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to
the Ecoworks Foundation, City of Portland, and Gerding Edlen:

DEVELOPING DESIGN TOOLS FOR ESTIMATING THE ENERGY AND WATER PERFORMANCE OF GREEN ROOFS

David Sailor, Mechanical Engineering, PI
503-725-4265 sailor@cecs.pdx.edu

Graig Spolek, Mechanical Engineering, Co-PI
503-725-4290 spolek@pdx.edu

David Ervin, Environmental Sciences and Management, Co-PI
503-725-3935 ervin@pdx.edu

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Overview of Progress on Green Roof Research at PSU

This project represents the major component in a growing program of funded green roof research at Portland State University. In fact, funding from the present project has been instrumental in leveraging additional resources. As a result it is useful to preface this annual progress report with a brief summary of progress in green roof research at PSU.

As a direct outgrowth of the this Green Roof Performance project, Drs. Sailor and Spolek co-authored a proposal to the recently created Built Environment and Sustainable Technologies (BEST) research center. This center was established by the Oregon legislature to build infrastructure and contribute to Oregon's economy by investing in research in the areas of renewable energy and green buildings. Our BEST proposal – "*Measurement and Modeling of Green Roof Performance Leading to the Development of an Energy Savings Calculator*" – was funded for 1 year in the amount of $75,000. While the BEST proposal was still in review we wrote a pre-proposal to the US Green Building Council (USGBC) to expand the scope of the BEST project. Specifically, the BEST project will take the model and data developed as part of our ongoing research and generate a green roof energy savings calculator applicable to US cities. The USGBC proposal expands the scope to cover many more US cities and a number of Canadian cities. The USGBC proposal also includes collaborators at University of Toronto and the industry trade organization – Green Roofs for Healthy Cities. As part of this collaboration, the USGBC project would conduct an intercomparison and validation between two green roof energy models – the EnergyPlus-based model developed by Dr. Sailor during the past few years and an empirically-based model developed by a collaborator (Brad Bass) at the University of Toronto.

Shortly after learning that our BEST proposal was successful the USGBC accepted our pre-proposal and invited us to submit a full proposal. That full proposal (for $150k of USGBC funding) is currently in review and we should receive notification of the outcome by August 1, 2008.

Project Objectives

In the current project we proposed to develop a framework to evaluate the energy savings and rainwater discharge characteristics of green roof designs as a function of soil composition, plant selection, and environmental factors. Specific tasks outlined as part of our initial proposal include:

1. implement a green roof module in an existing building energy simulation program
2. gather data necessary to parameterize the model and validate its performance
3. conduct a comprehensive suite of green roof simulations exploring multiple factors in green roof implementation and design
4. identify the construction, operation and maintenance costs and energy saving and other potential benefits of various green roof designs.

As of the writing of this second annual report the research team has completed the first task and made significant progress toward the second and third tasks. The second task can be divided into three subtasks (a) gathering field data; (b) soil media measurements; and (c) laboratory test facility (wind tunnel) apparatus. We have gathered field data from several studies across N. America and gathered 12-months of our own measurements on the Broadway Housing Building at Portland State University. We have also gathered laboratory measurements of soil media properties and conducted an initial suite of laboratory measurements with the environmental wind tunnel apparatus. The simulation findings will be used in conducting the economic analysis of alternative green roof designs in task 4.

Task 1 – The ecoroof (green roof) module

Starting with the initial EPA-funded effort to develop the framework of the model we used resources in the current project to finish the development of a baseline version of the green roof module. The U.S. Department of Energy has included this preliminary version of the Green Roof module starting with their April 2007 release of EnergyPlus v2.0. In addition to undergoing a peer review within the Department of Energy, this modeling approach was recently published in an external peer-reviewed journal article (Sailor, 2008).

We are currently developing further refinements and extensions to this module which we will likely incorporate in a future release of EnergyPlus. As discussed below, the data that we have gathered both in field measurements and in the lab will aid us in fine tuning our parameterizations for moisture transport within the soils and for assessing the total stomatal resistance of various common green roof plants.

