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Life-cycle cost–benefit analysis of extensive vegetated roof systems

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Abstract

The built environment has been a significant cause of environmental degradation in the previously undeveloped landscape. As public and private interest in restoring the environmental integrity of urban areas continues to increase, new construction practices are being developed that explicitly value beneficial environmental characteristics. The use of vegetation on a rooftop—commonly called a green roof—as an alternative to traditional roofing materials is an increasingly utilized example of such practices. The vegetation and growing media perform a number of functions that improve environmental performance, including: absorption of rainfall, reduction of roof temperatures, improvement in ambient air quality, and provision of urban habitat. A better accounting of the green roof's total costs and benefits to society and to the private sector will aid in the design of policy instruments and educational materials that affect individual decisions about green roof construction. This study uses data collected from an experimental green roof plot to develop a benefit cost analysis (BCA) for the life cycle of extensive (thin layer) green roof systems in an urban watershed. The results from this analysis are compared with a traditional roofing scenario. The net present value (NPV) of this type of green roof currently ranges from 10% to 14% more expensive than its conventional counterpart. A reduction of 20% in green roof construction cost would make the social NPV of the practice less than traditional roof NPV. Considering the positive social benefits and relatively novel nature of the practice, incentives encouraging the use of this practice in highly urbanized watersheds are strongly recommended.

Keywords: Green roof; Green building; Cost benefit analysis; Best management practices

1. Introduction

The relationship between the built and natural environment has traditionally been one of complete opposition. Both terrestrial and aquatic ecosystems are drastically, and often times irrevocably, altered during the process of urbanization (Pickett et al., 2001; Paul and Meyer, 2001). Water regulation and supply, erosion control and sediment retention, nutrient cycling, climate regulation, and waste treatment changes are all ecosystem services either eliminated or significantly degraded in highly developed landscapes (Costanza et al., 1997). The construction of man-made structures and impervious surfaces that are a defining feature of highly developed areas are an important causal element behind environmental decline in urban areas (Arnold and Gibbons, 1996).

One reason why construction practices lead to environmental problems is that the costs of environmental degradation are not fully realized by the party who caused the damage. Thus, when evaluating construction costs, developers have historically viewed environmental damage as exogenous to the development process. Federal and state environmental laws have altered this situation to some extent in the last several decades. Developers have been limited by laws and regulations concerning erosion and sedimentation control, post-construction stormwater control and urban tree preservation. Nonetheless, developers still make land use decisions without considering the full cost of the environmental damage that their activities create.

Positive incentives have been developed for more ecologically sensitive development, particularly for buildings. A rating system called leadership in energy and

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environmental design (LEED) has been created by the United States Green Building Council for certification of commercial buildings that have a reduced environmental impact. As of 2005, 393 projects had received LEED certification and many municipalities require buildings built with public funds to receive LEED certification (Cassidy, 2003). Other organizations such as the National Association of Home Builders have recently developed green building guidelines based on similar standards (NAHB, 2004).

Specific building construction practices are being refined to create structures which have a much smaller impact on the surrounding landscape than previously thought possible. At the broadest scale, sites are selected for their proximity to public transportation, their ability to maximize open space and protect habitat, effectively manage stormwater runoff, address the heat island effect found in urban areas, and reduce light pollution (www.usgbc.org). Sustainable water use for a building may involve xeriscaping, graywater reuse for irrigation, and the use of low-flow or composting toilets and non-water urinals, which are becoming increasingly cost effective (Gleick, 2003). A building's energy use is also an extremely important component of sustainable design. From simply designing smaller structures to installing active solar panels or other on-site sources of self-supplied energy, there are a wide range of practices available to reduce a building's reliance upon fossil fuel energy sources. Increasingly, building materials contain recycled material content in new construction and attempt to reuse as much of the existing structure in renovations as possible (Horvath, 2004). Indoor environmental quality is also an important feature of green buildings. Paints and adhesives designated "Low-VOC" or "No VOC" (volatile organic compounds) reduces the low level toxic emissions found in older materials and improves indoor air quality for building occupants. Day-lighting larger portions of the structure improve he working environment in commercial buildings as well as reducing energy costs when high performance windows are used.

1.1. *Designing rooftops for sustainability*

Of these many ways that buildings can be designed and constructed in a more sustainable manner, the roof surface can easily be overlooked as space that can be designed into an environmental amenity for the building, not simply contributing to environmental problems. The rooftop is typically the same size as the building's footprint and is the structure's prime barrier against precipitation and solar radiation. To the extent that the roof surface can be transformed into useful space, the building becomes economically and functionally more efficient and can have a more benign effect on the surrounding landscape.

Published research has focused largely on the energy savings associated with different types of roofing systems. Akbari et al. (2001) found that changing a roof from one with low albedo to high albedo in Sacramento, CA would decrease cooling energy use by 80%. Other studies have documented the affect of insulation on the heat flux at the roof surface (Al-Sanea, 2002), how to incorporate active and passive solar designs into rooftop systems (Heras et al., 2005; Maneewan et al., 2005), and the energy benefits associated with ventilated roof systems (Ciampi et al., 2005). These alternatives to traditional roofing systems are beginning to gain more of a market share and EPA has established an Energy Star rating system for roofing products, primarily identifying roofing membranes which have high albedos and the potential to significantly reduce building energy costs (www.energystar.gov).

While energy savings are an important function of alternative roof systems, other benefits may also be realized. In a traditional roofing system, rainfall hits the rooftop and is quickly channeled into the nearest gutter or storm sewer system with the goal being to have the roof shed water as quickly as possible. As regulations have mandated stormwater management plans for municipalities, rooftop runoff control has become an important management practice for minimizing degradation of aquatic ecosystems. One solution is to create rainwater storage tanks which can capture rainfall from the roof surface and store it for a time before it is reused or slowly discharged (Vaes and Berlamont, 2001).

