THERMAL BENEFITS OF GREEN ROOFS

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Abstract

Residential and commercial buildings consume a large proportion of all energy produced; a good portion of this energy is used to heat and cool spaces. Green roofs can decrease cooling loads in the summer via 4 main methods of action: Urban Heat Island effect, Shading, Insulation, and Evapotranspiration, together they allow Green roofs to significantly lower the air conditioning load. Factors such as Reflectance, Leaf Area Index, Medium density and depth, Evapotranspiration rate, and location are factors that can affect these different methods of actions. These pathways together can lead to significant financial savings via a reduction in thermal flux therefore decrease in demand for air conditioning. There is also much more research that needs to be conducted in order to understand the thermal benefits of Green roofs. However; with intelligent well researched decisions; designers can design efficient and economical Green roofs.

Introduction

Vancouver Convention Centre, Van Dusen Botanical Gardens, are two high profile publically owned buildings in the city of Vancouver, both of which carry the proud nametag of being environmentally friendly buildings, and both featuring Green roofs, but what is the scientific merits of specifying a green roof? Living Roofs are known to have many positive effects on the environment; increasing habitat for animals within the urban environment, improving micro-climate air quality, improved aesthetics, and a major one being storm-water mitigation which decreases peak flow and quantity of storm water during rain events, but another major performance claim is that Living Roofs significantly enhance thermal performance. This research paper endeavours to find out if installing green roofs on our buildings will improve thermal performance and therefore decrease demand for space heating and cooling. Firstly, a review of the existing situation in the United States will be discussed to set the scene, next the methods of action of Green roof thermal performance enhancement will be reviewed; Urban Heat Island Effect, Shading, Insulation, and Transpirational cooling. After which; a review of the economic realities of Green roofs and how energy savings may be translated to financial savings. Lastly, directions for future research will be discussed; as where the future well-being of man-kind is reliant on further research to point us in the proper direction. According to the

Thermal performance and energy consumption

United States Energy Information Administration; nearly 40% of all energy consumed in 2012 was by Residential and Commercial buildings; numbering approximately 40 quadrillion BTU's; when put in laymen's terms is the equivalent energy output to 600,000 'Little Boy' atomic bombs that were dropped in Hiroshima in 1945. (CBECS & RECS 2013) In commercial buildings; space heating and cooling consume 35% of the total energy used by a building, meanwhile in residential buildings; heating and cooling make up 48% of total energy consumed; this means that approximately 16% of all energy produced by the entire United States in consumed in order to just heat and cool our environments. This number is especially relevant when we consider that more than 70% of energy produced by the US Department of Energy is via fossil fuels; Coal fired plants providing 42% and the remaining 28% is provided by gas and oil burning power plants. These plants consume limited fossil fuels while generating tonnes of greenhouse gases every year, these gases in turn heat up the planet which increases need to cool our home thus increasing HVAC energy consumption, it is a viscous cycle. According to the US Environment Protection Agency; these plants release a third of the American man-made carbon dioxide output, therefore the heating and cooling of buildings is responsible for 5% of the total carbon dioxide output. Thus the environmental impact of heating and cooling our buildings stretch beyond just the performance of the particular green roof equipped building but the entire planet as a whole.

Firstly; the usage of the term 'buildings' is very loose as it encompasses many types of buildings; residential, and commercial buildings have very different thermal needs and priorities thus must be analyzed separately. 'Residential buildings' encompasses both condominium high rises and single family homes; considering that most people spend the majority of their day at home; the thermal needs of residential buildings are quite important. Accordingly; EIA research has shown that 48% of all energy consumed by residential buildings is being used to heat and cool. As seen in Figure 1; heating consumes 42% of the energy budget, meanwhile cooling consumes 6%. Of most concern is that total energy consumption for thermal regulation is actually trending upwards despite them taking up a smaller piece of the pie, a result of total energy expenditure per household going up over time. Next; commercial buildings; according to the EIA Commercial Buildings Energy Consumption Survey; 25% of the energy consumed by commercial buildings in the United States are for space heating and cooling; where the heating and cooling are almost equal in consumption; thus commercial buildings prioritize cooling more than residential buildings; and therefore the importance of Green roofs potentially lessening cooling loads. Considering the large amount of activities that occur within these buildings; simply heating and cooling these spaces consumes more than an eighth of the entire national energy budget. For reference; based on the United States DOE 2013 annual report; an improvement of 1% in both heating and cooling performance in both residential and commercial buildings will yield a savings of 100 terawatt hours nationwide; which is enough to power a 60 watt incandescent light-bulb for 191 million years.