Task 2a – Data gathering: Field Measurements

Near the beginning of this project we established a weather station on the Broadway Housing building on Portland State's campus. This 10-story building has an extensive green roof which uses a pumice-based soil and a variety of bunch grass and sedum plantings. Prior to the start of this project Dr. Spolek had installed sensors that enable the determination of stormwater discharge quantity, roof deck temperatures, and heat flux through both the green roof and a small control section of more traditional built-up roofing. (Spolek, 2007a; Spolek, et.al., 2007b)

In the summer of 2007 Dr. Sailor installed a weather station on the Broadway building complete with sensors for atmospheric temperature, humidity, wind speed, wind direction, solar radiation, precipitation, and barometric pressure. In addition, this weather station logs soil temperature and moisture at two depths as well as the leaf wetness. These data are sampled in 30-minute intervals and the data are downloaded via a remote radio connection. These data in combination with the heat flux and water discharge data will form the basis of an extensive dataset for further testing and validation of our green roof building energy simulation module. They will also provide a useful resource to others in the research community interested in modeling the energy and stormwater performance of green roofs. At the present time we have 12 full months of data (July 2007- July 2008) from this weather station (See **Figure 1**).

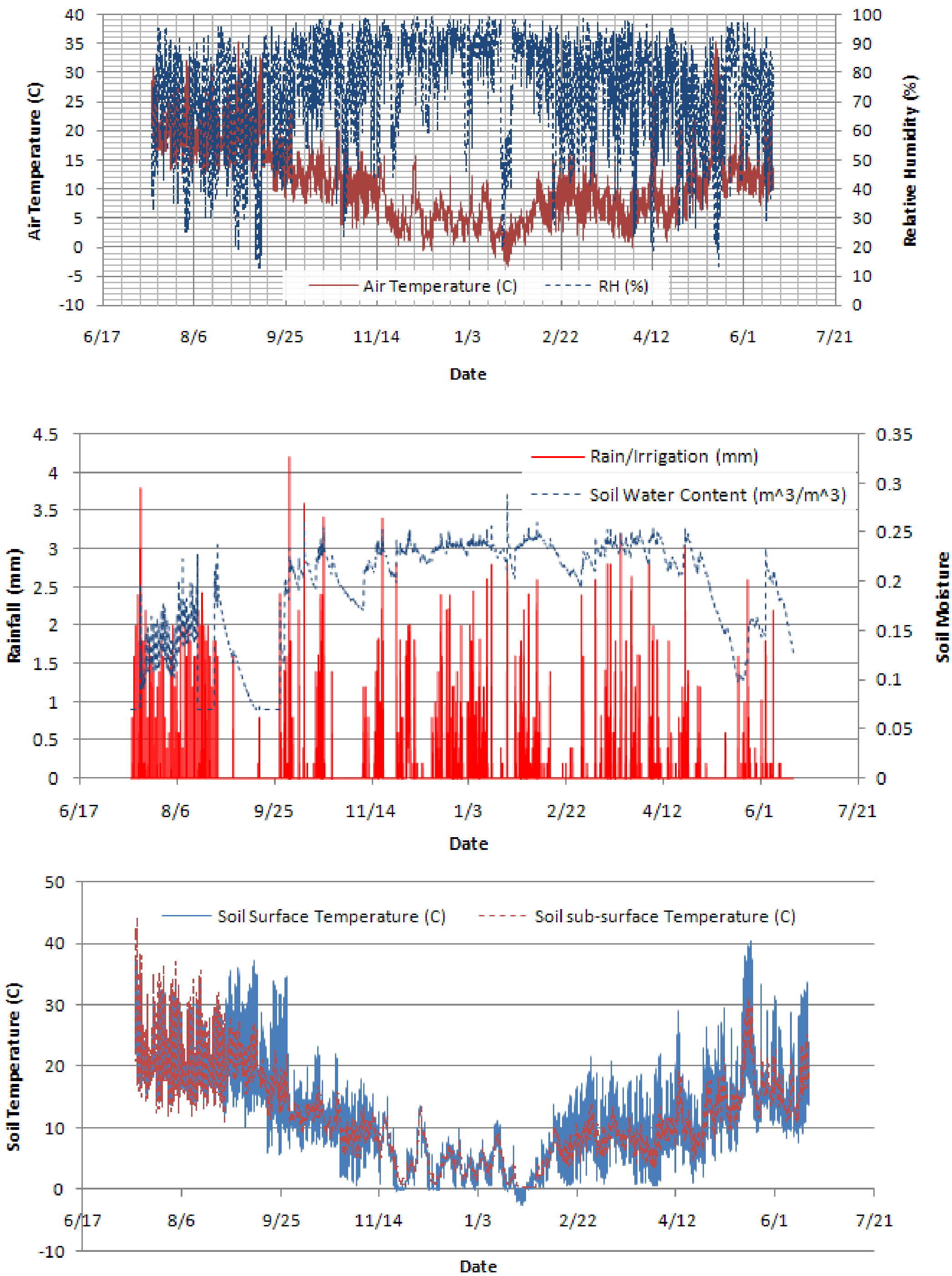

Figure 1. Representative data from the Broadway Housing Building green roof data collection effort at Portland State University. The period of the data is from July 2008 through July 2008 (data collection is ongoing).