1.2. *Green roofs: multifunctional roof surfaces*

The application of vegetation and growing media to the roof surface is an increasingly popular practice which produces improvements in both energy conservation and stormwater management. These green roofs are multifunctional in that they provide numerous environmental benefits simultaneously. These benefits include: decreasing the surface temperature of the roof membrane and energy use in the building (Kumar and Kaushik, 2005), retaining stormwater for small storm events (Carter and Rasmussen, 2006), increasing biodiversity and habitat in urban areas largely devoid of such space (Kim, 2004; Brenneisen, 2005), and improving ambient air quality (Clark et al., 2005). While these benefits are inherent in all green roof systems to some degree, depending on the design of the roof there is potential for other amenities as well. Accessibility and esthetic appeal for the building occupants, sound insulation and the potential for urban agriculture are all realistic benefits provided by green roof applications (Peck et al., 1999).

There are two general types of modern green roof systems: intensive and extensive. Intensive systems are characterized by deep (>6 in) growing media, opportunities for a diverse plant palate on the rooftop and high cost and maintenance requirements. Extensive systems are designed to be lightweight and easily retrofitted on existing roof surfaces. They contain thin growing media depths (2–6 in) and can support a limited number of drought-tolerant plants that thrive in the limited water and nutrient conditions. Over 80% of green roofs in Germany are extensive systems and these types of green roofs are expected to offer the most cost-effective approach for roof greening (Harzmann, 2002).

1.3. Economic analysis of green roofs

While green roof projects have recently generated significant interest in design fields such as landscape architecture, little research has been done to evaluate the costs and benefits of green roof systems for urban applications. Much of the peer-reviewed literature on the economics of green roofing systems is found in conference proceedings and evaluate the private benefits at a single roof scale. Lee (2004) compared green roof and traditional roof life-cycle costs over 60 years for a single roof in Oregon. They found the green roof to be 7% more expensive than the conventional roof over this time. This analysis included extended roof life, energy savings, and stormwater fee reduction in the economic benefits that the green roof provided. Clark et al. (2006) demonstrated a return on investment of 11 years on a single green roof in Michigan when low green roof installation costs and high environmental benefits were considered. Alternative metrics to monetary values such as Eco-indicator values and energy analysis have been used to compare green roofs to conventional roofs in a sustainability context. These studies find green roofs provide significant environmental benefit over a traditional roof relative to the life cycle and embodied energy of its materials (Alcazar and Bass, 2006; Coffman and Martin, 2004; Kosareo and Ries, 2006). Other published reports typically focus on a single green roof benefit (Wong et al., 2003) or qualitatively describe a series of benefits derived from different types of green roofs (Peck et al., 1999; Banting et al., 2005).

Benefit cost analysis has been widely recognized as a useful framework for assessing the positive and negative aspects of prospective actions and policies, and for making the economic implications alternatives an explicit part of the decision-making process (Arrow et al., 1996). Benefit–cost analysis compares alternatives over time as well as space, and uses discounting to summarize its findings into a measure of net present value (NPV) (Hanley and Spash, 1993) The test of NPV is a standard method for assessing present value of competing projects over time. In the case of this study, the roofing scenario with the lowest NPV is the preferred option as the low value indicates the least costly alternative.

This study quantifies the costs and benefits of thin-layer, or extensive, green roof systems as they compare to typical flat roofs in an urban watershed. The authors combine local construction costs for an established green roof test site with experimentally collected stormwater retention data and building energy analysis data into a single metric using conventional cost–benefit analytical techniques applied over the life cycle of a typical green roof. In order to carry out this analysis we rely in part on published data from other green roof research and practice for estimating these effects. This may introduce some bias, and indicates that this work is subject to revision as increasing experience with green roofs produces more and better data. We then use this information to evaluate an entire local watershed, using a variety of spatial scales as a case study for application of widespread green roofs. As green roof popularity continues to grow, it is important for accurate life-cycle benefit–cost analyses (BCA) of green roof systems to be performed to inform both policy makers who may allocate public funds for projects with public benefits, and private building owners who may see a future financial incentive to invest in new and relatively unproven technology.

2. Materials and methods

2.1. Project site and test plot

The project examines the feasibility of replacing all the flat roofs in an urban watershed with green roof systems. The Tanyard Branch watershed was selected as a study site. This highly urbanized watershed contains a second-order stream system and is located in Athens, GA approximately 60 miles east of Atlanta, GA. The watershed contains significant portions of the downtown commercial district of Athens, the University of Georgia, and both single and multi-family residential areas. Using 2003 aerial photography, the impervious surfaces including rooftops were digitized into a geographic information system (GIS). About 53.8% of the land cover is impervious surface with rooftops accounting for 15.9% of the total land cover in the watershed (Fig. 1). The Tanyard Branch creek is listed as not meeting its designated use due to elevated fecal coliform counts with the cumulative effects of urbanization in the watershed cited as the cause of this degradation (Herbert, 2003). Flat roofs are the most viable candidates for greening as they often require no additional structural support and minimal design expertise for green roof installation (Banting et al., 2005). Flat roofs constitute 176,234 m^2 or 7.4% of impervious surface in the watershed (Fig. 2).

A 42.64 m^2 green roof test plot was established in October 2002 on the campus of the University of Georgia (Fig. 3). The test plot was designed to be simple to build and easy to replicate using American Hydrotech's extensive garden roof. American Hydrotech, Inc. is a single source supplier for the specialized green roofing materials. These materials included a WSF40 root protection sheet, an SSM 45 moisture retention mat, a Floradrain FD40 synthetic drainage panel, and a Systemfilter SF geotextile filter sheet (American Hydrotech, 2002). The growing media was a Lightweight Roof Garden mix provided by ItSaul Natural, LLC. This soil mix is a blend of 55% Stalite expanded slate, 30% USGA sand, and 15% organic matter composed primarily of worm castings. This mix was spread to a depth of 7.62 cm. Six drought-tolerant plant species were selected for their ability to survive low nutrient

Fig. 1. Tanyard Branch watershed impervious cover and stream network.

conditions and extreme temperature fluctuations found at the roof surface. No irrigation or fertilization was applied except for the initial three days of planting.

