Environ. Sci. Technol. **2009,** *43,* 7564–7570

Carbon Sequestration Potential of Extensive Green Roofs

KRISTIN L. GETTER,*,†
D. BRADLEY ROWE,†
G. PHILIP ROBERTSON,‡
BERT M. CREGG,† AND
JEFFREY A. ANDRESEN§

Departments of Horticulture and Geography, Michigan State University, East Lansing, Michigan 48824, and Department of Crop and Soil Sciences, W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, Michigan 49060

Received May 26, 2009. Revised manuscript received August 10, 2009. Accepted August 17, 2009.

Two studies were conducted with the objective of quantifying the carbon storage potential of extensive green roofs. The first was performed on eight roofs in Michigan and four roofs in Maryland, ranging from 1 to 6 years in age. All 12 green roofs were composed primarily of *Sedum* species, and substrate depths ranged from 2.5 to 12.7 cm. Aboveground plant material was harvested in the fall of 2006. On average, these roofs stored 162 g C·m^{-2} in aboveground biomass. The second study was conducted on a roof in East Lansing, MI. Twenty plots were established on 21 April 2007 with a substrate depth of 6.0 cm. In addition to a substrate only control, the other plots were sown with a single species of *Sedum* (*S. acre*, *S. album*, *S. kamtshaticum*, or *S. spurium*). Species and substrate depth represent typical extensive green roofs in the United States. Plant material and substrate were harvested seven times across two growing seasons. Results at the end of the second year showed that aboveground plant material storage varied by species, ranging from 64 g C·m^{-2} (*S. acre*) to 239 g C·m^{-2} (*S. album*), with an average of 168 g C·m^{-2}. Belowground biomass ranged from 37 g C·m^{-2} (*S. acre*) to 185 g C·m^{-2} (*S. kamtschaticum*) and averaged 107 g C·m^{-2}. Substrate carbon content averaged 913 g C·m^{-2}, with no species effect, which represents a sequestration rate of 100 g C·m^{-2} over the 2 years of this study. The entire extensive green roof system sequestered 375 g C·m^{-2} in above- and belowground biomass and substrate organic matter.

Introduction

Establishing green roofs, or vegetated roofs, can improve stormwater management (*1*–*4*), conserve energy (*5, 6*), mitigate urban heat island effects (*7*), increase longevity of roofing membranes (*8*), improve return on investment compared to traditional roofs (*9*), reduce noise and air pollution (*10, 11*), increase urban biodiversity (*12, 13*), and provide a more aesthetically pleasing environment (*14, 15*). Green roofs are either "intensive" or "extensive". Intensive green roofs may include shrubs and trees and appear similar to landscaping found at natural ground level. As such, they require substrate depths greater than 15 cm and have "intense" maintenance needs. In contrast, extensive green roofs consist of herbaceous perennials or annuals, use shallower media depths (less than 15 cm), and require minimal maintenance. Due to building weight restrictions and costs, shallow substrate extensive green roofs are more common than deeper intensive roofs and will be the focus of this study.

Although green roofs are often adopted for energy savings and heat island mitigation, rarely has this technology been promoted for its ability to mitigate climate change. By lowering demand for heating and air conditioning use, less carbon dioxide is released from power plants and furnaces. Sailor (*6*) integrated green roof energy balance into Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. This simulation found a 2% reduction in electricity consumption and a 9–11% reduction in natural gas consumption. Based on a model of a generic building with a 2000 m^2 of green roof, these annual savings ranged from 27.2 to 30.7 GJ of electricity saved and 9.5 to 38.6 GJ of natural gas saved, depending on climate and green roof design. When considering the national averages of CO_2 produced for generating electricity and burning natural gas (*16, 17*), these figures translate to 637–719 g C per m^2 of green roof in electricity and 65–266 g C per m^2 of green roof in natural gas each year. Another 25% reduction in electricity use may additionally occur due to indirect heat island reduction achieved from large-scale green roof implementation throughout an urban area (*18*).