Task 2b – Data gathering: Soil Media Measurements

Figure 2. A PSU student conducts soil thermal property measurements in the Energy and Environment lab.

As noted in last year's annual report we have begun (and now completed a suite of experiments to determine the fundamental thermal properties of a variety of green roof soils. Soils with varying composition (sand, aggregate, organic matter), and under varying moisture levels were tested in a factorial experiment design to determine density, thermal conductivity, and thermal diffusivity. The experimental process involves testing of 3 replicate samples of soil under each moisture condition. **Figure 2** shows a student conducting some of these soil property tests. This data gathering effort was initiated with prior EPA funding, but concluded under the current project. The results have now been published in the peer-reviewed literature (Sailor et al., 2008). In this past year we received additional samples of green roof soil media materials which we will be testing soon and adding to our database of green roof material thermal properties.

Task 2c – Data gathering: Laboratory Test Facility

Measurement of green roof heat transfer

If a green roof provides an energy benefit for the roof, it does so through the insulating effect of the soil, the insulating & shading effects of the plant canopy, and evapotranspiration of the plants and soil. While these are readily identified mechanisms, the magnitude of the overall effect is not generally known. Hence, basic experiments to measure the heat flux through a green roof, under controlled conditions, are performed to allow calculation of the overall steady-state thermal resistance, the R-value.

The basic method employed is to measure directly the heat flux through a green roof as it is exposed to outdoor conditions representative of the local climate. A laboratory facility has been designed and constructed that can continuously expose a green roof to constant temperature, wind speed, humidity, and sunlight. The design and construction of that facility were described in detail in the 2007 Annual Report. For review, the main features are:

- Green roof plant trays are 2’ x 2’ each, and two trays are accommodated simultaneously to provide average data for two replications. Tray height extensions allow for soil depth of either 2-3” or 6-7”.
- Plants are exposed to ambient temperature controllable between 75F and 140F
- Plants are exposed to ambient relative humidity between 10% and 50%
- Wind is speed is held constant at about 5 mph
- Simulated sunlight of about 100 W/m^2 at soil surface is supplied.
- The green roof bottom is exposed to constant cold temperature simulating indoor conditions.
- Irrigation supplies constant water to plants and soil evapotranspiring.
- Basic instrumentation includes:
  - Temperature – Type T thermocouples are used to measure air temperature on the hot side (green roof) and cold side. Hot side thermocouples are protected by radiation shields.
  - Relative humidity – Thin film capacitance relative humidity sensors are suspended in two locations above the green roof.
  - Heat flux – Thermopile heat flux meters are mounted on the surface between the hot side and cold side, located in the center of each green roof tray to measure basically one-dimensional heat transfer. By measuring the heat flux Q and the temperature difference $\Delta T = (T_{hot}-T_{cold})$ across the green roof, the steady state R-value is calculated from the relationship $R = \Delta T/Q$. Thermal resistance of the wind tunnel floor is measured separately and subtracted from the measured value, yielding the R-value for just the green roof alone.

Measurement of green roof rainwater retention

One of the main advantages of a green roof is its ability to retain rainwater, which is subsequently utilized by the plants, evaporated from the soil surface, or is discharged onto the storm drain. The amount of discharge can be reduced and its timing may be delayed in time, potentially allowing for discharge surges from open surfaces to clear the sewer before the green roof discharge enters, thereby reducing peak discharge and reducing the peak system capacity required. When rainwater flows freely over an open roof surface, it may pick up and transport solids such as dust and pollen into the storm sewer. But green roof drainage may also leech out other chemicals as it traverses the soil bed. These parameters of green roof discharge, rainwater retention and discharge water quality, were measured using the facility described in detail in the 2007 Annual Report. For review, the basic method simulates using an array of nozzles to spray water onto the green roof. The rain flow rate, along with its duration, is controlled and measured. Discharge water collection monitors both quantity and timing, and is retained for laboratory analysis for suspended solids, nitrate nitrogen, phosphorus, and metals (As, Cd, Cr, Cu, Pb, Zn).

Green Roof Construction

For our experiments green roof sections were created in special-purpose trays designed to fit the wind tunnel. Each tray allows for easy and repeatable measurement of heat flux and runoff water drainage, while allowing for use of conventional green roof construction materials. Trays accommodate soil depths from 2.5" – 6.5" with typical drainage layers and water retention pads. All tests have employed 2.5" of Pro-Gro intensive roof top media laid over a Henry DB-50 drainage mat, using four different plants: Sedum, Vinca (periwinkle), Clover, and Ryegrass; bare soil has been tested, as well, to serve as a control. All plants are grown in a commercial greenhouse, moved to the green roof laboratory during testing, and then returned to the greenhouse.

