greening rooftops
for sustainable communities
Minneapolis, April 29 - May 1, 2007

3.2: Stormwater Research

Integrating Stormwater and Greywater Treatment for Thermal Regulation and the Enhancement of Biological Diversity: Using Mass Balance of Water as a Design Criteria

Dr. Paul S. Mankiewicz & Daniel Bowman Simon LEED AP

The Gaia Institute

Abstract

Green roofs can regulate thermal conditions such that local temperature is substantially below maximum summer temperatures found on comparable non-green urban rooftops. Radiation partitioning and evapotranspiration by plant and soil systems are used to inform the hypothesis that green roof water budgets can impact favorably on energy usage in buildings and in their immediate surroundings. It has also been demonstrated that the optimal operating temperature for air conditioning condensers is, like the optima for photosynthesis, substantially below maximum summer temperatures found on typical roof surfaces.

To address and explore this optimization framework, two projects in New York City are under design, to be constructed in spring and summer of 2007. A Bronx commercial facility is being retrofitted with a green roof and photovoltaic array as well as a below grade stormwater capture and water-recycling system. Condensers for this building will be situated beneath a green roof and next to a vegetated landscape, forming cool air that is expected to increase air conditioning efficiencies. The conjecture informing this configuration is that overall energy efficiency, as well as photovoltaic performance, will improve when a green roof optimized for water treatment is coupled with photovoltaic energy capture. A bakery in Manhattan, with more exacting and precise temperature regulation requirements, will be outfitted with a metered water delivery system, to provide the potential for direct control of the quantity of evapotranspiration. Efficiencies of quantities of water application to green roofs for temperature control will be evaluated in both cases. Methods, equipment, and materials for optimizing stormwater capture, infiltration and reuse will be described for the Bronx commercial facility, oriented by the goal of zero stormwater discharge into the combined sewer.

Introduction & Overview

The flow of matter and energy are primary organizing forces in both ecology and economics.[1] These flows can play paradoxical, if not contradictory roles in these interrelated arenas. The aim of this paper is to uncover specific methods and applications to move water and partition heat through vegetation to reach complementary goals in both ecology and economics[2] of increasing plant coverage, decreasing urban summer temperature maxima, and removing the expense of treating stormwater and greywater by utilizing evaporative cooling.

Water

The growth and development of plant communities are sustained and powered by water, which runs the earth's Biosphere, in part, through participation in thermal regulation.[3] (At the same time, in hydrating soil, water supports the microbial biota that filters hydrocarbons, nutrients, and metals from runoff as well as the atmosphere, providing an additional ecosystem service, which will not be considered here.)

Alternatively, water in the storm drain system imposes costs by increasing pollutant and thermal loading in receiving waters. Any water, which may enter the sewer or combined sewer system carrying pathogens, pollutants, or nutrients, carries with it direct waste water treatment costs. (In New York City, for example, the New York City Water Board has pegged the waste water charge at $2.87 per 100 cubic feet of water (~748 gallons) for Fiscal Year 2007[4].) Biological and chemical processes which work in removing and processing pollutants operate increasingly well at higher waste and nutrient concentrations. Therefore, greywater from sinks and showers and other dilute sources of water disproportionately contribute to the overall waste water treatment costs: water with few nutrients or solids pass through the treatment infrastructure, requiring capacity and energy to treat; and because it is dilute, greywater and any ground or stormwater routed into the wastewater treatment plant decrease the overall operating efficiency.

Water flows through human-built structures at varying rates. A question raised in relation to the two projects presented here is, how much water is required to sustain a native plant community in the urban center of New York City? To run a green roof requires a minimum of about one to four millimeters per day in northeastern United States (see discussion of water quantities below).

Energy

---

[1] Odum, E.P. 1971. Fundamentals of Ecology, 3rd ed. W.B. Saunders Company. Philadelphia. p 39' Ulanowicz, R.E. 1986. Growth and Development: Ecosystem Phenomenology. Springer-Verlag. New York.

[2] Katz, G.H. 2003. "Green Building Costs and Financial Benefits". Published in USA for Massachusetts Technology Collaborative.