2.2. BCA framework

Green roof BCA was performed according to an 8-stage framework found in Hanley and Spash (1993). The stages are: definition of project, identification of project impacts, identification of which impacts are economically relevant, physical quantification of relevant impacts, discounting of cost and benefit flows, application the NPV test, and sensitivity analysis.

2.3. Discounting of benefit and cost flows and sensitivity analysis

The period of analysis was one green roofing cycle, which was estimated to be 40 years based on the doubling of the roof life due to the vegetated cover. Private BCA for greening a single flat roof of 929 m^2 as well as a social BCA of greening all the flat roofs in the watershed was performed. All roof greening occurred at year zero. Traditional roofs were greened at year zero and also underwent one reroofing cycle at year 20. Avoided stormwater costs were applied at year zero. Energy and air-quality benefits were applied every year of the analysis. A discount rate of 4% was applied to the reroofing scenario as well as all the green roof benefits.

3. Theory and calculation

The economically relevant impacts of widespread roof greening were established and physical quantification of these impacts were performed using the green roof test plot as a template for all new green roofs in the watershed. The benefits were divided into categories found in Table 1 with the conceptual framework outlined in Fig. 4. Analysis for the social BCA was performed at the watershed scale while a private BCA was performed using a typical one-story 929 m^2 roof. Details of each category follow below and the results are summarized in Table 2. All dollar amounts have been converted to \$2005 using the consumer price index.

3.1. Construction and maintenance

The first category deals with construction and maintenance expenses. The construction costs of a typical

Fig. 2. Rooftops in the Tanyard Branch watershed.

built-up bituminous roof system on a concrete roof deck were taken from personal interviews with three local roofing contractors and additional verification from the Means Construction Cost Data (2005). The traditional roof was assumed to have a 20-year guarantee on the waterproofing membrane and thus an effective 20-year life before replacement. The construction costs of a conventional roof were estimated to be \$83.78/m^2.

The cost estimate on the green roof was obtained from the test site as well as personal interviews with three single source green roofing manufacturers. The average cost from these sources was compiled into a unit cost estimate of for initial construction of an extensive (7.62 cm of growing media) roof system. No additional waterproofing cost was added. While each installation would not have identical costs depending on accessibility, structural integrity, and design considerations, an estimate of \$158.82/m^2 was used based on average costs from the manufacturers and the local test plot (Table 3). Maintenance on a thin-layer green roof is considered equivalent to the maintenance schedule of a traditional roof with visual inspections twice per year. Many industry groups claim green roofs can extend the life of the waterproofing membrane over 200%. This is due to the vegetation and growing media protecting the membrane from harmful ultra-violet radiation and physical damage. Since green roofs have only been used extensively in the United States in the past decade and there are few examples to verify this claim. However, engineered green roofs in Europe have been shown to function for over twice the life span of conventional roofing systems (Kohler et al., 2001). For this study, green roofs are assumed to last for 40 years—twice the life span of conventional roofs.

While the unit construction cost of \$158.82/m^2 is used for our base case analysis, this most likely is at the high end of what would be experienced for widespread green roof construction in the Tanyard watershed. It is partially based on estimates of what would be required to build an initial demonstration roof, and thus ignores economies of scale in materials purchasing as well as innovations in construction techniques developed as local contractors gained experience. Second, in Germany where the industry has been established for over 30 years, construction costs may be as much as 50% lower for larger installations (www.greenroofs.com).

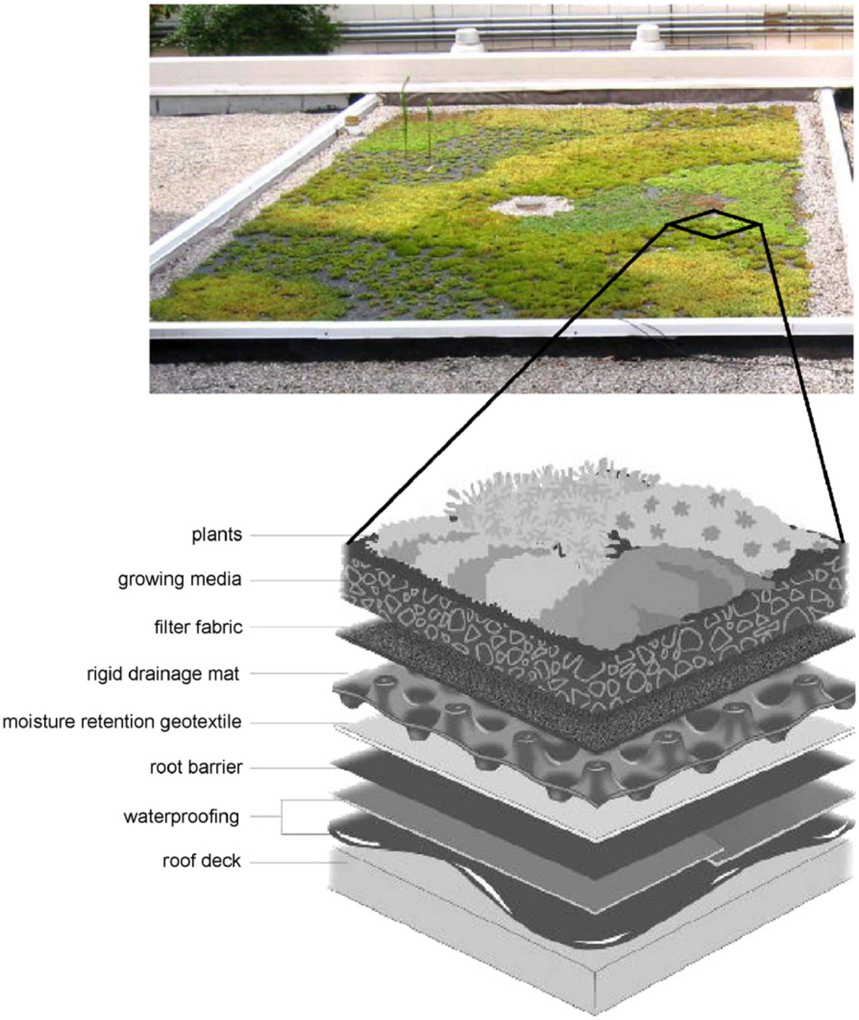


Fig. 3. Green roof test plot and layer cross-section.

