Metal buildup in stormwater bioswales: effects of land use and impacts to microbial communities

INTRODUCTION
Polluted stormwater from urban areas is the biggest source of pollution to surface waterbodies (NRC 2009), and is a growing problem because urbanization is increasing. As more land is covered by impermeable surfaces such as streets, rooftops and parking lots, more stormwater flows over land as runoff, picking up pollutants including nutrients such as nitrate and phosphate, sediments, and heavy metals (Pitt et al. 1995; USEPA 1999). When this polluted runoff flows to creeks and the ocean, it may cause excessive plant growth, reduce water clarity and introduce toxic pollutants that threaten human health and marine life.

The impacts of polluted runoff on receiving water bodies can be mitigated via the use of infiltration and detention based stormwater control measures (SCMs) that are built into the landscape, slowing down runoff, storing pollutants and providing water quality improvements. One such example is the use of bioswales, or shallow vegetated depressions that detain runoff and allow infiltration. Treatment processes include adsorption to soil particles, filtration by plants, chemical and biological transformations, biological uptake (Walker and Hurl 2002), and predominantly sedimentation (Stagge et al. 2012).

When sediments deposit in bioswales, particle-associated pollutants such as metals are retained in the soil media and to a lesser extent may be taken up by vegetation (Sun and Davis 2007). Metal buildup in bioswale soil media is of concern due to potential toxicity to biota (Davis et al. 2001, 2003), trophic transfer due to plant uptake and consumption by biota, and inhibition of microbial functions relevant to pollutant attenuation processes. These potential effects would likely manifest themselves in the long term, undermining the sustainability of bioswales.

Metal buildup in different SCMs has been studied, including detention ponds (Yousef et al 1990; Guo 1997; Liebens et al. 2001; Casey et al 2006; Wik et al 2008; Karlsson et al. 2010; Egemose et al 2014; Roinas et al 2014; Stephansen et al 2014), constructed wetlands (O-Connor et al 2012; Gill et al 2014) and in bioretention practices that use a specially defined filter media (Davis et al. 2001, 2003; Marsalek et al 2006; Sun and Davis 2007; Hatt et al 2008; Blecken et al 2009; Lim et al. 2015). The potential for long term metal buildup to harmful levels in bioswales is lesser studied.

Increasing our understanding of how metals accumulate and are distributed in bioswale sediments and how different land use cover in the catchment area contributes to this buildup can help inform management of these systems and evaluate their long term sustainability. Although numerous studies have linked urban non-point pollution sources and differences in watershed land use to stormwater runoff quality (Helsel et al 1979; Davis et al 2001; Heijerick et al 2002; Van Metre and Mahler 2003; Browne and Peake 2006; Jartun et al 2008; Lye 2009), studies evaluating the relationship between land cover and stormwater derived heavy metal build up in sediments of SCMs are lacking.
One study performed in roadside swales showed that heavy metals accumulated to higher concentrations than background levels, but that there were no significant differences between commercial and agricultural swales, except for copper, lead and zinc (Liebens 2001). Overall, there is a paucity of studies examining metal buildup in bioswales in relation to watershed use.

The goal of this study is to evaluate the extent of metal buildup in bioswales that have been operational for over a decade, in a semi-developed area with Mediterranean type climate. The relationship between differences in pervious and impervious land cover and metal content in soils will also be assessed. Results will be analyzed in the context of potential toxicity to biota. In particular, because microbial communities’ response to environmental stressors is more sensitive than other biological species, their use as indicators of biological integrity has been suggested (Sims et al. 2013). Future work will explore the use of microbial indicators to assess biological performance of bioswales, by investigating microbial communities in bioswale soils.

Research and data analysis carried out over the summer of 2016 was guided by the following questions:

(i) What is the evidence for metal buildup and how are metals distributed in soils of bioswales that have been receiving stormwater runoff for over a decade?
(ii) To what extent are differences in pervious or impervious land cover in the bioswale drainage linked to differences in nutrient and metal buildup in the bioswale soils?
(iii) How relatively bioavailable are the metals that deposit in bioswale soils and what are the implications for microbes or other biota?

SITE DESCRIPTION
The project site, Manzanita Village, is a residential housing complex located on the UCSB Campus, Santa Barbara, CA. This site was chosen because there is a gradient in surface cover characteristics in the catchment areas for different bioswales. This provides an ideal setting to explore land cover influence on metal buildup in soils in residential areas.