[3] Loomis, R.S. & D.J. Connor. 1992. Crop Ecology: Productivity and Management in Agricultural Systems. Cambridge University Press.

[4] Public Information Regarding Water and Wastewater Rates. New York City Water Board, 2006.

The energy sector intersects strongly with every other portion of the economy. Its byproducts and outputs are critical global climate regulators. Its cost is a determinant, sometimes a key contributor to the size, and even the sign, positive or negative, of the profit line in many business ledgers.

Most all human built structures occur within an envelope of radiant energy, flowing into and out of our buildings at rates in range of five hundred to a thousand or more watts per square meter each day. Depending on how buildings are structured, these energy flows may be positive or negative components of operating costs. Photovoltaic cells and solar hot water heaters can each make contributions to the cost-benefit columns for a business. The costs of the collection array and the price of electricity and hot water will determine the time-horizon for payback. For these investments, the point where the cost of the savings equals that of the installation is likely to be more than ten years in the former case, and one to a few years in the latter.[5]

Green roofs must be fitted into a more complicated equation. Because covering roofing material with plants and growth medium is expected to extend the lifespan of a roof membrane, the economic argument for green roofs has been made in terms of re-roofing frequency. Without a green roof, roof replacement would need to occur every ten to fifteen years, at a likely cost of less than $10 per square foot. This cost over time can then be compared to installing high quality waterproofing every forty years or more covered by a green roof installation, at a cost of +/- $25 per square foot, our current price of installation here in New York.

While this form of comparison is useful, the flow of new and waste roofing materials needs also to be considered, since it is a significant fraction of the material budget of a city. The quantities are substantial: “Every year, an estimated 9 million tons (8 million metric tons) to 10 million tons (9 million metric tons) of asphalt roofing waste are sent to U.S. landfills with a price tag of more than $400 million in disposal fees.”[6]

The thermal fluxes and ‘waste heat’ from roofs, however, may be even more significant for life in cities. Energy flows, in and out, can be measured on the order of about a hundred watts per square foot per day. Such flows can have multiple impacts, however, and can substantially impact expenditures of building owners and occupants, as well as those living within the thermal regulation envelope to which roofscapes,- black, cool, or green, contribute.

The behavior of water on rooftops also dramatically impacts energy flow locally and regionally. While we do not often equate evaporation or evapotranspiration with power, this may be a serious misapprehension. By way of example, the evaporation (or condensation) of 6 mm of water over a one hectare field (two and a half acres,) is the energy equivalent of about 15 tons of dynamite.[7] This daily energy release is the approximate average in the mid-latitudes.[8] The potential impact of this energy partitioning, controlled by vegetation and water, may contribute

---

[5] Liu,K. 2006. Green, Reflective, and Photovoltaic Roofs. Construction Canada, v. 48, no. 5, Sept. 2006, pp. 44-46, 48-50, 52-54

6 Snyder, R.K. 2001. 21st century recycling: ARMA and other industry organizations are leading the way for waste-reduction and recycling programs. Professional Roofing, August 2001.

[7] Loomis & Connor, p 147

[8] Loomis & Connor, p 145

substantially to changing, and hopefully enlarging, the sphere of analyses of green roofs. A focus on cost-benefit implications of the flow of energy forms the body of what follows.

A New Paradigm: Transforming Costs into Benefits on Green Roofs

This paper describes two businesses in New York City which have taken on a program of changing specific dimensions of the flow of materials through their facilities. Different implications follow on their business types, their surroundings, and the sources and quantities of water which may be treated on their green roofs.

Type of business, customer base, cash flow, and other parameters influence whether a company purchases or rents a facility at a specific location. While it might be expected that only owners would have an interest in green roofs, this case study shows how an understanding of ecosystem services, i.e., value contributed directly to environmental quality as a result of ecological processes, can contribute to the operating cost column of an enterprise.