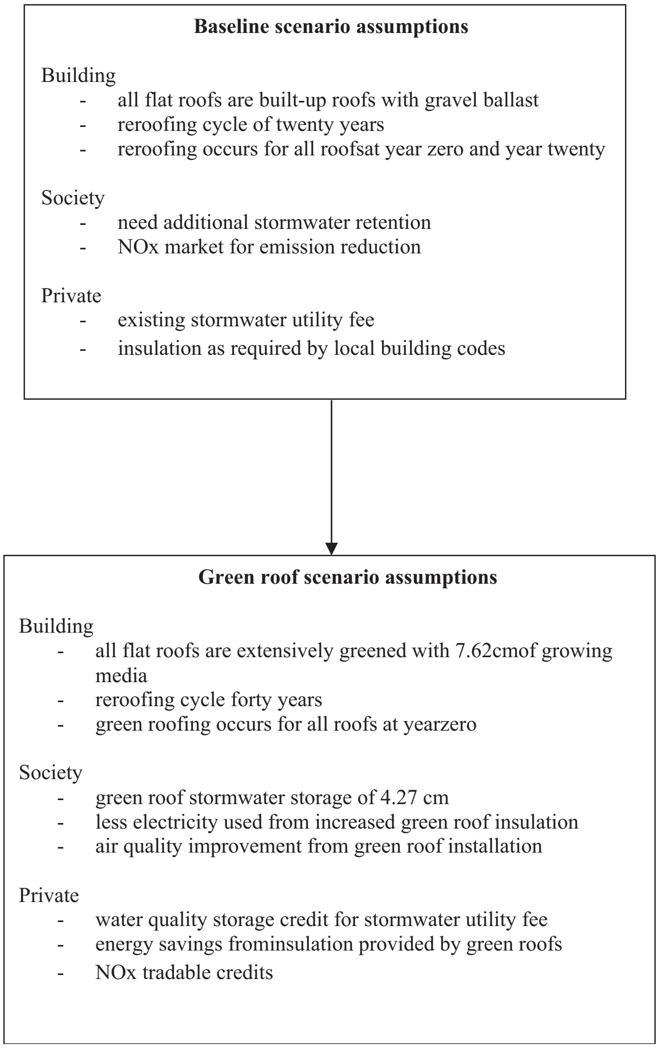
Table 1
Benefits from extensive green roof systems

Category	Benefit	Quantified?
Construction and maintenance	Double the roof life	Yes
Stormwater management	Storm sewer pipe size reduction Reduces need for alternative stormwater BMPs Stormwater utility fee reduction	Yes
Energy and insulation	Additional insulation Energy savings	Yes
Air quality	Nitrogen oxide uptake	Yes
Habitat/greenspace	Increase bird and insect habitat	No
Urban heat island	Reduction in ambient air temperatures	No

It is therefore assumed that true construction costs will vary between 50% and 100% of this initial estimate when the sensitivity analysis is performed.

3.2. Stormwater management

Stormwater management is a second economically relevant category. Under the US Environmental Protection Agency's National Pollutant Discharge Elimination System (NPDES) Phases I and II stormwater rules, jurisdictions with municipal separate storm sewer systems (MS4s) are required to develop a stormwater management program relying upon stormwater best management practices (BMPs) to control stormwater discharges. Green roofs may potentially be one of the BMPs used to accomplish the goals of this program. Green roofs have been shown to retain a significantly higher percentage of stormwater when compared to a traditional roofing system. A recent study in Michigan documented how, during medium volume rain events, a thin-layer green roof system retained 48% more rainfall than a gravel ballast roof (VanWoert et al., 2005). The local test roof was monitored for its ability to retain stormwater from November 2003–November 2004. The green roof retained, on average, more than 77% of the rainfall throughout the year with retention performance determined primarily by total storm



Baseline scenario assumptions

Building
- all flat roofs are built-up roofs with gravel ballast
- reroofing cycle of twenty years
- reroofing occurs for all roofsat year zero and year twenty

Society
- need additional stormwater retention
- NOx market for emission reduction

Private
- existing stormwater utility fee
- insulation as required by local building codes

Green roof scenario assumptions

Building
- all flat roofs are extensively greened with 7.62cmof growing media
- reroofing cycle forty years
- green roofing occurs for all roofs at yearzero

Society
- green roof stormwater storage of 4.27 cm
- less electricity used from increased green roof insulation
- air quality improvement from green roof installation

Private
- water quality storage credit for stormwater utility fee
- energy savings frominsulation provided by green roofs
- NOx tradable credits

Fig. 4. Modeling assumptions for private and social BCA.

Table 2
Costs and benefits per square meter of roof

	Year	Unit values (\$/m^2)
Cost		
TR construction and maintenance	0.20	83.78
GR construction and maintenance	0	155.41
Social benefits		
Avoided stormwater BMP cost	0	9.06
Energy	1–40	0.37
Air quality	1–40	0.11
Private benefits		
Stormwater utility fee credit	1–40	0.04
Energy	1–40	0.37
Air quality	1–40	0.11

Table 3
Additional green roof unit construction costs

	Cost range (\$/m^2)	Cost used (\$/m^2)
Specialized roofing material	5.92–32.61	32.61
Growing media	5.62–6.78	6.59
Plants (21 plugs/m^2)	9.69–10.12	9.69
Crane rental	14.90	14.90
Labor	7.84	7.84
Total	43.97–72.25	71.63

Table 4
Avoided cost of urban BMPs (source: EPA, 1999)

BMP	Cost (\$/m^3 treatment)	Total cost (\$) using flat green roof storage in Tanyard Branch
Bioretention area	232.37	1,752,593.21
Porous pavement	141	1,063,461.04
Sand filter	263.09	1,984,319.06
Equal distribution of the three BMPs	212.15	1,600,124.44

rainfall volume. Details from this study can be found in Carter and Rasmussen (2006).

