Ecological impacts of replacing traditional roofs with green roofs in two urban areas

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Abstract

Urban land cover is dominated by impervious surface that degrades both terrestrial and aquatic ecosystems relative to predevelopment conditions. There are significant opportunities for designers of urban landscapes to use alternative land covers that have multiple functions, benefiting both human and nonhuman components of the urban ecosystem. Vegetated (green) roofs are one form of alternative land cover that has shown the potential to provide a variety of ecological benefits in urban areas. We evaluated how stormwater retention, building energy and temperature, and rooftop habitat are influenced by the use of green roofs using test plots in Georgia and Massachusetts. Green roofs were shown to recreate part of the predevelopment hydrology through increasing interception, stormwater storage, evaporation, and transpiration on the rooftop and worked extremely well for small storm events. Temperature reductions were found on the green rooftop as compared to an asphalt surface, although other roof technologies that minimize temperatures, such as lighter colored membranes, provide similar benefits. Novel habitat was created on the rooftop, although the extent of this habitat was limited in part by plant survivability and the need for additional water inputs for diverse plant communities to survive. Despite the challenges, the green roof benefits reported here suggest that green roofs can be used effectively as a multifunctional land cover in urban areas.

Keywords

Green roof; urbanization; stormwater; energy; habitat.

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INTRODUCTION

In the past 40 years, the global human population has doubled to over 6.5 billion people, and the U.S. population alone exceeds 300 million (US Census Bureau 2006). Urban areas, in particular, are growing rapidly with over 8% of the land area in the United States projected to be urban by the year 2050; this will be over double the amount measured in 2000 (Nowak and Walton 2005). As cities are built, pervious land cover, such as forest and grasslands, is being replaced with impervious surfaces like roads, rooftops, and parking lots. Instead of infiltrating into the soil, precipitation flows over impervious surfaces transporting pollutants, such as oil, heavy metals, and fine particulates. This altered hydrology in an urban area can generate five times as much surface runoff as an equivalent area in a forested condition (U.S. Environmental Protection Agency 2003). Often this surface runoff is routed directly into the nearest water body through the storm sewer system, thus bypassing potential infiltration areas and floodplain connections that are highly effective at pollutant removal (Kaushal et al. 2008).

Impervious surfaces also absorb and reradiate solar radiation creating the well-documented "urban heat island" (UHI) effect, where average air temperatures in highly developed areas are consistently higher than the surrounding landscape (Rizwan et al. 2008). This elevated temperature leads to increased building cooling costs, particularly in warmer areas of the United States. Additionally, creation of impervious surfaces reduces the amount of land in urban areas available for biological communities to develop. While researchers have documented how some structures in the built environment create unique habitats (Larson et al. 2004), the conditions both in terrestrial and aquatic urban ecosystems tend to favor a limited number of generalist species adapted to the harsh ecological conditions of the city (Mckinney 2006). The cumulative environmental impacts of impervious surfaces in urban ecosystems have led to widespread interest in investigating how detrimental effects of impervious surfaces can be diminished.

Strategies to mitigate the negative impacts of impervious surfaces in urban areas take three general forms. The first, and most common, practice is to treat the symptoms of impervious surface through engineered practices. Since altered hydrology is a trademark of urban systems, much effort has been invested in engineering ways to manage and treat stormwater runoff. Structural stormwater best management practices (BMPs) are designed and constructed to retain stormwater volume, filter pollutants through growing media, and remove pollutants through biological uptake. Commonly used structural practices include stormwater ponds, constructed wetlands, bioretention areas, and sand filters. Governmental regulation such as the Clean Water Act's National Pollutant Discharge Elimination System (NPDES) Phase I and II requirements have accelerated the installation of these post-construction stormwater management practices in urban areas to diminish impervious surface impacts (White and Boswell 2007; U.S. Environmental Protection Agency 2005).

A second strategy for mitigating impervious surface ecological impacts is to identify areas containing high ecological value in the landscape and prevent conversion of additional areas of the landscape to impervious surface. This may be accomplished through the creation of parks or wildlife corridors through a variety of policy instruments, such as conservation easements and greenspace requirements (Arendt 1999). Often, riparian areas are targeted and incorporated into a community's greenspace plan with regulatory protection guaranteeing that the land cover will remain in an undeveloped condition. This use of "green infrastructure" (Benedict and McMahon 2006) to protect functional landscapes can also be applied to areas experiencing urban growth. For example, new residential subdivisions may use cluster development and other low impact development (LID) techniques to minimize impervious surface cover of the site (Arendt 2004). While this strategy is effective for areas experiencing urban growth, it is not always practical in urban areas that are already highly developed.

A third strategy involves the conversion of impervious surfaces in urban areas into a multifunctional land cover that serves both human demands, such as transportation and housing, as well as ecological functions, such as stormwater retention, energy conversion resulting in primary production, and habitat creation. The transportation network, for example, can use porous pavements to permit both traffic flow on the surface and water flow through the pore spaces, allowing infiltration into the soil.