Results - Energy

A summary of preliminary results for steady-state R-values (ft^2 hr ºF / Btu) is listed in Table 1. All results listed are compiled based on a total of 57 separate experiments, providing replication and allowing reporting of average values. The overall average R-value for all tests was 2.4 ft^2 hr ºF / Btu. For a roof built to the R-19 building code, addition of a green roof with this R-value would add about 13% additional thermal insulation, on average.

As seen in Table 1, soil depth appears to have little effect on R-value while plant type does effect the R-value. The measured increase in R-value for Vinca or Ryegrass, when compared to bare soil, is statistically significant at P = 0.95. This implies that the insulating effect of the plants themselves is strong when compared to the effect of soil alone. The measured difference between Vinca and Sedum arose due to enhanced evapotranspiration from a leafy plant like Vinca. This result is borne out by two other trends observed from the entire data set:

- R-value increases with higher ambient temperature. Evaporation rate increases with higher vapor pressure, which depends on temperature. So the insulating benefit of green roofs would be greater for warm climates.
- R-value decreases with higher ambient relative humidity. Evaporation rate depends on the difference in vapor pressure between plant surface and surrounding air, which is indicated by relative humidity. So the insulating benefit of green roofs would be lower for humid climates.

Table 1. Average R-values (ft^2 hr ºF / Btu) for different green roof plants and soil depths.

Plant	R-value
Vinca	3.2
Clover	2.2
Ryegrass	3.0
Sedum	1.8
Bare soil	1.7

Soil Depth	R-value
2"	2.7
6"	2.2

Results – Rainwater Retention and Quality

Water retention rates by green roof trays tested thus far are similar to those reported for field studies, with 22% - 62% being retained by the green roof, depending on the rainfall intensity and soil depth; see Table 2. Retention of low intensity events is typically greater than that for high intensity events, whereby the soil rapidly saturates and loses capacity to store or significantly evaporate water. Lag time lag, as listed in Table 2, is the time between the center of the rain event and the discharge time centroid (half before and half after). Measured time lags appear to be on the order of several minutes, ranging from about 12-24 minutes. The effect of plant type on these results appears to be small.

Table 2. Average rainfall retention and lag time for all tests

	Heavy Rainfall (13.3 in/hr)		Light Rainfall (1.0 in/hr)	
	2” Soil Depth	6” Soil Depth	2” Soil Depth	6” Soil Depth
Retention (%)	22	55	33	62
Lag Time (min)	11.9	12.4	18.8	23.6

Water quality shows some variation by plant type, as shown in **Figure 3** for a green roof with six-inch depth. In general, both clover (CL) and sedum (SH) tend to have similar results as for bare soil (BS) while ryegrass (RG) and vinca (VI) are lower.