One of the green roofs presented here was planned by a building owner-occupant of an accounting firm on the eastern edge of the Bronx. The other project described here will be incorporated into the operations of a downtown Manhattan bakery that leases their facility. The green roof designed for this location has the capacity to treat greywater and, through plant coverage and evapotranspiration, lower cooling costs. Keeping their facility cool is a process essential to the operation of a bakery. They must maintain working conditions that support and facilitate the proper mixing and blending of ingredients essential to the making of bakery products.

In both cases, the costs of cooling the buildings are referable to solar load and ambient temperatures of the surrounding area. Both of these impacts, direct solar radiation and ambient temperature, are regulated by the building structures, as well as vegetation cover and water. It is here predicted that green roof cover will contribute directly to increased efficiencies of cooling equipment in both locations. Based on air conditioning studies cited below, it is expected that energy usage will drop by 10% or more.

An additional array of equipment on the Bronx site, photovoltaic cells, also have temperature-dependent performance. While there will not be an opportunity for before and after measures of temperatures above a non-vegetated black roof versus a vegetated green roof, adjacent non-vegetated roof space is available on a neighboring building, and may make it possible to assess added benefits resulting from mounting photovoltaic cells above a green roof.

The scaling of green roof soil depth will rarely be sufficient to capture more than a two or three year storm, i.e., more than about two inches of rainfall, given the 30 to 40 lb per square foot bearing capacity of most New York City roofs. For this reason, and because storms may become increasingly large and variable with climate change/global warming, coupling green roofs with terrestrial stormwater capture systems may provide additional benefit in that water which exceeds the capture capacity of the green roof may still contribute to plant community growth and development, local biodiversity, and thermal regulation of the neighborhood context of the green roof. Such off-roof capture capacity, stored in cisterns, may also be used following storms, allowing a green roof to work with little or no input of potable water. Green roofs can thus aid to the solution of the urban stormwater problem, but need to be coupled in series and in parallel with street-side stormwater capture techniques.[9]

Location, again, will contribute strongly to the applicability and constraints on street-side capture of excess runoff from a green roof installation. For Manhattan, with multi-story buildings and the subsurface area occupied by water piping, power lines and phone lines, space in many areas is limited or entirely unavailable. Stormwater conduit within buildings is often already directly connected to the combined sewer, making retrofits for alternative distribution costly.

The Bronx, and all the outer boroughs of New York City, however, offer many opportunities for coupled stormwater catchment and treatment trains, increasing the value of the green roof as a primary filter, and using the excess runoff to further cool the environment in which the structure is situated. The green roof here can act as a classic regulator, slowing water down, to flatten out or lengthen the hydrograph, so to speak, and thereby increase the capture capacity of street side infiltration areas.

To maximize street-grade capture in the plan for the Bronx commercial facility, the access and parking slip at the rear of the building will be outfitted with four StormChambers capable of holding, in aggregate, 460 cubic feet of runoff. Water capture here in the planted parking zone edge is analogous to the bakery roof, since the compressors for the air conditioning unit are located directly adjacent to this rear parking zone.

The direct benefit of the green roof here will be cool air, which, by virtue of the density difference with the surrounding atmosphere, is expected to drop down from the roof to the parking area below. At the same time, plantings in the parking area will behave in a similar manner, reradiating solar input, and evaporating water stored in the ground and soil. At the scale of a hundred acres, similar phenomena have resulted in greenspace decreasing temperature more than half a mile downwind.[10] Decreases in energy demand have also been shown in models at the scale of multiple buildings and trees in the urban canyon.[11] The economic question for building owners is whether specific green roof, vegetated wall, and/or surrounding vegetation and stormwater capture which the building owner or leaser constructs can contribute directly to the energy efficiency and reduction of energy costs for the specific structure of interest, i.e., the one in which they work.

Quantifying Impacts to Local Climate and Efficiencies of Thermal Control

Green roof capacities to regulate building temperature are becoming better documented and understood.[12] Earlier work in biophysics, synthesized in the early 1970s to 1980s, documented

---

[9] Mentens,J., D. Raes, & M. Hermy. 2005. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning 77 (2006) 217–226.

