Green Roof Design Selection: Factors of Influence and Resulting Performance

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Abstract

Green roofs have exhibited thermal and hydrologic properties that can decrease the energy usage of a building and safeguard the environment from excessive or contaminated storm water runoff. Though green roofs are being increasingly implemented globally, there is a lack of knowledge regarding what design choices are best suited for certain climates in order to achieve desired performance results. This review outlines and discusses the factors that influence design selection, the elements of green roof design, and the aspects of performance that are affected as a result. The examination of various green roof studies on a global scale facilitated breaking down those three concepts into their main components. Further review developed insight into the role of each component, and showed that they are all interconnected and influence each other. Green roofs are currently regarded as a sustainable building practice, so more knowledge about how to optimize the design functions would be very helpful to take advantage of the services that green roofs provide.

1. Introduction

A green roof is a vegetative surface on top of a building that supports its own small ecosystem containing different plant types. Some are a flat or grassy surface (extensive), while others resemble more of a roof top garden (intensive). Examples of both are shown in Figure 1. Green roofs are known to have certain benefits for buildings including having to do with energy usage reduction, long term cost savings, and environmental protection. These performance aspects can be optimized through the design selection, but not much information is known about how to choose design aspects based on the conditions of the region and for the desired performance needs (Simmons et al., 2008). This paper outlines and discusses the factors that influence design selection, the elements of design selection (focusing on vegetation and planting medium), and the aspects of the resulting performance. Each of these is broken down into its main components in order to point out the different roles that each component plays as well as to show that they are connected and influence each other.

In the case of thermal performance, Sonne’s (2006) studies have shown that green roofs have significant abilities to cool buildings during summer months. Palomo Del Barrio (1998) concluded that green roofs have not solely cooling properties, but more generally have insulative abilities by regulating heat transfer in and out of the building. With less drastic indoor temperature changes throughout the year, energy can be more conserved as the result of less demand for cooling and heating. Proper selection of vegetation and substrate according to the local climate conditions can maximize the potential energy savings and reduction of the urban heat island effect. This reduction in energy usage also can directly relate to the amount of money saved by a building. Although start up costs for green roofs can be three to six times that of a typical roof, Patterson (1998) notes that the performance of green roofs can exceed that of conventional roofing in the long-term and may not be as expensive as one might originally think. Potential money saved from using less energy can have a better cost-benefit risk if it is known what green roof designs function the best for the characteristics of a particular region.

Environmentally, the hydrologic performance of green roofs includes reducing runoff quantity as well as increasing runoff quality. Through retaining water, this buffer to runoff can decrease the likeliness of flooding, including the flooding of sewer systems (Oberndorfer et al., 2007). Green roofs can reduce the negative impact that heavy metals from iron rooftop runoff (Timperley et al., 2005) and nutrients in storm water (Hathaway et. al, 2008) have on freshwater ecosystems. Different environments will have varying levels and qualities of precipitation, and certain planting materials are better at retaining water and removing contaminants than others. If this was known to more depth then design could be chosen appropriately to decrease these environmental risks.

2. Methods

Research articles were chosen if they had done a study on green roofs, or an experiment evaluating an aspect of green roof design in relation to either the region’s influencing factors or to a facet of performance. Analysis and comparison of the main results of these different studies were used to construct a flow chart displaying the main components that branch out of factors due to location, design and performance. This chart in Figure 2 can be looked at in tandem with the discussion starting at section 3.2.

3. Discussion

3.1 Standard Green Roof Design

Though all green roofs will need to be inherently different, they for the most part should contain certain components that have been considered as standards by the green roof industry (Wark & Wark, 2003). The typical design of a green roof includes vegetation and substrate supported by a container which lays on top of successive layers for filtering planting medium, draining the water, protecting the roof membrane, waterproofing the roof, and insulating the roof if the insulation provided by the vegetation and substrate is not enough (Wark & Wark, 2003). A cross section of these layers is displayed in Figure 3. The choices for vegetation and planting medium play the largest role in determining thermal and hydrologic performance. The rest of the layers, while still having variations of design, are used more as a means of connecting the natural aspects of the green roof to the existing roof structure without any adverse affects on the building. Though these layers will not be discussed in detail in this paper, brief descriptions are included in Figure 3.