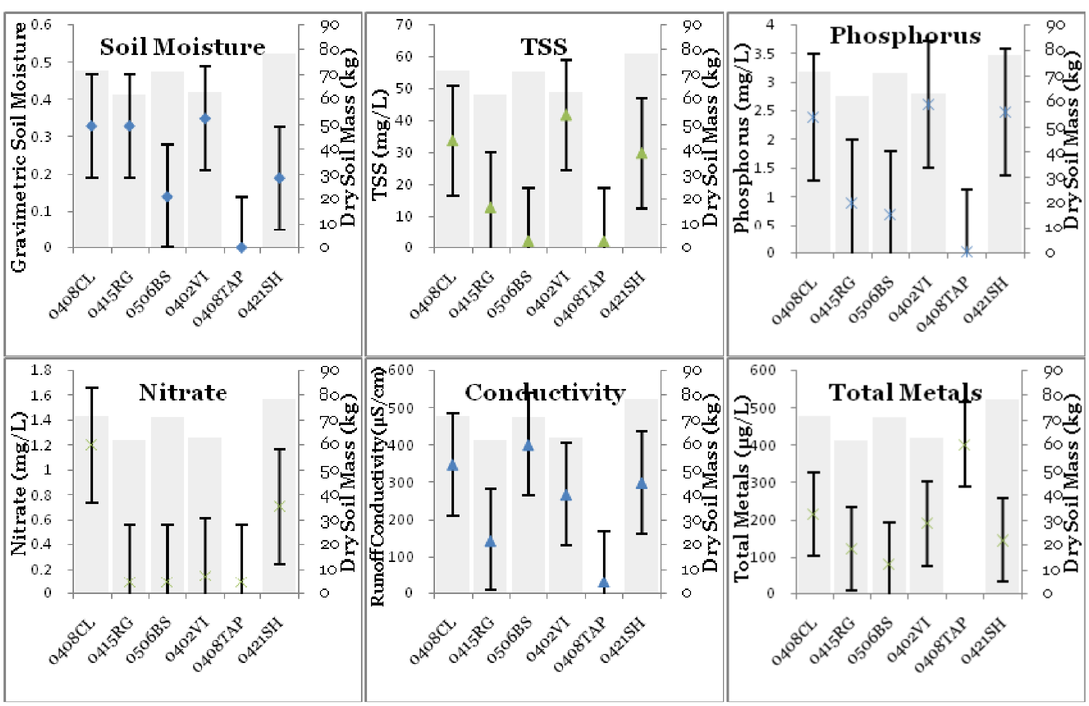

Figure 3. Measured nutrient and metal concentrations for different green roof plants with soil depth of six inches.

Detailed Results

Complete results for all tests, segregated for plant type, soil depth, and initial soil moisture, are being compiled in two master's theses. Harriet McDonald's masters thesis focuses on energy results and will be completed in December, 2008. Norman Buccola's masters thesis focuses on stormwater discharge quantity and quality and will be completed in August, 2008.

Task 3 – Green Roof Energy Simulations

As a first step toward understanding the role of green roof design options in affecting energy consumption we have designed a parametric study focusing on 4 cities – Phoenix, Houston, Portland, and New York. These cities represent a range of hot/mild and arid/humid climates. For each city we have defined 4 general building types – tall & short office and tall & short mullti-family residential. The test matrix of building types is summarized in Table 3.

Table 3. Test matrix of building types for parametric tests of green roof energy performance.

CITY/CLIMATE		
	Hot	**Mild**
Arid	Phoenix	Portland
Humid	Houston	New York City
TYPE/HEIGHT		
Office	Short (2 stories)	Tall (8 stories)
Residential	Short (2 stories)	Tall (8 stories)
SIDE LENGTHS (m)		
Short buildings	15,30,45,60,75	
Tall buildings	30,45,60,75,90	

For each of the 80 building type/city combinations we decided to run 7 distinct roofing options. These include a black roof (solar reflectivity of 10%), a white "cool" roof (solar reflectivity of 65%), and 5 variations on a green roof as illustrated in Table 4.

Table 4. Test matrix of green roof design options.

Green roof design	Leaf Area Index (LAI)	Soil Depth (cm)
Base	2	15
High LAI	5	15
Low LAI	0.5	15
Deep Soil	2	20
Shallow Soil	2	10

While we are still in the process of conducting these simulations and analyzing the results there are some early observations that can be made. First, as expected, the thicker soils are generally (but not always) resulting in lower energy consumption due to their insulative effects. Also, the relative lushness of green roofs is an important determinant of energy performance. A somewhat unexpected result is that the size of the building is also an important determinant in the energy performance of a green roof. This is in part due to the role of roof vs. wall contributions to environmental loading; the effect of internal loads within the interior core of the building relative to the overall heat transfer between the envelope and the environment; and the different types and efficiencies of equipment that are installed for different size/function buildings. Overall, the results seem to indicate that in many locations a carefully designed green roof can provide summer cooling energy savings that are comparable to those of a white "cool" roof, and also provide wintertime heating energy benefits. As noted, however, we are still analyzing these results and will provide more details in the next annual report. Also, we intend to develop a journal article based on these findings.

Task 4 - Economic Analysis

Studies of the costs and benefits of green roofs were reviewed to gather the latest information on their economic effects. The costs and benefits of green roofs are segregated into either private or public as determined by the primary beneficiary or bearer of the cost. The public economic effects are included to gauge the potential payments to building owners or developers that may be offset by public benefits.

The main economic costs associated with green roofs are for construction/installation and operation and maintenance. These expenses are borne primarily by the private building owner but some are subsidized by governmental agencies. Literature reviews show the installation costs have ranged from $15 to $18 per square foot beyond the cost of a traditional roof (Acks, 2006). However, recent information suggests that the cost may have dropped during the past three years. Interviews with private contractors suggest the added cost may now be $7 to $10 per square foot (Wayburn, 2007). Maintenance costs are generally in the form of garden maintenance but also include irrigation and drainage equipment issues not associated with standard roofs. These costs are expected to exceed those of a standard roof by about $10 to $12 per square foot over the lifetime of the green roof, approximately 50 years, or about 150% that of a standard roof (Kats, 2003). However, the average annual maintenance costs may actually be equal to or less than that of a standard roof when the longer life expectancy of a green roof is considered. Direct public costs of green roofs are generally only those associated with the administration of promotional programs but can also include subsidizing construction. These latter subsidies vary widely based on the willingness of a particular municipality to cover them.