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While porous paving strategies create an additional and important function in providing infiltration capacity in urban areas, they are limited in their ability to fully replicate predevelopment conditions. An obvious limitation is that the opportunities to grow vegetation in porous pavement systems are typically relegated to turf grass used in a grass paver application (Ferguson 2005).

Vegetated (green) roofs are another example of this third strategy. Nearly 50% of impervious surface in highly urbanized areas is unused roof space (Dunnett and Kingsbury 2004). Green roofs convert the impervious surface of a rooftop into multifunctional spaces in urban areas using vegetation, growing media, and specialized roofing materials. This practice has been used expansively in Germany for over 30 years. In 2002, over 12% of the flat rooftops in Germany had some type of a planted roof (Harzmann 2002). Both flat and sloped roofs of new commercial and residential buildings can be converted into green roofs. Green roof retrofitting onto existing structures is also a common practice, particularly with lightweight green roofs and structures that can support the weight of the vegetated system (Gedge and Kadas 2004).

Green roofs are typically divided into two categories: extensive and intensive. Extensive green roofs have thin substrates (5-15cm), limited plant palates, relatively low costs, and minimal weight requirements. In Germany, extensive systems are by far the most common application, representing over 80% of all green roofs (Harzmann 2002). In contrast, intensive green roofs, sometimes referred to as "rooftop gardens," have deeper substrates (>15 cm) which allow for higher potential for increased plant diversity, but also come with increased weight and higher cost and maintenance requirements. Following the German example and with current market conditions that emphasize maximum cost-effectiveness, it is likely that the majority of new green roof installations in North America will be extensive systems.

Many factors influence how green roofs perform ecologically in urban areas with green roof functions limited by the unique conditions found on the rooftop. One example is green roof habitat. Data collected in Europe and the United States suggest that green roofs can provide habitat for spiders, mites, beetles, grasshoppers, butterflies, and birds (Brenneisen 2003; Brenneisen 2005; Coffman and Davis 2005; Getter and Rowe 2006). With this paradigm shift toward a focus on habitat and biodiversity has come a rejection of traditionally used green roof species, such as *Sedum,* in favor of a more diverse palette of plants, especially plants native to the region where the green roof is located. Unfortunately, this strategy has achieved limited success with high mortality of non-*Sedum* species due to extreme rooftop climatic conditions (Monterusso et al. 2005; Rowe et al. 2006). Because green roofs are by definition uniquely human created and engineered habitats, rooftop plant nativity may need to be reconsidered and using regionally native plants on green roofs may not be a feasible or useful goal. However, increasing the diversity of green roof plants may help to increase a roof's value as habitat for other species. Research has also demonstrated that diversity increases productivity of an ecosystem (Tilman 1997), increases stability of that ecosystem (Tilman and Downing 1994), and increases retention of soil nutrients (Ewel et al. 1991).

This paper will evaluate the potential for extensive green roofs to provide increased ecological function in urban areas as compared to impervious surface rooftops by discussing two green roof case studies from the Southeastern and Northeastern United States as well as previously published data. We will focus on three benefits – stormwater retention, temperature mitigation, and habitat creation – and qualitatively and quantitatively compare a green roof's function with the functions created by typical impervious surface roofs. In addition, we will discuss limitations of the current technology in replicating predevelopment land cover functions.

TWO GREEN ROOF CASE STUDIES

Data from two green roof field sites were evaluated in this study. The first study site was constructed on the Boyd Graduate Studies building on the campus of the University of Georgia (UGA) in Athens, Georgia in October, 2003. This green roof site contained two types of extensive green roof systems (Figures 1 and 2). One system, approximately 42 m^2 in area, was integrated into the roof membrane using a variety of synthetic green roofing material for drainage and water retention; this design

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is called the "Extensive Garden Roof" assembly (American Hydrotech 2002). This green roof system's growing media contained a 55:30:15 mix of expanded slate, USDA sand, and organic matter, respectively. Plant material was a mixture of *Sedum* and *Delosperma* species (Table 1). Additional details of the integrated UGA green roof system can be found in Carter (2006). An identically sized gravel roof section was constructed adjacent to the integrated green roof as a control plot. A modular extensive green roof system was also installed at the UGA site. This system, produced by St. Louis Metalworks and called Green Roof Blocks[TM], was approximately 37 m^2 and used a 61 x 61 cm aluminum container with 10.16 cm of growing media. No other specialized green roofing material was used. The growing media in the modular systems contained 80:20 mix of expanded slate and organic matter, respectively. The modular system used a randomized complete block design with 12 Green Roof Blocks[TM] containing three treatments (empty block, non-vegetated block, and vegetated block) replicated four times (Figure 3). Additional details of the modular UGA green roof system can be found in Hilten (2005) and Prowell (2006).

Figure 1. UGA integrated green roof system.

Figure 2. UGA modular green roof system.

