Analysis of Green Roof Runoff:
Implications for Design and Construction

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Introduction and Background

A green roof is generally defined as a conventional building roof that is covered with a layer of vegetation (ecopedia definition). Planting vegetation on a roof helps to replace the green space that is lost by the construction of the building. Green roofs have numerous reported benefits, including reducing the volume of rainwater runoff from the roof, delaying rainwater runoff, improving the quality of runoff water by removing contaminants, and conserving energy by providing insulation (thus reducing heating and cooling costs). Additionally, green roofs help to reduce the urban heat island effect, reduce noise pollution, provide habitat for wildlife, last longer than traditionally roofs, and are aesthetically pleasing (Getter and Rowe 2006, Oberndorfer et. al 2007).

In general, any plant can be grown on a roof. Plant selection is limited only by climate, budget, structural design of the roof, and the imagination of the landscaper. Sedum is a popular flowering ground cover plant used on most green roofs in North America. It is a hearty, low-maintenance plant with leaves designed to retain water. A variety of other shallow-rooted grasses and hearty wildflowers are also used on green rooftops (Wark and Wark, 2003).

Numerous studies have demonstrated that the quantity of stormwater runoff from green roofs is significantly reduced as compared to traditional roofs (Hutchinson et al. 2003, Moran et al. 2003, VanWoert et al. 2005, Liu and Minor 2005). Following a period of little to no rain, up to 100% of rainwater can be absorbed and no roof runoff is generated (Hutchinson et al. 2003). Even during winter months when roofs were saturated, green roofs in Portland, Oregon demonstrated significant water absorption (Hutchinson et al. 2003). Not only do green roofs reduce the amount of roof runoff, but they have also been shown to reduce flow rates of runoff and to extend runoff duration past the actual rain event, reducing the number and intensity of flood events (VanWoert 2005, Liu and Minor 2005).

There is also evidence to suggest that green roofs may be able to improve the quality of rainwater runoff. Concentrations of heavy metals in green roof runoff are generally lower than concentrations of heavy metals in urban runoff from hard surfaces, and green roofs have been shown to retain significant portions of heavy metals (Berndtsson 2010). Decreased concentrations of iron, lead, and zinc have been found in runoff from green roofs as compared to rainwater (Berndtsson 2009).

Previous studies have also shown that Green Roofs can raise the pH of runoff, making the water less acidic. This can be particularly beneficial in areas where acid rain is a problem (Berndtsson 2009).

Another benefit of green roofs is a reduction in heat flow and thus a reduction in the energy demands for heating and / or cooling the building (Liu and Minor 2005, Berndtsson 2010). Heat flow reductions of 70-90% in the summer and 10-30% in the winter have been observed for green roofs compared to traditional roofs (Liu and Minor 2005). Green roofs can help block UV radiation from entering into a building. The thick layers of growing medium plus waterproof membranes function as insulation, making buildings with green roofs more economically and functionally efficient and reducing the impact of the building on the surrounding ecosystem (Carter and Keeler 2007, Oberndorfer et. al 2007). It has also been suggested that green roofs can help to reduce the urban heat island effect by emitting less heat than traditional dark-colored building roofs (Berndtsson 2010).

However, several studies have also found an important negative consequence of green roofs-higher concentrations of phosphorus and nitrogen compounds in green roof runoff than in rainwater (Hutchinson et al. 2003, Moran et al. 2003, Hathaway et al. 2008). These studies did find that the levels of nitrogen and phosphorus in runoff decreased as more rain events occurred. The authors also believe that these nutrients were coming from the growing medium and that choosing a different substrate and minimizing the use of fertilizer could significantly reduce phosphorus and nitrogen levels in green roof runoff. Conversely, another study found decreased levels of nitrogen compounds in green roof runoff, and concluded that roof vegetation can act as a nitrogen sink rather than a source (Berndtsson 2009).