Manzanita Village is characterized by a Mediterranean climate that is influenced by maritime winds and receives fog moisture inputs during the summer. The temperatures are mild throughout the year, with little seasonal variation. Rainfall is variable and occurs mostly during November-April. Annual precipitation for the period 2001 to 2014, measured at a weather station close to the site, averaged 16.3 inches. This is lower than the historical average of 17.4 inches for the years 1952-2014 (County of Santa Barbara Public Works).

The total project area comprises 12 acres, of which approximately 75% drain into a bioinfiltration system that is composed of cobble drains that intercept rooftop runoff, four upper bioswales, a large infiltration marsh and a main bioswale that flows into a tidally-influenced coastal lagoon (Figure 1). The upper bioswales and large marsh comprise 35% of the watershed, while the main bioswale receives runoff from 40% of the watershed, directly and indirectly via underground stormwater drains.

The watershed that drains into the upper bioswales is comprised of vegetated soil in the USDA Natural Resource Conservation Service’s Hydrologic Soil Groups C or D, 25% service road, and 20% pitched roofs (Manzanita 5-year Report). The soils are planted with shrubs or low input lawn that is irrigated with
reclaimed water, which may be a source of nutrients, but is not expected to be a major source of metals. No fertilizers are applied to the vegetated soils, but occasionally glyphosate-based herbicides are applied for weed control, typically on a yearly basis and following recommended application rates. The service roads are used mostly by electric powered vehicles. The pitched roofs consist of single ply membrane roofing that has been waterproofed and standing seam metal roofing that includes aluminum, copper, steel and galvanized metal. Ocean aerosols rich in phosphate may deposit on the roofs, which also receive droppings from seagulls and pigeons.

Figure 1: Locations of stormwater control features on Manzanita Village. The study bioswales are indicated by dashed lines and ID in red: BW1 (Rattlesnake), BW2 (San Jose), BW3 (Cold Springs) and BW4 (Sycamore) (Manzanita Village Storm Water and Urban Runoff Biofiltration System PowerPoint by Lisa Stratton, CCBER).

The bioswales were constructed in 2001-2002 and receive maintenance in the form of annual vegetation trimming to cut the basin bed vegetation to a height of several inches. Vegetation clippings are removed and used elsewhere for composting. Invasive species are removed manually or via herbicide application. The upper bioswales consist of a string of shallow basins separated by rock check dams with an average 2% slope and total lengths ranging 200-400 ft. The basins are 15-20 ft long and 8 ft
wide, they have a trapezoidal cross section with a basin bed of 4 ft. When full, the basins have a depth of approximately 6 inches. The bioswales are planted with native sedges and rushes which are well suited to the high clay subsoil. The bioswales are lined with coconut netting and straw wattles to limit erosion losses. Runoff from roofs is conveyed via downspouts into cobble drains, and then into the bioswales. There are several roof downspout inputs per bioswale.

**Subwatershed study to delineate pervious and impervious areas**

To determine differences in land cover for the subwatersheds draining to individual bioswales, an existing subwatershed map provided by CCBER was analyzed (Figure 2) to delineate different land cover areas using ArcMap 10.1. The following surfaces were distinguished: paved areas, rooftops, lawns, and natural cover (shrubs and gravel). Once the surfaces were marked, their areas were calculated.

![Figure 2: Watershed and subwatershed map for Manzanita Village](image)

*Figure 2: Watershed and subwatershed map for Manzanita Village (Manzanita Village Storm Water and Urban Runoff Biofiltration System PowerPoint presentation by Lisa Stratton, CCBER). Portions of the project area, shown in dark green, are conveyed via underground drains (shown as dashed lines) into the main bioswale, which discharges into the coastal lagoon. The area shown in yellow receives no bioinfiltration and represents 25% of the total watershed. Direction of flow is shown by blue arrows.*
The total drainage area was obtained by summing the different land surface areas. The individual contribution from each land surface is expressed as a percent of this total area (Table 2). The differences in pervious and impervious land cover amongst the bioswales allow for analyzing differences in sediment deposits, with bioswale 1 having a mostly pervious watershed and bioswale 3 receiving runoff mostly from impervious surfaces. Bioswales 2 and 4 have a relatively even split between impervious and pervious land cover in their subwatershed.