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Figure 3. Experimental design of UGA modular green roof system.

Table 1. Plant species on the green roof study sites.

Family	Genus and species	Variety	Location
Apiaceae	*Eryngium yuccifolium*	--	Tufts
Asclepiadaceae	*Asclepias verticillata*	--	Tufts
Asteraceae	*Echinacea tennesseensis*	Rocky Top	Tufts
Asteraceae	*Aster ericoides*	--	Tufts
Asteraceae	*Antennaria plantaginifolia*	--	Tufts
Aizoaceae	*Delosperma cooperi*		UGA
Aizoaceae	*Delosperma nubigenum*		UGA
Caryophyllaceae	*Dianthus petraeus*	noeanus	Tufts
Crassulaceae	*Sedum album*	--	Tufts, UGA
Crassulaceae	*Sedum sexangulare*	--	Tufts, UGA
Crassulaceae	*Sedum rupestre*	--	Tufts
Crassulaceae	*Sedum spurium*	--	Tufts
Crassulaceae	*Sedum kamtschaticum*	--	UGA
Fabaceaee	*Baptisia australis*	Purple Smoke	Tufts
Lamiaceae	*Agastache rupestris*	--	Tufts
Lamiaceae	*Salvia nemorosa*	Marcus	Tufts
Onagraceae	*Oenothera tetragona*	Cold Crick	Tufts
Poaceae	*Festuca glauca*	Sea Urchin	Tufts
Poaceae	*Eragrostis spectabilis*	--	Tufts
Plantaginaceae	*Veronica oltensis*	--	Tufts
Plumbaginaceae	*Armeria maritima*	Compacta	Tufts
Rosaceae	*Fragaria vesca*	Lipstick	Tufts

The second case study green roof was located on the Tisch Library at Tufts University in Medford, Massachusetts, 8 km northwest of Boston (Figure 4). This extensive green roof used a modular system to allow for independent replication of experimental treatments. Modules were made of black plastic with the dimensions 38.1 x 38.1 x 15.24 cm. Before the addition of substrate, each Module received a drainage fabric layer (fused, entangled filaments and non-woven geotextile Colbond Enkadrain® 9611) to prevent waterlogging and a filter layer (Easy Gardener WeedBlock ®) to minimize soil loss. Each Module was filled with an industry-standard green roof substrate (55:30:15 expanded shale aggregate, USGA sand, leaf compost). Substrate was 13 cm deep with a dry weight of 1.08 g / ml, saturated weight of 1.42 g / ml, and field capacity of 0.35 cm^3 water / 1 cm^3 substrate. At the start of the experiment, controlled release fertilizer was mixed into the substrate at a concentration of 3.6 g fertilizer per liter (Scott's Osmocote® Plus 15-9-12, 3-4 months at 70 ° F).

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At the Georgia site, annual rainfall averages approximately 123.2 cm/year with March typically having the highest rainfall total. Average annual temperatures range from 30° C in the summer to 3° C in the winter (National Oceanic and Atmospheric Administration 2007). The Massachusetts site receives 130 cm annual precipitation, has an average summer temperature of 21°C and an average winter temperature of -2°C.

Figure 4. Experimental modular green roof on Tisch Library at Tufts University Medford, MA

For both studies, a number of environmental parameters were measured to determine how an alternative land cover like green roofs would function differently from impervious surfaces in the urban landscape. However, the green roof study sites were constructed with different research objectives in mind. The Georgia study site was monitored for stormwater retention and temperature mitigation while the Massachusetts site was designed to test for plant growth and habitat creation. The measurements for each case study are described below.

FUNCTIONAL PARAMETER MEASUREMENTS

Stormwater

At the UGA site stormwater runoff was monitored from both the integrated and modular green roof assemblies. From November 2003 – November 2004, runoff flow and volume were measured using a two stage weir, pressure transducers, and data logger which were linked to an on-site tipping bucket rain gauge to collect detailed rainfall-runoff relationships from the green and conventional roofs. Details of the monitoring set up can be found in Carter and Rasmussen (2006). The modular green roof system was monitored from October 2004 – September 2005 and tested both total stormwater retention and the effect of plants and growing media on stormwater retention performance. Details of the modular monitoring setup can be found in Prowell (2006). Stormwater runoff was not collected from the Massachusetts green roof site.

Energy and temperature

At the UGA site the modular green roof system was monitored from January to August of 2005 for physical parameters including: humidity, air temperature, wind speed, radiation, soil temperature, volumetric moisture content and heat flux. Measurements were taken every 15 minutes. These data were used to inform a HYDRUS 1D moisture transport model and describe the thermal conductivity of the engineered green roof soil. Building energy loads were calculated using eQuest. More descriptions from

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this study can be found in Hilten (2005). Temperature and energy data were not collected at the Massachusetts site.

