{SZ}\text{prior to dosing} = \left[\frac{(\text{maximum volume of } \text{SZ})-(\text{inflow volume during dosing}-(\text{outflow collected after dosing})}{(\text{maximum volume of } \text{SZ})}\right] \times 100
\]

where the maximum volume of SZ is: Depth of SZ $\times$ area of column $\times$ porosity of the media in SZ.

Eq. (2). Submerged zone volume before dosing.

2.4. Plant sampling

Three out of five replicates of each design configuration were randomly sampled during the last week of the experiment for plant and filter media analyses. This is with the exception of columns with mint where mint did not grow and therefore none was harvested. The plants were divided into above- and below-ground portions and washed three times with deionised water to remove attached filter media. The plants were then patted dry and weighed to obtain the fresh weight before being frozen prior to heavy metal analysis. Plant moisture contents were also determined by drying a subsample in an oven at 60 °C until constant weight is achieved. Filter media cores (30 mm diameter, 350 mm depth) were collected using a stainless-steel corer and the top 5 cm were analysed for the same six heavy metals. Six metals were analysed: Cd, Cu, Ni, Zn, Pb and Cr by a NATA accredited lab. All samples were homogenised and digested with HNO₃ before metal dosing. Following this, the columns were dosed with 100 mL of semi-synthetic stormwater on the 2nd day and 300 mL of semi-synthetic stormwater on the 5th and 7th day. Each column was dosed twice weekly with 2.25 L of semi-synthetic stormwater from the 9th day onwards. The dosing volume and frequency were designed to simulate typical biofilter sizing and climatic conditions for Melbourne, Australia. This was based on an annual rainfall of 532.5 mm and the surface area of the biofilter column representing 2% of its impervious catchment area (Australian Government Bureau of Meteorology, 2016).

It should be noted that the amount of slurry added was increased from 200 mL to 260 mL on the 26th day of the experiment because initial inflow TSS concentrations were lower than the target value. While care was taken to ensure that metal concentrations in the inflow were close to the global average found in stormwaters (Duncan, 1999), average Cu, Cr and Cd concentrations in the inflow were six times higher, 1.6 and 1.7 times lower than the global average values, respectively (Table 1). The deviation in mean metal concentrations found in this study is due to a few factors such as natural variations in sediment metal concentrations, settling of sediments or inadequate amount of Cd added into the semi-synthetic stormwater in the form of laboratory-grade chemicals. Nevertheless, Cu, Cr and Cd values in this study were within the range of metal concentrations found in urban stormwater (Duncan, 1999).
concentrations were determined using ICP-MS (Agilent 7900) or Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) (Varian 730-ES) according to USEPA 6010, 6020 and AOAC methods 986.16, 974.14 (16th edition) (U.S. Environmental Protection Agency, 1983, 1990, AOAC, 1999).

2.5. Data analysis

Statistical analyses were used to determine the effects of plant species on pollutant concentration reduction (Eq. (3)).

\[
\frac{C_{in} - C_{out}}{C_{in}} \times 100
\]

where \(C_{in}\) and \(C_{out}\) represents pollutant concentration in the inflow and outflow, respectively. Eq. (3). Concentration reduction rates.

Metal concentrations in plants were normalised by the soil metal concentration: it was calculated as the ratio of metal concentration in plant part (roots or shoots) to the metal concentration in the soil (this is referred to as metal concentration factor from hereon). In cases where soil metal concentrations were below the detection limit (\(n = 33\)), the value used is the detection limit. Since the soil concentration used for calculation is only an upper estimate of the actual concentration, this might underestimate the actual concentration factor.

Multivariate analysis of variance (ANOVA) was used to determine differences between plant species and sampling rounds. Correlations were also conducted to identify possible links between changes in the system (such as infiltration rates and submerged zone volumes) and concentration reduction or load removal rates of pollutants and metal concentrations in plants. Based on the homogeneity of variances, either Tukey post hoc test (\(p \leq 0.05\)) or Games Howell post hoc test (\(p \leq 0.05\)) was used. In some cases where errors arose due to sampling errors (incorrect inflow volume, errors in outflow collection), those samples were removed to avoid bias.

3. Results and discussion

3.1. Pollutant removal capacity of vegetable-biofilters

3.1.1. Heavy metal treatment

The mean metal concentrations in the semi-synthetic stormwater were within the range of the average stormwater metal concentrations reported by Duncan (1999). Outflow Cd concentrations were below the detection limit (0.0002 mg/L) in both sampling rounds (representing removal rates of > 94% and > 91% in the first and second sampling rounds, respectively). The biofilter columns demonstrated consistently good removal of metals; concentrations were reduced by > 90% for Cd, Cu, Pb and Zn and > 70% for Mn and Ni. Metal removal rates in this study were comparable to previous stormwater biofilter studies (e.g. Blecken et al., 2009a), with the exception of Cr removal which was 46%.