Now, armed with a clearer picture of the scale of the energy that is used for heating and cooling our spaces as well as the demands that these spaces may need based on programming; a clearer picture of the thermal benefits of a Green Roof can be painted and evaluated.

Methods of Action

Green roofs are known to provide thermal performance enhancements in both Winter and Summer, but warm climate performance will be the main focus of this paper as the potential performance gains are much higher in the summer; as studies have shown that Green roofs can decrease cooling load significantly during the summer months. This section will attempt to explain the process by examining the four primary methods of action; Urban Heat Island effect, Shading, Insulation and Evapotranspirational cooling. Several important variables that may affect these methods of actions will also be examined.

Urban Heat Island Effect

Firstly, what is the Urban Heat Island Effect? The Urban Heat Island Effect is when a metropolitan area is significantly hotter than surrounding rural areas as a result of human activity. As you can see in Figure 2, surface and air temperatures are higher in the metropolitan area compared to the rural area both during the day and the night. One major thing of note is that Urban Heat Island operates on a diurnal cycle: meaning it occurs on a daily cycle; solar energy is absorbed during the day by dark urban surfaces such as asphalt, concrete and is radiated into the environment during the night. This can be seen in Figure 2; the highest temperature peak is observed during the night in the metropolitan downtown. The Urban Heat Island effect is a result of 4 different methods of action; firstly; the Urban Canyon; a highly reflective canyon created by the tall man-made structures where heat is reflected and absorbed therefore ultimately trapped. Secondly; the thermal properties of building materials such as high thermal capacity and high emissivity increases absorption and radiation; thermal capacity is the measure of how much heat a material can hold, whereas emissivity is the relative ability of a material to emit energy via radiation. Thirdly; urban development replaces evapotranspiring cooling green areas with structures, and lastly a decrease in urban albedo, which is a measure of reflectance.

Urban Heat Island affects more than just the immediate micro-climate of a building or a neighbourhood; it severely impacts many environmental aspects in the region; it wreaks havoc on local water bodies as it can increase water temperatures via increasing storm-water temperatures by heating run-off as it runs over heated dark urban surfaces as well as increasing the water temperature via an increase in the urban ambient temperature. This increase in water temperatures results in a decrease in biodiversity; by increasing Carbon dioxide content and lowering Oxygen content, thus potentially leading to algae blooms and fishkill. (EPA 2009) According to several American studies; UHI can also lead to local meteorological changes such as increase in cloud formation, increase in precipitation, humidity, and fog formation; this is all a result of the creation of a upward thermal draft that moves warm air up; thus creating a low pressure area which allows surrounding cooler moist air to fill its void thereby increasing water content. (Chiel et al. 2008) A recent 2013 study has found significant statistical relation between UHI and rainfall in 23 American cities. While this is not immediately related to the thermal performance of a building; this increases the amount of rainfall falling on urban surfaces significantly and thus increases storm-water production; this worsens the already dire storm-water situation. Rainfall in downwind rural areas have also been observed to be significantly higher than rural areas upwind or areas that are further away from urban areas.(Ganeshan et al. 2013) Why is the impact of UHI important? The answer lies in the Living Roof's ability to decrease the Urban Heat Island effect: widespread usage of Living roofs can actually decrease the ambient temperatures of urban environments as seen in a study in Chicago published in 2008; where the researchers analyzed landsat and infrared photos of Chicago over a 13 year span where they saw an increase in green roof coverage which increased the albedo of the entire city by 0.016. (Mackey et al. 2008)