<table>
<thead>
<tr>
<th>Bioswale ID</th>
<th>Drainage area (m²)</th>
<th>Total impervious (%)</th>
<th>Total pervious (%)</th>
<th>Land Surface Detail (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Paved</td>
</tr>
<tr>
<td>Rattlesnake (BW1)</td>
<td>6,360</td>
<td>31</td>
<td>69</td>
<td>14</td>
</tr>
<tr>
<td>San Jose (BW2)</td>
<td>5,350</td>
<td>55</td>
<td>45</td>
<td>32</td>
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<tr>
<td>Cold Springs (BW3)</td>
<td>3,120</td>
<td>77</td>
<td>23</td>
<td>43</td>
</tr>
<tr>
<td>Sycamore (BW4)</td>
<td>2,300</td>
<td>60</td>
<td>40</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 2. Drainage area for each bioswale, with detail regarding the percent pervious and impervious cover and types of surfaces that contribute runoff. Major land cover contribution in each bioswale is highlighted in green (lawns, natural) or grey (paved surfaces).

**SAMPLING DESIGN**

A total of 18 soil samples were collected from each study bioswale during spring 2016; 9 from the basin bed and 9 from the outer margin. The samples were obtained to a depth of 10 cm using metal corers. Three cores were collected for each sample and composited into a clean plastic bag (Figure 3). One reference sample was collected during each sampling event to capture natural metal background levels. Samples were chilled on ice (4 °C) until return to the lab for processing within 6 hours. A total of 76 samples were collected and processed with the help of a student intern.

![Sampling schematic showing detail of sampling locations within each bioswale](image)

**Figure 3.** Sampling schematic showing detail of sampling locations within each bioswale
In the lab, the soil samples were sieved (2 mm) and subsampled for the different analyses including gravimetric moisture, pH, organic matter determination, and substrate induced respiration. Subsamples were also taken for nutrient and metal analysis (total and bioavailable), as well as for DNA extraction for microbial community analysis. Soils were characterized by measuring their moisture, pH, soil organic matter and nutrient content.

RESULTS

The four study bioswales (Table 2) were sampled once over a two-week period between March 21st and April 4th, 2016 at the end of the wet season. No rainfall occurred in-between sampling dates, but soils were considerably wet during the first sampling event (BW2), due to a rainfall event (0.5 inches) ten days prior.

All proposed analyses have been completed, except for DNA extraction for subsequent microbial community analysis, which is ongoing.

Data analysis for the results has been initiated, as was originally outlined in the submitted proposal. Final data analysis will be completed once DNA extraction for the collected samples is finalized. An overview of results is presented. A final detailed analysis will be included in a manuscript in progress.

**Moisture, soil organic matter (SOM), pH and potential soil respiration**

Moisture content varied considerably in each bioswale and across bioswales (min = 8.9% in BW1, max = 31.0% in BW2 and mean = 16.8%). No general trends were observed depending on location. Moisture was lower in the reference soil samples with values in the range 5.1% - 9.6%.

SOM was positively and significantly correlated to potential soil respiration ($r = 0.636; p < 0.001$). There were no general trends in SOM within or between bioswales. SOM was in the range 2.18-10.43% for all bioswales (mean = 6.30%) and was lower in the reference sites (2.13% - 5.54%).

Potential soil respiration, which is a function of microbial biomass, varied an order of magnitude across all samples (3.1 E-03 to 2.2E-02 ppm CO$_2$ per second per gram of dry soil). Respiration was lower in bioswale soils relative to the reference sites.

Mean nitrate concentration was significantly different across bioswales (Welch’s ANOVA $F = 29.34, p < 0.001$) and was significantly higher in BW1 and BW2 relative to BW3 and BW4 (Turkey HSD, $p < 0.0002$). This could be explained by the fact that these two bioswales receive more inputs from irrigation runoff from reclaimed water that is applied to lawns.