3.2 Factors Due to Location

Climate

The climate of a region has the greatest influence on how a green roof functions. Different temperature and precipitation levels will require specific vegetation and planting medium for optimal desired performance. Intense rainfall can erode the substrate (Kohler et al, 2001), while droughts can kill the plants (Nagase & Dunnet, 2010). Plants also need to be adapted for both extreme warm and cold temperatures (Oberndorfer et al, 2007). Wark (2003) claims that in warm and dry climates, the thermal protection provided by the plants and substrate is enough to eliminate the need for additional insulation. Other research suggests that green roofs will have the most benefits in subtropical climates (Simmons et al., 2008). Although it is acknowledged that there is limited research to support this, this is justified by the idea that the high temperatures and intense rainfall events can be moderated by the thermal insulation and water retention of a green roof. The results of Simmons' study in Texas supported his hypothesis but also concluded that the performance is highly dependent on the design, and therefore green roofs should be designed according to specific goals (2008). However, this designing for performance goals is limited to what can first survive in the specified climate.

Existing Roof Structure

The potential for the productivity of a certain green roof design on a specific building is not only dependent on the climate but also on the existing roof structure. If a roof is being retrofitted for a green roof it needs to have the structural integrity to support the added weight (Fassman et al., 2010). Fassman details the factors calculations that go into determining loads, which includes increases due to plants growing in mass over time, and the added weight of retained water. These loads will dictate the structural design that the existing roof needs to have in order to support a green roof.

3.3 Design Selection

Extensive vs. Intensive

The two main types of green roofs are extensive and intensive. Extensive roofs have low-lying plants and grasses with substrate depths of typically up to ten or twenty centimeters. These are mostly used for thermal and hydrologic performance at a light load (Wark & Wark, 2003). Intensive green roofs have larger and more varied plants and deeper planting media. They can still have useful performance qualities but are more used to play the role as a rooftop garden or park that is accessible to the public (Wark & Wark, 2003). These roofs however require more maintenance and structural support (Ignatieva et al, 2008).

Vegetation

Both types of green roofs have their vegetation choice limited by the climate and characteristics of the substrate. However in extensive green roofs there is the added limitation of needing plants that can be stress tolerant (Oberndorfer et al, 2007). While having a thin substrate, the plants need to not only survive, but also perform with an environment that can give them excessive moisture, drought, and extreme temperatures. Many studies have shown that in northern continents, the low growing succulent stonecrop is ideal for these conditions (Ignatieva et al, 2008). However, native plants should first be considered for use because they have already adapted to the area (Oberndorfer et al, 2007), and because stonecrop cannot always be used since it is a weed in some regions, such as New Zealand (Ignatieva et al, 2008). It has also been shown that diverse plant mixes have a better chance of survival during droughts (Nagase & Dunnett, 2010).

Substrate

The vegetation chosen for a green roof needs to be compatible with the planting medium or substrate. This is usually a man-made aggregate mixture (Wark & Wark, 2003) In order to maximize efficiency, the substrate should be lightweight, be able to retain large quantities of water while having good drainage, and be able to hold nutrients without leaching them into the runoff (Rowe et. al, 2006). Expanded clays (Wark & Wark, 2003) and expanded slates (Rowe et. al, 2006) have been exemplified as displaying these qualities. Rowe's study showed that for succulents such as stonecrop, this can decrease the load on the building while performing adequately and facilitating proper plant growth. A study in a tropical environment used recycled mud build up from the bottom of reservoirs as a substrate, which displayed high thermal reduction and high water retention (Lin & Lin, 2011).