The biggest concern when discussing Urban Heat Island Effect reduction is the Reflectance of the surface; which is described as the "…fraction of incident electromagnetic power that is reflected at an interface…" contextually; reflectance is the measure of the quantity of solar energy that hits the surface is reflected away thereby decreasing heat gain of the material. (Klein and Furtak, 1986) Reflectance is commonly measured in Albedo; on a scale from 0 to 1; with 1.0 being a perfectly reflective surface, and 0 reflecting no energy. For reference; a common dark bitumen based roof has an albedo of 0.05, while a Green Roof commonly has an albedo of 0.2, and a white roof has an albedo of 0.5, therefore a Green Roof is 4 times more reflective than an ordinary dark coloured roof; this increase in reflectance allows for more heat to be reflected back into the atmosphere therefore creating cooler microclimates. Thus, hypothetically; the green roof should result in significantly lower ambient air temperatures; this is supported in an 2003 study where there results are shown in the left graph of Figure 3; the ordinary black coloured Bitumen based roofs show significantly higher ambient air temperatures as well as higher radiation. On top of reflectance; radiation is quite important as one material may be more readily able to radiate absorbed heat over another; and thus could affect the peak temperatures; this can be seen in the right graph of Figure 3; where the roof without plants displayed significantly higher radiation measurements than the roof with plants; the data is especially significant during the night as the difference in temperature between the two roofs varied by as much as 100%, confirming the diurnal cycle of the Urban Heat Island Effect. (Wong et al., 2003) The Albedo of plants can also vary minutely from plant to plant depending on the colouration of the plant as well as the finish of the leaves themselves.

To sum it up; the Urban Heat Island Effect is a phenomenon that has far reaching impacts on our environment and is generated by the absorption of solar energy by dark coloured urban materials that is radiated at night; and this can be mitigated by the usage of green roofs that can increase reflectance.

Shading

Another important mechanism of action is shading; which plays a large role in thermal regulation as what solar energy isn't reflected back into the atmosphere by the higher albedo surfaces of the pants is either absorbed by the plants for photosynthesis and transpiration; the remaining energy is absorbed by the un-shaded growing medium that radiates the heat back out later. This translates to; the greater the amount of shading, the lower the amount of solar energy that is transferred to the growing medium, therefore less thermal flux into the building. Two factors affect the total area that is shaded by the plants; first is the density of planting; as increased density increases growing media coverage. The other factor that can affect shading is the amount of shading provided by leaf surfaces per plant and this is unique with each plant; thus the development of the Leaf Area Index measurement; each plant possesses a unique LAI number indicative of expected number of leaves per plant as well as size. This is supported by a 2008 Singaporean study; where the researchers recorded the ambient and global temperatures; as well as solar radiation, as seen in Figure 4: the results show that the shading effect was highly dependent on LAI as denser species such as Pandanus (E), Spider lily (B), and Raphis palm (D) resulted in more shading and thus the resulting ambient temperatures below their leaves were lower. The results also showed that the hard surface reached a maximum temperature of 57 degrees Celsius, bare soil reached 42 degrees Celsius, and the spaces located beneath the plants never exceeded 36 degrees celsius. Meanwhile the difference in temperature seen between two plant species was up to 10°C, with the Heliconia with the lowest LAI displaying the highest temperatures among the plants. (Wong et al. 2003) Therefore, the considerations for palette selection of a green roof must extend beyond the aesthetics, drought resistance, but also must consider LAI as it has a significant impact on the Shading effect and thus the thermal performance of the roof.

