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Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits

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Green (vegetated) roofs have gained global acceptance as a technology that has the potential to help mitigate the multifaceted, complex environmental problems of urban centers. While policies that encourage green roofs exist at the local and regional level, installation costs remain at a premium and deter investment in this technology. The objective of this paper is to quantitatively integrate the range of stormwater, energy, and air pollution benefits of green roofs into an economic model that captures the building-specific scale. Currently, green roofs are primarily valued on increased roof longevity, reduced stormwater runoff, and decreased building energy consumption. Proper valuation of these benefits can reduce the present value of a green roof if investors look beyond the upfront capital costs. Net present value (NPV) analysis comparing a conventional roof system to an extensive green roof system demonstrates that at the end of the green roof lifetime the NPV for the green roof is between 20.3 and 25.2% less than the NPV for the conventional roof over 40 years. The additional upfront investment is recovered at the time when a conventional roof would be replaced. Increasing evidence suggests that green roofs may play a significant role in urban air quality improvement. For example, uptake of NO_X is estimated to range from \$1683 to \$6383 per metric ton of NO_X reduction. These benefits were included in this study, and results translate to an annual benefit of \$895—3392 for a 2000 square meter vegetated roof. Improved air quality leads to a mean NPV for the green roof that is 24.5—40.2% less than the mean conventional roof NPV. Through innovative policies, the inclusion of air pollution mitigation and the reduction of municipal stormwater infrastructure costs in economic valuation of environmental benefits of green roofs can reduce the cost gap that currently hinders U.S. investment in green roof technology.

Introduction

Urbanization increases stress on private and public utilities resulting increases the demand for energy, water and sewer services, and transportation (*1*). To meet increased energy demand, more than 150 new coal-fired power plants are proposed in the U.S. alone by 2030 with residential and commercial buildings currently contributing to 39% of energy consumption (*2, 3*). Converting green space into neighborhoods, shopping malls, and other developments increases the need for infrastructure investment in storm sewer systems (*4*). New road infrastructure leads to increased vehicle emissions and, along with parking lots and rooftops, roads contribute to elevated urban surface temperatures by reducing a city's albedo. Increased urban temperature, commonly referred to as the urban heat island effect (UHIE), in combination with emissions from the electric utility industry, impact local and regional air quality (*5*). As growth is inevitable, a multifaceted and scalable solution is needed to temper the environmental impacts of growing cities. Increasingly, developers, architects, and city planners recognize that green (vegetated) roofs may be part of the solution. Composed of a drainage layer, a solid matrix "soil" layer, and vegetation, green roofs reduce the thermal gain directly beneath the roof (*6*) and improve the water balance between evapotranspiration and runoff (*7*).

Much of the research on green roofs focuses on the insulation capability during summer months, which reduces the flux of solar radiation in a building (*8*). A study by Takebayashi and Moriyama (2007) on the surface heat budget of a green roof and a high reflectivity (white) roof revealed that both systems have a small sensible heat flux compared to a concrete roof surface (*9*). The small heat flux on the white roof is due to the low net radiation, whereas that of the green roof was attributed to the large latent heat flux by evaporation (*9*).

There are two main parameters that influence the solar radiation reaching the roof deck, leaf foliage and soil media. The more extensive the foliage density of a particular plant, the more the heat flux through the roof decreases (*8, 10*) and the greater the decrease in surface temperatures (*11*). Thick soil layers reduced cooling needs during summer months while thin substrate layers resulted in little to no cooling benefit (*10*). Additionally, a dry environment and wind speed increase the rate of evapotranspiration, thereby aiding the absorbance of solar radiation by plants (*10*). Generally, heat transfer is greater on roof surfaces that are not vegetated (*11*).

Green roofs retain as much as seventy percent of annual rainfall precipitation depending on regional climate (*12*). Rainfall retention is also affected by slope and substrate depth: in general, the flatter the roof, the greater the retention and peak flow reduction (*12*). While increased thickness provides increased storage capacity, moisture is also retained for a longer period of time limiting the effectiveness of retention for subsequent storm events. Villarreal and Bengtsson (2005) found that the moisture content of the media had a greater affect on peak flow and total stormwater volume reduction than slope (*13*).