When choosing substrate depth, the details need to be taken into consideration are water retention and the needs of the chosen plant type. One study's findings show that for maximizing retention, both substrate depth and slope need to be addressed (VanWoert et al, 2005). Its results corroborate with other studies in that water retention is usually increased by deeper media depth. Relatively deeper substrate can also support more diverse plant life (Oberndorfer et al, 2007). Even though some Sedum species can function at extremely shallow substrates if needed (Getter and Rowe, 2008), their roots are susceptible to freezing during winter months (Boivin et al, 2001).

3.4 Performance

Thermal Insulation

Green roofs can regulate the temperature of a building, which saves energy and money. Studies have shown that green roofs should not replace thermal insulation, but are efficient and recommended (Eumorfopoulou & Aravantinos, 1998). Fang (2008) found that the thermal reduction is enhanced with increasing leaf coverage and leaf thickness of the chosen vegetation. If a roof is already insulated, the amount of additional insulation provided by the green roof is mostly determined by the amount and height of the vegetation rather than the specific material in the planted part of the roof (Eumorfopoulou & Aravantinos, 1998). According to this proposition, if a green roof is being utilized solely for thermal protection, the only limitations on plant type and substrate is survival in the climate of the region. In this case native species would work well. Additionally, a highly vegetated roof with no initial insulation can have approximately the same thermal behavior of a bare insulated roof. It is in this case that tests would need to be done to determine the best plant materials to ensure enough thermal protection (Eumorfopoulou & Aravantinos, 1998). Substrates with high porosity and water holding capacity can also positively influence thermal reduction capabilities (Lin & Lin, 2011)

Storm Water Management

The hydrologic functions of a green roof are influenced by the climate of the region, rain depth and intensity, as well as the dry days prior to rainfall (Voyde et. al, 2010). Whereas research shows thermal performance is controlled mostly by vegetation, hydrologic performance in the form of storm water management is greatly impacted by substrate choice. Pumice based substrates are beneficial as a lightweight material for retaining storm water and still facilitating proper plant growth (Fassman & Simcock, 2011). In order to maximize water retention during large rain events, drought tolerant plants should be chosen. This is because if the plants need to be irrigated, the substrate will have less retention capacity remaining (Voyde et. al, 2010). An additional issue for green roofs in tropical environments is that larger rain events are more common, which can lead to erosion of the green roof if the saturation rate of the substrate is not quick enough (Kohler et al, 2001). Vegetation type can also have an influence on water retention as rainwater is intercepted differently by the structural qualities of various plants (Dunnett et al, 2008). This applies more to herbaceous plants, while succulents can actually retain some water inside of them as well.

Although it is not a direct design quality, green roofs can be expected to have some level of ability to remove pollutants from rainwater runoff (Berndtsson et al, 2009). Using plants that need less fertilizer will decrease nutrient leaching, while incorporating less organic material in the substrate will help avoid dissolved organic carbon as a pollutant (Berndtsson et al, 2009). Having fewer nutrients initially in the substrate, while still supporting enough plant growth would result in optimizing runoff quality (Hathaway 2008).

3.5 Further Connections and Comments

Some of the studies discussed have shown that vegetation type and coverage is the main influence on thermal reduction and that substrate type mainly determines water retention. Conversely, other research has shown that thermal performance is more significantly enhanced by substrate depth and that retention is mostly influenced by vegetation type (Nardini et al, 2011). Since each of these studies were conducted in a different country and climate, it supports the idea that for each unique environment, each component of a green roof will have varying amounts of control on the behavior of the system. In general, all of the studies examined in this review were conducted in different places. This resulted in varying and sometimes contradicting results on the recommendations for green roof design. These papers were intentionally selected in this way, in order to review them against each other to show that green roofs will behave and function differently in distinctive environments when utilizing a range of designs.

