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LONG TERM USE OF BIORETENTION FOR HEAVY METALS REMOVAL

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Executive Summary

Bioretention has been shown to effectively remove heavy metals from stormwater runoff, which makes it a very useful design tool. However, there are two common concerns related to long term use of bioretention for heavy metals removal:

1) When will breakthrough occur, i.e. when will the binding sites be saturated so that dissolved heavy metals start leaching out of the bioretention systems?

And

2) When will heavy metal concentrations in the bioretention soil reach regulatory threshholds?

Research to date related to both concerns are addressed in this memo. Implications for lifespan of Silva Cell Tree & Soil Stormwater Control Measures (SCMs) for heavy metals are also discussed. Based on research to date we believe the benefits of bioretention systems typically far outweigh the concerns.

Sources of heavy metals in stormwater runoff

Heavy metals from normal pavement and vehicle wear are washed from pavements into stormwater runoff when it rains or snows. Unless they are intercepted, for example through Stormwater Control Measures (SCMs), stormwater runoff carries these heavy metals into receiving surface waters. If allowed to reach excessively high concentrations in downstream surface water bodies, these heavy metals threaten the survival of aquatic organisms at all levels of the food chain.

Heavy metals can also be toxic to humans, and most can be lethal. At sub lethal levels, they can negatively impact the central nervous system, lungs, kidneys, liver, blood composition, urinary system, and reproductive systems. Long term exposure can also cause cancer. For more detailed information on human health effects of each individual heavy metal, see Occupational Safety & Health Administration's (OSHA's) website, accessed 5 May 2014 at: https://www.osha.gov/SLTC/metalsheavy/
Heavy metals of concern typically include copper, chromium, mercury, nickel, zinc, lead, arsenic, and cadmium. Primary sources of these heavy metals in stormwater runoff include vehicle and pavement wear and maintenance, buildings, and atmospheric deposition. Table 1 below lists sources of the heavy metals of primary concern in roadway runoff in more detail.

Metal	Sources
Aluminum	Natural, as well as anthropogenic sources such as aluminum works industries
Cadmium	Tire wear, brake pads, combustion of soil, insecticides are also other sources
Chromium	Corrosion of welded metal plating, moving engine parts, brake lining wear
Cobalt	Wastes from tire and vehicle appliance manufacturing
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, fungicides and insecticides
Iron	Auto body rust, steel roadway structures, moving engine parts, corrosion of vehicular bodies
Lead	Leaded gasoline, tire wear
Nickel	Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving
Zinc	Tire wear, motor oil, grease

Table 1: *Sources of cadmium, chromium, copper, lead, nickel, and zinc in roadway runoff. (From Torno 1994)*

Heavy metals removal mechanisms in bioretention

Heavy metals removal mechanisms in bioretention
Many studies have shown that bioretention SCMs, including trees and soils, as in a Silva Cell system, are very effective at removing heavy metals from stormwater runoff. Mechanisms for heavy metal removal from stormwater runoff in bioretention SCMs include sedimentation, filtration, adsorption and vegetation uptake.

Sedimentation and filtration effectively remove particulate forms of heavy metals. Particulate heavy metals are therefore expected to be removed from stormwater runoff as long as the bioretention cell's soil is not clogged (i.e. as long as it drains adequately).

Dissolved heavy metals are removed from stormwater by sorption onto soil organic matter and clay. Once the sorption capacity of a soil is saturated, dissolved heavy metals will "breakthrough" and dissolved heavy metals will be discharged to receiving waters. Because dissolved heavy metals are more bioavailable than particulate bound heavy metals, they may be more detrimental to aquatic ecology (Kominkove and Nabelkova 2007 in Hatt et al 2011), so long term retention of dissolved heavy metals is especially important (Hatt et al 2011).

In many studies, most heavy metals were found primarily in particulate forms in stormwater runoff (e.g. literature review in Morquecho, R. 2005), with the exception of zinc, which is found primarily in dissolved form. However, whether heavy metals are in dissolved or particulate can vary depending on many factors, including, pH, temperature, and the presence of binding sites (e.g. literature review in Morquecho 2005).

Summary of Research Related to Efficiency of Bioretention for Heavy Metals Removal

Both traditional bioretention and trees and soil below paving, as in a Silva Cell system have been found to have high heavy metal removal rates (e.g. Davis et al 2003, Page et al 2014).

Organic matter provides binding sites for heavy metals, so it is not surprising that organic matter has been found to improve a bioretention cell's dissolved heavy metal removal lifespan. Morgan et al (2011) compared columns with varying amounts of compost, ranging from no compost to 50% compost (by bulk volume) and found that increasing organic matter content increased time to breakthrough for dissolved cadmium and zinc (i.e. bioretention lifespan for dissolved cadmium and zinc removal). More specifically, they found that "Increasing the compost fraction from 0% to 10% more than doubles the expected lifespan for 10% breakthrough in 15 cm [6 inches] of filter media removing cadmium and zinc" (brackets added). Time to breakthrough continued to increase significantly from 10% to 30%, and from 30% to 50% compost. Copper removal also increased with increasing compost fraction. They concluded that "Based on the field study results, organic matter is the most important constituent when considering removal of dissolved toxic metals in a bioretention facility."