Green roofs may also sequester carbon in plants and soils. Photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant biomass, a process commonly referred to as terrestrial carbon sequestration. Carbon is transferred to the substrate via plant litter and exudates. The length of time that this carbon remains in the soil before decomposition has yet to be quantified for green roofs, but if net primary production exceeds decomposition, this man-made ecosystem will be a net carbon sink, at least in the short term.

However, this ecosystem will not likely sequester large amounts of carbon due to the types of species used and shallow substrate. Many species used on extensive green roofs exhibit some form of Crassulacean acid metabolism (CAM; 14). CAM photosynthesis operates by opening stomata during the night to uptake CO_2 and storing it in the form of an organic acid in the cells' vacuoles. During the following daylight period, stomata remain closed while stored organic acid is decarboxylated back into CO_2 as the source for the normal photosynthetic carbon reduction cycle (*19*). When operating in CAM mode, rates for daily carbon assimiliation are 1/2 to 1/3 that of non-CAM species (*20*).

The goal of this research was to evaluate the intrinsic carbon storage potential of extensive green roofs and the effect of species selection on carbon accumulation. Two studies were conducted in the United States to meet these objectives.

Materials and Methods

Study 1. Aboveground biomass was determined on eight *Sedum* based extensive green roofs in Michigan and four roofs in Maryland (Table 1). Roofs ranged from 1 to 6 years in age and from 2.5 to 12.7 cm in substrate depth. Aboveground biomass was sampled in quadruplicate on each roof with a 13.0 cm ring during the fall of 2006 (see Table 1 for specific dates). Any aboveground biomass that was within the ring was clipped at substrate level, placed in paper bags, and dried in an oven at 70 °C for 1 week. Samples were then

---

* Corresponding author e-mail: smithkri@msu.edu.

† Department of Horticulture, Michigan State University.

‡ Department of Crop and Soil Sciences, Michigan State University.

§ Department of Geography, Michigan State University.

10.1021/es901539x CCC: $40.75

TABLE 1. Location and Description of Sampled Green Roofs[a]

roof	date originally planted	sample date	location	comments
CA2.5	May 2005	9/6/2006	Michigan State University (MSU) Communication Arts (CA) Building, East Lansing, MI	Research plots placed directly on roof. Primary species included *S. album*, *S. middendorffianum*, *S. sexangulare*, and *S. spurium*.
CA3.2	May 2005	9/6/2006	MSU Communication Arts Building, East Lansing, MI	Research plots placed directly on roof. Primary species included *S. album*, *S. kamtschaticum*, *S. middendorffianum*, and *S. sexangulare*.
FORD	fall 2002	9/1/2006	Ford Motor Company (FORD), Rouge Plant, Dearborn, MI	4047 m^2 extensive green roof. Primary species included *S. acre*, *S. album*, *S. kamtschaticum*, and *S. middendorffianum.*
HTRC2.5	June 2003	9/5/2006	MSU Horticulture Teaching and Research Center (HTRC), East Lansing, MI	Roof platform. Primary species included *S. acre*, *S. album*, *S. middendorffianum*, and *S. spurium.*
HTRC5	June 2003	9/5/2006	MSU HTRC, East Lansing, MI	Roof platform. Primary species included *S. acre*, *S. album*, *S. kamtschaticum*, *S. middendorffianum*, *S. reflexum*, and *S. spurium*.
HTRC6	May 2002	9/5/2006	MSU HTRC, East Lansing, MI	Roof platform. Primary species included *S. acre*, *S. album*, and *S. spurium*.
HTRC7.5	June 2003	9/5/2006	MSU HTRC, East Lansing, MI	Roof platform. Primary species included *S. album*, *S. kamtschaticum*, *S. middendorffianum*, *S. reflexum*, and *S. spurium*.
MDG	Sept 2005	9/7/2006	MDG Corporation, Columbia, MD	752 m^2 extensive green roof. Primary species included *S. album*, *S. kamtschaticum*, *S. middendorffianum*, *S. spurium*, *S. boehmeri*, and *Talinum* spp.
MF	spring 2002	9/7/2006	Metfab (MF), Jessup, MD	232 m^2 extensive green roof. Primary species included *Delosperma* spp., *S. hispanicum*, *S. kamtschaticum*, *S. middendorffianum*, *S. sexangulare*, and *S. spurium*.
PSSB	May 2004	9/1/2006	MSU Plant and Soil Sciences Building (PSSB), East Lansing, MI	325 m^2 extensive green roof. Primary species included *S. acre*, *S. album*, *S. kamtschaticum*, *S. reflexum*, and *S. spurium*.
RC	fall 2002	9/7/2006	Renaissance Center (RC) at South River Colony, Edgewater, MD	1300 m^2 extensive green roof. Primary species included *Allium* spp., *S. album*, *S. reflexum*, *S. sarmentosum*, *S. sexangulare*, and *S. spurium*.
SEV	May 2006	9/7/2006	Severn (SEV) Savings Bank Headquarters, Annapolis, MD	1161 m^2 extensive green roof. Primary species included *S. album*, *S. kamtschaticum*, and *S. spurium*.