Green roofs exhibit the capacity to reduce pollution in urban environments from ground level ozone (*14*). Vegetation plays a role in lowering surface temperatures through latent heat removal from soils via evaporation and transpiration in the presence of high moisture levels (*15*). The absorption of incoming solar radiation by impervious surfaces creates an urban heat island where temperatures are elevated. Anthropogenic heat and pollution can further intensify the UHIE by creating an inversion layer, resulting in increased air conditioning demand (*16*), and heat-stressed related mortality and illness (*17*).

With vehicular and power plant emissions, the reactive chemistry in urban areas can be greatly affected by nitrogen oxides. Nitrogen oxides (NO_X) alone or in combination with

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other air pollutants such as ozone, sulfur oxides, and particulate materials (PM) can cause respiratory diseases and increase the risk of heart attacks (*18*). Damage from NO$_X$ can extend to plants as well reducing growth, respiration, photosynthesis, stomatal conductance, and enzyme activities (*19*). While no studies modeling the effects or removal of air pollutants by green roofs have been reported in the peer-reviewed literature, there is extensive work on the uptake of reactive nitrogen species by vegetation (*20*).

Although green roofs have been shown to mitigate stormwater runoff volume and to reduce the heating and cooling loads of buildings, the challenges for widespread integration of green roofs include the premium cost over conventional roofs, and widely diverging municipal management practices for stormwater and air pollution control. For example, in the USA, the financial burden of managing stormwater is rarely applied to property owners according to area and intensity of impervious area. Reducing the uncertainty in the quantification of economic benefits of green roofs is a necessary first step to develop policies aimed at stimulating widespread acceptance of the technology in the United States.

The objective of this paper is to quantitatively integrate probabilistic ranges of stormwater, energy, and air pollution benefits in an economic model capturing the building-specific scale. A secondary goal is to assess the impact and opportunities of market-based air credit valuation as a policy tool for green roof diffusion.

Materials and Methods

The first step describes a cost-benefit analysis that can be applied to a range of green roof projects through a probabilistic evaluation procedure. This analysis provides information relevant to building owners, developers, or designers regarding the costs and environmental benefits (stormwater reduction, energy savings, and air quality) of green roof technology. This section summarizes the steps for the cost-benefit analysis at the building scale.

Installation Costs for Conventional and Green Roofs. To determine how the environmental benefits reduce the installation cost gap between green and conventional roofs, the magnitude of the gap was first determined. Cost and size data were obtained from reroofing cost and time estimates provided by plant operations for seventy-five campus roofs from the University of Michigan in Ann Arbor, Michigan. Within this sample, the mean cost of a conventional flat roof was $167 per m^2 (standard deviation: $28 per m^2). The mean campus roof is 1870 m^2 and the mean building floor area is 9730 m^2.

The distribution of green roof installation costs was based on available green roof case data (*21*). As the price of green roofs can vary according to design and function (e.g., intensive green roof can serve as a garden), the cases used in the data analysis were limited to extensive roofs with a depth between 5 and 15 cm. The collected data represent the additional cost of the green roof components. The distributions of the conventional roof and green roof were summed to obtain the total cost of installation for a new green roof with a new conventional roof. The mean difference between the cost of the green roof and the conventional roof is defined as the cost gap. The internal rate of return was then determined for each environmental benefit.