Habitat creation

The goal of the experiment at the Massachusetts study site was to measure survivorship of potential green roof plant species. The Massachusetts green roof contained 19 plant species, representing 12 families. Plants were sampled broadly across angiosperm phylogeny to determine if there are non-*Sedum* drought-tolerant plants that can survive on an extensive green roof in New England. Plants were chosen based on their drought tolerance and growth habit (low-growing herbaceous perennials) (Table 1). In contrast to many previous green roof experiments, it was not assumed that native plants would show higher growth and survival than non-native plants. Although not all of the species were native to New England or North America, none of the species had a record of being invasive (U.S. Department of Agriculture 2008).

Plugs were planted during the first two weeks of June 2007. Due to infrastructure reasons, modules were planted elsewhere on campus and were subsequently moved to the Tisch Library roof on July 5, 2007. Ten replicate modules were created for each of the 19 species. Each replicate module contained 9 plugs of a single species. Due to limited number of plants, the following species contained 5 plugs per module: *Armeria maritima*, *Dianthus petraeus*, *Festuca glauca*, and *Veronica oltensis*. Plants were watered to saturation daily until July 5, 2007. After this, plants received no supplemental water, except on August 28, 2007, when all plants were watered after an unseasonably long drought of 20 days without rain. Limited weeding took place throughout the growing season. Weekly overhead photos of each module were analyzed with Image J (National Institute of Mental Health 2008) to obtain a value of percent plant coverage per module.   Percent cover was used as an approximation of growth. A formal analysis of plant growth was not performed at the UGA site.

RESULTS AND DISCUSSION

Stormwater

Green roofs have been shown to change the hydrologic characteristics relative to impervious surface cover. Mentens et al. (2006) used data from 121 experimental extensive green roofs throughout Europe and found that on average, these roofs retained 50% of total annual precipitation. Moran (2004) evaluated green roof field sites in North Carolina finding over 60% reduction in stormwater volumes and large peak flow reductions from storm events sampled throughout the year.

Results from the monitored green roof sites in Georgia demonstrated clear benefits from both the integrated and modular systems relative to traditional impervious roofing. The first documented benefit is additional stormwater storage provided by the roof system. This is measured by the total amount of rainfall retained during the study period at the site. In the case of the integrated roof system, nearly 78% of the rainfall was held on the roof surface (Carter and Rasmussen 2006). The modular roof system provided slightly less retention with approximately 67% of the average rain event throughout the course of the year held on-site. The overall annual retention was approximately 43% due to the distribution of the rainfall as 23 of the 70 rain events throughout the year contributed more than 73% of the total annual precipitation (Figure 5). Additionally, as tested in the modular system, vegetation provided negligible stormwater retention (Figure 5). The total amount of stormwater retained on a traditional roof is negligible with surface runoff commencing upon initiation of rainfall and green roof runoff hydrographs behaving similarly to the traditional roof only after reaching saturation (Figure 6).

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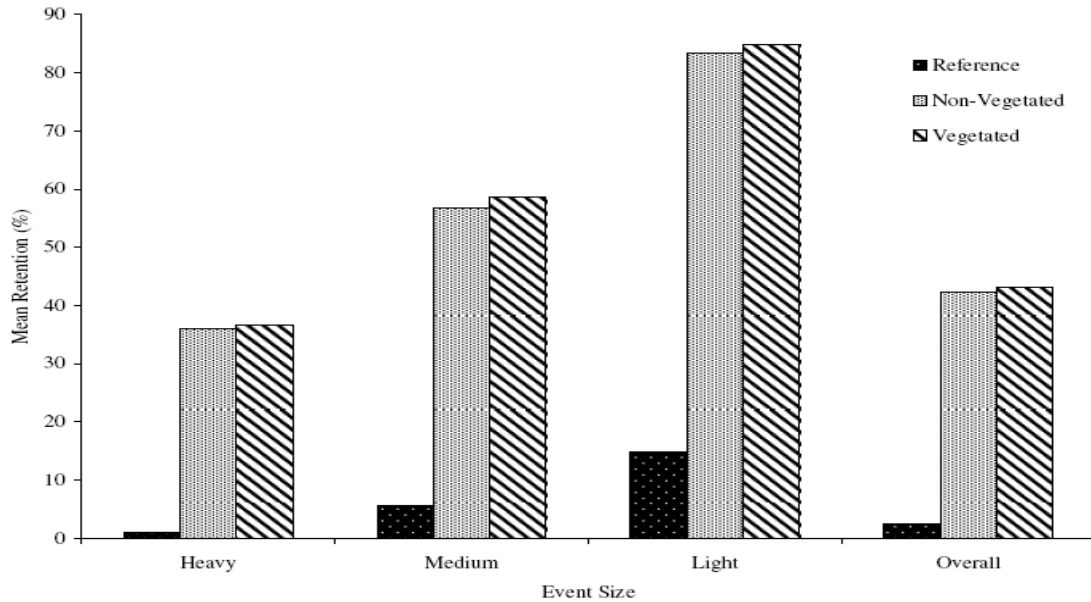**Figure 5.** Percent retention for different sized storms and three treatments on the UGA modular system (from Prowell, 2006). Light storms were <6mm, medium storms were 6-25 mm, heavy storms were >25 mm.