The presence of plants does not seem to be a factor in governing the metal removal performance of the biofilters. In general, the metal removal performance of the un-vegetated control columns was not found to be statistically different to the vegetated columns. A comparison of metal concentration reduction between vegetated columns showed that while significant, the correlation between plant mass and concentration reduction rates of Cr and Mn was weak (\(r = 0.566\) and \(r = -0.485\), respectively). In addition, the effects of plant species on metal removal could only be demonstrated for Cr and Mn removal (\(p = 0.014\) and 0.033, respectively; Fig. 2) when averaged across species. However, post hoc analysis only found significant differences between broad beans with kohlrabi and mint for Cr removal where mint was the worst performing species for Cr removal. No significant differences were found between species for Mn removal but spinach had the lowest Mn removal. This further highlights the importance of straining and adsorption to filter media in metal removal compared to plant mass or species as found in previous studies and demonstrated by the positive, although not significant, correlation between heavy metal removal and soil metal concentrations (Blecken et al., 2009b, Read et al., 2008).

While infiltration rates and SZ volumes were hypothesised to influence the removal of heavy metals in these systems, as has been found in previous studies (Pham et al., 2012, Blecken et al., 2009a, Bradi, 2004), no conclusive results could be obtained in this study due to uncertainties. The short length of the study meant that the columns were not fully established in that the plants roots did not fill the columns to cause significant differences in infiltration rates and drawdown of the SZ between columns. Nevertheless, the range of metal removal of all columns (except for Cr) were small such that the relationship between SZ volume, infiltration rates and metal concentration reduction rates is not of any practical significance.

3.1.2. TSS, TN and TP removal

TSS, TN and TP average concentration reduction were found to be lower (\(< 10\%), > 10\% and > 30\% lower; respectively) than the findings from previous studies (Bratieres et al., 2008, Payne et al., 2014) (Table 3). As concentration reduction rates are dependent on inflow concentrations (average TSS and TP inflow concentration in this study was 70 ± 34 mg/L and 0.36 ± 0.03 mg/L as opposed to 160 mg/L and 0.427 mg/L respectively, found in the study by Bratieres et al. (2008)), the lower concentration reduction rates of TSS and TP found in this study is not surprising. Additionally, relatively higher TSS concentration in the effluent may be due to the leaching of the filter media (Hatt et al., 2007). As TP is largely particulate bound and its removal can be dependent on TSS removal, it is expected that the TSS and TP concentration removal rates would improve if the experiment was conducted over a longer term (Hatt et al., 2007).

The lower TN concentration reduction rate in this study compared to other lab-based study is most likely due to the types of vegetation used (Table 2). While previous studies have looked at TN removal performance of biofilters with plant species such as Carex appressa (tall sedge) and Malaleuca incana (grey honey-myrtle), which are known to be highly efficient at nitrogen uptake (Payne et al., 2014), this study used vegetables which have different nutrient uptake and usage patterns. However, to date there has been no other studies on nutrient removal performance of biofilters with vegetables, preventing a direct comparative assessment of the current system against previous studies.

This study further confirms findings on the importance of vegetation in nutrient removal (Zhang et al., 2011). Un-vegetated columns had statistically significantly lower TN and TP removal compared to vegetated columns (except for kohlrabi and spinach for TP; mint and spinach for TN) (Table 3). Read et al. (2009) demonstrated that root length and mass can influence nutrient removal. Indeed, biofilters columns with more established plants and extensive root systems such as broad beans and sweetcorn had higher TP concentration reduction rate of almost 25% compared to kohlrabi columns. Plant species played a more significant role than plant weight in TN concentration reduction, as evident by columns with kale and radish that had significantly higher TN concentration reduction than columns with broad beans and sweetcorn. This is in agreement with the findings by Bratieres et al. (2008) in which some plant species may be more efficient in nitrogen usage and hence nitrogen removal.

