Cost-Effectiveness of Green Roofs

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Abstract: Life-cycle assessment was used to evaluate the widespread installation of green roofs in a typical urban mixed-use neighborhood. Market prices of materials, construction, energy conservation, storm-water management, and greenhouse gas (GHG) emission reductions were used to evaluate private and social costs and benefits. Results suggest green roofs are currently not cost effective on a private cost basis, but multifamily and commercial building green roofs are competitive when social benefits are included. Multifamily and commercial green roofs are also competitive alternatives for reducing greenhouse gases and storm-water runoff. However, green roofs are not the most competitive energy conservation techniques. GHG impacts are dominated by the material production and use phases. Energy impacts are dominated by the use phase, with urban heat island (UHI) impacts being an order of magnitude higher than direct building impacts. The quantification of private and social costs and benefits should help guide green roof policy. Results should encourage green roof enthusiasts to set appropriate life-cycle assessment boundaries, including construction material impacts and UHI effects.

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Introduction

While green roofs have been used for centuries, their introduction into the U.S. urban environment is much more recent, gaining popularity only in the last few decades (Dunnett and Kingsbury 2004). A green roof covers a building roof with vegetation and soil, usually above a waterproof membrane, drainage layer, and insulation. While green roofs have higher initial costs than traditional roofing, green roofs have a diverse array of potential benefits (Dunnett and Kingsbury 2004), such as

1. Reducing building cooling loads by preventing excess heat from entering buildings;
2. Mitigating the urban heat island at appropriate scales and density by providing a medium that uses excess heat to create water vapor;
3. Reducing storm-water runoff by retaining precipitation;
4. Sequestering carbon dioxide and pollutants in biomass;
5. Improving aesthetic values or providing recreational benefits;
6. Creating wildlife habitat; and
7. Providing noise reduction in buildings.

In this paper, we will focus on the first four benefits listed above, considering what valuation of these benefits make green roofs cost-effective. Past green roof research is limited in scale and scope. Studies often focus on a single benefit for a specific building or group of buildings. Stovin (2009) and Bliss et al. (2009) found through experimentation that green roofs significantly reduce both the peak and volumetric flow of urban storm-water runoff. Saiz et al. (2006) found a 6% reduction in summer cooling load for a multifamily building in Madrid, Spain. Wong et al. (2003b) and Sfakianaki et al. (2009) have found similar reductions to building cooling demands resulting from green roofs.

Several researchers have considered the impact of green roofs on the urban heat island. Through modeling, Bass et al. (2003) found a 1% reduction in the ambient temperature for 50% green roof coverage in Toronto. Rosenzweig et al. (2006) found a 0.3°F–0.9°F reduction in New York City neighborhood temperatures depending upon the extent of green roof coverage. Planning officials expect a 1.5°F reduction in Tokyo with a green roof coverage of 1,200 ha (Peck 2001).

Green roof enthusiasts suggest that green roofs have a longer service life than conventional roofs due to: (1) reduced membrane heat exposure; (2) reductions in water ponding; and (3) stringent waterproofing standards (Dunnett and Kingsbury 2004). Coffelt and Hendrickson (2008) found that conventional, commercial roofs have a minimum cost service life of 30 years for a location in Pittsburgh (United States). Peck et al. (2003) claimed that a green roof service life is twice that of a conventional roof in Europe but do not provide supporting data.

Green roof design standards have become available only recently, and their application in the United States is uncertain. Until recently, the German FLL guidelines were the only standards applied in the United States (Roofscapes Inc 2010). However, the FLL standards have only been published in English since the mid-1990s, and it is unclear to what extent these standards have been applied in the United States. ASTM has been introducing American standards only over the past five years (ASTM 2010).

Carter and Fowler (2008) summarized existing federal, state, and local green roof policies with a particular emphasis on storm-water management. Both Carter and Fowler (2008) and Corburn (2009) suggested a lack of empirical data and uncertain benefits

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Table 1. Functional Unit—30% Green Roof Replacement on Typical Urban Building Stock

Building type	Number of households	Conditioned space per household (sq ft)	Average number of floors	Annual energy use (Mill BTU/HH resid; kBTU/sf comm)	Total roof area (1,000 sq ft)	Total replaced roofing (1,000 sq ft)
Single-family detached	3,000	2,500	1.5	59	5,000	1,500
Single-family attached	500	1,800	2	59	450	140
Multifamily, 2–4 units	500	800	3	51	130	40
Multifamily, >5 units	1,400	700	5	18	200	60
Commercial	—	3,400	5	57	680	200

across public and private agents make green roof policy development challenging. No doubt a lack of design standards contributes to the risk of paying increased costs for green roofs.