While the biggest potential benefits of green roofs include both thermal protection and storm water management, it may be more ideal in some cases to focus the design for primarily one of these goals. This is due to the fact that based on the environment, changes in the design aimed to improve one performance aspect may affect other aspects in a negative way or have an unfavorable feedback mechanism. An example of this is that although research supports that deeper substrate supports more diverse plant life (Oberndorfer et al, 2008) and more diversity promotes higher survival rates during droughts (Nagase & Dunnett, 2010), deeper substrates will also increase the load on the building which can be a limiting quality for the feasibility or cost benefits of the system. Therefore it may be more advantageous to focus future research efforts on determining what vegetation and substrate combinations are the best for a specific performance goal. It would still need to be modified to survive in different climates, but this can be easier when there is only one performance goal to keep functioning. Also, many studies monitor the progress of several green roofs that have multiple design variables. However, it will not be known which feature, or combination of features lead to a roof's advantages or shortcomings. Having one variable determining one goal will yield more easy to analyze results. This method may require more or longer studies to choose a full design, but at least the results of each study would be more definitive, and possibly more applicable to green roofs in other parts of the world.

4. Conclusion

Green roofs have shown enormous potential as a sustainable way to benefit buildings both thermally and as a storm water management practice. There are intrinsic regional climactic conditions that should be taken into account for the design selection of a green roof. This design selection will affect how the roof functions and performs. There are many different components that play roles in that whole system. However, these components are all interconnected and influence each other, which is part of the reason why there is not much knowledge about how to design a green roof to survive in a specific climate and exhibit a desired performance. Different combinations of vegetation and planting medium will never yield a perfect green roof, which is why they need to be designed with specific performance goals in mind. The more definitive and concentrated those goals are, the easier it will be to research for and create a roof that can achieve them, without needing as much compromise. The studies for this should also be done with fewer variables in the design elements so that the results will be more revealing as to how the roles of each component affect the end product. If more research is done to determine how varying designs function for specific climates, then implementing green roofs will become a more strategic sustainable practice with energy usage, environmental and economic advantages.

Figure 1. Left: Extensive green roof in Sweden (Berndtsson et al, 2009). Right: Intensive green roof in Florida (Sonne, 2006).