Li and Davis (2008) found that metals are captured in the top 10 cm [4 inches] of the bioretention soil, and Jones and Davis (2013) also found that metals were most concentrated near the inflow point and in the top 3-12 cm [1.2 to 4.7 inches] of the bioretention cell.

Research Related To Lifespan of Bioretention For Heavy Metals Removal

Although bioretention has been shown to effectively remove heavy metals from stormwater runoff, there are two concerns related to long term use of bioretention for heavy metals removal:

1) When will breakthrough occur, ie. when will the binding sites be saturated so that dissolved heavy metals start leaching out of the bioretention systems?

And

2) When will heavy metal concentrations in the bioretention soil reach regulatory threshholds?

Both concerns are addressed in the research summary below.

1. *When will breakthrough occur, ie. when will the binding sites be saturated so that dissolved heavy metals start leaching out of the bioretention systems?*

Since dissolved heavy metals are more bioavailable that particulate bound heavy metals, long term retention of dissolved heavy metals is particularly important. Of all the heavy metals of concern, zinc has been shown to be the most mobile, and it is therefore typically the first heavy metal to break through. Based on column experiments using synthetic stormwater to investigate the removal and retention of cadmium, copper and zinc, Morgan et al (2011) found that, "at stormwater concentrations of zinc and cadmium, 15 cm [6 inches] of filter media composed of 30% compost and 70% sand will last 95 years until breakthrough, when the effluent concentration is 10% of the influent concentration" (brackets added). This 95 year lifespan is significantly longer than a typical useful pavement or bioretention lifespan, so based on this study, a typical bioretention system should not experience breakthrough of heavy metals. Moreover, with breakthrough defined as "when the effluent concentration is 10% of the influent concentration", 90% of the heavy metals are still retained in the bioretention system at breakthrough.

2. *When will heavy metal concentrations in the bioretention soil reach regulatory thresholds?*

Several field studies indicate that at typical stormwater concentrations, concentrations of heavy metals in bioretention soils are not expected to reach regulatory thresholds for at least a few decades (see summaries below). The timespan for heavy metals to accumulate to concentrations that exceed regulatory thresholds could be significantly increased with pretreatment to capture suspended solids.

Even if high levels of heavy metals are captured in bioretention cells, this is typically still preferable to the alternative of no treatment: piping the heavy metals to surface water bodies. Heavy metals are more easily cleaned out of bioretention cells than out of surface waters. Where bioretention cells are designed under pavement, for example, with Silva Cells, it is more difficult to access the soil if/when soil replacement is desired, BUT, at least as importantly, the risk of human ingestion of bioretention soil under pavement is also much smaller than the risk with open bioretention cells (i.e. not under pavement). These heavy metal concentrations are not typically harmful to trees.

Results from representative studies estimating bioretention lifespan for heavy metals removal based on soil concentrations are summarized below.

The Toronto and Region Conservation Authority (2008) studied a 3 year old demonstration project as well as 7 older pervious interlocking concrete paver (PICP) sites (ranging from 4 to 17 years old) and 5 bioswales (ranging from 2 to >18 years old). Soil quality results (copper, zinc, lead, iron) from older PICP and bioswale sites indicated that land fill disposal or remediation of the underlying soils would typically not be required when the pavers or swales need to be replaced. The concentrations of metals in the bioswale cores were below background concentrations for agricultural soils. Metal concentrations in soils at the demonstration site in 2005 and 2007 were similar, indicating little if any accumulation of metals in surface soils over a two year period.

Jones and Davis (2013) assessed accumulated lead, copper, and zinc media samples from a 4-year-old bioretention cell. They found that "After 4 years of operation, total metal concentrations are well below the regulatory cleanup thresholds stipulated by the Maryland Department of the Environment (MDE) and the U.S.EPA. Significant capacity for metal accumulation, *at least* on the order of *several decades*, is estimated to remain … The media sequential extraction results indicate that accumulated metal will remain largely sequestered within the cell rather than become mobilized into the environment."

Davis et al (2003) studied the effect of constructed bioretention boxes and 2 field scale bioretention cells on copper, lead and zinc removal. US hazardous waste disposal legislation does not yet include regulations for

BMP sediment and soil. However, several states are beginning to adopt the US EPA Part 503 biosolids regulations to regulate stormwater BMP sediment disposal. These regulations limit cumulative metal loadings allowed through the application of wastewater biosolids. Several researchers have used these regulations to evaluate metal accumulation in bioretention soils. Davis et al (2003) found that "after 20 years, cadmium, lead and zinc accumulations reach or exceed regulatory limits for biosolids application (U.S EPA, 1993). The time required for metal accumulations to reach these limits are 20, 77, 16, and 16 years for cadmium, copper, lead, and zinc, respectively."