By expanding both the scale of green roof installations and scope of benefits analyzed, we attempt to clarify the role of green roofs in the urban environment. While green roofs offer environmental benefits over a building's lifetime, (i.e., during the "use" phase), they typically cost more and require more materials for construction (the "materials" and "construction" phases). While the added expense of a green roof is a private cost, many of the benefits are public and external to the building owner.

Life-Cycle Analysis Method

Life-cycle assessment techniques were used to evaluate the environmental impacts of the widespread installation of green roofs on a typical urban building stock. The functional unit for base-case analysis is replacing approximately 6.5 million sq ft of traditional roofing with a green roof in an urban neighborhood. Table 1 summarizes the functional unit, which represents 30% of the roofing in a typical mixed-use urban neighborhood serviced by combined sewers. The building stock characteristics summarized in Table 1 are generally consistent with those defined by the Energy Information Administration (2005, 2008), which suggest commercial floor space is typically about 35% of residential floor space in urban areas. We assumed an annual average rainfall of 40 in per year, which is representative of Pittsburgh.

The base case planning horizon is 30 years and the discount rate is 5%. Green roof replacements are evenly distributed over a 10-year period. While green roof studies typically cite a 45-year service life, we conservatively assume 30 years based upon the uncertainty in expected green roof service life discussed above. An annual "background" replacement of traditional roofing of 3% is assumed. In other words, 3% of existing roofs would be replaced annually absent any green roof retrofit program, and we assume these replacements are new green roofs. The costs and impacts of green roofs thus represent incremental changes relative to background traditional roof replacement during the planning horizon.

Three life-cycle phases are considered: (1) material production; (2) on-site construction; and (3) use. Three impacts are modeled: (1) energy use; (2) greenhouse gas emissions; and (3) storm-water runoff.

For example, the GHG impact is the difference between the emissions resulting from roof material preparation and construction and the emissions mitigated during the use phase. Use phase emissions are mitigated in three ways: (1) direct building cooling demand reductions; (2) indirect building cooling reductions resulting from urban heat island impacts; and (3) the reductions to the energy required to treat storm water in combined collection systems.

Economic-input output life-cycle assessment (EIO-LCA) techniques are used to track impacts for the material production phase [Carnegie Mellon University (CMU) 2009; Hendrickson et al. 2005]. The literature was reviewed to develop material profiles and prices specific to each green roof layer (Guggemos 2006; Green Roofs for Health Cities 2006; Ngan 2004; Dunnett and Kingsbury 2004; Kosareo and Ries 2007; Chandler 2001). A summary of EIO-LCA inputs can be found in the Supplemental Materials in Table S1. Direct on-site impacts are modeled using an EIO-LCA vector developed for the construction industry (Sharrard 2007). Use phase impacts are modeled using literature values of expected storm-water runoff reductions, direct building cooling energy savings, and indirect energy savings resulting from urban heat island reductions.

Land Use and Hydrology

Traditional roofs divert all precipitation to runoff. Green roofs retain a fraction of precipitation, thus reducing storm-water runoff and associated impacts. Empirical and modeling studies indicate that green roofs reduce approximately 50% of annual storm-water runoff (Carter and Rasmussen 2006; Hoffman 2006; DeNardo et al. 2003; VanWoert et al. 2005; Stovin 2009; Bliss et al. 2009). Here, the total storm-water runoff reductions were estimated by multiplying the area of green roof coverage times the annual average rainfall reduction (20 in. = 40 in. × 50% reduction). Land use changes that result in CO2 sequestration in the green roofs were based on grassland literature values (Tilman 2006). However, these amounts are small, ranging from 0.02 to 1.1 lb per square foot of green roof for grassland growth over a 30-year planning horizon (Tilman 2006).

Storm-Water Treatment

In combined sewer service areas, storm water from buildings is typically piped to the collection system. As a result, excess runoff may be conveyed to a treatment plant or overflows into a receiving water body. Here, we assume all excess runoff is treated. The energy required to treat storm-water runoff was assumed to be equal to that required for municipal wastewater (Tchobanoglous et al. 2003; Sahely et al. 2006; Lundin and Högskola 1999).