Increased nutrient concentrations from green roof runoff could be a serious concern in the Macatawa Watershed, an area of land that drains into Lake Macatawa. The soils of the watershed are naturally high in phosphates and nitrates, which has caused the lake to gradually become hypereutrophic, and sediment gradually builds up in the lake at a faster rate than is considered normal (Sharpley et. al 2003). Application of fertilizer has amplified the naturally high levels of phosphates and nitrates in the watershed and has increased the number of algal blooms occurring on Lake Macatawa. This in turn has reduced the Lake's dissolved oxygen content, resulting in high mortality and low diversity in the lake (Schindler 1974, Breitburg et. al 1997). As wetlands that absorb runoff are diminishing and more impermeable surfaces are being created, the speed with which water is reaching Lake Macatawa is increasing (MWA). Runoff from water-resistant surfaces, such as roofing, is typically not collected and treated, but rather enters the lake and / or its rivers directly (MWA).

This study used green roof models to addresses 5 hypotheses regarding the effects of green roofs:

1. The quantity of rainwater runoff from green roofs is less than that from traditional roofs
2. The concentration of heavy metals in runoff from green roofs is reduced compared to traditional roofs
3. The concentration of phosphates in runoff from green roofs is elevated compared to traditional roofs
4. Runoff from green roofs is less acidic than runoff from traditional roofs
5. Green roofs conserve energy by acting as insulation

Materials and Methods

In order to address these hypotheses, we constructed two scale models of a house, as seen in figure 1. One unit had a normal asphalt roof and the other had a green roof. The dimensions of the models were identical. Roof runoff was collected during and after natural rain events using a rain gutter running along the edge of the roofs to guide water into collection buckets. Rainwater was collected and its contents were compared to roof runoff. Each of the models contained a small door in the back to allow for placing a heat lamp inside, and a sealed hole was added where a temperature probe could be inserted. The models were placed side by side on a rooftop patio where they were exposed to natural rain events but had some shelter from wind.

Figure 1: Front, side, and back views of the constructed roof models

Hypothesis 1 (The quantity of rainwater runoff from green roofs is less than that from traditional roofs):

Rainwater samples were collected in 5-gallon buckets during the months of October and November. The 5-gallon buckets were placed underneath the rain gutters attached to each of the roofs. A rain event was classified as the start of the rain until after eight hours after it had stopped. Data was collected for every natural rain event, regardless of duration or intensity. A meter stick was used to determine the water level in the buckets. One liter Nalgene bottles were used to collect one liter rainwater sample from each bucket, when there was enough rainwater to collect. Small vials were used to collect the sample if the one liter sample size could not be met. The samples were then labeled with the roof type, rain event number, and date.

Hypothesis 2 (The concentration of heavy metals in runoff from green roofs is reduced compared to traditional roofs):

In order to assess the concentrations of metals in rainwater and in samples of runoff water from each of the roofs, approximately 15 mL of water from each sample were acidified by adding 1 drop of 18 M nitric acid. Acid was added to ensure that all metals were in the solution. All samples were then analyzed using Inductively Coupled Plasma- Optical Emission Spectroscopy (ICP). Calibration curves were made for each metal that was found to be present in the samples. Standard solutions of known concentration were prepared and were analyzed on the instrument. The intensity reading from the instrument was then correlated to the concentration and linear equations were derived for each metal's calibration curve. These equations were used to determine the concentrations of metals in the runoff samples based on the intensity readings from the instrument. Samples of pure rain water and tap water were also analyzed, as baseline data to compare the roof runoff to.

Hypothesis 3 (The concentration of phosphates in runoff from green roofs is elevated compared to traditional roofs):

To analyze samples collected form the model roofs we used a continuous flow analyzer. This method uses continuous flow to facilitate mixing between a small amount of sample and a reagent. This mixing speeds up the reaction which causes a slight color change. The samples pass by a digital colorimeter which detects how much light is absorbed by the sample. The concentration of phosphate and the absorbance in a sample are proportional thus we can calculate the concentration of phosphate with a calibration curve. In order to prepare our samples for analysis we diluted the samples collected from the green roof model 100 fold in order to meet the detection limits of the instrument. All samples were filtered before being analyzed on the instrument.