Insulation

The third method of action discussed is the insulation that is provided by the plant biomass and the growing medium and how they may contribute to a decrease in thermal flux. Firstly; the growing medium greatly affects the ability of the green roof system to insulate the building; the depth of the growing medium greatly affects the thermal resistance of the roof. Thermal resistance is a measure of a material's ability to resist heat flow; thus the higher the thermal resistance; the greater the insulative properties, and is indexed with the R-value which is a measure of thermal resistance of a material: the higher the more insulative. A 2003 Singaporean study supports this claim as the results showed that for every 10 centimetre increase in medium depth; it increased the thermal resistance of dry clay soil significantly; every increasing 10 cm increment resulted in approximately 8% improvement in peak resistance to heat transfer. (Wong et al. 2003) As evident in Figure 5; where with increasing growing medium thickness; the annual energy consumption decreases therefore supporting that with increasing thickness, thermal performance increases as well. This was corroborated by the National Research Council of Canada's 2003 study; where they found that deeper green roofs resulted in lower heat gain and loss than roofs with shallower growing mediums. (Liu & Baskaran 2003) Additionally, the density of the growing medium also greatly effects the thermal resistance of the growing medium as an increase in medium density means a decrease in number of air pockets between substrate particles; and as air is a great insulator; this decreases the insulative effect of the medium. A 2003 research used a mathematical model to analyze the effects of soil densities on thermal flux; the results show that as the density of the growing medium decreased, the observed thermal flux decreased as well, suggesting the conductivity of the medium decreased; inversely meaning the insulative thermal resistance increased. (Wong et al. 2003) Furthermore; the water content within the soil can also greatly affect the thermal conductivity of the medium as water is a great conductor thereby increasing the thermal conductivity and thus the heat flux as well. The same study also observed that water content of the medium greatly impacted the thermal conductivity of the medium, as the R value for the soil decreased with increasing moisture content. Additionally, high water content in the medium can also cool the building via evaporative cooling; akin to sweating in humans. Lastly, the growing medium also provides more thermal mass therefore it provides thermal inertia which delays the daily temperature fluctuations; growing medium is cooled at night, and it continues to cool building during the day; this dampens the temperature swings, decreasing the need for air conditioning. (Liu & Baskaran 2003) This thermal mass phenomenon when paired with increasing insulation of increasing soil depth could explain the significant energy savings seen with increasing soil depth in Figure 5.

While Green Roofs are predominantly seen in warm dominated climates; the performance of Green roofs in winter is important as well as much of North America see extremes of temperature in both winter and summer. The primary method of action of Green Roofs for thermal flux benefits is the added insulation provided by the growing medium and plant mass. Since Green roofs act as passive coolers in the summer with heat flux from the interior to the exterior via the conductive water molecules; some experts believed that Green Roofs would be detrimental to winter thermal performance. But a year-long National Research Council of Canada study conducted in Ottawa claims that green roofs can actually prevent heat losses by 10-30% when compared to an ordinary control roof, a result of additional insulation as well thermal mass provided by the additional mass of the medium and plant matter. (Liu & Baskaran 2003) Furthermore, snow build-up is a great equalizer; as the air trapped in between the solid ice crystals allows snow to act as an insulator and thus may offset whatever thermal losses that may have occurred otherwise.

All in all; the growing medium and the plant biomass provides significant insulation; which decreases thermal conductivity and thus thermal flux; the effectiveness of the growing medium as a insulative layer depends on the depth, density, and moisture content of the growing medium. The thermal mass of green roofs as well as evaporative cooling in the moist medium may also provide benefits in cooling. Lastly, winter performance of green roofs appears to be a mixed bag as; experts disagree on the performance during winter, with one fastidious study seeing a significant improvement.