This storage provided by green roofs replicates the evaporation, transpiration, and interception component of the water budget which tends to be lost from the land once it is covered with a building footprint (Wang et al. 2008). This storage is also particularly important for small storm events, which green roofs do a particularly good job of retaining on-site (Figure 7). In urban areas, the increased frequency of surface runoff from small storms has been implicated as a likely cause of degradation to stream biotic communities (Walsh et al. 2005). As an alternative land cover, green roofs can function as part of stream restoration efforts through re-establishing part of the predevelopment hydrology in urban catchments.
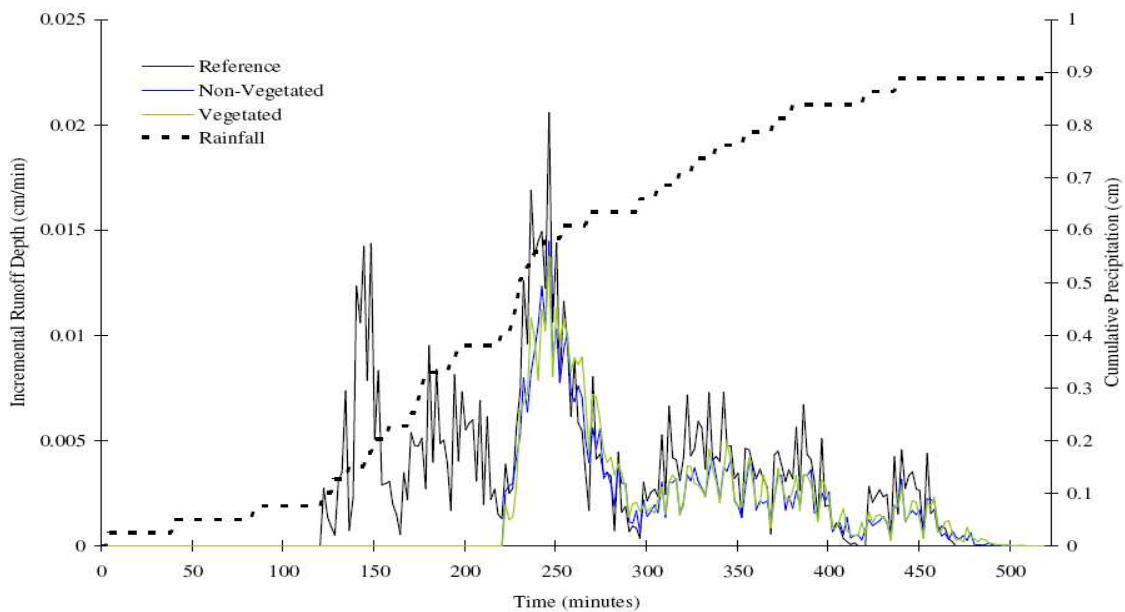

Figure 6. Runoff hydrograph of a representative storm in July 6, 2005 from the UGA modular system.

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Energy and temperature

A number of studies have attempted to model how green roofs may mitigate the effect of the urban heat island (UHI). Alexandri and Jones (2008) modeled the thermal effect of both green roofs and green walls in nine cities around the world concluding that the practices had the greatest effect in hot, dry climates. Takebayashi and Moriyama (2007) determined that green roofs accounted for reduced heat flux into the building because of the large latent heat flux generated by evaporation. Other studies have focused on the evaporative cooling effect provided by a variety of green roof systems (Lazzarin et al. 2005; Onmura et al. 2001; Saiz et al. 2006). Energy studies have also demonstrated how green roofs can act as an additional layer of insulation for the building (DeNardo et al. 2005; Niachou et al. 2001; Kumar and Kaushik 2005).

Figure 7. Retention percentage on the UGA integrated roof system for three precipitation depth categories from 2003 – 2004 (Carter and Rasmussen 2006).

Data from the UGA modular roof system support the conclusions that green roofs provide an insulative barrier for the roof surface. Hilten (2005) studied the UGA test site and found the UGA modular roof to provide insulation equivalent to preformed cellular glass at a 25 mm depth. The eQuest energy model also demonstrated increased performance of the rooftop as it relates to energy savings for the building. For Athens, GA, the model demonstrated that the modular green roof reduced the amount of energy needed to heat or cool a typical office building by 0.3 – 5.0% depending on the build type and configuration (Table 2). Additionally, the energy data from UGA's modular green roof was modeled for a one-story "big box" store of 14,000 m^2. In this case, the ratio of rooftop to internal volume of the building is higher than a commercial building and the reduction in cooling energy loads increased to 12.1% and reductions in heating energy loads increased to 31.7% for Atlanta's climate (Table 2).

Table 2. Energy load reductions using a modular green roof system using UGA modular green roof data compared with an uninsulated built up roof.