Hypothesis 4 (Runoff from green roofs is less acidic than runoff from traditional roofs):

An OakTon® pH meter was used to determine the pH of each of the samples. The instrument was first calibrated using solutions of known pH. Three pH readings were taken for each runoff sample in order to determine the consistency of the instrument.The pH of pure rain water was also determined to provide baseline comparison data.

Hypothesis 5 (Green roofs conserve energy by acting as insulation):

To determine the heat retention of the models, heat had to be put in the models at the same rate. A 100-watt light (approximately 350 BTU) without a reflector, was placed in each of the models and turned on for a designated time depending on the trial. For the first trial, the light was left on for 2 hours, but it was realized that an hour was sufficient for the models to reach their peak temperature. At this point, the light was turned off, and the loss of heat was measured. An extra-long temperature probe was used to measure temperature within the models during the experimental trials, and the data was recorded with Go!Link software. The software recorded the decrease in temperature until the model maintained a constant temperature. This procedure was repeated four times for each roof model. For the last trial, the procedure was repeated, although there was an additional step; the green roof modules were placed inside the greenhouse to allow the water in the plants to evaporate.

Results

Hypothesis 1 (The quantity of rainwater runoff from green roofs is less than that from traditional roofs):

A wide range of results from the water levels from the green roof versus the plain roof were observed. On the collection date of October 24 in table 1, it is seen that the water level in the 5-gallon bucket under the green roof was 18.6 centimeters while the water from the plain roof was over 37 centimeters. On next rain event collection date, October 30, the water level was only 4.6 centimeters while the plain roof was 19.1 centimeters. Further down in table 1, the level of water collected in the green roof bucket increases between the 3rd, 8th and 9th of November. Overall the ratio of the plain roof versus the green roof water collection ranges from less than one to almost four times as much. However, the ratio that was less than one was found from skewed data.

Table 1: Summary of rainwater retention data for both roof models

Date (2011)	H20 level (Green Roof): cm	H20 level (Plain Roof): cm	Plain Roof: Green Roof Ratio
Oct. 24	18.6	37+*	1.98
Oct. 30	4.6	19.1	4.15
Nov. 3	too little to measure	1.1	-
Nov. 8	10	6.2*	0.62
Nov. 9	18.8	20	1.10

Hypothesis 2 (The concentration of heavy metals in runoff from green roofs is reduced compared to traditional roofs):

The metals that were consistently found in samples of runoff from each of the roofs were iron, manganese, zinc, copper, and barium. The results of the metals analysis indicate that metal concentrations tended to be higher in the runoff from the green roof than from the plain roof.

Table 2: Metal concentrations in runoff from each roof and from tap water and rain water

Sample	Fe	Mn	Zn	Cu	Ba
Tap Water	6.2	1.1	-	-	0.1
Rain Water 1	25.6	3.4	141.5	0.3	4.6
Rain Water2	13.5	3.4	27.1	-	3.6
Green Roof 4	236.5	1.4	439.6	89.7	6.9
Plain Roof 4	7.7	2.6	79.0	-	5.3
Green Roof 5	437.5	4.6	513.2	174.3	5.8
Plain Roof 5	6.9	2.3	39.8	-	4.0
Green Roof 6	359.8	3.0	473.8	144.3	5.4
Plain Roof 6	8.9	3.1	52.2	-	4.3