Direct Building Energy

Historical household energy use estimates were taken from Energy Information Administration (EIA) (2005, 2008). The literature indicates that a green roof reduces annual household energy consumption by 1% (Saiz et al. 2006; Wong et al. 2003b). The reduction stems from using less electricity for cooling. A literature comparison indicates similar green roof thermal performance in a variety of climates (Saiz et al. 2006; Wong et al. 2003a; Dunnett and Kingsbury 2004; Liu 2002; Onmura et al. 2001). In multistory buildings, we account for reductions in only the top floors. The two highest floors are impacted at 100%; floors greater than four stories from the roof are not impacted; and impacts marginally decrease between these floors. This approach is consistent with building energy modeling results from Saiz et al. (2006). We assume similar impacts for commercial buildings.

Urban Heat Island Reductions—Indirect Building Energy

Green roofs reduce the urban heat island (UHI) by providing a medium for evapotranspiration and altering the surface albedo. A reduction to the UHI indirectly reduces building cooling demands. The indirect building energy demand reductions were modeled as proportional to the percent of the total service area converted to green roofs based upon values reported in the literature (Akbari et al. 2001; Bass et al. 2003; Rosenzweig et al. 2006; Peck 2001; Taha et al. 1999).

Table 2 summarizes the base-case impact assessment methods. All base-case model parameters, as well as other model input diagnostics, are shown in the supplemental material in Table S2. Table 3 summarizes national average retail prices of storm-water management (Fisher et al. 2008), energy costs [Energy Information Administration (EIA) 2009], and greenhouse gases (Capoor and Ambrosi 2008) used to quantify benefits and perform a shadow cost analysis. Environmental benefits were not discounted.

We assume all costs are private and borne by building owners. Direct building energy reductions are the only benefit considered to be private. Reductions to the urban heat island, GHG reductions, and storm-water runoff reductions are all considered social benefits. While building energy savings associated with reductions to the UHI would be realized by building owners, we assume these benefits can only be realized through a coordinated extensive green roof construction program such that UHI impacts should be considered public benefits.

Results

Table 4 shows the estimated capital costs and material and construction phase impacts for the functional unit shown in Table 1. Table 4 indicates that energy use and GHG emissions associated with the material production phase dominate those associated with the construction phase.

Tables 5–7 show the environmental impacts and public and private benefits associated with the use phase. Table 5 indicates that the private benefits of reduced electricity use are an order of magnitude lower than the public benefits created by reducing the urban heat island. Table 6 indicates that reductions in GHGs during the building use phase are dominated by reductions in the urban heat island. GHG reductions from using less electricity directly are an order of magnitude lower. Table 7 indicates that storm-water runoff reductions are on the order of 20 million gal per year (around 600 million gal over a 30-year period).

A traditional cost effectiveness analysis is complicated by the fact that a single cost results in multiple benefits. As an alternative to cost effectiveness, we use shadow pricing to estimate the implied value of the each benefit. If the market value of all but one

Table 2. Base-Case Impact Assessment for Green Roofs Relative to Conventional Roofs

Phase	Method	Boundary		Impact assessment		
				Incremental cost ($/sq ft)	Incremental GHGs emissions (lb CO2e/sq ft)	Incremental energy use (kWh/sq ft)
Material production	EIO-LCA	Supply chain				
			Single-family	$3.30	23	37
			Multifamily	$5.00	37	56
			Commercial	$7.80	45	74
On-site construction	EIO-LCA	Direct	Single-family	$4.80	3.2	0.26
			Multi-family	$7.80	5.2	0.43
			Commercial	$13.00	8.4	0.66
Use	Electricity emissions factor of 1.5 lb CO2e/kWh	Direct	Cooling	1% reduction in annual electricity demand for affected floor space in affected buildings		
			UHI	1 kWh/sq ft annual electricity demand reduction for each % roof converted for all buildings in neighborhood		
			Runoff	50% annual reduction in excess runoff; 1 kWh/1,000 gal.		

Table 3. Assumed Market Values of Resources and Externalities

	Greenhouse gases	Electricity	Storm water
Units	$/MT	$/kWh	$/kgal
Market value	$21.47	$0.0982	$2.27
Reference	Capoor and Ambrosi (2008)	Energy Information Administration (2009)	Fisher et al. (2008)

of the benefits is subtracted from the total cost, the remaining cost is the "shadow cost" of the remaining benefit. For example, the total cost of green roof replacements for all building types is $17 million (Table 4), and the sum of the GHG and storm-water benefits is $2.6 million (Tables 6 and 7). This means that the shadow cost of $14.4 million ($17 million−$2.6 million) was implicitly spent on reducing 110,000 MWh of electricity, at a shadow price of approximately $0.13 per kWh.