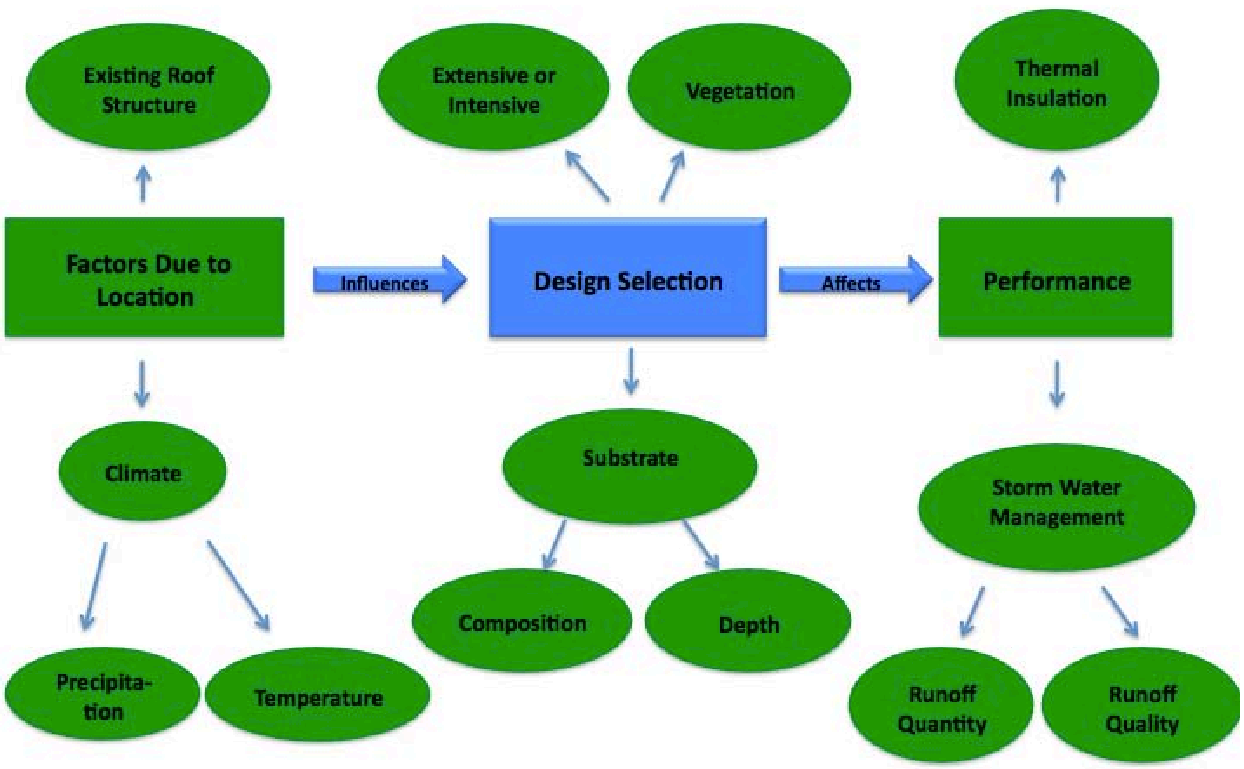

Figure 2. A visual representation of how green roof design selection is influenced by various factors, and how it dictates green roof performance.

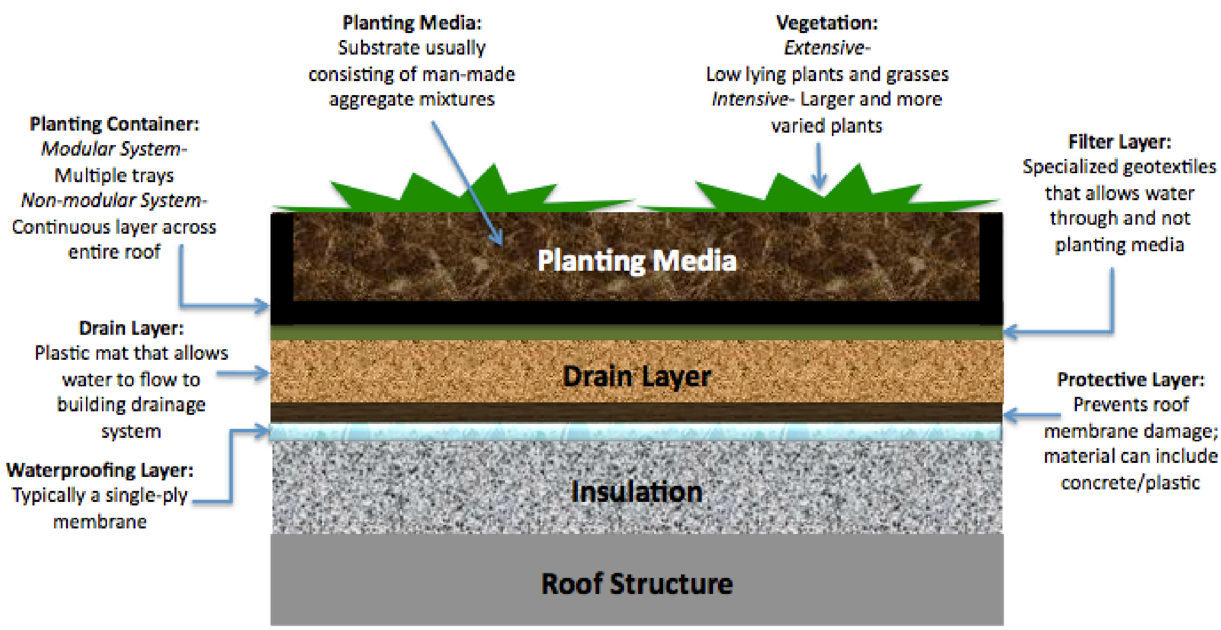

Figure 3. A cross-sectional representation of the typical layers of a green roof. Descriptions from Wark & Wark (2003).

References

Berndtsson, J. C., Bengtsson, L., & Jinno, K. (2009). Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering*, *35*(3), 369-380.