[a] Each location was sampled in four random places on the sampling date.

weighed and ground to pass a 60-mesh stainless steel screen using a Wiley mill. The material was stored in glass vials in a desiccator to prevent moisture uptake prior to carbon analysis. Total carbon concentration was determined with the use of a Carlo Erba NA1500 Series 2 N/C/S analyzer (CE Instruments, Milan, Italy). Carbon accumulation was determined by multiplying dry matter weight by total C concentration. Regression analysis was performed with location of the roof (Michigan or Maryland) as a categorical independent variable and age of roof (in months) and substrate depth of the roof (in cm) as independent variables against grams of carbon per square meter of green roof as the dependent variable (PROC REG, SAS version 9.1, SAS Institute, Cary, NC).

Study 2. The second study was performed on the roof of the Plant and Soil Sciences Building on the campus of Michigan State University in East Lansing, MI. An existing extensive green roof was expanded on 21 April 2007 to include a study area measuring 2.84 × 4.6 m with 20 plots, each measuring 0.71 × 0.92 m. The study area was covered with a Xero Flor XF108 drainage layer (Xero Flor America LLC, Durham, NC) installed over the waterproofing system. Above the drainage layer, substrate (Table 2) was installed to a uniform depth of 6.0 cm, which represents the physical limitations of this building and many other roofs in the U.S.

Each plot was covered with one of four species of *Sedum* typically used on U.S. green roofs: *Sedum acre* L. (biting stonecrop), *Sedum album* L. (white stonecrop), *Sedum kamtschaticum* var. *ellacombianum* Fisch. (stonecrop), and *Sedum spurium* Bieb. “Summer Glory” (creeping sedum). A fifth “substrate only” treatment was also used. Planted plots were sown with 0.65 g of seeds of the treatment species (Jelitto Staudensamen, GmbH, Schwarmstedt, Germany) mixed with 20.0 g of fine vermiculite (Therm-O-Rock, Inc., New Eagle, PA) and distributed evenly. The “substrate only” treatment had 20.0 g of fine vermiculite distributed evenly across it. This arrangement resulted in a randomized complete block design, with four replicates and five treatments. To improve seed germination, the entire study area was covered with shade cloth until 27 June 2007. In addition, the roof was irrigated for the first three months, three times daily for 20 min, with 2.8 mm applied at each irrigation cycle. Weeding occurred on a monthly basis when needed, and weeds were not included in the carbon analysis.

Carbon analysis was performed by sampling aboveground biomass, belowground biomass (roots), and substrate carbon content over two growing seasons. Sampling occurred every second month (30 June 2007, 23 August 2007, 17 October 2007, 15 April 2008, 12 June 2008, 15 August 2008, 13 October 2008) in order to capture the full variability of the green roof ecosystem, especially since different species exhibit varying growth rates and timing of peak biomass. To keep track of which portions of a plot had been sampled, a transect was used to split each plot into 12 equal portions. The portion that was sampled was randomized and recorded so that no portion was sampled twice.