Table 8 summarizes the shadow price analysis and shows benefit-cost ratios for the public and private sectors. Table 8 indicates that green roofs are not economically competitive on a private benefit-cost basis, with the private benefit-cost ratio being less than 5% for all building types. Results indicate that multifamily and commercial buildings are cost effective on social basis, with the social benefits being nearly equal to the costs.

Shadow pricing indicates that green roofs are cost-effective alternatives for GHG mitigation and storm-water reductions for multifamily and nearly so for commercial buildings. None of the building types are cost effective energy reduction strategies. The energy savings shadow costs for multifamily and commercial green roofs are approximately 10 and 5% less than national average market prices, respectively.

Table 7. Reductions in Storm-Water Runoff from Green Roof Installations over a 30-Year Planning Horizon

		Public benefits
Building type	Runoff reductions (million gal.)	Market value of runoff reduced ($1,000)
Single family	540	$1,200
Multifamily	33	$74
Commercial	67	$150
All categories	640	$1,500

Table 9 summarizes the relative distribution of costs and impacts for the functional unit. Negative values reflect a cost, emissions generated, or energy used. Positive values reflect a savings. Table 4 indicates that use phase GHG and energy impacts are dominated by reduction to the heat island, with direct energy use, storm water, and sequestration impacts being relatively negligible. Green roof material production accounts for 20–30% of the GHG impacts but contributes negligibly to energy use. The relatively high GHG impacts result for extensive use of plastics for

Table 4. Costs, Energy Used, and GHGs Released from Producing and Replacing 30% of Existing Roofs with Green Roofs in a Typical Urban Neighborhood over 30 Years

		Private costs ($1,000)			Energy used (MWh)		GHGs released (MT CO2 eq)	
Building type	Roofing replaced (1,000 sq ft)	Materials	Construction	Total	Materials	Construction	Materials	Construction
Single family	1,600	($5,100)	($7,600)	($13,000)	(59)	(0.41)	(19,000)	(3,000)
Multifamily	100	($690)	($690)	($1,400)	(5.9)	(0.042)	(1,800)	(270)
Commercial	200	($1,400)	($2,200)	($3,600)	(15)	(0.14)	(4,600)	(840)
All	1,900	($7,200)	($10,000)	($17,000)	(79)	(0.59)	(25,000)	(4,100)

Table 5. Reduced Electricity Use from Green Roof Installation over a 30-Year Planning Horizon

	Electricity use reductions (MWh)				Private benefits	Public benefits
	Private	Social				
Building type	Direct energy savings	UHI energy savings	CSO energy savings	Total	Market value of energy savings ($1,000)	Market value of energy savings ($1,000)
Single family	4,700	67,000	530	67,000	$210	$7,200
Multifamily	790	11,000	32	11,000	$34	$1,200
Commercial	3,500	28,000	67	28,000	$150	$3,100
All categories	9,100	110,000	640	110,000	$390	$12,000

Table 6. Greenhouse Gas Reductions from Green Roof Installation over a 30-Year Planning Horizon

	GHG reductions (MT CO2 eq)					Public benefits
Building type	Direct energy mitigation	UHI energy mitigation	CSO energy mitigation	Sequestered	Total GHG mitigation	Market value of CO2 mitigated ($1,000)
Single family	3,300	47,000	370	390	51,000	$630
Multifamily	530	7,700	20	24	8,300	$130
Commercial	2,300	19,000	46	49	21,000	$340
All categories	6,100	74,000	436	470	81,000	$1,100

green roofs, which demonstrate emission intensive production processes.

Historical national energy use averages [Energy Information Administration (EIA) 2008] suggest multifamily and commercial buildings are less energy efficient per floor space than single-family homes. In addition, single-family homes have significantly more roof space per household then multifamily homes. As a result, single-family homes are less cost effective than multifamily and commercial buildings.

A one-way sensitivity analysis was performed to quantify regional variation in costs and benefits. Sensitivity results, summarized in Fig. 1, suggest that electricity pricing, the number of building floors, heat island impacts, and the scale of green roof conversions are dominant parameters. The model is less sensitive to material and construction costs, household size, and hydrologic impacts. The model is highly insensitive to assumptions regarding market values of storm-water management and GHGs.