Of particular interest in this study is the ability of broad beans, a nitrogen fixer, to remove TN. It was shown that broad beans facilitated higher TN concentration reduction than the un-vegetated control columns despite being a nitrogen fixer plant. This may mean that the TN uptake of the plant may be greater than the nitrogen fixed. In a study on isoflavonoid exudation in soybean plants at varying nitrogen concentrations, it was found that the exudation of isoflavonoids was reduced with increasing influent nitrogen concentration (Zhang et al., 2000, Wojtaszek et al., 1993). As a chemical compound involved in the
Fig. 2. Concentration reduction rates in outflow for six metals in all configurations (n = 10). Values are metal concentration reduction rates calculated over two sampling rounds. Outliers are represented by * (mild outliers: Q1-1.5 × IQR/Q3 + 1.5 × IQR) and o (extreme outliers: Q1-3 × IQR/Q3 + 3 × IQR) (where Q1 = 25th percentile, Q3 = 75th percentile and IQR = inter-quartile range).
<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Plants</th>
<th>TSS</th>
<th>TN</th>
<th>TP</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current study</td>
<td>100 mm diameter biofilter columns, 50 mm amended sand, fine sand, and woodchips</td>
<td>Broad beans (Vicia faba), kohlrabi (Brassica oleracea Gongylodes Group), kale (Brassica oleracea Acephala Group), lettuce (Lactuca sativa), mint (Mentha spicata), mustard spinach (Brassica juncea), radish (Raphanus sativus), spinach (Spinacia oleracea) and sweet corn (Zea mays)</td>
<td>81% (70 mg/L)</td>
<td>47% (2.5 mg/L)</td>
<td>69% (0.36 mg/L)</td>
<td>Cr – 29% (0.015 mg/L), Cu – 94% (0.308 mg/L), Pb – 90% (0.116 mg/L), Mn – 83% (0.208 mg/L), Ni – 75% (0.024 mg/L), Zn – 90% (0.29 mg/L)</td>
</tr>
<tr>
<td>Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study Britinver et al. (2008)</td>
<td>375 mm diameter biofilter columns, 70 mm medium sand, 70 mm coarse sand, 70 mm gravel</td>
<td>Carex appressa (Tall sedge), Melilotus officinalis (Swamp paperbark), Micranthus stipoides (Weeping grass), Desmodium rotundifolium (Black-anther-flax-lily), Leucopogon brownii (Cushion bush)</td>
<td>97%–99% (160 mg/L), 83%–95% (0.427 mg/L), – 241% to 71% (2.21 mg/L)</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy metal fates in laboratory bioretention systems Sun and Davis (2007)</td>
<td>31 cm diameter pots, 5 cm media (50% planting soil and 50% leaf mulch), 20 cm mixture (50% sand, 30% planting soil, 20% leaf mulch)</td>
<td>Coarse perennial grass (Punica virgatum, Kentucky-31, Bromus ciliatus)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Hydraulic and pollutant removal performance of fine media stormwater filtration systems Hutt et al. (2009)</td>
<td>10 cm diameter biofilter columns, 80 cm filter media (fine sand), 60 cm coarse sand and gravel</td>
<td>N/A</td>
<td>99% load reduction (29 g/m²), 97% load reduction (0.08 g/m²), 38% load reduction (0.45 g/m²)</td>
<td>Cu – 97% load reduction (0.06 g/m²), Mn – 94% load reduction (0.01 g/m²), Pb – 99% load reduction (0.15 g/m²), Zn – 99% load reduction (0.22 g/m²)</td>
<td>(continued on next page)</td>
<td></td>
</tr>
</tbody>
</table>
formation of nodules in legume plants, which acts as a host to rhizobium bacteria that are responsible for nitrogen fixing, the inhibition of iso-flavonoid exudation with increasing nitrogen concentration reduces nitrogen fixing activity (Phillips and Tsai, 1992). Therefore, it is most likely that the nitrogen concentration in the stormwater used for irrigation is high enough to inhibit the nitrogen fixing activity of rhizobium bacteria.

### 3.2. Heavy metal concentration in plants

Heavy metal concentrations in vegetables grown in stormwater biofilters varied by plant and metal types. In general, leafy vegetables exhibited higher metal concentration factors than legumes and root vegetables. This is consistent with the literature, where leafy vegetables are known for being high accumulators while legumes are low accumulators of metals (Alexander et al., 2006). Metal concentrations in plants were highest for Zn (average 49 mg/kg) and lowest for Cd (average 1.2 mg/kg). This corresponds to inflow metal concentrations: Cu > Zn > Mn > Pb > Ni > Cr > Cd and is largely consistent with the patterns of metal concentration uptake reported by Tom et al. (2014), where plants contained the highest concentrations of Zn followed by Cr, Pb, Ni, Cr, and Cd.