TABLE 2. Initial Physical and Chemical Properties of Substrate[a]

component	unit	method
total sand	0.79 g·g^{-1}	*41*
very coarse sand (1–2 mm)	0.13 g·g^{-1}	*41*
coarse sand (0.5–1 mm)	0.25 g·g^{-1}	*41*
medium sand (0.25–0.5 mm)	0.29 g·g^{-1}	*41*
fine sand (0.10–0.25 mm)	0.11 g·g^{-1}	*41*
very fine sand (0.05–0.10 mm)	0.01 g·g^{-1}	*41*
silt	0.15 g·g^{-1}	*42*
clay	0.06 g·g^{-1}	*42*
bulk density[b]	1.17 g·cm^{-3}	*43*
capillary pore space	0.34 cm^{3}·cm^{-3}	*43*
non-capillary pore space	0.09 cm^{3}·cm^{-3}	*43*
water holding capacity at 0.01 MPa	0.29 cm^{3}·cm^{-3}	*43*
pH	8.2	*44*
conductivity (EC)	10.36 mmho·cm^{-1}	*44*
organic matter by LOI @ 360 C[c]	5.6 g·kg^{-1}	*44*
organic carbon[d]	810 g·m^{-2}	*45*
nitrate	2.0 μg·g^{-1}	*44*
phosphorus	53.9 μg·g^{-1}	*44*
potassium	2174.0 μg·g^{-1}	*44*
calcium	208.0 μg·g^{-1}	*44*
magnesium	57.0 μg·g^{-1}	*44*
sodium	439.0 μg·g^{-1}	*44*
sulfur	434.0 μg·g^{-1}	*44*
boron	1.5 μg·g^{-1}	*44*
iron	74.0 μg·g^{-1}	*44*
manganese	25.4 μg·g^{-1}	*44*
zinc	24.5 μg·g^{-1}	*44*
copper	3.0 μg·g^{-1}	*44*

[a] Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, Indiana. [b] Including gravel. [c] Gravel free. [d] Calculated from organic matter LOI per Jolivet et al. (*45*).

At each collection time, aboveground biomass was sampled and analyzed as in study 1. Belowground substrate carbon content and belowground biomass were also determined at each sampling time. All substrate and belowground biomass were removed from the 13.0 cm ring into a plastic bag. The entire bag was weighed, and the substrate was passed through a 4.0 mm sieve. Gravel that was retained on the sieve was saved and weighed. Roots were removed from the retained and sieved matter with forceps. Roots were then cleaned with a phosphate-free dilute detergent followed by a 0.01 mol·L^{-1} NaEDTA solution for 5 min; each cleaning was followed by a rinse with deionized water. The cleaned roots were placed in paper bags and dried for 2 days at 65 °C. Dried biomass was ground and analyzed for carbon as previously described. Remaining sieved substrate was mixed, and a portion (25.0 g) was removed and oven dried at 105 °C in a small paper bag. Dried substrate and bag weight were subtracted from original weight to determine moisture content. All substrate material was ground with a roller mill until it was a completely pulverized powder and then analyzed for carbon as above.

Mean percent carbon and grams of carbon per square meter were analyzed using an ANOVA model with species as a fixed effect. Significant differences between treatments were determined using multiple comparisons by LSD (least significant difference) (PROC MIXED, SAS version 9.1, SAS Institute, Cary, NC).

Results and Discussion

Study 1: Aboveground Harvest of 12 Green Roofs. Average aboveground carbon stored at the time of sampling for the 12 roofs was 162 g C·m^{-2} (Table 3). These figures are based on the end of the growing season (after flowering) and, therefore, should be the maximal biomass of most *Sedum* species. However, there was a high degree of variability. Carbon sequestered ranged from 73 to 276 g C·m^{-2}.