Stormwater Fees and Reductions. The reduction of stormwater volume by green roofs benefits municipalities; however, not all local water authorities pass the economic savings on to the owner of the green roof. Traditionally, the budget for stormwater management is provided through property taxes or potable water use fees. In recent years, municipalities have been moving toward stormwater fees based upon total impervious surface on a property, creating an opportunity to "credit" green roofs for stormwater reduction. Two methods were used for determining stormwater fees and the reduced fee for a green roof. The first method is limited to the City of Ann Arbor, Michigan and its new stormwater ordinance. The commercial stormwater fee is $279.10 per acre per quarter ($0.28 per square meter per year) (*22*). The second method takes an average fee based on available data from eleven municipalities with established stormwater management fees (Supporting Information Table S1). It was assumed that the reduction in stormwater fees due to a green roof is normally distributed at fifty percent of the stormwater fee for the building footprint according to data on fee reduction policies in Portland, Oregon; Minneapolis, Minnesota; and Ann Arbor, Michigan (*23–25*).

Energy Savings Determination and Valuation. The energy savings were based on mixed-use administrative/laboratory buildings at the University of Michigan campus in Ann Arbor, Michigan. Total expenditures for energy (natural gas and electricity) consumption (mean $225 00), total energy consumption (mean 4050 MWh), and energy consumption by fuel source (mean 2370 MWh from electricity and 1670 MWh from natural gas) were obtained for 75 university buildings for fiscal year 2003. National commercial building energy consumption statistics provided additional data (e.g., average commercial conductance, system load factors) (*26*). To determine the roof's contribution to the HVAC energy requirement, the heat flux through the roof was determined according to two methods.

The first method is based on EnergyPlus v2.0.0, a building energy simulation software program supported and made available by the US Department of Energy (*27*). It can model building heating, cooling, lighting, ventilating, and other energy flows, based on climate and building use, material, and size inputs. Version 2.0.0, released in April 2007, contains the capability to include a green roof (referred to as *ecoroof*) on a building. The ecoroof component accounts for heat flux through a 1-dimensional heat transfer model. The model accounts for heat transfer processes within the soil and plant canopy, but it does not account for the soil moisture dependent thermal properties of the green roof (*28*).

The second method is a simplified 1-dimensional heat flux equation that assumes an R-value of 1.2 ft^2 × °F × h/Btu (conductance of 4.7 W/m^2/K) per centimeter depth for a 10.2 cm soil media of a green roof.

$$\dot{Q} = h \times A \times \Delta T = \frac{A \times \Delta T}{R}$$

where Q is the heat flux through the roof (W), A is the area of the roof (m^2), ΔT is the temperature difference between the building interior and the ambient temperatures (K), and h is the heat transfer coefficient (W/m^2/K). This coefficient is a function of the thermal conductivity of a material and the material thickness. The inverse of h is the R-value, which represents a material's resistance to heat flow. The larger the R, the less heat flux Q. In the construction industry, R-value (ft^2 × °F × h/Btu) is commonly used to compare the effectiveness of insulation in building materials. For this method, an average R-value of 11.34 ft^2 × °F × h/Btu (conductance of 0.50 W/m^2/K) was assumed for the conventional roof according to national commercial building data (*26*). The total combined R-value for a conventional roof with a green roof is 23.4 ft^2 × °F × h/Btu (total conductance of 0.24 W/m^2/K). The requisite energy consumption by the HVAC system to compensate for the loss through the roof was then determined. Annual totals for heat loss and cooling loss were multiplied by a system factor as suggested by Huang and Franconi (*26*).

Energy costs due to the heat flux were determined assuming natural gas for heating and electricity for cooling.

Pricing for energy was based upon available university energy expenditure information, \$0.08/kWh for electricity and \$0.02/kWh of natural gas. Heating and cooling degree-days were used for the R-value analysis, while hourly weather data was supplied for the EnergyPlus model (*29*).