Plant weights of the same species were not very different, however the intra-species metal concentration factors were more variable (Table 3). For most of the metal and plant species, a negative correlation was found between plant weight and metal concentration factor, both between and within plant species. In their study on Cd accumulation in plants of varying age, Peronnet et al. (2003) found that the concentration of Cd in *Thlaspi caerulescens* (alpine pennygrass) was highest in young leaves and remained constant as plant biomass increased. It is likely that higher metal uptake rates occur when plants are early in the developmental stage because more water, essential nutrients and therefore metals contained in the water solution are taken up during their growth (Lapouge et al., 1997, Marchiol et al., 2004).

As they grow, the uptake rate remains constant while the mass increases, which drives the negative correlation between plant mass and metal concentrations seen in this study. This is further solidified by the results from the correlation analysis between 1/Cd$_{plant}$ and plant mass which was significantly positive, demonstrating higher metal concentration in plants with smaller biomass.

Metal concentration factors in the edible portions of plants (roots of radish, shoots for all other species) were found to be lower than the metal concentration factors in the non-edible portions, with the exception of Cr (Fig. 3), suggesting that vegetable crops may be capable of restricting metal accumulation in their edible portions. Previous studies on metal accumulation in vegetable crops have also found this to be true especially for leafy or fruiting vegetables where metal accumulation is lowest in the edible portions (Tiwari et al., 2011). However,
Fig. 3. Concentration factor in the roots and shoots of plants for all metals (* signifies significant difference between metal concentration factor in the roots and shoots, p < 0.05). Vertical dotted lines indicates the division between leafy, fruiting and root vegetable. Higher concentration factor values indicate higher metal concentration in the plant parts in comparison to the soil.
there is not one vegetable species that is particularly good at excluding or accumulating metals as the rate of accumulation differs between metals. Nevertheless, the ability of vegetable crops to restrict metal uptake into their edible portions is promising in terms of using stormwater for irrigation.

3.3. Comparison of metal concentration in plants and guideline values

Out of the six metals that were tested, Pb and Cd were the only metals with specific guideline values set by World Health Organization (WHO) and FSANZ due to their ability to cause serious health issues. Comparison of the metal concentrations in the edible portions of each vegetable species with guideline values demonstrates that the Pb and Cd concentrations in all vegetables in this study exceeded both the WHO (1996) and FSANZ (2011) guideline values (Table 4). In some cases, such as spinach, concentrations of Pb were 18 times the guideline values. It can be expected that Cd concentrations in the edible portions of vegetables in actual biofilter systems may be higher than what was found in this study since Cd concentration in the inflow stormwater in this study was 1.6 times lower than average stormwater concentrations. Vegetables irrigated with contaminated water have previously been shown to contain heavy metals above the permissible limits set by various guidelines (Alexander et al., 2006, Muchuweti et al., 2006).

Khan et al. (2008) found that Cd concentration in crops irrigated with wastewater were between 0.39 and 0.93 mg/kg, several times above China's State Environmental Protection Administration (SEPA) guideline values of 0.1–0.2 mg/kg. Since the edible portions of vegetables irrigated with stormwater are unsafe for consumption, with respect to metal concentrations, ways to reduce the transfer of metals from stormwater to plants must be identified before stormwater biofilters can be used for simultaneous food production and water treatment. Future research should focus on reducing the bioavailability of metals to reduce heavy metal uptake by the plants.

4. Conclusion

Metal removal from inflow stormwater was consistently high where > 90% concentration reduction was achieved for Cd, Cu, Pb and Zn while Mn and Ni was reduced by > 70%. While this study was only conducted over a short period, the results are indicative of the potential of using vegetable crops in biofilters for pollutant removal. A longer-term study where plants are allowed to go to fruiting requires further exploration prior to confirming their ability to consistently remove pollutants from urban stormwater. However, vegetable crops grown in stormwater biofilters, irrigated with raw stormwater still allows significant uptake of heavy metals due to their bioavailability in the influent and those that are retained in the soil. Variations exist in the metal accumulating ability of different vegetable species, and leafy vegetables are more adept at accumulating metals while root and fruiting vegetables have lower metal accumulation. Metals are also found to accumulate most in the non-edible parts of the plants which demonstrates the potential of using stormwater for irrigation. However, metal concentrations in the edible portions of vegetable crops exceeded WHO and FSANZ guideline values and therefore pose potential health threats. It is therefore imperative that future work includes identifying ways of retaining metals in the filter media and reducing its bioavailability, such as through the use of soil amendments, to ensure the safety of those that consume these crops.

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Declarations of interest

None.

References