Using the stormwater retention performance data and watershed spatial information, total additional stormwater storage from greening all flat roofs could be estimated for Tanyard Branch. The spatial analysis was done using ArcView 3.2, a commonly used GIS software package (ESRI, 1999). 2003 full color aerial photographs with 0.15 m pixel resolution were obtained from the city of Athens. From these photographs, flat roofs in the watershed were digitized at a scale of 1:500 (Fig. 2). Ground-truthing was also performed. Extensive greening provided an additional 4.27 cm of stormwater storage depth which results in total storage for the watershed of 7542 m^3. This retention data then compared with published retention and cost data from other stormwater BMPs for determining the cost for an equal amount of storage using other practices given the land cover in the watershed (EPA, 1999). Since the watershed is already highly urbanized, only BMPs which are typically used in an ultra-urban application were considered. These BMPs include sand filters, bioretention areas, and porous pavement. Depending on the type of BMP used in the comparison, different cost savings may be realized (Table 4). The avoided cost of using alternative stormwater BMPs is considered part of compliance with Phase II stormwater rules in Athens and the benefits are included in the social BCA. Analysis was run by dividing the total stormwater storage volume provided by green roofs equally among the three alternative BMPs and calculating the total cost of this alternative scenario (Table 4).

An additional private stormwater benefit for green roofs may be realized in the regulatory arena. Increasingly, jurisdictions are creating stormwater utilities, which are charge fees to parcel owners based on their parcel's stormwater contribution to the system. These utilities generate income used exclusively for stormwater management operations. Parcel owners are commonly given exemptions or credits if they can demonstrate that they are keeping their site from contributing runoff to the stormwater system. Athens has enacted a stormwater utility and incorporated a system of credits for demonstrated on-site management. With the proper documentation, green roofs are assumed to accomplish the water quantity standards required for the stormwater credit. In the case of the roofs in Tanyard Branch, this results in a savings ranging from \$0.04/m^2 to \$0.08/sm depending on building type (Table 5). Calculations were performed based on the spatial information of the buildings in the watershed. The majority of the savings came from commercial, government, and multi-family buildings with the average unit cost being \$0.04/m^2. The total value was applied to the private BCA. This is a transfer payment which does not increase social welfare and therefore is not included in the social BCA.

Another aspect of stormwater management is the drainage collection of pipes, inlets and junction boxes collectively termed the storm sewer system. Retention of stormwater before it reaches the system may result in resizing of the pipes during maintenance and repair of the infrastructure. Athens contains an MS4 and spatial data for the storm sewer system was acquired for the watershed from the city of Athens and the University of Georgia. Stormwater pipes in Athens-Clarke County are a minimum of 38.1 cm (15 in) and most are designed for the 25-year storm event, which in Athens is 15.85 cm. Pipe costs were estimated according to Means (2005) with unlisted pipe dimensions priced using the power function derived from Means (2005):

$$C = 0.6318D^{1.4086},$$

where C is the cost of pipe (\$/lf) and D the diameter of the pipe (in).

Reductions in the storm flow volumes from the watershed outfall were calculated for a variety of storm events using StormNet Builder, a comprehensive stormwater modeling package (Boss International, 2005). This study is detailed in Carter (2006). The cost savings from a reduction in pipe size was then calculated and converted to a cost per linear meter of pipe. This cost saving showed a 4.6% reduction in size for the 25-year event and a 4.4% reduction for the 100-year event. These reductions are not significant enough to result in changes in pipe sizing due to green roof implementation; therefore no economic benefit from pipe resizing was used in the analysis.

Table 5
Stormwater utility benefits by building type

Building type	Benefit (\$/m^2/year)	Total annual benefit in Tanyard Branch (\$)
Commercial	0.04	3306.65
Government	0.04	3908.66
Multi-family residential	0.04	1003.02
Single family residential	0.08	28.47
Total		7485.95

Other relevant features of stormwater management affected by widespread green roof implementation were determined not to be applicable to this particular watershed. Included in this is the effect of green roof stormwater retention on the reduction of combined sewer overflows (CSOs), a phenomenon having large environmental impacts resulting from the stormwater systems found in many larger cities. It was estimated in the city of Toronto, for example, that avoiding CSOs using green roofs would save the city \$46.6 million in infrastructure savings (Banting et al., 2005). Athens, however, has separate sewer systems for stormwater and waste water and therefore this analysis could not be performed. Also, a reduction in nuisance flooding, which is a commonly quantified through flood insurance premiums, is not appropriate for this stream system as the stream is piped or highly incised with no flood risks in the residential sections of the watershed.

3.3. *Energy and insulation*

The third economically relevant category is energy and insulation. Green roofs act to reduce the rooftop surface temperatures through leaf shading direct solar radiation, evaporation of moisture at the surface and transpiration of the plants which cool the ambient air above the roof. Thin-layer green roof systems have consistently been shown to reduce the temperature fluctuations at the roof surface (Onmura et al., 2001). Whether this translates into significant energy savings is not clear from the literature as in one study, energy use was evaluated for small experimental sheds containing green roofs and the vegetated treatments had little effect on total energy use in each structure (DeNardo et al., 2003). Other research, however, suggests that considerable energy cost savings can be realized when green roofs are used; enough for the life-cycle cost of a green roof to be less than a traditional roof when energy savings were included in the analysis (Wong et al., 2003).