Air Quality Improvement and Valuation. Impact on air quality was limited to the mitigation of nitrogen oxide (NO_x). Nitrogen oxide emission allowances are currently traded in the U.S.; market-based economic valuations for 2005–2006 ranged from \$900 per ton (\$992 per Mg) to \$4282 per ton (\$4721 per Mg) (*30, 31*). To quantify nitrogen oxide uptake by plants (per unit area), data from Morikawa, et al. (1998) were used (*32*). That study evaluated the NO_X uptake potential of 217 plant taxa under controlled conditions in a greenhouse environment. Although sedums, the traditional vegetated roof plants of choice, were not evaluated, the study included a member of the same family, *Crassulaceae*. Published results were in terms of mg N g^{-1} dry weight per 8 h of daylight exposure. The following assumptions were made to obtain the uptake capacity per unit area ($kg_{NO2}\ m^{-2}\ y^{-1}$): (i) Ninety percent of plant mass is water; (ii) Leaf thickness is 2 mm; (iii) Leaf area index (LAI) is 5 (m^2 leaf area per m^2 surface area) according to a global mean (*33*); (iv) Average hours of daylight per day (12) (*34*). Calculations were performed to capture the potential impact of all 217-plant taxa on NO_X uptake. The distribution of uptake potentials (Supporting Information Figure S1) is assumed to be log-normal with a mean of 0.27 ± 0.44 $kg_{NO2}\ m^{-2}\ y^{-1}$. An implicit assumption was that the uptake capacity is constant on a year-to-year basis.

Once the annual uptake of NO_X was determined, the result was translated to health benefits. These calculations were based upon two estimation methods developed by the U.S. Environmental Protection Agency (EPA) as part of a regulatory impact analysis of NO_X reductions in 1998 (*35*). The conclusion of the analysis for the Eastern U.S., was that fewer premature deaths and fewer cases of chronic bronchitis translated into an economic benefit between \$1680 and \$6380 per Mg adjusted to 2006 dollars (*35*). The two estimates were based upon the results of several atmospheric models that provided estimates for secondary ozone, nitrogen deposition, and particulate formation (*35*). The range of economic benefit accounts for uncertainty in atmospheric acid sulfate concentration, which affects ammonium nitrate particulate formation (*35*). For the purposes of this study, the estimates are referred to as the *low estimate* (\$1680 per Mg) and the *high estimate* (\$6380 per Mg). It should be noted that these values are in a similar range of emission allowance values.

Economic Analysis and Sensitivity Analysis. Once the costs and benefits were determined on a per unit area basis, the results were integrated into an economic model to determine the length of time required for a return on investment in a 2,000 m^2 green roof using a net present value (NPV) analysis (Supporting Information Table S2). An interest rate of five percent (based upon the 2006, 20 year U.S. government bond interest rate) and inflation rate of three percent (based upon the 2005–2006 Consumer's Price Index) were used (*36, 37*).

It was assumed that the conventional roof would be replaced after twenty years (*38, 39*). Maintenance costs have not been included in this analysis. A sensitivity analysis evaluated model sensitivity to economic parameters, climate factors, and variability in air pollution uptake.

Results and Discussion

The following summarizes the NPV analysis. The implications of the benefits on city environmental policy are also discussed.

Stormwater Benefits. For the Ann Arbor assessment, a per square meter area cost was assumed (instead of the full cost for one acre). The stormwater fee for a conventional roof of 2000 m^2 is then \$520 per year (*22*). As Ann Arbor considers a green roof to be a pervious surface, then the green roof fee would be \$0 per year. The mean stormwater fee was found to be \$0.17/m^2 (standard deviation: \$0.12/m^2) (*40–49*). Potential fee reductions for green roofs resulted in a mean stormwater fee of \$0.08/m^2 (standard deviation: \$0.06/m^2). For the 2000 m^2 roof, conventional roof fees would be \$340, whereas the green roof scenario would have fees of \$160 per year. A few municipalities offer fee reductions to green roof projects (assuming reduced impervious area and adequate storm capture) to pass the value of the public benefit of stormwater reduction to the building owner (e.g., Minneapolis, Minnesota) (*24*).