The sensitivity results also suggest that many regional factors can cause a "switchover" from cost effective to not cost effective, especially for commercial buildings. Regional grid emissions, local labor rates, and hydrologic factors all cause "switchovers" for multifamily and commercial buildings. These results highlight the need for local policies to be informed by regionally specific technical analysis.

Discussion

These results suggest that green roofs have a role in achieving more environmentally sustainable cities, but that role may be limited to regionally specific commercial and multifamily buildings. Results suggest green roofs are more effective in regions with higher than average electricity rates, multistory building stock, and climates that readily demonstrate reductions to heat islands with the introduction of green roofs. Note that this model does not adjust material and construction prices based upon the number of building floors, an assumption that may limit the results and conclusions.

We promote considering urban sustainability interventions relative to at least three metrics: initial cost, annualized cost effectiveness, and total effectiveness (Blackhurst et al. 2009). The annualized cost effectiveness should reflect operating costs or savings generated by the intervention. The total effectiveness should reflect physical limitations. For green roofs, the total effectiveness would be limited by the maximum green roof coverage.

For example, the 1,900 multifamily green roof conversions in this study's scope have an initial cost of $1,400 per household, an annualized cost effectiveness of $8 per MT of GHG mitigated, and a total effectiveness of approximately 6,600 MT mitigated over 30 years (8,700 MT mitigated minus 2,100 MT generated during materials production and construction). Attic floor insulation has an initial cost of $340 per household, an annualized effectiveness of $16 *saved* per MT of GHG mitigated, and a total effectiveness of 850 MT of GHG mitigated. By comparison, attic floor insulation is less expensive and generates savings while mitigating GHGs. However, attic insulation can only mitigate 5% of the carbon that green roofs can.

Shadow cost analysis suggests that green roofs are cost effective strategies for managing storm water and reducing GHGs. These benefits are generally considered social goods, whereas the costs of green roofs are primarily private. These results should encourage localities interested in green roof implementation to

Table 8. Base-Case Results (30-Year Planning Horizon; 5% Discount Rate)

Building type	Present value capital cost[a] ($1,000)	Present value private benefits ($1,000)	Social benefits[b] ($1,000)	Private benefit-cost ratio	Social benefit-cost ratio	Shadow cost GHG ($/MT)	Shadow cost energy ($/kWh)	Shadow cost CSO treatment ($/kgal.)
Single family	($13,000)	$210	$9,100	0.016	0.72	$143	$0.15	$8.80
Multifamily	($1,400)	$34	$1,400	0.024	1.0	$19	$0.097	$1.83
Commercial	($3,600)	$150	$3,600	0.042	0.99	$24	$0.10	$2.96
All categories	($17,000)	$390	$14,000	0.023	0.80	$91	$0.14	$7.83
				Market cost		$21.47	$0.0982	$2.27
				Market cost ref		Capoor and Ambrosi (2008)	Energy Information Administration (2009)	Fisher et al. (2008)

[a] All costs assumed to be private.

[b] Social costs/benefits include private.

Table 9. Relative Costs and Impacts by Building Type

	Materials (%)	Construction (%)	Use phase Direct energy (%)	Heat island energy (%)	Storm water (%)	Sequestration (%)
Cost						
Single family	−31	−46	1.3	18	3.5	—
Multifamily	−36	−36	1.8	25	1.8	—
Commercial	−28	−44	3.0	24	1.4	—
All categories	−31	−44	1.7	20	2.9	—
GHG emissions						
Single family	−26	−4	4.5	64	0.51	0.53
Multifamily	−17	−3	5.1	74	0.19	0.23
Commercial	−17	−3	8.6	71	0.17	0.18
All categories	−23	−4	5.6	67	0.40	0.43
Energy use						
Single family	−0.08	0	6.5	93	0.73	—
Multifamily	−0.05	0	6.6	93	0.27	—
Commercial	−0.05	0	11.2	89	0.21	—
All categories	−0.07	0	7.7	92	0.55	—
Storm-water reductions						
Single family					84	
Multifamily					5	
Commercial					11	

Note: Negative values indicate a cost, emissions generated, or energy use.

formulate policies and funding strategies that bridge the gap between public and private costs and benefits.

Similar recent research has demonstrated that the environmental benefits of green roofs may not exceed their costs. Carter and Keeler (2008) demonstrated that the cost of green roofs installed in a watershed near Atlanta are approximately 10% higher than the environmental benefits of storm-water management, energy reductions, and improvements to air quality over a 40-year period. Carter also found that the social benefits exceed the private benefits.