The key benefits of green roofs fall into four categories: stormwater mitigation, energy savings, urban heat island impacts and roof life expectancy. Stormwater mitigation is a public benefit that can result in substantial savings. It is estimated that a 50% green roof infrastructure in New York City would result in a saving of $18 million per year for storm-water treatment (Rosenzweig *et al*, 2006). The city of Toronto estimates green roofs could save $25 million per year in erosion damage and mitigation programs. It is also estimated that Toronto would have fewer combined sewer overflow events which would benefit the city by as much as $500,000 each year (Banting *et al*, 2005). Green roofs reduce the energy demand of a building. This savings comes primarily as a result of reduced summer cooling requirements but there is also a slight impact on the winter heating load (though this is negligible if the roof is frozen). The net result is a reduction in heating/cooling requirements of as much as 75% as documented for one test facility. Previous studies put the expected energy savings at about 2.5 Kilowatt-hours each year per square foot of green roof (Bass and Baskaran, 2003). This energy savings also translates to a carbon emission reduction of about .25 metric tons per square foot of green roof (Bass and Baskaran, 2003). Carbon emission is an externality not currently accounted for by energy pricing or regulatory policies. Therefore, the value of reduced carbon emission is counted in addition to the value of reduced energy consumption. The carbon emissions reduction is a public benefit unless policies allow building owners and developers to claim such credit in carbon trading schemes. The current price or cost of one carbon credit (one metric ton) for EU carbon allowances is about 27 British Pounds Sterling, or approximately $54 per ton (US). (http://www.pointcarbon.com). If such a similar price would aply to a US cap and trade system, the annual benefit from reduced carbon emissions would be just under $14 per square foot of green roof. The urban heat island effect can be partially mitigated by green roofs. Greening 50% of all roofs in a city is estimated to reduce temperature by 1 degree Celsius (Banting *et al*, 2005). This would likely result in a 2% reduction in cooling energy needs throughout the city (Banting *et al*, 2005). The City of Los Angeles estimates the potential savings to be $100 million per year and a peak electricity demand reduction of 720 megawatts (Kats, 2003, City of Los Angeles, 2006). Carbon offset value would be present in this scenario as well The expected life span of a green roof has been asserted to be about 50-100% longer than that of a traditional roof (Lee, 2004; several sources make this claim but empirical data to support it are not available). This savings alone, if empirically supported, could provide enough incentive to influence most builders to consider green roofs as a viable option. Maintenance costs are distributed over the expected life of the roof. Given that green roof maintenance costs are 150% that of a standard roof but the life span is also expected to be 150-200% that of a standard roof, it is likely that the amortized expenditures approach parity. Other potential benefits of green roofs, such as air/water quality improvements, commercial crops, wildlife habitat, recreational areas, improved esthetics and an overall improved sense of wellbeing clearly exist but credible monetary values have not yet been established. These values will be described quantitatively in the economic analysis.

Green-Roof Cost and Benefit Typology

The first phase of the economic analysis identified the potential costs and benefits of alternative green-roof designs based on reviews of the literature and expert interviews. The following outline gives a comprehensive typology of private and public economic effects. Both private and public effects are included for completeness, but the modeling analysis will only use the private values.

Typology of Economic Effects

1. Cost
    a. Private
        i. Installation
            1. Labor
            2. Materials
                a. Roof Construction
                b. Soil
                c. Irrigation system
        ii. Maintenance
            1. Plants
            2. Repairs
            3. Irrigation
        iii. Administrative
            1. Design costs
            2. Legal and insurance, e.g., added liability
    b. Public (Government or others)
        i. Administrative, e.g., permitting
        ii. Direct payments (subsidies) to developer

2. Benefits
    a. Private
        i. Energy Savings
            1. Reduced usage; incorporate time of day rates if available
        ii. Government fee reductions, e.g., lower stormwater discharges
        iii. Plant Sales, e.g., crop propagation
        iv. Owner or Occupant Satisfaction
            1. Aesthetics
            2. Recreation value
        v. Lower Vacancy Rate (due to increased rental demand)
        vi. Resale Value (a benefit or a cost depending upon the market)

    b. Public
        i. Energy (savings in peaking capacity; not applicable for single roof)
        ii. Stormwater Runoff
            1. Reduced infrastructure, e.g., Combined Sewer Overflow
            2. Buffering pH: Surface Water Conditions
        iii. Reduced Heat Island Effect
        iv. Lower Carbon Emissions

Green-Roof Economic Model

The second phase constructed a protoype cost-benefit model that compares the two streams of values to inform private decisions on various green roof designs. The Excel spreadsheet model (**Figure 4**) portrays the quantifiable costs and benefits for a conventional (baseline) roof and a specified green roof design in selected years. The user could replace the conventional roof with a 'cool ' or other roof configuration to alter the baseline for comparison. The 'Meta' tab shows the assumed values for energy, water, economic rates and other inputs and their sources used in the model computations.