TABLE 1. Roof Conductance According to Different Energy Models

	roof Conductance ($W/m^2/K$)		
roof type	R-value model	EnergyPlus model	ESP-r model
conventional	0.5	0.38	0.59 (45)
green	0.24	0.36	0.42 (45)

Energy Assessment. The heat flux was based on a 2000 m^2 roof utilizing hourly climate data from nearby Detroit, Michigan for the EnergyPlus simulation and heating and cooling degree days for Ann Arbor, Michigan for the R-value analysis. Roof conductance values and energy savings between conventional and green roof systems were different according to model method, and are summarized in Table 1. A study by Saiz et al. (2006) compared several roof systems for a roof in Madrid, and the conductance of the roofs are provided in Table 1 (*50*). The conductivity estimates for the conventional roof and green roof by Saiz et al. is larger than the results from both models presented here. This may be due to their use of an existing building in Madrid, Spain for the analysis (age, different insulation requirements) and the assumption of pine bark and compost as the primary constituents of the soil media for the green roof, which would affect soil moisture properties. For the EnergyPlus analysis, the difference in consumption for a one floor commercial facility with a green roof versus a conventional roof is 16.4 MWh with 6.6 MWh saved from electricity and 9.8 MWh from heating. Based on energy costs for 2003 and adjusted to 2006 dollars (2003 energy expenditure data was available from the university and energy prices for 2004 and 2005 were unusually high), this translates to a savings of \$710 of the green roof over the conventional roof. For the R-value analysis, there was a 66.1 MWh savings for the green roof with 59.5 MWh attributable to heating and 6.6 MWh for cooling. This translates to a savings of \$1670 of the green roof over the conventional roof. While the two models agree on electricity savings, they differ in estimates for heating. The EnergyPlus model accounts for the other envelope heat loss pathways such as walls, windows, and slab, which have higher conductivities, 0.51, 3.25, and 2.69, respectively. When heat flux occurs, the EnergyPlus model suggests that greater losses would occur through these pathways than the roof. During periods of heating, the difference between interior and exterior conditions are greater than during periods of cooling, so the magnitude of error in heat flux between the models would be greater under conditions of heating than under cooling conditions. Uncertainty for these calculations is not included in the NPV analysis as the dependency on soil moisture and green roof soil media conductance has not yet been investigated in the literature.

To verify the appropriateness of the assumptions used in the analysis, calculated energy costs through the conventional roof were compared to actual expended total natural gas and electric energy costs for university buildings. Assuming

TABLE 2. Net Present Values of Roof Systems under Various Benefit Scenarios after 40 Years Assuming Conventional Roof Replacement at 20 Years

benefit scenario	roof type		percent change in NPV
	conventional	green	
R-value; mean stormwater	\$613 969	\$468 366	23.72
EnergyPlus; mean stormwater	\$587 465	\$468 366	20.27
R-value; high stormwater	\$619 828	\$463 944	25.15
EnergyPlus; high stormwater	\$593 324	\$463 944	21.81
low air valuation; R-value; mean stormwater	\$613 969	\$443 644	27.74
low air valuation; EnergyPlus; mean stormwater	\$587 465	\$443 644	24.48
low air valuation; R-value; high stormwater	\$619 828	\$439 222	29.14
low air valuation; EnergyPlus; high stormwater	\$593 324	\$439 222	25.97
high air valuation; R-value; mean stormwater	\$613 969	\$374 611	38.99
high air valuation; EnergyPlus; mean stormwater	\$587 645	\$374 611	36.25
high air valuation; R-value; high stormwater	\$619 828	\$370 190	40.28
high air valuation; EnergyPlus; high stormwater	\$593 324	\$370 190	37.61

that 35% of total building energy consumption is due to heating, ventilation, and air conditioning (HVAC) system use (*51*), 90% of all buildings (75 total) were within the expected costs attributed to HVAC use. The eight buildings with higher energy expenditures had roof area-to-floor-space ratios much greater than one (R/F area > > 1). The ratio can be explained by the inclusion of roof areas outside the interior building floor area (e.g., exterior walkways, loading docks), including these areas in the heat flux calculations would overestimate contribution to the HVAC consumption.