For the energy-related benefits in this study, local data were used. Adjacent to the stormwater green roof test plot, a second experimental roof was constructed and an analysis of the thermal conductivity of growing media as well as energy load modeling was performed. Automated measurement of in situ micrometeorological parameters such as humidity, air temperature, windspeed, radiation, and soil temperature were combined with laboratory analysis of the engineered growing medium providing local data for simulation modeling. The simulation programs used were eQuest and HYDRUS-1D, a building energy model and a combined heat and moisture simulation, respectively. The modeled buildings used were 929 m^2 with both square and rectangular orientations. Modeling was performed at three different heights: 1, 3, and 8 stories. Additional details from this study can be found in Hilten (2005). Cost savings from the additional insulation provided by the green roof as well as the reductions in the heating and cooling loads were found for the building and converted into unit savings to be applied across the watershed. The green roof's insulating value was equivalent to R-2.8, which is similar to 2.54 cm of fiberboard, fiberglass, or perlite. These types of insulation average to \$3.98/m^2 and this value may be considered an avoided cost in the green roofing analysis. If this avoided cost is used, however, the building owner will not realize any energy savings as there is no net increase in insulation.

A more likely scenario is that the green roof will be added and provide additional insulation, not used as replacement for traditional insulation. This additional insulation value creates energy savings for the building owner. The authors used the building energy savings modeled from a single-story 929 m^2 building (Hilten, 2005). This type of building was selected because it represents the majority of flat-roofed buildings in the watershed. The energy load reduction from the green roof system was modeled at 4222.56 kWh/year. This is an energy savings of 3.3% which is less than half of the 8% used in the Wong et al. (2003) study. Residential rate surveys for the 2005 year were acquired from the Georgia Public Service Commission and the 2005 average rate of \$0.082/kWh was applied to the energy savings modeled in the building. This current price is used for the conservative base case BCA, but we believe that assuming electricity prices will remain constant in real terms over the next 40 years is extremely optimistic. Policies to limit air pollution and climate change are likely to bring about significant increases in this price. For the sensitivity analysis, it is assumed that the actual rate of increase in energy prices will vary on a uniform distribution between 0% (the base case assumption) and 8% (a pessimistic but plausible assumption under significant future environmental regulation). All buildings in the watershed were estimated to have the same energy savings, although savings may vary based on the number of stories and orientation of each structure. The unit energy savings for current energy rates was \$0.37/m^2 (Table 6).

Table 6
Energy benefits associated with green roofs

Benefit	
Building energy savings (kWh/year)	4222.56
Energy cost (\$/kWh)	0.08
Building energy savings (\$/m^2/year)	0.37
Total annual savings in Tanyard Branch (\$)	65,871.73

3.4. Air quality

A fourth economically relevant category is air quality. While the potential may be great for green roofs to improve air quality in densely developed areas, the type of vegetation found on the rooftop largely determines the amount of air-quality improvement. Trees, grasses, and shrubs both filter pollutants and transpire moisture much differently than the Sedum plant species commonly found on modern green roof applications. Cross-applying air-quality improvements from one type of green roof application to another can be very misleading. For example, air-quality benefits have been modeled for grass roofs in Toronto with the authors-finding significant economic benefits to air quality under grass roofing scenarios (Currie and Bass, 2005). The Georgia test plot, however, was designed to be simple and easily replicable using Sedum plants. These plants do not have the same leaf area index, photosynthetic activity, or growth pattern as grasses thus making this particular air-quality benefit unsuitable for this study.

Other researchers evaluated nitrogen oxide uptake made by the *Crassulaceae* plant family of which Sedum is a member (Sayed, 2001). While this CO_2 uptake is well documented, the air-quality improvements provided by the function are less certain, but basic estimates for economic quantification of these improvements are possible by including Sedum green roofs as part of a cap-and-trade emissions credit system. Using 2005 market value for NO_x emission credits of \$3375/ton, Clark et al. (2005) estimated the credit for a Sedum green roof to be \$0.11/m^2. This value was applied to the current analysis as the air-quality benefit since it was deemed more appropriate for the roof system used in this study. Both the private and public sectors benefit from this technology as green roofs reduce the pollutant loads in the ambient air of the city improving social welfare while allowing the private building owner to receive economic compensation from providing a service for industries looking to offset their polluting activities.

3.5. Unquantifiable categories

Other categories may be economically relevant in particular green roof applications, but were not included in this analysis either because of a lack of reliable data or incompatibility of the benefit with the type of green roof used in this study. Urban green space and habitat is clearly a benefit provided by green roofs and rooftop greening has been incorporated into plans to maintain urban habitat networks (Kim, 2004). Valuation of urban greenspace is typically done through hedonic analysis relating house prices to greenspace type and location (Morancho, 2003). While accessible rooftops provide the building owner or tenant with additional space for recreation or growing vegetables, the roof designed in this study does not perform these functions. The greenspace value must be derived strictly by the habitat value for biotic communities on the roofs themselves which is difficult to quantify and outside the scope of this project.

Urban centers have air temperatures higher than surrounding rural areas, a phenomenon commonly known as the urban heat island. In theory, since green roofs reduce the surface temperature of the rooftop, the ambient air temperature is lowered thus reducing the heat flow into the building and concomitant energy use needed to maintain comfortable interior building temperatures. Energy models demonstrate that widespread roof greening could lower temperatures city-wide by 0.1–0.8° Celsius, a negligible amount considering the uncertainty in the models (Bass et al., 2003). Until more robust studies demonstrate otherwise, the energy cost savings from reducing the urban heat island due to widespread roof greening will be considered speculative and not included in this analysis.

4. Results

4.1. Green roof private and social benefits

Green roof benefits were estimated for both private and social institutions. Results from these runs are shown in Tables 7 and 8. The benefits are considered conservative estimates where current pricing conditions are assumed and values base on the campus test plot are used.