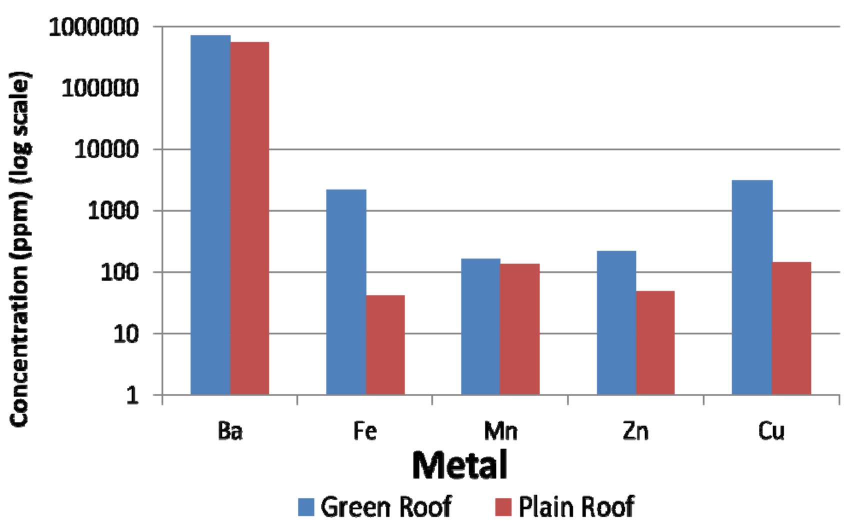

Figure 2: Summary of concentrations of metals of interest in runoff from green and plain roofs

Hypothesis 3 (The concentration of phosphates in runoff from green roofs is elevated compared to traditional roofs):

The total phosphate concentrations found in the runoff from the two model roofs can be seen in table 3. The results show a significant elevation of total phosphates coming off with green roof runoff than with plain roof runoff. To test if the amount of phosphates would decrease with time we simulated three years of rain events, taking samples every half year. When we tested the samples for phosphates we found that there was a decrease with time in the total phosphate concentrations (figure 3). In order to put the amount of phosphates coming off the model roofs in perspective we compared it to the estimated amount of phosphates entering Lake Macatawa (about 138,500 lbs / year) to our green roof model (about 5.41E-4 lbs / year). To make the numbers more comparable we estimated the amount of phosphates that would enter Lake Macatawa if the whole watershed was covered in green roofs (about 330,046 lbs / year).

Table 3: Concentration of phosphates (ppb)

Rain Event	Green Roof	Error	Plain Roof	Error
Initial wash	1015	±8.83	72	±0.63
1	7660	±54.39	71	±0.62
2	7090	±50.34	39	±0.34
4	7390	±52.47	43	±0.31
5	111470	±791.43	55	±0.39
6	2040	±15.50	39	±0.30

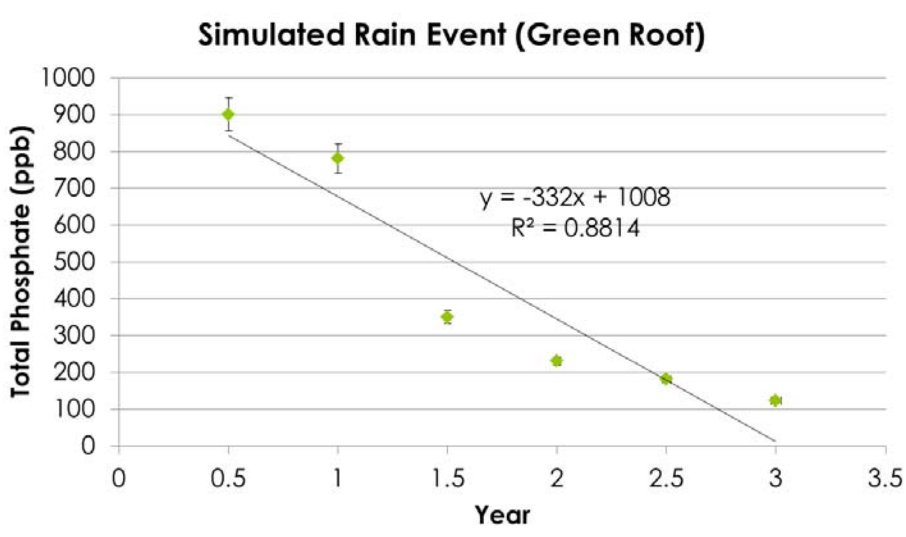

Figure 3: Phosphate concentrations over time during the 3-year rain event simulation

Hypothesis 4 (Runoff from green roofs is less acidic than runoff from traditional roofs):

The pH of the green roof runoff water was found to be consistently higher (less acidic) than the runoff water from the traditional roof. The average pH of runoff from the green roof was 6.45, the average pH of the runoff from the traditional roof was 5.26, and the average pH of pure rainwater collected in the rain gauge was 5.27.