Air Pollution Mitigation. The benefit assessment included both direct and indirect methods of uptake. The uptake capacity per area for the 217 plant taxa evaluated by Morikawa et al. (1998) had a mean of 0.27 $kg_{NO2}/m^2/y$ (variance: 0.17 $kg^2_{NO2}/m^4/y^2$) (*32*). For a building with a roof area of 2000 m^2, this results in an uptake of 530 kg_{NO2}/y (variance: 700 kg^2_{NO2}/y^2). The public health benefits for greening a 2000 m^2 roof were determined to be \$890 (variance: 2.0E6 $\$^2$) for the low benefit estimate and \$3390 (variance: 2.8E7 $\$^2$) for the high benefit estimate.

There are limitations to this benefit estimate. The data were obtained from greenhouse estimates, and plants may behave differently under stress or vary the rate of uptake according to the time of year. Although NO_2 utpake is affected by closure of the stomata under stress or at night, NO uptake appears to remain constant independent of stomatal opening (*52*). Contradictory evidence has shown that specific plant species such as kenaf exhibit high nocturnal uptake of NO_2 (*53*). Clearly, further research is needed to understand the (*1*) performance in the field (or on the roof), and (*2*) specific plant uptake potentials.

For large-scale urban greening projects, it should be noted that not all roofs may be conducive to green roof implementation due to restrictive architectural features (e.g., roof slope, HVAC system placement, structural limitations of building). However, if greening occurred on all 35 ha of roofs evaluated in this study at the University of Michigan, potentially 94.31 Mg_{NO2}/y could be removed from the air annually with an estimated value to public health between \$158 720 and \$601 930 per year.

Net Present Value Analysis. The environmental benefit results were integrated into an economic model to determine the length of time required for a return on investment (ROI) for an individual building's green roof system. The mean green roof upfront cost is 39% higher than the conventional roof at installation (\$464 000 versus \$335 000). The NPV was calculated using both energy estimates and stormwater estimates. The NPV of the green roof is between 20.3 and 25.2% less than the conventional roof over 40 years under the current methods (stormwater fees and energy savings) with the difference in calculation of energy savings accounting for greater variation than the difference in calculation of stormwater fee savings (Table 2). Under novel methods (stormwater fees, energy savings, and air pollution uptake) over the 40 year lifetime of the roof, the NPV of the green roof system is between 25% (low air pollution benefit estimate with mean stormwater fee reduction and energy savings modeled from EnergyPlus) and 40% (high air pollution benefit estimate with high stormwater fee reduction and energy savings modeled from R-value analysis) less than the NPV for a conventional system (Table 2). The current valuation scenarios reveal that over 40 years, green roofs cost less than conventional roofs. Additionally, all valuation scenarios showed that the NPV of the conventional roof only exceeds the NPV of the green roof beginning when the cost of the roof replacement at the end of twenty years is included in the NPV.

To assess the dependency on roof longevity and to further assess the contribution of air pollution mitigation, the NPV of the conventional roof was assessed with replacement at 15 and 20 years (*39*). Figure 1 shows the net present value from year 0 to year *t* over the lifetime of the green roof system, considering the green roof valuation of (a) stormwater and energy savings and considering (b) all three environmental benefits. The incorporation of air pollution benefit reduces the green roof NPV by more than 5% under a low valuation estimate and by more than 20% for a high valuation estimate when evaluated against a conventional roof with a 20 year lifetime. Shifting the replacement up to year 15 increases the NPV of the conventional roof by 4% holding fees and energy costs constant.

While stormwater fees affect the NPV over 40 years, air pollution mitigation and energy savings have greater impact on the NPV as shown in the annual environmental benefits summary (Figure 2). Additional savings due to reduced onsite stormwater infrastructure are not included at the building scale as infrastructure savings at individual building sites could only be realized for new building construction or significant renovation projects. Similarly, while system loads to HVAC were taken into account to determine the total reduction in energy, infrastructure savings (from size reduction) were not included. This analysis focused on the opportunity for green roofs on existing buildings that could support an extensive vegetated roof with minimal impact on the building and roof.