Evapotranspiration

The last method of action is Evapotranspiration; the only active cooling method of the four main methods of action. As a plant carries out photosynthesis; water from the growing medium travels up the phloem and is used to take part in the photosynthetic Calvin cycle to generate sugars; an important reactant in the cycle is Carbon dioxide which requires the opening of small pores on the underside of leaves called stomata to open up; these pores also allow the escape of water molecules. These escaped water molecules undergoes an endothermic phase change from liquid to gas meanwhile absorbing heat energy from the environment, thus cooling the air beneath the leaves, which ultimately actively cools the building. (Freeman 2007) The rate at which transpiration and the time of day it occurs is largely dependent on the plant species, but also heavily relies on the height of the plant, wind speed, humidity and the ambient temperature. (Sailor 2008) Wind speed is of particular importance as it allows for convection currents to occur on the leaf surface; thus increasing rate of evapotranspiration. (Skaggs and Irmak 2011) Humidity in the air determines the rate at which water evaporates; therefore determining the rate at which water evaporates when the stomata are open. Ambient temperature has a similar effect on evapotranspiration rate; as temperature affects the rate of water evaporation since it dictates how many water molecules have the minimal amount of energy to phase change into a gas. Moreover; some plants evapotranspire at night therefore this allows for the cooling phase to occur at night and could be a powerful tool to offset the heat released by the diurnal cycle of the Urban Heat Island effect. (Skaggs and Irmak 2011) Therefore the species of plants chosen must be carefully selected to take advantage of evapotranspiration; beyond their ET rate; the timing of the evapotranspiration phase as well as their efficiency of evapotranspiration must be considered when designing green roofs.

Economics of Green Roofs

While the fact that Green roofs save energy and reduce carbon dioxide emissions as a result is great for the environment; that alone is not going to trigger widespread adoption. But, the economics of the energy savings can be a persuasive argument to sway stakeholders. The biggest issue facing widespread adoption is the initial capital investment: it is significantly more expensive than a conventional roof system due to the expensive technologies and specialists required to properly design, and install the roof system. This does not include the additional costs that may be incurred with the structural system that needs to be in place to support the increased weight load of the roof. On the other hand; all the mechanisms of actions discussed earlier in this paper can lead to a significant decrease in interior temperature and therefore reduction in air conditioning energy; research shows that green roofs can reduce air conditioning energy usage from anywhere between 25 to 80%. (Wong et al. 2003) Additionally, according to the NRC study, green roofs can also decrease heating thermal flux in winter by 10-30% therefore also decreasing heating loads. Thus, there are energy savings in both winter and summer. (Liu & Baskaran 2003) Green roofs also even out the temperature swings in interior spaces allowing the temperature to remain relatively consistent; decreasing the unnecessary energy spent by HVAC systems that often overshoot the target. One Chinese study has come to the conclusion that one square metre of green roof can save 0.14 kWh per day. Accordingly, as of April 2014, a kilowatt hour costs 10 cents in British Columbia, therefore using these numbers; a building the size of the Vancouver Convention Centre can save approximately $125,000 dollars per year in energy costs. (Yan 2011) Moreover, a 2005 study conducted by Ryerson University for the City of Toronto used software analysis and calculated that if all compatible roofs surfaces; approximately 50 million square metres were to be changed to Green Roofs in the City of Toronto; energy savings as a result of direct cooling savings of approximately $69 million dollars could be possible. This number does not include the potential in savings such as Storm-water, Sewage Overflow, Urban Heat Island Reduction also generated by the Green roofs. (Banting et al. 2005) One study simulated the effects of a green roof in different cities around the world set in different climate zones taking into account wind speed, humidity, temperature, and solar radiation. The results revealed that a significant savings in energy expenditures in all cities and thus climates, but ultimately; the hotter and drier the climate such as Riyadh; the more effective the green roofs at mitigating urban temperatures. Whereas colder climates like Montreal, Moscow, and London benefited the least, Riyadh saw a peak difference in temperature of 26°C. (Alexandri et al. 2008) Maintenance costs also vary wildly depending on location, species palette, climate, etc.; one Taiwanese study concluded that maintenance costs can be nearly insignificant if located in a tropical climate. (Chen 2013) The importance of this study is that Green roofs can save you energy in any climate but the level of performance will vary depending on environment; and can be a great tool to decrease energy costs but only when the location and climate are carefully considered.

Future Research Suggestions

Lastly, future research suggestions need to be discussed as it is with only more knowledge can mankind make educated decisions to point us in the right direction. The issues discussed in this section are the most troubling and obvious issues that need to be addressed if widespread adoption of green roofs are to occur.