4.2. Applying the NPV test

Compiling all the discounted costs and benefits associated with these two roofing systems allows for an NPV test to be performed. Using a 4% discount rate over 40 years, the total costs of installing thin-layer green roof systems on the flat roofs in the Tanyard Branch watershed are $27,451,153. The total costs of traditional built-up roofing systems the over this same time period is $21,552,206. If an equal distribution of all three stormwater BMPs across the watershed is assumed, social benefits equal $3,283,488.37 and a social NPV of $24,167,665 which is 12.14% more than traditional roofing (Table 9).

The private analysis performed on an individual roof shows NPV of green roofs to be relatively more costly for the building owner when compared with the social BCA. Private costs differ in that they include a stormwater utility fee credit rather than avoided stormwater BMP costs. This results in a total construction cost of $144,478 for green roofs and 113,353 for conventional roofs at a 4% discount rate on a 929 m^2 building. Total private benefits from green roofing for the private building totaled $9634. This is 18.87% more than typical roofing.

Table 7
Conservative green roof social benefits ($) at the watershed scale

Green roof benefit	Unit benefit ($/m^2)	4% discount rate
Avoided BMP cost	9.06	1,600,124.44
Energy	0.37	1,306,318.84
Air quality	0.11	377,046.09
Total social benefits	9.54	3,283,488.37

Table 8
Conservative green roof private benefits for a 929 m^2 roof

Green roof benefit	Unit benefit ($/m^2)	4% discount Rate ($)
Stormwater utility credit	0.04	780.80
Energy	0.37	6870.53
Air quality	0.11	1983.06
Total private benefits	0.52	9634.38

4.3. Sensitivity analysis

The NPV test was recalculated with changes to various key parameters for sensitivity analysis. Sensitivity analysis helps determine on which parameters the NPV outcomes depend the most (Hanley and Spash, 1993). The parameters were allowed to vary randomly between ranges of expected values over 10,000 trials. An average value from these trials was then calculated and compared with values found for the green roof NPV base case (Fig. 5). Sensitivity analysis was run for both the private and public green roofing scenarios.

The first parameter was the discount rate. Discount rates were modeled around the initial 4%, between the rates of 2% and 6%. Another key parameter was roof construction costs. As the industry continues to mature in North America it is likely that initial construction costs will decrease. Analysis was run with the cost of the green roofing system ranging from the existing cost to a 50% reduction in green roof construction costs. Finally, volatility in energy prices was considered with energy prices ranging from existing prices to a yearly increase of 8%.

Table 9
Comparison of green and conventional roof NPV

	Private roof ($)		Public watershed ($)	
	Conservative	Average	Conservative	Average
Green roof costs	144,378.20	108,474.13	27,451,153.64	20,624,589.43
Green roof benefits	9634.38	19,040.24	3,283,488.37	5,077,495.58
Green roof NPV	134,743.80	89,433.89	24,167,665.27	15,547,093.85
Conventional roof NPV	113,352.95	113,352.95	21,552,206.10	21,552,206.10
Green/black roof cost ratio	1.19	0.79	1.12	0.72

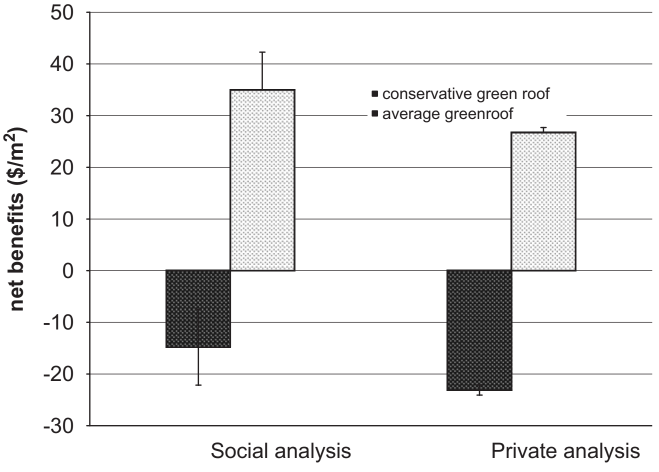


Fig. 5. Comparison of conservative and average net benefits for private and social green roofing scenarios.

Our sensitivity analysis is asymmetric, that is while discount rates vary around the central estimate, both green roof construction costs and energy costs vary only in the direction that is more sympathetic to the economics of using green roofs relative to conventional roofs. This is done because the current point estimates are in fact at the extremes. Green roofs are not going to be more expensive than our demonstration roof under conditions of dramatically increased construction, and electricity prices are not going to be lower than current prices given the expected course of environmental regulation and energy supply and demand. The assumptions used in this sensitivity analysis give a better picture of what the real economics of green roof construction are likely to be, while the base case estimate is a conservative or almost-worst-case scenario.

The results from the sensitivity analysis demonstrated that given realistic assumptions about the changes in the costs and benefits of implementing green roof systems, the average NPV of green roofs is less than the current NPV of black roofs meaning that over the roof's life cycle it is cheaper to install green roofs than their traditional counterpart. The most important parameter was the construction cost estimate, which averaged $116.76/m^2, down from $155.41/m^2. Change in green roof benefits due to increased energy prices translated into significantly more energy benefits over the life cycle of the roof, up to $17.46/m^2 from $7.32/m^2. In total, the average social benefit from using green roofs totaled $34.95/m^2 and the average green roof private benefit was $26.70/m^2 using the mean values created by the sensitivity analysis (Fig. 5). Comparing the cost ratio between green and traditional roofing for the conservative NPV estimate and the average estimate generated by the sensitivity analysis show green roofs drop $0.40 on every dollar down to $0.79 from $1.19 for the private scenario and down to $0.72 from $1.12 when social accounting is performed (Table 9).