Note that our results pertain to replacing traditional roof in typical urban mixed-use neighborhoods with green roof systems common in the literature. Green roofs may perform very differently under different circumstances, such as applications to "big box" commercial buildings or new construction. Using alternative materials—such as systems that do not use plastic layers—may also limit our results.

While not well understood, the impact of green roofs on the urban heat island may be significant. Our approach is to model reductions in building energy use as a linear function of total green roof coverage. While we leverage a limited pool of existing literature to prepare our model, a linear response is likely overly simplistic. However, the limited information available suggests that urban heat island reductions may be the most significant environmental benefit of green roofs. Future research should elucidate these benefits, recognize regional climate variations, and

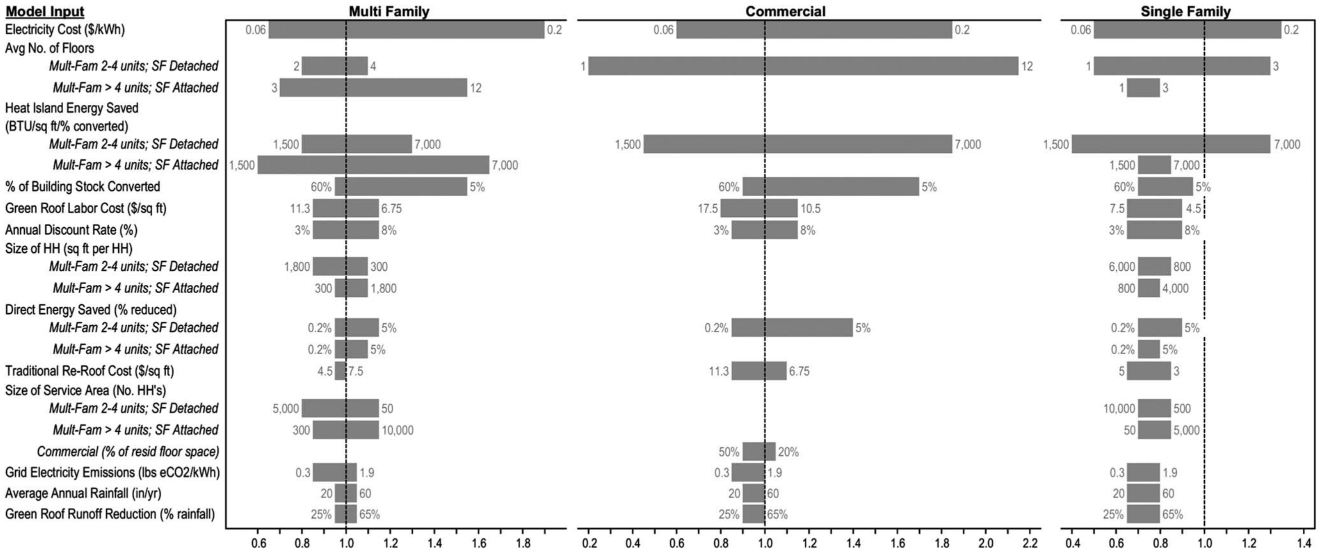

Fig. 1. Sensitivity analysis of social benefit-cost ratio

should be useable by local policy makers for incorporation into land use plans and building codes.

Material phase life-cycle assessments are uncertain without detailed green roof designs and specifications as well as pricing details. Existing specifications are loosely based upon a description of green roof layers, without reference to specific materials for impact assessments. Life-cycle assessments of green roofs would be greatly improved by standardization. Recent work by Theodosiou (2009) echoes a similar need for standardized material specifications.

Green roofs are not as marginally expensive relative to traditional roofs in Europe as they are in the United States. This could be due to limited intellectual capital, limited physical capital, or both. Understanding these differences may lead to cost reductions in green roof installations, which would significantly improve the environmental cost effectiveness of green roofs.

Finally, we emphasize that our functional unit, pricing, and environmental impacts reflect national averages. The one-way sensitivity analysis partially captures the impact of regional variations, with the social benefit-cost ratio being highly sensitive to regional factors such as the price of electricity, building size, and labor costs. Regional conditions should be considered by local authorities when designing green roof policy programs.

Supplemental Data

Tables S1 and S2 are available online in the ASCE Research Library (www.ascelibrary.org).

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