They also evaluated the media with respect to hazardous waste classification criteria based on allowable toxicity characteristic leaching procedure (TCLP) concentrations. The EPA developed the Toxicity Characteristic Leaching Procedure (TCLP) to determine whether a waste may be accepted into a typical municipal landfill (as defined by RCRA Subtitle D) based on its potential to leach dangerous concentrations of toxic chemicals into groundwater. If TCLP analytical results are above the TCLP D-list maximum contamination levels (MCLs), the waste cannot be accepted at a typical municipal landfill and must be taken to a hazardous waste disposal facility. Only cadmium and lead have TCLP limits. Results from the bioretention media study by Davis et al (2003) showed that "After20 years, accumulated levels of these two metals approach, but do not exceed, the allowable TCLP extraction levels. The time required to reach the TCLP limits are 50 years for cadmium and 26 years for lead. This example, however, assumes that all metals are readily available and will be extracted in the TCLP; it is, thus, conservative. Greater metal accumulation could occur before TCLP limits are reached."

Li and Davis (2008) studied lead, copper, and zinc removal in a bioretention cell 3 years after installation and again 4 years after installation and found that "the captured metals exhibited a strong association with the media, suggesting that they are not washed out by subsequent wet weather flows." Lead was the limiting metal in bioretention accumulation and exceeded regulatory values for heavy metals in residential soils (based on mean of values of 30 states in the US, typically based on child soil exposure at home). This lead was tightly bound to the soil and not likely to be washed out.

Applying the Research to the Design of Silva Cell Tree & Soil SCMs for Heavy Metal Removal

Lessons learned from the above research regarding expected lifespan of a Silva Cell Tree & Soil SCM for heavy metal removal are summarized below.

Lifespan of trees and soil under paving is expected to exceed lifespan of heavy metal removal under typical stormwater concentrations

Based on Morgan et al, 2011, breakthrough is not expected to occur at typical stormwater concentrations in bioretention cells with at least 30% compost by volume for at least 95 years. This is significantly longer than the typical 20-30 year useful lifespan of pavement.

Estimated timespan for soil heavy metal levels to reach regulatory thresholds is heavily dependent on influent concentrations

Stormwater heavy metal concentrations are highly variable from site to site. Estimated timespan for soil heavy metal levels to reach regulatory thresholds will depend greatly on influent concentrations of heavy metals. Based on studies to date, it is likely that it would take several decades at a minimum for soil heavy metal levels to reach regulatory thresholds in Silva Cell soils. Measuring influent stormwater heavy metal concentrations will indicate how the lifespan of a Silva Cell system is expected to compare to the average expectations above. For example, if stormwater concentrations at a site are already very low before treatment, life span for heavy metal removal would be expected to be even greater than the lifespan above, all other factors being equal.

Silva Cell systems are typically designed with pretreatment for sediment capture. Capturing sediments with pretreatment also captures particulate bound metals, so it reduces influent concentrations into the tree with soil under pavement. Pretreatment with appropriate maintenance will therefore increase the time it will take for heavy metals concentrations to reach regulatory thresholds in Silva cell soils.

Effects of pavement on concerns regarding heavy metals build up in Tree and soil systems under pavement

If heavy metal levels reach regulatory thresholds in above ground bioretention, the top few inches of soil could theoretically be scraped out and replaced to renew the bioretention cell's lifespan. While this is not possible when the soil is under pavement, chances of human ingestion of the soil are even less likely when the soil is under pavement. These heavy metal concentrations are not typically harmful to trees.

Organic matter in the soil improves heavy metal removal lifespan

Based on the research above, increasing soil organic matter in the bioretention media improves heavy metal removal lifespan for dissolved metals (see Morgan et al 2011). Bioretention soils high in phosphorus have been shown to leach phosphorus, so where nutrient leaching is not acceptable, care must be taken to either (1) use organic matter with reasonable phosphorus content or (2) design the bioretention cell with a way to mitigate excess phosphorus contributed by the organic matter.

Conclusion

Heavy metals are often found at elevated levels in stormwater runoff, and can be detrimental to receiving surface waters, as well as cause human health concerns. Bioretention has been shown to be very effective for capturing heavy metals from stormwater runoff before reaching receiving surface waters. Heavy metals cannot be broken down into non-toxic components, so, because they are effectively captured by bioretention cells, they accumulate in bioretention cells over time. This raises two concerns:

1) When will breakthrough occur, i.e. when will the soil's binding sites be saturated so that dissolved heavy metals start leaching out of the bioretention systems?

And

2) When will heavy metal concentrations in the bioretention soil reach regulatory thresholds?

Research has shown that on an average site, breakthrough is not likely to occur within the useful lifespan of pavement. Time to breakthrough can be increased by increasing soil organic matter to provide more binding sites in the soil. Time before heavy metal concentrations in the bioretention soil reaches regulatory thresholds will vary a lot depending on influent concentrations. Several field studies indicate that at typical stormwater concentrations, concentrations of heavy metals in bioretention soils are not expected to reach regulatory thresholds for at least a few decades. The timespan for heavy metals to accumulate to regulatory thresholds could be significantly increased with pretreatment to capture suspended solids. Even if toxic metals do accumulate to regulatory thresholds, covering bioretention soil with pavement, such as in a Tree in Soil under Suspendended Pavement, will minimize the chance of human ingestion of the soil.

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