Regression analysis showed no significant correlations between the data variables collected and grams of carbon sequestered (data not shown). However, age of the green roof and substrate depth may be confounding factors, because substrate depth has been shown to influence plant growth on a green roof (*21*, *22*). For example, three roofs have a mean substrate depth of 2.5 cm (Table 3) and increase in carbon with respect to age.

TABLE 3. Mean Carbon (g·m^{-2}) ± Standard Errors for Aboveground Biomass on Twelve Extensive Green Roofs[a]

roof[b]	mean substrate depth (cm)	age at sampling (months)	plant aboveground carbon (g·m^{-2})
CA2.5	2.5	15	97 ± 27.9
CA3.2	3.2	15	127 ± 19.0
FORD	2.5	48	196 ± 64.8
HTRC2.5	2.5	39	144 ± 16.0
HTRC5	5.0	39	159 ± 32.4
HTRC6	6.0	52	224 ± 52.6
HTRC7.5	7.5	39	202 ± 11.1
MDG	7.0	12	73 ± 16.0
MF	7.1	53	189 ± 33.5
PSSB	4.0	28	149 ± 26.7
RC	6.4	48	276 ± 28.0
SEV	10.8	4	112 ± 30.1
mean			162 ± 11.7

[a] Each location was sampled in four random places on a single sampling date. [b] See Table 1 for descriptions and other sampling information.

It is likely that other variables that were not captured here may be contributing to the wide variability in carbon storage. For example, management techniques would likely affect how much carbon can be sequestered in aboveground material at any given time. Fertilizer applications or the use of supplemental irrigation may increase plant biomass since nitrogen and water often limit primary production in many ecosystems (*23*). Design choices may also influence carbon

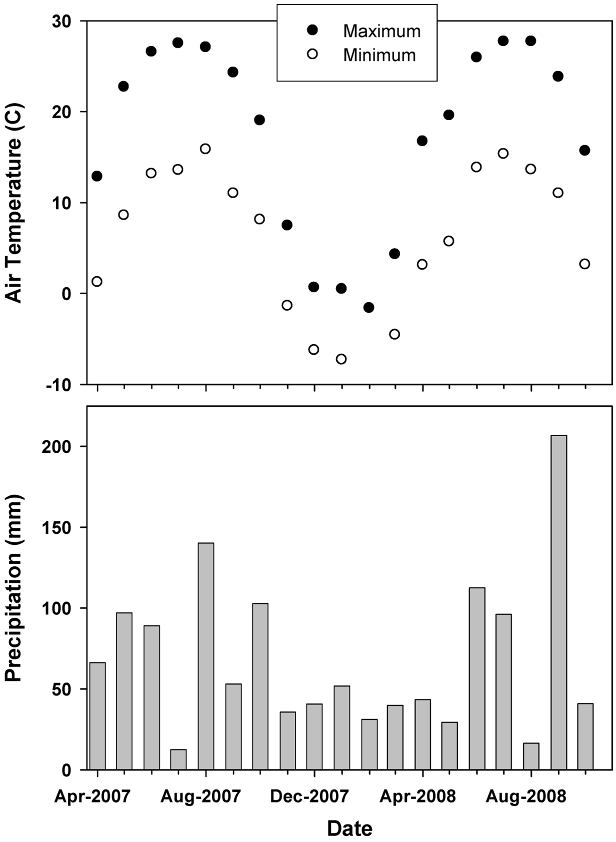

FIGURE 1. Monthly average maximum air temperatures (°C), monthly average minimum air temperatures (°C), and monthly total precipitation (mm) throughout the study (1 April 2007 to 31 October 2008). Data are from the nearby Michigan Automated Weather Network's East Lansing, MI, weather station.

storage. For example, substrate composition has been shown to affect plant growth on an extensive green roof (*24, 25*), which in turn affects total aboveground carbon. Species selection may also impact aboveground carbon stores, as species vary in their net primary production and allocation to biomass (*26*).