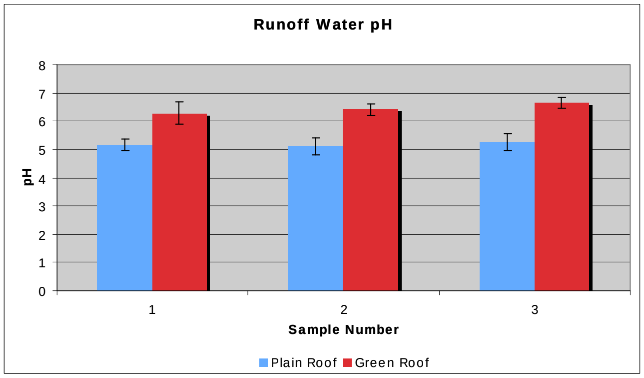

Figure 4: Summary of pH values of runoff from each roof

Hypothesis 5 (Green roofs conserve energy by acting as insulation):

Contrary to what we predicted, the green roof module did not retain heat at a significantly higher rate than the plain roof.

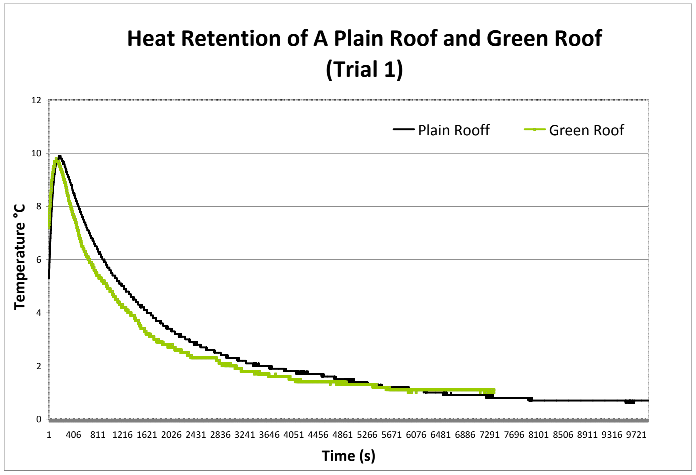

Figure 5. Trial 1. This graph shows how temperature decreases with time. The green roof stabilizes at approximately 1°C, whereas the plain roof continuous to decrease to ambient temperature.

To determine if the slopes of the lines differed, the linear portions of the slopes were fit to a linear trend line.

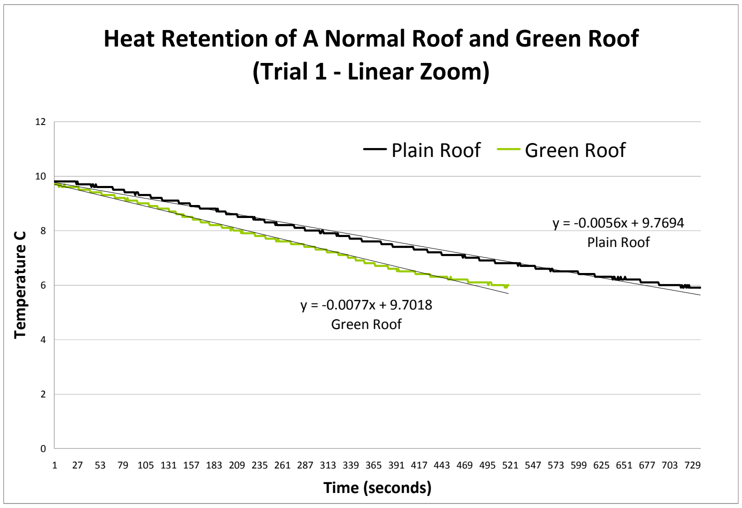

Figure 6. Trial 1. This graph shows how temperature decreases with time. The green roof releases heat at a slightly faster rate than the plain roof, which was not what was expected. The linear portion of Trial 1 was zoomed in on, and a linear trend line was fit to the data points.

The trial was repeated to determine if something was not functioning correctly in Trial 1. For Trial 2, the green roof heat retention decreased at a slightly lower rate, but again, the results were not significantly different from one another.