[10] Vu. T.C., T Asaeda, E.M. Abu. 1998. Reductions in air conditioning energy caused by a nearby park. Energy and Buildings 29 (1998) 83-92

[11] Sánchez de la Flor, F., and S. Alvarez Dom´ınguez. 2004. Modeling microclimate in urban environments and assessing its influence on the performance of surrounding buildings. Energy and Buildings 36 (2004) 403–413.

[12] Alexandria, E. and P. Jones, 2006. Developing a one-dimensional heat and mass transfer algorithm for describing the effect of green roofs on the built environment: Comparison with

the relations between thermal loading and partitioning at multiple scales, from leaf shape to canopy geometry.[13] Applied work in crop growth pressed the biophysical and physiological ecology results into the service in the agricultural landscape, evaluating optima for water application to support plant growth.[14] In this work, the density of plant coverage, the quantity of available water, and the output of cereals and other crops were studied in detail. Because green roof evaluation has begun to focus on the ability of plants to discharge quantities of water into the atmosphere,[15] and because this water movement pathway has large physical chemical impacts on the thermal environment, the interdependent criteria of thermal partitioning, water loss, leaf coverage/leaf area index, and green roof energetics have begun to receive attention.[16]

Just as biophysics advanced as more refined and interrelated relations of leaf area, timing and quantity of water application, and plant growth were analyzed in agricultural applications, important conceptual advance can be seen in the recent work of Theodosiou and Kumar and Kaushik, characterizing leaf area index as a basic regulator of heat flow in and around green roofs.[17] The classic literature on plant interactions with local climate makes note of leaf area as important for ecological productivity,[18] but the more recent, applied work on green roofs may offer a unique opportunity for fundamental advances, documenting, in controlled conditions of known soil depths, soil water tensions, and radiation load, the ways in which heat is partitioned differentially dependant on the interaction of water availability and plant coverage/leaf area index.

The hypothesis that local climate, controlled by the ratio of vegetated and impervious urban landscapes, is presently under investigation in modeling enterprises utilizing the global tool of

---

experimental results. Building and Environment 42 (2007) 2835–2849; Santamouris M, et al. Investigating and analyzing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. Energy (2007), doi: 10.1016/ J. Energy.2006.11.011; Wong, N. H., T. P. Yokb, and C/ Yua. 2005. Study of thermal performance of extensive rooftop greenery systems in the tropical climate. Building and Environment 42 (2007) 25–54

[13] Horn, H.S. 1971. The Adaptive Geometry of Trees. Princeton University Press; Gates, D.M. & R. B. Schmerl, eds., 1975. Perspectives of Biophysical Ecology. Springer-Verlag, New York; Gates, D.M. 1980. Biophysical Ecology. Springer-Verlag, New York; Nobel, P.S. 1983. Biophysical Plant Physiology and Ecology. Freeman Press, San Francisco.

[14] Loomis & Connor. opp. cit.

[15] Compton, J.S. 2006. An Examination of Green Roof Plant Selection and Design to Optimize for Evapotranspiration. Masters of Science Thesis. Cornell University; Carter, T, and C. Rhett Jackson. 2006. Vegetated roofs for stormwater management at multiple spatial scales. Landscape and Urban Planning 80 (2007) 84–94

[16] Theodosiou, T.G. 2003 Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings 35 (2003) 909–917; Kumar,R. and S.C. Kaushik. 2005. Performance evaluation of green roof and shading for thermal protection of buildings. Building and Environment 40 (2005) 1505–1511

[17] Theodosiou p 912; Kumar and Kaushik, p1510.

[18] See, for example, Jones, H.G. 1983. Plants and Microclimate. Cambridge University Press, New York; Oke, T.R. 1978. Boundary Layer Climates. Halstead Press, John Wiley & Sons, New York; and, Rosenberg, N.J. 1974. Microclimate: The Biological Environment. John Wiley & Sons, New York.

GIS.[19] At smaller scale, that of individual buildings and properties, however, leaf coverage, and the partitioning of radiation and temperature are hypothesized to be the critically important variables which govern how vegetated roof cover contributes to the economic balance sheet, especially the cooling costs, of buildings.