Mean phosphate concentration was significantly different across bioswales (Welch’s ANOVA $F = 4.859, p < 0.0065$). Phosphate content in BW1 was significantly higher than in the other bioswales (Turkey HSD, $p < 0.014$), which had no significant differences (Turkey HSD, $p > 0.5$). Potential phosphate sources include ocean spray, guano deposits on roofs (multiple downspouts feed this bioswale) and irrigation runoff from reclaimed water that is applied to lawns.
Total and bioavailable metals

Metal content in bioswale soils was low and within the same order of magnitude as observed for reference sites (Figure 4). Some locations had significantly higher metal concentrations, at least in localized spots, as evidenced for Cu and Zn, for example. There was slight evidence for Cu buildup in BW1 and BW2 (Figure 4a), and for Zn buildup in BW3 (Figure 4b). BW3 has the highest percent of impervious cover, with significant contribution from rooftops, which might explain the higher measured Zn content.

Figure 4. Total Cu (a) and total Zn (b) in bioswales (sample IDs 1-4) and reference sites (sample ID 5). The boxes in the boxplot show the median and interquartile range. The whiskers show the minimum and maximum value. In figure (a) copper in BW2 is significantly different than in the other bioswales (Welch’s ANOVA, F = 4.966, p = 0.007; Turkey HSD, p<0.023). In figure B there are significant differences (Welch’s ANOVA, F=11.858, p<0.0001), with BW1 and BW2 being different than BW3 (Turkey HSD, p < 0.05).

Bioavailable metal concentrations were at least two orders of magnitude smaller than total metal concentrations, indicating low bioavailability and potential for toxicity. Total and bioavailable Zn were significantly negatively correlated (r = -0.274, p = 0.017) (Figure 5), which has been observed in previous studies (Ge et al. 2000).

Relationship between total metals and land cover in the watershed

The trace metal Zn (r=0.24, p=0.044) was positively and significantly correlated to impervious cover. Total Zn also showed significant positive correlation to roofs (r=0.354, p=0.024) and a strong negative correlation to lawns (r=-0.419, p=0.008).

Nickel had a significant positive correlation to roofs (r = 0.322, p = 0.006) and a very strong negative correlation to lawns (r = -0.674, p < 0.001) (data not shown). Roofs have been identified as a potential source of Zn and Ni due to the construction materials used in roofs and downspouts.

Copper showed no significant correlation to land cover in the watershed, although it is often associated to vehicular use since it is included in brake pads.
Figure 5. Total Zn in the bioswale soil is negatively and significantly correlated to bioavailable zinc (n = 72). This figure shows that most samples have total Zn content in the range 20-75 mg/kg, but that hot spots may occur. The data point to the far right corresponds to 129.5 mg/kg dry soil, measured at BW3, location 10). Only Zn is represented since no other trace bioavailable metals could be quantified (below MDL).

**Potential for metal toxicity**

Both the total and bioavailable metal concentrations measured in this study fall well below most sediment quality guidelines based on consensus-based probable effect concentrations (PEC) (McDonald et al. 2000). These guidelines set threshold values above which there might be detrimental effects to sediment-dwelling organisms. Values for nickel are close to the PEC (48.6 mg/kg) in one sample (46.8 mg/kg in location 12 on bioswale 2). Zinc shows a moderately high concentration (129.5 mg/kg) in one location in bioswale 3 (location 10) but this is still much lower than the PEC (459 mg/kg).

Due to the inherent spatial heterogeneity in soil, the existence of hot-spots of contamination is not overruled. Also, PECs are not specific to microbial organisms, so the potential for harmful effects on sensitive microbial taxa is not ruled out.

**CONCLUSION**

The extent of metal buildup in bioswales on the UCSB campus, and the influence of land cover on pollutant buildup in bioswale soils were studied via a field-scale investigation. Results indicate that metal distribution in bioswale soils is heterogeneous, and that metal content is similar to reference sites that receive no runoff from urban surfaces. However, there is evidence for slight metal buildup in some localized spots and significant correlations between land surface (e.g. impervious cover) and total metal content. Toxicity risk is likely minimal because only a minor fraction of total metals are in a bioavailable form, and because measured metal content is below PECs.

Future work will potentially include studying microbial communities in bioswale sediments from extracted DNA to increase our understanding of how microbial assemblages are shaped by chronic inputs of stormwater runoff and/or reclaimed water with low levels of pollution.
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REFERENCES


Manzanita Village Storm Water and Urban Runoff Biofiltration System PowerPoint presentation by Lisa Stratton, CCBER