	Green Roof	Conventional	Difference			
Installation Cost	55000	20000	35000			
Replacement Cost	0	41876	41876			
Annual Maintenance Cost	800	400	400			
	Discounted (Present) Value of Roof Costs in Selected Years					
	Year 1	**Year 5**	**Year 10**	**Year 25**	**Year 50**	**Total**
Green	$55,000	$693	$600	$390	$190	
Conventional	$20,000	$347	$300	$9,952	$95	
	Discounted (Present) Value of the Benefits and Costs of a Green Roof over a Conventional Roof in Selected Years					
	Year 1	**Year 5**	**Year 10**	**Year 25**	**Year 50**	**Total**
Benefits	$2,600	$2,261	$3,523	$1,299	$10,963	
Costs	$35,988	$810	$600	-$9,367	$1,849	
Net	**-$33,388**	**$1,451**	**$2,922**	**$10,665**	**$9,114**	

Figure 4. Excel spreadsheet model for green roof economic effects.

The assumptions used in formulating this model are summarized in **Figure 5**.

Category	Value		Data Source
Energy and Water			
Green Roof			
Initial Cost Per sq-ft	$28	per sq ft	Industry Data 2007
Annual Irrigation Water Consumption	50	1000-gal/yr	Calculated
Irrigation Time Duration	2	yr	LEED
Storm Water Retention per unit	5.00	1000gal/area	Calculated
Reduced Electricity Consumption kWh per unit		kWh	Calculated
Reduced NG Consumption therms per unit		therms/Load	Calculated
Conventional Roof			
Initial Cost Per sq-ft	$10	per sq ft	Industry Data 2007
Annual Irrigation Water Consumption	0	gal/yr	Baseline
Irrigation Time Duration	0	yr	Baseline
Storm Water Retention per unit	0.00	vol/area	Baseline
Reduced Electricity Consumption kWh per unit	0.000	kWh	Baseline
Reduced NG Consumption therms per unit	0.00	therms/Load	Baseline
Maintenance and Replacement			
Green Roof			
Annual Labor cost	$20	$/hour	Estimated
Annual Labor time	40	hours	Industry Data 2007
Lifespan	50	years	Industry Data 2007
Conventional			
Annual Labor cost	20	$/hour	Estimated
Annual Labor time	20	hours	Industry Data 2007
Lifespan	25	years	Industry Data 2007
Economic Data			
Discount Rate (real)	0.06		User Chosen
General Inflation Rate	0.03		User Chosen
Energy Inflation Rate	0.05		User Chosen
Energy and Water Prices			
Commercial Electricity Price	$0.090	$/kWh	EIA 2007
Residential Electricity Price	$0.097	$/kWh	EIA 2007
Water Rate per 1000 Gallons	$2.77	$/1000 gal	PWB
Commercial Gas Price	$1.17	$/Therm	EIA 2007
Residential Gas Price	$1.34	$/Therm	EIA 2007
Stormwater Mitigation Value	$0.50	$/1000 gal	Estimated
R-Value to kw			Calculated
R-Value to therm			Calculated
Carbon Dioxide Emissions Factors			
Electricity Carbon Emission Factor	1.535	lbs CO_2/kWh	EPA 2006
Gas Emission Factor	116.97	lbs CO_2/MMBtu	EPA 2007
CO_2 Equivalents			
Annual CO_2 sequestration per forested acre	8,066	lbs CO_2/year	EPA 2004
Annual CO_2 emissions for "average" passenger car	11,470	lbs CO_2/year	EPA 2004
Geographic Areas	Coastal		
	Desert		
	Great Lakes		
	Northeast		
	Pacific NW		
	Midwest		
	South		

Figure 5. Assumptions used in the green roof economic impact spreadsheet model.