In general, it appears that green roofs contribute to thermal regulation and energy savings. A major appliance manufacturer has evaluated the thermodynamics of green versus black roofs and their measurable impacts on compressor performance.[20] The Carrier Corporation data shows a kilowatt usage difference of 20% or greater for black versus green roofs. While the two basic variables, plant coverage and the quantity of available water, are likely major contributors here, they are not evaluated, which provides one of the opportunities of the present work.

Planting density is likely to contribute to coverage. While this is widely known in agricultural, forestry, and ecology generally, its importance has probably been recognized more as an aesthetic than a functional parameter in green roof installations to date. Since cooling is an essential goal for each of the two design frameworks addressed here, a planting strategy to reach coverage densities that optimize thermal regulation is integral.

Modeling coupled with mass balance evaluation on green roofs in New York City, however, has shown that the ratio of latent to sensible heat loss ranges from about 0.35 to 0.12, indicating that latent heat loss is between three and eight times greater than re-radiation, convection, advection, etc., i.e., all the other physical mechanisms acting in concert. While the well-controlled modeling efforts comparing fluxes in New York did not directly address leaf area index or other measures of coverage,[21] we should expect that coverage or leaf area of green roof vegetation is a major regulator of this thermal signal.[22]

To achieve plant coverage goals, planting strategies that integrate plugs and seeding distribution have been programmed into each site. The aim is to achieve a plant density on the order of a one to ten or more shoots per square foot, akin to secondary successional seres of the northeast United States, like the one pictured below. At the same time, since the temperature of input air is know to control condenser efficiencies,[23] air intakes will be coupled here with vegetated surfaces. Plant coverage is planned to extend to vertical brick walls exposed to high radiation loads adjacent to intake air, and vegetating landscapes next to

---

[19] Wu, L. 1996. An Integration of a Surface Energy Balance Climate Model with TIN and GRID in GIS. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/wu_lin/wu_lin.html; Gaffin et al. op cit.

[20] Bernhardt, A. 2006. Carrier Corporation Green Roofs and Packaged HVAC Equipment: A study to quantify the energy savings associated with using packaged HVAC equipment on green roofs versus traditional black top roofs. (unpublished)

[21] Gaffin, S., C. Rosenzweig1, L. Parshall, D. Hillel, J. Eichenbaum-Pikser, A. Greenbaum, R. Blake, D. Beattie, R. Berghage. 2006. Quantifying Evaporative Cooling from Green Roofs and Comparison to Other Land Surfaces. Proceedings of 4th North American conference: Greening Rooftops for Sustainable Communities.

[22] Theodosiou 2003; Kumar and Kaushik 2005, opp. cit.

[23] Bernhardt, opp. cit.

condenser mounts, as well as capturing and distributing stormwater and greywater to this vegetation.[24]

Image 1: A secondary successional seres of the northeast United States

To achieve these coverages, a green roof soil would need to support growth rates of approximately a kilogram per square meter per year. If such coverages are to be reached in a growth season, this implies a soil nutrient source capable of delivering approximately 2 – 4% 20 to 40 grams of nitrogen,[25] and approximately 10 grams of phosphorus[26] per square meter during this growth phase.

For full coverage then, given a 1% nitrogen content in the lightweight-growing medium, with 500 grams of soil per cubic foot, it would require 20 cubic feet of soil to deliver 100 grams of nitrogen. Because the soil depth is limited to about 15 cm or six inches, however, each square meter of soil contains about 5 cubic feet of soil, and, therefore, could only supply about an eighth of the 200 grams of nitrogen required to sustain a kilogram of biomass production.

To address this problem, top dressing plantings with compost is included as an integral maintenance specification for native plant communities to achieve green roof coverage. About a half inch of top dressing with compost can provide about a hundred grams of nitrogen per square meter.

---

[24] McPherson, E.G., L. P. Herrington and G. M. Heisler. 1988. Impacts of Vegetation on Residential Heating and Cooling Energy and Buildings, 12 (1988) 41 – 51.