First and foremost; a standardized testing procedure needs to be clearly designed and published; almost every study referenced in this essay used a slightly different method of gathering data and building green roofs; this can lead to confounding variables that may affect the data. Chemistry, Medicine, Biology, Physics and many other hard sciences use standardized test procedures that are easily reproducible and thus tested and validated by peers; this allows for sharing of data that can be used to create a more complete picture when analyzing the results. This is especially valuable when the performance of Green Roofs are so dependent upon the siting and location of the building; having data with the same set of variables and testing procedures will allow for the pooling of data for the assembly of a database with common data points such as albedo, average wind speeds, rainfall, snowfall, etc. that can assist designers in making efficient and economical decisions when designing Green Roofs. This is not a small undertaking and will require the cooperation of professionals from different disciplines, backgrounds, and nationalities, but will benefit the entire field, and even more importantly; the environment and all those who reside in it.

Secondly, more research needs to be conducted on the performance of Green roofs during the winter season. Some researches claim that Green Roofs are a detriment to thermal performance in the winter, yet others like the National Research Council of Canada says otherwise. This research also needs to account for winter climates in different regions; such as Vancouver; where very little snowfall is seen, and thus the insulative layer of snow does not exist, and a lot of rainfall is common; does this mean that green roofs operate as giant heat sinks in Vancouver during the winter? Additionally; the potential to actively cool buildings by artificially increasing evapotranspiration can be quite potent, but there is very little scholarly research into this topic at the moment. Allegedly; the Vancouver Convention Centre increased irrigation during the peak summer months to increase evapotranspiration rate which resulted in a decrease in air conditioning energy usage by 30%. This paired with a Grey or Black water recycling system can be a very effective and cheap alternative to air conditioning but more research needs to be done before it can be widely adopted.

Lastly, there needs to be a translation of these hard scientific data into terms where stakeholders and developers can easily access and understand for widespread adoption. This is a task for practitioners such as Architects and Landscape Architects to tackle; to convert raw numbers and data that can sometimes be hard to grasp into easily accessible information that is easily relatable to all end users.

Conclusion

To synthesize; buildings consume up to 40% of the energy being produced and therefore contributes up to 5% of the carbon dioxide released by fossil fuel power plants, thus decreasing the consumption of energy by any amount will result in significant impacts on the environment. Green roofs are known to decrease cooling loads in the summer and do so via 4 main methods of action; which can be further divided into two possible categories; preventative: preventing heat flux from the environment into the interior and this category includes urban heat island reduction where plants have higher reflectance than ordinary dark roofs and therefore a greater proportion of the solar energy is reflected back into the atmosphere. The next preventative pathway is shading; where the energy that isn't reflected back is absorbed by the plants for photosynthesis which in turn shades the building from the direct sunlight. The third preventative pathway is Insulation; prevents the remaining light that manages to hit the bare growing medium from fluxing into the building; the energy that remains will have to flux across a cool insulative layer of medium with a lot of thermal mass, and only very little energy manages to actually enter the building. The second category is made up of only one pathway; evapotranspiration and it is characterized by the active cooling of the building where the phase change of water molecules to steam during evapotranspiration in plants actively cools the space beneath the leaves and thereby the building as well. Moisture in the growing medium also undergoes the same phase change, further cooling the building. Together these mechanisms lead to significant decreases in cooling and heating needs therefore leads to energy and financial savings. Furthermore; all of these pathways can be greatly affected by factors such as leaf colour, reflectance, Leaf Area Index, density of planting, medium depth, medium density, medium moisture content, ambient temperatures, climate, wind speeds, among many others. Additionally; several studies have shown that significant savings have been observed in energy costs due to these mechanisms, and thus there is a sound economical case that can be made for the implementation of a green roof. Also, there needs to be much more research done on the performance of Green roofs before it can be widely adopted based only on thermal performance, as there are currently too many unanswered questions regarding; winter performance, active cooling, among many others.

The key takeaway from this entire discussion is that knowledge is key; knowing what the main target objectives are, knowing which factors will affect those objectives, knowing how the location of the roof will affect those factors or what additional factors will it provide; are all key in designing an intelligent and efficient green roof, and actually impact the environment in a positive manner.

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