City	Building type	Cooling load reduction (%)	Heating load reduction (%)
Athens	commercial (1 story)	5.0	0.9
Athens	commercial (3 stories)	2.6	0.7
Athens	commercial (8 stories)	2.5	0.3
Atlanta	"big box"	12.1	31.7

Green roofs clearly provide additional temperature mitigation for individual rooftops. This provides benefit for the private building owner through reduced energy costs (Carter and Keeler 2008) as well as decreasing the temperature of the stormwater runoff which improves conditions for receiving water bodies. What is not clear is the effect that green roofs would have on the UHI phenomenon since rooftop temperature is only one of UHI's causes. Bass et al. (2003) modeled the effects that green roofs would have on Toronto's UHI and projected that roof greening would lower temperatures city-wide by 0.1-0.8 ° C. This reduction was considered insignificant due to uncertainty in the model predictions.
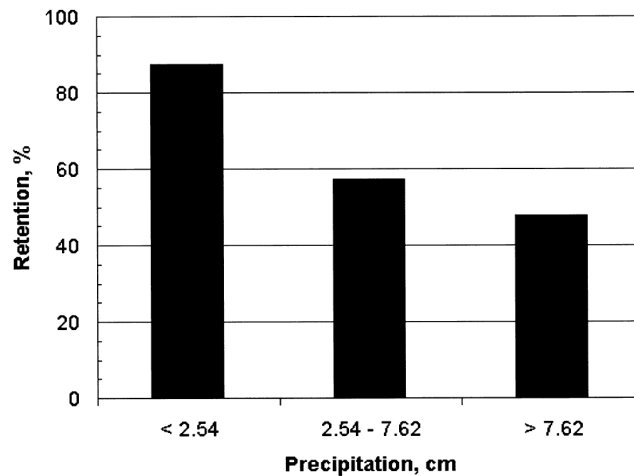
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Regardless of the extent of effect, however, the UGA energy modeling study demonstrates that improvements in rooftop performance from an energy and temperature perspective can be realized using relatively simple, modular green roof systems.

Habitat creation

The results of the Massachusetts green roof experiment underscore the importance of conservative plant choice. While the 2007 summer weather in eastern Massachusetts was highly unusual – August 2007 was the driest August in Boston since 1883 – results from the experiment added to the wealth of data on the extreme drought tolerance of *Sedum* species. With the exception of two large storm events on July 28 and 30, the precipitation for July was typical of New England summers (Table 3). August showed greatly decreased precipitation, only 1.65 cm. These novel weather patterns allowed us to examine plant growth and survival in two distinct precipitation scenarios: normal and extreme drought.

Table 3. Precipitation and temperature in Boston over the study period (July – Oct 2007) compared to 30 year climate averages.

Month	Precipitation (cm)		Temperature (^{o}C)	
	30 year mean	2007	30 year mean	2007
July	7.77	13.41	23.28	22.72
August	8.56	1.65	22.39	22.61
September	8.81	4.6	18.17	19.83
October	9.63	5.28	12.28	15.11

As previously shown (Monterusso et al. 2005; Durhman and Rowe 2006), *Sedum* can withstand extreme water stress. All *Sedum* species showed rapid growth (as seen by increased percent plant cover) between July 18 and August 2, then showed a slight decrease in percent cover between August 2 and August 31 (Figure 8a-c and Figure 9). We found that in periods of the growth season with average rainfall, several non-*Sedum* plants grew and some showed rapid growth (such as *Asclepias verticillata* and *Agastache rupestris*) (Figure 8a-c and Figure 9). However, only *Sedum spp*. had any living aboveground biomass after the August drought. In the spring of 2008, *Festuca glauca* began to re-grow and kept aboveground living biomass throughout the winter, spring, and summer. Several individuals of *Armeria maritima*, *Eryngium yuccifolium*, *Fragaria vesca*, and *Salvia nemorosa* have since grown back and have been growing without supplemental irrigation. Interestingly, the surviving plants (excluding *Festuca glauca* and *Sedum* spp.) were all located in low spots on the roof where water pools after rain (up to 0.5 cm deep). These oases dry up within a few days and consequently, do not represent a continued increase in water availability. This seemingly negligible volume of water seems to have allowed survival of these plants. The results from this experiment are consistent with previous studies examining the efficacy of non-*Sedum* plants on green roofs. Rowe et al. (2006) grew 2 species of *Sedum* and 6 species of Midwestern US prairie species under varying substrate and nutrient regimes. The non-*Sedum* species showed high mortality in all treatments. Monterusso et al. (2005) tested 18 Michigan native plants and found that only 4 were suitable for non-irrigated extensive green roofs. In a study by Licht and Lundholm (2006), 15 Northeastern coastal native plants and 3 *Sedum* species were tested for survival on a non-irrigated extensive green roof in Massachusetts. After a summer without irrigation, only 2 of the 15 native plants survived in comparison to 100% survival of the 3 *Sedum* species. Together, these data suggest that non-*Sedum* plants can only be used on extensive green roofs if supplemental irrigation is available during droughts.
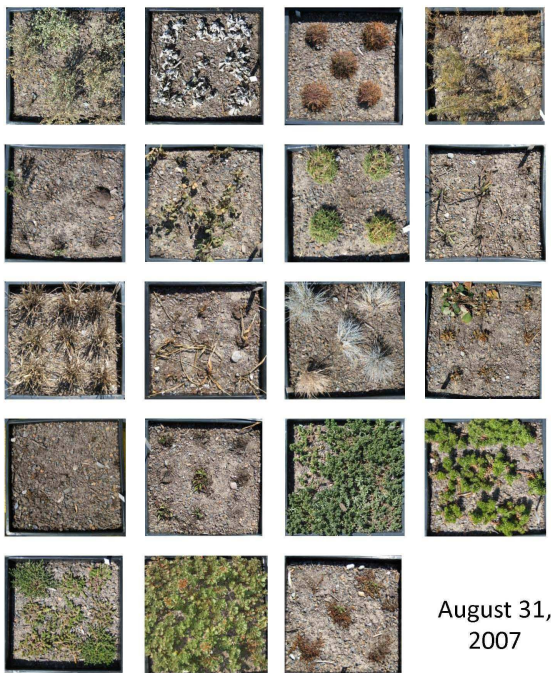
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Figure 8 a-c: Representative overhead photos of each of the 19 species at 3 time points at the Massachusetts site: (a) July 18, 2007, (b) August 16, 2007, and (c) August 31, 2007. Each module pictured is the 3rd replicate of each species.