Inputs

The model requires two general types of inputs: (1) the physical dimensions and energy and water performance of the roofs, and; (2) the applicable economic values. The model user first enters the area of the green-roof in square-feet and the depth of the soil in inches. The soil depth translates into an effective R-value of the insulating properties of the soil. The user is able to select the desired soil from a drop-down menu under construction to evaluate the relative performance of different soils. The resulting R-value is used to calculate the expected savings in electrical and/or natural gas (NG) costs. The conversion factor is based on laboratory calculations conducted by Professor Sailor and the engineering graduate research assistants on the green roof project team. This factor is multiplied by the cost of electricity and/or natural gas as entered in the Meta data section of the worksheet. The electricity and natural gas costs shown in **Figure 5** are national averages but the user can insert local energy market prices. The initial costs of construction for both a green-roof and a conventional roof are also calculated based on the area of the roof. The national average construction costs can be regionalized by the user by selecting from a group of areas/cities on a drop-down menu (under construction).

The user may enter values for the discount rate, general inflation, energy inflation rate, stormwater mitigation values, and other government payments for their situations. 'Stormwater values' are the payments made by a municipality to the owner of a building to reward the stormwater mitigation properties of the roof, e.g., decreased runoff rates and volumes. The "other payments" section is for items such as the market value of a Floor-Area-Ratio (FAR) increase for green roof buildings or other types of transfers to the building owner. This section could also be used to capture any special administrative costs such as additional permitting. A cost of this nature should be entered as a negative value.

The annual cost of irrigation water is also entered. This cost is based on the total amount of water needed to properly irrigate a green roof of the entered dimensions. The dollar value is based on volume of water needed by standard green roof vegetation in a typical weather year. LEED building requirements call for the removal of irrigation equipment at the end of the second year. Therefore, the cost of irrigation is not considered here beyond year two. However, this can be extended to the full life of the building if the developer or owner wishes to consider that option.

Results

The results section presents calculated values driven by the user-inputted data. The first part contains the installation/construction cost of both roof types and a column that shows the difference in the initial investment for the construction costs. The replacement cost is based on data that shows a green-roof will have a lifespan of fifty or more years and a conventional roof requires replacement after twenty-five years. The replacement cost is based on the initial construction cost inflated at the general rate over a twenty-five year period. Annual maintenance cost is based on a labor rate of $20/hour and assumes 20 hours per year for a standard roof and 40 hours per year for a green roof (Lipton, personal communication).

The next part “Discounted (Present) Value of Roof Costs in Selected Years” presents the total of construction, maintenance and replacement costs of the green and conventional roofs in selected years (1, 5, 10, 25 and 50). Each annual cost is discounted to the initial period to put it on an equivalent basis for present period comparisons. The largest annual costs are incurred in year 1 for construction materials and installation expense. The conventional roof also has a sizeable cost in year 25 when it is scheduled for replacement. The final column shows the present value of the total costs for each roof type over the 50 year analysis period.

The final section compares the benefits and costs of installing a green roof over a conventional roof in selected years under the assumed values specified in the ‘Meta’ sheet. The potential benefits include the sum of payments for stormwater mitigation, electrical energy savings, natural gas (NG) savings, and other values, such as a FAR bonus. The costs cover the differences in construction, maintenance and replacement expenses for the two roofs in the selected years. The various benefits and costs in the selected years are calculated by applying the general or energy inflation rate as appropriate and discounted by the assumed discount rate. The final row shows the net value of the difference in the present value of benefits and costs for the roofs in selected years. Negative values reflect an annual loss for constructing a green roof in that year, and a positive value reflects a gain over a conventional roof in that period when accounting for inflation and the time value of money. The final column (to be computed) shows the total present value of benefits and costs and the net difference for the two roofs under comparison. Note that the net in this example is highly negative in year 1 reflecting the additional construction costs for a green roof but becomes positive and larger over time. The sum of net present values over the 50 years (under construction) is the standard economic benefit-cost decision rule.

This prototype spreadsheet model is being refined by adding the drop-down menus for soil type, regions, etc. When complete, it will be tested with a set of green roof design alternatives for different regions, including soil depth, plant cover and irrigation options, and alternative assumptions about the time patterns of construction cost, energy inflation, general inflation and stormwater and FAR payments.

Student Assistants

In the second project year the grant has supported 4 graduate research assistants, who have received matching tuition waivers from the PSU administration. These students are Norman Buccola and Debbie Beck in Environmental Engineering, Harriet McDonald, and Vishal Sharma in Mechanical Engineering, and Paul Hendricks in Environmental Sciences and Management. We have also used grant resources to support the hourly assistance of several students – John Maidoff, Brian Frasnelly, and Seth Moody (both from Mechanical Engineering). In addition we have started to use resources from the BEST funding to support two students to supplement the modeling efforts – Tim Elley a Mechanical Engineering MS student and Max Gibson, a Mechanical Engineering undergraduate. Most of Mr. Elley's funding actually has come from a Maseeh College Fellowship.

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