5. Discussion

BCA of widespread extensive roof greening in the Tanyard Branch watershed reveals a number of important considerations for both the private and public sectors when considering green roof installation. The most significant economic benefits are the increase in roof life, stormwater BMP cost avoidance, and energy savings. The main construction benefit, and best overall benefit in economic terms, of the extensive green roof is that it extends the life of the waterproofing membrane and eliminates the need for frequent reroofing. Without this benefit, green roofs would cost over 85% more than their traditional counterpart. One problem in realizing this benefit is that many waterproofing companies will still only guarantee their premium membranes for 25 years, which may reduce the incentive for a building owner to invest in a green roof during initial construction. As long-term green roof projects are built and monitored, more experience and ultimately green roof life warrantees may help institutionalize this benefit.

Avoiding the cost of other more expensive stormwater BMPs is an important green roof benefit. Since green roofs do not consume valuable urban land, there is no opportunity cost associated with them as there may be with other stormwater BMPs such as bioretention areas. Additionally, green roofs are independent of watershed soil type. They can be implemented anywhere there is a building as opposed to porous pavements, for example, which must have adequate soil permeability before installation is possible (Ferguson, 2005). This analysis demonstrates that green roofs are most practically implemented in densely developed urban centers where other practices are impossible or cost-prohibitive. This stormwater benefit is also public, accomplishing water quality and quantity goals for the jurisdiction, and therefore justifies the use of public funds to encourage private building owners to use green roofs for stormwater mitigation.

Annual energy savings for building owners total over $65,000 in the watershed. While not as significant as extended roof life, this private benefit will be continuously realized each year and help offset some of the initial upfront cost for the building owner. If the building is rented, as many commercial structures are, the tenant will receive this savings. This benefit may function as a marketing tool for the building owner to attract new tenants when leases are renewed. Given uncertainties about energy prices due to the possibility of increased regulation due to air quality and climate change concerns, it is possible that the conservative case has significantly underestimated these benefits. Sensitivity analysis shows that increasing energy prices would result in over $3,000,000 savings over the life cycle of the roof.

The benefit to the existing storm sewer system in the Tanyard Branch watershed is relatively small in economic terms. This is primarily due to the nature of the stream system and the type of sewerage found in the watershed.

The highly impacted urban stream shows little potential for economically quantifiable improvement strictly with green roof implementation. Much of the stream is piped and culverted with no change in the sizing of these facilities when green roofs are implemented. This is because extensive green roofs are highly effective at retaining stormwater for small storm events with recurrence intervals of 1–2 years, but are less effective at retaining significant portions of runoff from the larger 25–100-year storms. Stormwater systems are typically designed for these larger storm flows.

Additionally, the flood mitigation benefit is minimal. The geomorphology of Tanyard Branch creek has been dramatically altered by urbanization to the point, where the incised banks will only flood on a recurrence interval of a few billion years or effectively never for the purposes of this study (Herbert et al., 2003). There may potentially be marginal improvement in the stream ecosystem with reduction of sediment transport capacity and reduced volume and frequency of runoff from small storm events. Contingent valuation studies or hedonic property valuation of these improvements are difficult as the majority of the day-lit stream reaches are on a single parcel of the campus of the University of Georgia. These site-specific conditions are important qualifiers that may not be true when evaluating green roof benefits in other watersheds. In addition, caution should be used in making inferences based on these results because construction and maintenance techniques, as well as estimates of their energy-saving, stormwater-retention, and air-quality improvement benefits, may change as greater experience brings both innovation and better information.

Sensitivity analysis demonstrates that application of green roofs under varying market conditions can significantly influence whether or not green roofs pass the NPV test when compared to traditional roofs. The base green roofing case used in this analysis is more of a ‘‘worst case scenario’’ than a realistic picture of future green roof installations. The average costs represented in the sensitivity analysis may be a more realistic picture of the pricing that future green roof installers will face. Since construction costs are the most likely of the parameters to decrease as well as the most influential in the NPV performed in this analysis, the conditions appear favorable for thin layer green roof systems to become more profitable than built-up asphalt roofs with further cost reductions among firms in the industry. Direct production and specialization in Germany has led to low unit costs of green roofing materials relative to the United States. A reason for this is that many of the single-source green roof suppliers in the United States simply are dealers of green roof products imported from German green roof companies, which increases the total cost of these materials. Further maturation of the industry in the United States should expand opportunities for more efficiency and price reductions across the spectrum of green roof products and services.

6. Conclusions

Expansion of urban areas and the built environment, combined with greater public interest in maintaining the integrity of ecological systems in these areas, has caused the construction industry to begin developing practices that have less environmental impact. Innovative new materials and techniques will be largely governed by economic returns on this investment. Since many of the environmental goods affected by development are public in nature and rarely internalized by private firms, it is important to comprehensively evaluate each new practice so that there is a clear accounting of the costs and benefits to society as well as to private building owners.

This study evaluated one such innovative practice: the extensive green roof system. Applying a life-cycle BCA to this practice demonstrates that under current conditions, the NPV of traditional roofs is substantially less than the when green roofs are built in the Tanyard Branch watershed. This may not be surprising, however, due to the novelty of the technology and the unique conditions in the Tanyard Branch watershed which are not ideal for realizing all green roof benefits. Changing reasonable assumptions about this analysis shows that green roofs may be more cost effective than traditional roofs given changes in green roof construction costs, higher energy prices, or possibly inclusion of other watershed-specific benefits. If energy costs rise or stormwater protection becomes more of a public priority—both highly plausible possibilities—then green roofs become more economically attractive.

Green roofs can provide both private and public benefits and should be included as a potential tool in watershed management manuals for use in highly developed areas. Architects, stormwater professionals and watershed planners can only benefit from having more options to alleviate the environmental impacts of urbanization. An assortment of techniques allows for interested parties to use the practices most effective given their particular location, goals, and resource constraints. As areas continue to become more highly urbanized, reconciling development interests and environmental concerns is essential. The greater the number of practices available to accomplish this goal, the easier it will be to reconcile this future conflict between the built and natural environment.

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