Policy Implications. The current method of valuation shows that the investment in green roof systems in the Mid-West may break even in 14–22 years, depending on the input variables and methods of benefits estimation (Figure 1). While roof replacement drives the outcome of the model in the absence of air pollution mitigation, the combination of energy and health benefits has the potential to impact the NPV prior

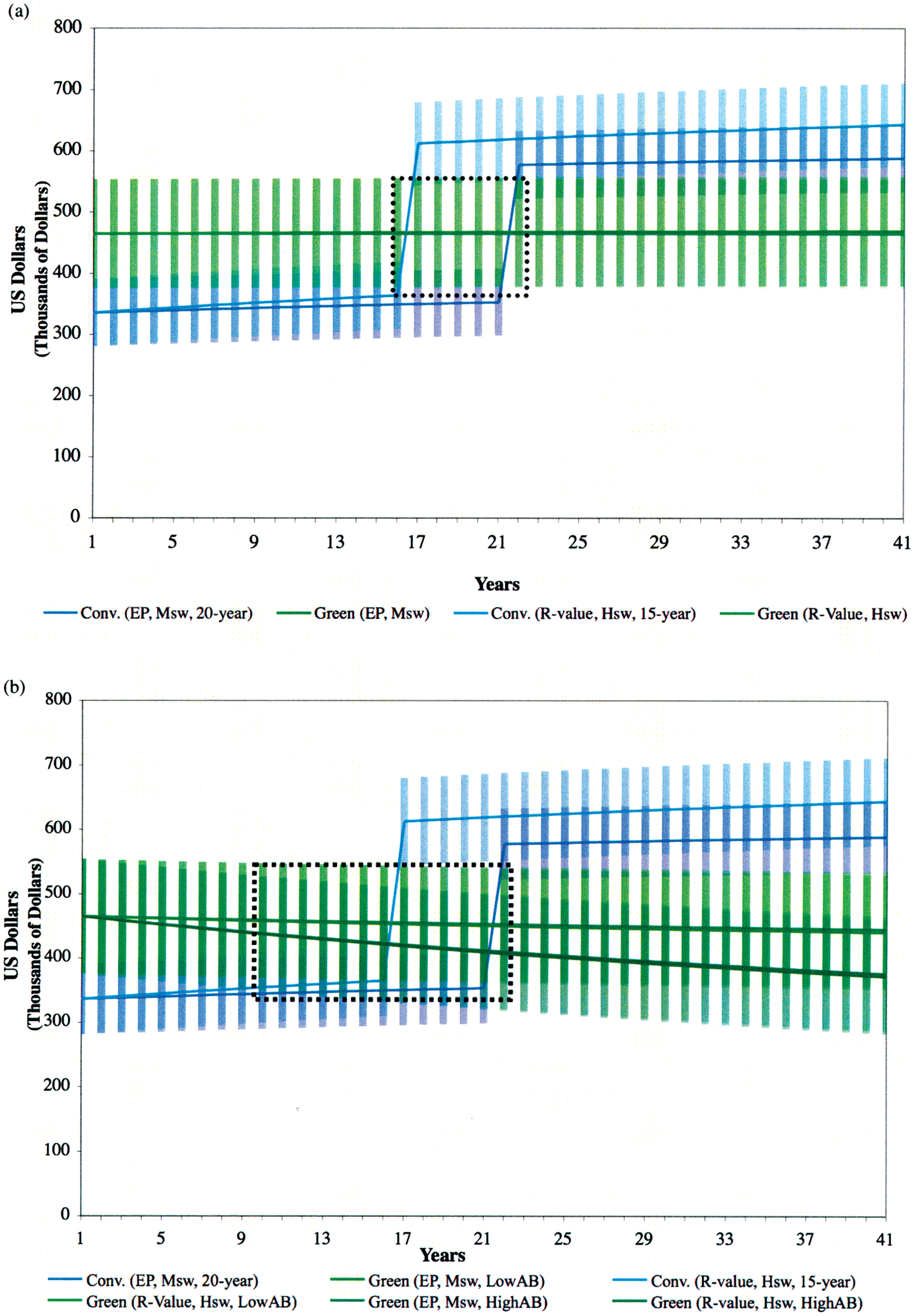

FIGURE 1. Net present value (NPV) from 0 to year *t* over 40 years under (a) current methods of valuation (stormwater fees and energy savings), and (b) novel methods of valuations (stormwater fees, energy savings, and air pollution uptake). The range of NPV of the costs of the conventional roof is bounded according to (i) the mean NPV assuming a 15 year lifetime using the R-Value analysis method for energy expenditure and high stormwater fee, and (ii) the mean NPV assuming a 20 year lifetime using the EnergyPlus model and mean stormwater fees. The range for the NPV of total green roof costs is bounded according to (i) the mean NPV assuming the R-Value analysis method for energy and no fee, and (ii) the mean NPV assuming the EnergyPlus model for energy and 50% reduction in mean stormwater fee in both a and b. The bars represent 1 standard deviation above and below the mean for each NPV scenario. The lower left side of the black box indicates where the lower bound of the green roof NPV is less than the mean NPV of the conventional roof. The upper right side of the black box indicates where the upper bound of the green roof NPV is less than the mean NPV of the conventional roof. The time required for this to occur for the mean costs is highly dependent upon the conventional roof replacement.

to roof replacement. All other parameters remaining constant, more moderate climates would see less energy benefit from a green roof system while climates that require cooling or heating through much of a season may have a greater energy

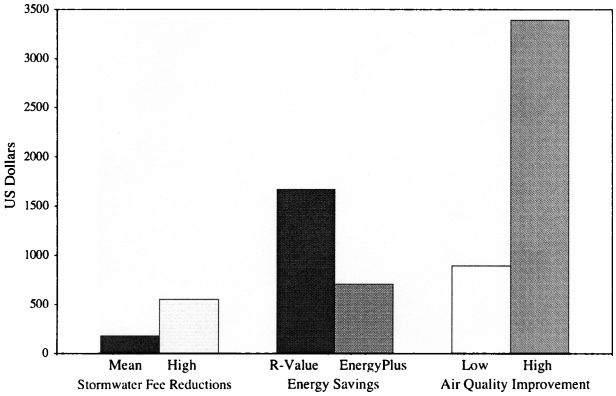