Boivin, M., Lamy, M., Gosselin, A., & Dansereau, B. (2001). Effect of Artificial Substrate Depth on Freezing Injury of Six Herbaceous Perennials Grown in a Green Roof System. *Response, 11*(September), 1994-1997.

Dunnett, N., Nagase, A., Booth, R., & Grime, P. (2008). Influence of vegetation composition on runoff in two simulated green roof experiments. *Urban Ecosystems*, *11*(4), 385-398.

Eumorfopoulou, E., & Aravantinos, D. (1998). The contribution of a planted roof to the thermal protection of buildings in Greece. *Energy and Buildings*, *27*(1), 29-36.

Fang, C.-F. (2008). Evaluating the thermal reduction effect of plant layers on rooftops. *Energy and Buildings*, *40*(6), 1048-1052.

Fassman, E.A., Simcock, R., Voyde, E. (2010). *Extensive Green (Living) Roofs for Stormwater Mitigation Part 1 : Design and Construction*. *Environmental Engineering* (Vol. 504).

Getter, K. L., & Rowe, D. B. (2008). Media depth influences Sedum green roof establishment. *Urban Ecosystems*, *11*(4), 361-372.

Hathaway, A. M., Hunt, W. F., & Jennings, G. D. (2008). A Field Study of Green Roof Hydrologic and Water Quality Performance. *Transactions Of The Asabe*, *51*(1), 37-44.

Ignatieva, M., Meurk, C., van Roon, M., Simcock, R., Stewart, G. (2008). *How to Put Nature into Our Neighbourhoods.* Landcare Research Science Series No. 35. Urban Greening Manual. Manaaki Whenua Press. Landcare Research New Zealand Ltd.

Köhler, M., Schmidt, M., Grimme, F. W., & Laar, M. (2001). Urban Water Retention by Greened Roofs in Temperate and Tropical Climate. *Development*, *2*(1).

Lin, Y.-J., & Lin, H.-T. (2011). Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. *Building and Environment*, *46*(2), 345-355.

Nagase, A., & Dunnett, N. (2010). Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity. *Landscape and Urban Planning*, *97*(4), 318-327.

Nardini, A., Andri, S., & Crasso, M. (2011). Influence of substrate depth and vegetation type on temperature and water runoff mitigation by extensive green roofs: shrubs versus herbaceous plants. *Urban Ecosystems*.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman R., Doshi, H., Dunnett, N., Gaffin, S., Kohler M., Liu K. & Rowe, B. (2007). Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *BioScience.* 57(10), 823-833.

Palomo Del Barrio, E. (1998). Analysis of the Green Roofs Cooling Potential in Buildings. *Energy and Buildings*. 27:179-193.

Patterson M. (1998). "What color green? Experts spill the dirt on environmental roofing, from gardening to saving electricity." *Buildings.* 92(5): 80–2.

Rowe, D. B., Monterusso, M. A., & Rugh, C. L. (2006). Assessment of Heat-expanded slate and fertility requirements in green roof substrates. *Hort Technology*. 16(3): 471-477.

Sonne, J. 2006. Evaluating Green Roof Energy Performance. *ASHRAE Journal*, 48, 59-61.

Timperley, M., Williamson, B., & Horne, B. (2005). Sources and loads of metals in urban storm water Sources and loads of metals in urban storm water.

VanWoert, N. D., Rowe, D. B., Andresen, J. a, Rugh, C. L., Fernandez, R. T., & Xiao, L. (2005). Green roof stormwater retention: effects of roof surface, slope, and media depth. *Journal of environmental quality*, *34*(3), 1036-44.

Voyde, E., Fassman, E., & Simcock, R. (2010). Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *Journal of Hydrology*, *394*(3-4), 384-395.

Voyde, E., Fassman, E., Simcock, R., & Wells, J. (2010). Quantifying Evapotranspiration Rates for New Zealand Green Roofs. *Journal of Hydrologic Engineering*, (June), 395-403.

Wark, B. C. G., & Wark, W. W. (2003). Green Roof Specifications and Standards. *Construction*, *56*(8).