July 18, 2007
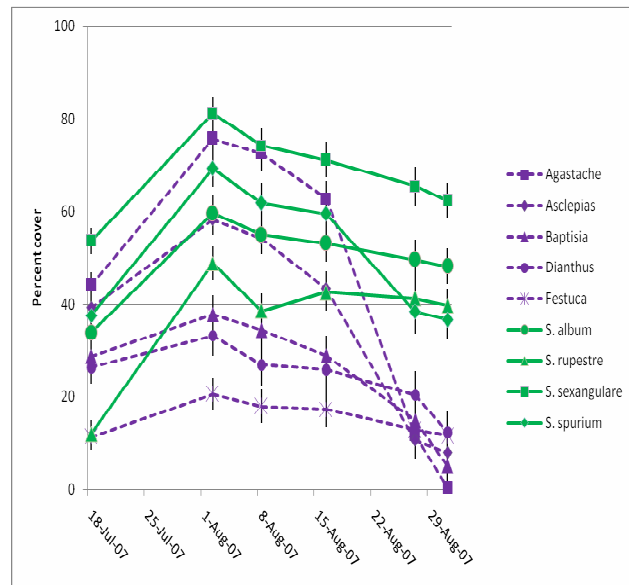
(a)

August 16, 2007

(b)

August 31, 2007
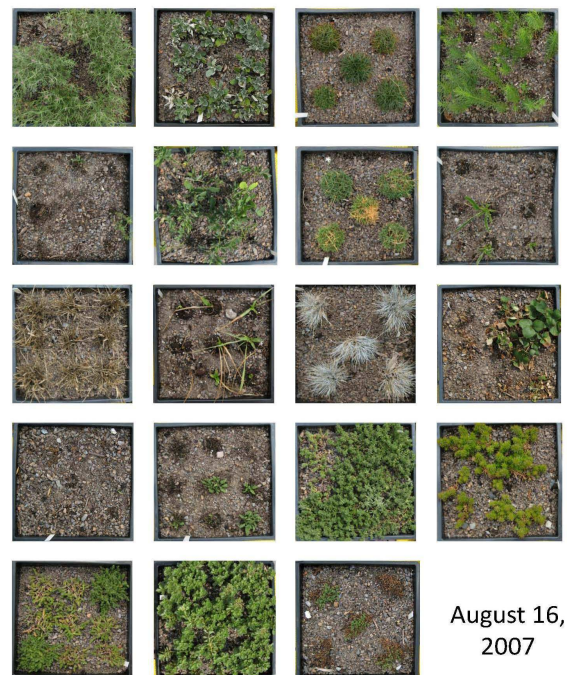
(c)

Figure 9. Change in percent plant cover during July and August 2007 on experimental green roof at Tufts University. *Sedum* species are shown in green and non-*Sedum* species are shown in purple. For clarity, only the 5 fastest growing non-*Sedum* species are shown in this figure. Percent plant cover was determined by analyzing overhead photos of plants using Image J. Data presented are means ± standard error (n=10).

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Future opportunities for green roof study

This study focused on the additional functions provided by extensive green roof systems when compared with traditional roofing systems. As the land consumed by urbanization continues to outpace population growth (Benedict and McMahon 2006), efforts must be made to create multi-functional land cover if some predevelopment ecological function is to be preserved. While complete preservation of these predevelopment functions may not necessarily be achievable or even appropriate, there is often institutional and regulatory considerations that would drive environmental concerns in urban areas in addition to public demand for ecological services (Grimm et al. 2008).