FIGURE 2. Annual environmental benefits for a 2000 m^2 green roof system in Ann Arbor, Michigan. These benefits were incorporated into the net present value analysis. Error bars were not displayed as uncertainty was not quantifiable for all benefits.

savings than that reported here. Further, since the benefit attributable to NO_X uptake exceeds the modeled range of benefits from energy savings, the importance of including the social cost factor into the economic analysis is substantial. Further work is required to incorporate HVAC size reductions, stormwater infrastructure size reductions, and multiple air pollutant reductions. Results from this analysis show that the ability of green roofs to improve air quality should not be ignored by policymakers as its inclusion in a cost-benefit analysis influences the NPV.

Proper valuation of environmental benefits requires changes to current policies that affect green roofs. Two strategies that have potential to rectify the price discrepancy include (i) proper valuation of infrastructure costs via stormwater fees, and (ii) market-based tradable permit schemes for contribution to impaired local waterways similar to what currently being explored for nutrient runoff (*54*). In addition to these policies, the air pollution mitigation ability of green roofs into an economic benefit would further reduce the NPV by 5−20%. This could be achieved through direct incentives (which would reduce the upfront cost of a green roof) or through the incorporation of green roofs as an abatement technology into existing regional air pollution emission allowance markets. Further research into these policy alternatives will aid the design and development of strategies to translate the societal and environmental benefits of green roofs to building owners that ultimately construct green roofs.

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Supporting Information Available

Technical attributes for economic analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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