[25] Larcher,W. 1995. Physiological Plant Ecology, 3rd Ed. Springer, New York. p 189.

[26] Larcher, p 176.

Image 2: A green roof planted in June 2005

While a green roof planted in June 2005 has achieved substantial coverage, the total cover optimal for thermal regulation, with a leaf area index of 3.5 and 4.5, has not been reached, as may be noted by comparing the photograph above with the preceding image of the old field.

There are thus two components of the problem of coverage which must be solved together. The first is nutrient delivery, which may be addressed with top dressing with nutrient rich composts at key times during plant development, and by optimizing water and nutrient holding capacity in the underlying soil. The Gaia Institute is working with the Soil Health Testing group at Cornell University to characterize key components for plant growth support.

Beyond the mass balance of nutrient application, an appropriate planting strategy is necessary to achieve full soil coverage and optimal leaf area index. Plug and seed planting regimes have been combined, with the aim of supporting seedling survival, growth and development. Seeding between plants on the established roofs will be compared with optimal hexagonal plug plantings, to compare coverage patterns and cooling capacities of existing and newly established green roofs. Data from the existing green roof indicate differences between ambient and green roof temperatures.

For the commercial facility to be constructed in the Bronx, beyond the local lager scale thermal regulation, e.g., thermal heat island effects and its regulation/reversal, there is the opportunity to measure the thermal envelope surrounding photovoltaic arrays which will be mounted on the roof above the green roof structure. While direct impacts will be limited because of spatial separation of the photovoltaic panels from the green roof, some panels are planned for directly above the one section of green roof, while others will be on a side of the building that is not above any green roof structure. Temperature impacts from these different sections will be assessed with separate metering of the panel array outputs.

The Regulating Role of Water

An essential component to achieve this cooling effect, however, is water. This must be supplied to the vegetated roof in sufficient quantity to regulate temperature, and, critically, the temperature of input air to condensers. To achieve a 5°F difference in the soil covering the bakery's 600 square foot roof will require daily evaporation of several millimeters of water. In physical terms, assuming that 15 lbs of soil covering each square foot of roof top must be cooled, with full shading over the soil, to achieve a 5°F difference, at least 60 grams of water would need to be evaporated per square foot per day, about 4 mm, or about ten gallons of water over the entire 600 square foot roof.

This is a low estimate, assuming no loss of cool air to the surrounding environment. The greywater design specifications provide for delivery of one to two hundred gallons to the green roof per day, providing a cooling capacity equivalent of twenty five to fifty tons of air conditioning per day. Stormwater and greywater combined allow for about a tenth of this quantity for the 2,400 square foot green roof of the Bronx facility.

Measures/Methods of Assessment

Because these are both commercial and not dedicated research facilities, assessment methods will need to be as automated and inexpensive as possible. For the bakery roof, it is expected that a tensiometer array will be used to trip water delivery, thereby maintaining a specific hydration level minimum in the soil system. Pump delivery will provide a measure of water use, while a thermocouple array will provide assessment of ambient and green roof temperatures.

In both commercial facilities, energy costs and kilowatt use will be used to assess the green roof's impact on the energy budget.

In both facilities, methods worked out for measuring plant coverage will be applied,[27] as well as application of a method for measuring leaf area index which involves removing leaves from specific measured sectors, scanning these into vector files, and summing up the leaf area per collected area sector.

Authors:

Dr. Paul S. Mankiewicz, Executive Director of The Gaia Institute, received his Ph.D. from CUNY/NY Botanical Gardens Joint Program in Plant Sciences. He holds patents on composting and lightweight plant growth media technologies and is the past president of the Torrey Botanical Society and Treasurer of the New York City Soil & Water Conservation District Board. (paul@gaiainstituteny.org)

Daniel Bowman Simon, Green Roof Coordinator/Low Impact Development Analyst
(daniel@gaiainstituteny.org)

---

[27] Hartley, A. 2007. Monarchs in Metropolis: A Case Study. Proceedings of 5th North American Green Roof Conference: Greening Rooftops for Sustainable Communities.