The extent of the above analyses was limited to three major benefits of green roofs including stormwater retention, temperature reduction, and habitat creation through vegetation establishment. Green roofs recreate part of the predevelopment hydrologic cycle through storing rainfall in the pore spaces of the growing media and specialized roofing materials and allowing evaporation, transpiration, and interception functions to remove water from the roof surface. On a non-vegetated roof this water would quickly enter the storm drain system and often a receiving water body as surface runoff. In parcels that contain large amounts of rooftop relative to the total amount of parcel area, green roofs offer an attractive and economically viable option for parcel owners looking to provide stormwater management on their site (Carter and Jackson 2007). A future research direction relating stormwater management and green roofs is to investigate how the complete predevelopment hydrology of a site may be replicated using green roofs as one component of the stormwater management system. To date, stormwater management is primarily focused on water quality or peak flow controls, but researchers have begun to investigate how to replicate a predevelopment hydrograph (Echols 2008). In this case the evapotranspiration of green roofs could be integrated with infiltration, subsurface flow path creation, and groundwater recharge of other engineered systems to recreate predevelopment hydrologic conditions.

The temperature reduction provided by green roofs is a benefit relative to conventional asphalt or built up roof. This benefit may be tempered somewhat, however, by the number of other options available to a building owner interested in reducing rooftop temperatures and building energy costs. For example, highly reflective Thermoplastic Polyolefin (TPO) and ethylene propylene (EP) roofs are becoming a common way for building owners to mitigate rooftop temperatures with EPA's Energy Star program recognizing these and many other types of roof materials and coatings that increase reflectivity and insulation (U.S. Environmental Protection Agency 2008). When energy savings are taken in isolation, green roofs are not economically viable when compared with potentially less expensive practices to mitigate rooftop temperatures. When combined with the stormwater management potential, however, green roofs may overcome the competitive advantage of selecting other roof systems strictly for the temperature and energy savings.

Another important consideration for green roof energy savings is the type of building itself. The green roof energy model demonstrated that energy savings were most pronounced on "big box" types of buildings that contain a large rooftop area relative to the internal heated/cooled space of the building while typical commercial buildings have relatively small energy benefits associated with modular green roof applications (Hilten pers. comm.). Existing and future urban and suburban development forms that contain large one-story structures may be well-poised to capitalize on the energy benefits green roofs provide. These building forms, however, are often found in "strip type" developments that may not be desirable from a planning perspective due to ecological impacts (Arnold and Gibbons 1996). These findings illustrate how more investigation is needed to determine which building designs may maximize particular green roof benefits such as energy savings while different environmental goals may be met within a different built context.

While there is potential for habitat creation on green roofs using non-*Sedum* plants, it is clear from this study that these diverse systems will require more water input to survive. This could be accomplished through the use of a water recycling system within a building to allow for both responsible stormwater management and habitat creation. Additionally, the exclusive use of *Sedum* species still

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provides habitat opportunities for macroinvertebrates. Coffman and Davis (2005) found a wide variety of insects on the Ford Motor Company's green roof which is dominated by *Sedum*. A future area of study may be to evaluate how variation within the *Sedum* genera may be used to encourage specific biotic assemblages. Since extensive green roofs are designed to involve minimal maintenance, another research project would be a long term study of the plant community on a green roof to observe any succession or changes through time that may affect the habitat and biotic community found on the roof.

One challenge facing green roof researchers is the ability to scale up these analyses from a roof scale to an entire jurisdiction and investigating what functions may be lost or gained in the process. A green roof scaling research initiative may be to test how habitat connectivity in urban areas can be increased as green roof installations are linked with regional greenspace plans and policies may be developed to encourage connected greenspace throughout the built landscape. One hypothesis may be that unless the practice occurred on a large proportion of the buildings within a designated green roof connectivity corridor, there would be little landscape-scale habitat benefit to individual green roof systems.

The data collected from these green roof sites demonstrates that a relatively novel urban land cover, a green roof, has the potential to provide ecological services in urban areas. This study also illustrated how the green roofs are specialized in their application and performance is highly dependent upon and constrained by design considerations and project planning goals. In considering green roofs as ecosystems, Oberndorfer et al. (2007) relate green roofs to other constructed ecosystems and extend future research directions to include water quality, air quality, ecosystem function, and cost-benefit analysis. These types of investigations can be performed as more green roofs are built and monitored over extended periods of time and greater spatial scales. As researchers continue to investigate ways to improve urban ecosystem function, the understanding and application of multi-functional land cover like green roofs will be expected to increase. While trade-offs and limitations are inherent in designed systems, the recognition that green roofs are a unique land cover will help drive realistic expectations for how best to incorporate them into urban ecosystems.

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