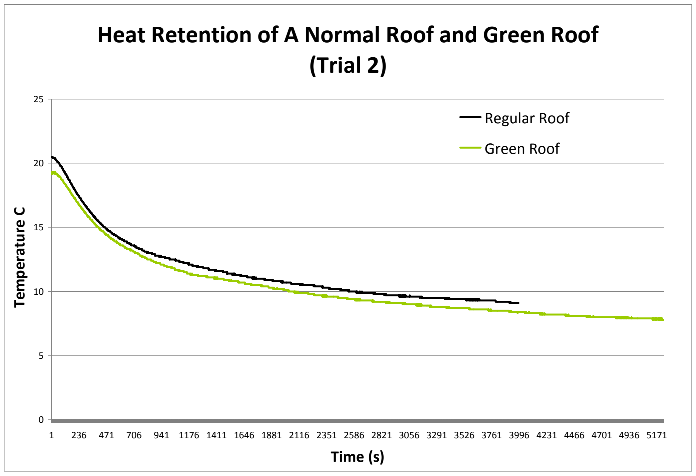

Figure 7. Trial 2. This graph shows how temperature decreases with time.

To determine if the slopes of the lines differed, the linear portions of the slopes were again fit to a linear trend line.

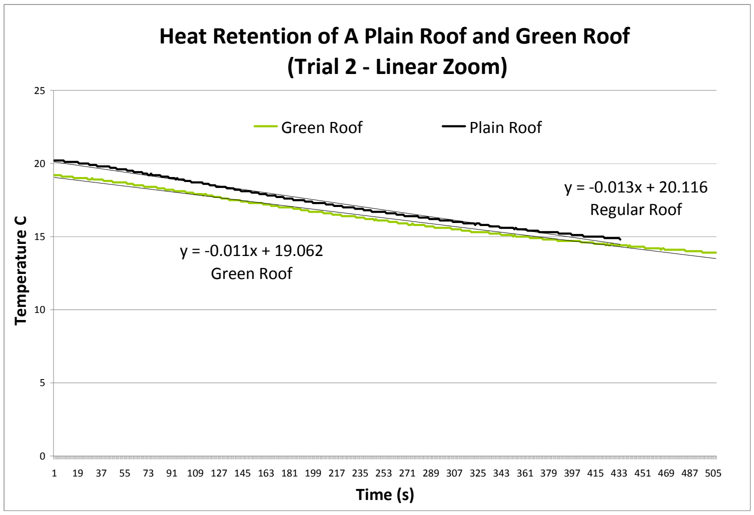

Figure 8. Trial 2. This graph shows how temperature decreases with time. The green roof releases heat at a slightly lower rate than the plain roof, which was not as significant as we expected. The linear portion of Trial 2 was zoomed in on, and a linear trend line was fit to the data points.

Lastly, the green roof modules were removed and placed inside the greenhouse to dry so that the soil contained little to no water (to ensure that all heat was not being absorbed by water in the soil).

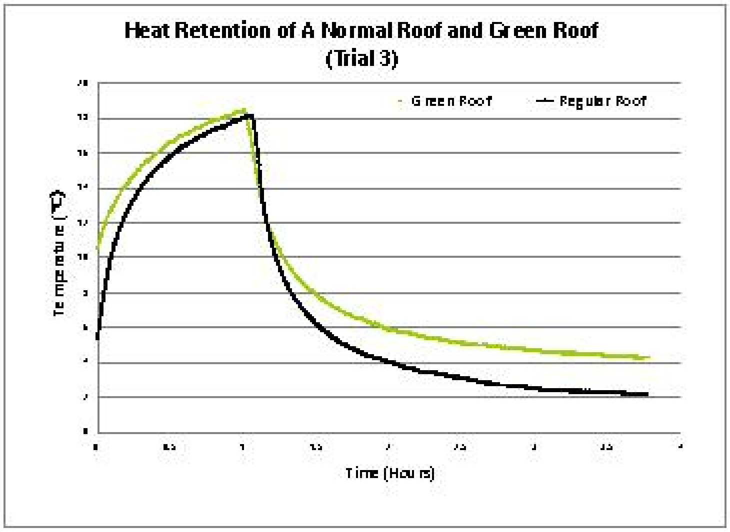

Figure 9. Trial 3. This graph shows how temperature decreases with time. The green roof releases heat at a slightly lower rate than the plain roof. Compared to the green roof data from Trials 1 and 2, the green roof releases heat at a slower rate, indicating the plants lack of moisture helped maintain heat better than when moisture was present.

Discussion

Hypothesis 1 (The quantity of rainwater runoff from green roofs is less than that from traditional roofs):

Overall it was found that the green roof did retain more water than the plain roof. However if the green roof was found to be oversaturated from an earlier rain event, its water retention capacity significantly decreased, as seen the November 8th and 9th dates in table 1. A wide variety of rain events occurred over the months of October and November. In some cases there was not enough rain runoff in the 5-gallon buckets placed under the green roof for sample collection (as seen on November 3rd in table 1). This was because all of the water that fell on the green roof during the even was retained by the green roof.

Hypothesis 2 (The concentration of heavy metals in runoff from green roofs is reduced compared to traditional roofs):

The most likely source of the higher concentrations of heavy metals in the green roof runoff is the soil in which the plants are growing. Soils are composed of the metals that were found in the analysis and a noticeably visible amount of soil ran off the roof with the rainwater. The amount of soil coming off did appear to decrease with time. By the end of the study period, the green roof runoff water was noticeable clearer in color. Metal concentrations in virtually all of the samples were below drinking water regulatory limits (EPA). Two samples from the green roof (collected after rain events 5 and 6) were just slightly above the drinking water limit for iron concentrations (limit = 0.3 mg/mL). Thus, although metal concentrations were elevated in runoff collected from the green roof, concentrations were still low enough that they do not constitute a significant concern.

These results are contrary to what was originally predicted and do not agree with what has previously been reported in other studies. This could be simply due to the fact that the soil in this study had not had enough time to compact and be leached of excess growing medium. It is predicted that the metal concentrations decrease over time as less soil runs off the roof with the rainwater.

Hypothesis 3 (The concentration of phosphates in runoff from green roofs is elevated compared to traditional roofs):

Based on the results found we believe that the amount of phosphate coming off of our green roof models is due to a slow release fertilizer that is incorporated into the LiveRoof modules. The results also indicate that the amount of phosphates will decrease with time however even after three years of simulated rain there was still an elevated level of phosphate coming off of the green roof.

Hypothesis 4 (Runoff from green roofs is less acidic than runoff from traditional roofs):

The results of pH analysis support the original hypothesis as well as the results of previous studies. The raising of the pH suggests that green roofs can act to rapidly neutralize acid deposits. The beneficial effect of acid reduction could be particularly helpful in this area, as the rainwater is fairly acidic.

Hypothesis 5 (Green roofs conserve energy by acting as insulation):

There was not a significant difference in heat retention between the two models. Water retained by the plants and soil acted as a heat sink, requiring heating before the internal structure could be heated. By allowing the green roof modules to dry out for the last trial, energy was not being spent heating the water; it was heating the internal structure. The green roof module only had a thin insulation layer on the inside, and a thin waterproof membrane on top of the shingles, which may not have successfully prevented heat from leaving the structure.

Conclusions / Considerations in Construction Green Roofs:

The green roof was found to reduce the quantity of rainwater runoff. This effect was greater when the roof was not saturated. Metal concentrations were found to be higher in runoff from the green roof, likely as a result of soil running off the roof and entering the samples. Phosphate concentrations were found to be alarmingly high in the runoff from the green roof. However, phosphate concentrations did decrease with time. The green was found to provide a slight insulation effect, but only when the green roof was not saturated with water.

When constructing a green roof, phosphate levels should be taken into consideration. Phosphate fertilizer should be added to the roof only in very limited quantities, if added at all. Additionally, a thick insulation layer should be included to prevent heat loss due to heating water from the vegetation; otherwise energy will be wasted heating the water contained in the plants and soil of the green roof, not the internal structure.

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