Study 2: Plant and Substrate Carbon Accumulation. Monthly average maximum air temperatures (°C), monthly average minimum air temperatures (°C), and monthly total precipitation (mm) (not including initial irrigation) are shown in Figure 1. East Lansing, MI is in the midwestern U.S. and is characterized as a temperate climate with four well-defined seasons. Thirty-year average mean low temperatures in January and high temperatures in July are −10.2 and 27.5 °C, respectively. The average number of days per year with precipitation greater than 2.54 mm is 70.3, which are generally well distributed throughout the year (*27*).

Harvest date, species, and their interaction affected total C for above- and belowground plant biomass but not for substrate (Table 4). Across all species, mean carbon on an area basis in aboveground biomass was comparable to the previous study, averaging 168 g C·m^{-2} at the end of the second year (Table 5). *Sedum album* held the greatest amount of carbon, followed by *S. kamtschaticum*, *S. spurium*, and *S. acre*. Carbon contained in root biomass averaged 107 g C·m^{-2} at the end of the second growing season (Table 5). Root biomass values for *S. kamtschaticum* were highest, while values for *S. acre* were lowest. The relatively low allocation to roots may help explain why *S. acre* seems to be the least heat and drought tolerant species among those tested.

At the end of the second growing season, substrate carbon content averaged 913 g C·m^{-2} (Table 5). Unlike the plant material, there were no significant differences among species treatments for substrate carbon content. At establishment, substrate consisted of 810 g C·m^{-2} (Table 2). As such, there was 100 g C·m^{-2} sequestered in the soils after two growing seasons.

Percent carbon averaged 42.1% C, 41.4% C, and 4.6% C for aboveground biomass, root biomass, and substrate, respectively (Table 5). The percentage of carbon stored in plant tissues is slightly lower than the expected 45−50% C in most other vascular plants (*28*−*30*) but is similar to other succulent species (*31*). Substrate values correspond well to other ecosystems (*32, 33*). Averaged across species, aboveground and root carbon (g·m^{-2}) increased the first year as plants established themselves and then remained steady throughout the second growing season (Figure 2). Substrate carbon also remained steady over the two growing seasons.

For individual species, first year above ground carbon for *S. acre* was similar to the other species, but by the end of the second season, *S. acre* held the lowest amount of carbon (Figure 3). This may be because the second growing season did not have supplemental irrigation and *S. acre* is known to die back in hot growing conditions (*34*). The other three species also declined through the hottest portion of the second growing season without irrigation (July and August 2008) but then rebounded by October 2008. For two species, aboveground carbon decreased slightly between the end of the first and the beginning of the second growing season (Figure 3). This likely occurred because these species are either semievergreen (*S. spurium*) or deciduous (*S. kamtschaticum*) and full spring leaf-out had not yet occurred on the first sampling of 2008. In contrast, aboveground carbon values for *S. acre* and *S. album*, both evergreen species, are very similar before and after the winter dormant season.

Over time, *S. kamtschaticum* contains the greatest carbon in root biomass (Figure 3). This is likely due to the woody nature of this species' roots (personal observation). However, all species generally increased in root carbon across both growing seasons. *Sedum acre* allocated the least amount of

TABLE 4. ANOVA Table for Mean Carbon (g·m^{-2}) over Two Growing Seasons (April 2007 to October 2008) for Four Species and a Substrate Only Treatment Replicated Four Times[a]

	aboveground			roots			substrate		
source of variation	**DF**	***F***	***P* > *F***	**DF**	***F***	***P* > *F***	**DF**	***F***	***P* > *F***
block	3	3.57	0.0176	3	2.21	0.1414	3	1.26	0.2640
date harvested[b]	6	22.1	<0.0001	6	43.16	<0.0001	6	1.87	0.0951
species[c]	3	5.91	0.0011	3	82.92	<0.0001	4	1.9	0.1174
date harvested × species	18	2.73	0.0011	18	5.83	<0.0001	24	0.56	0.9440

[a] Grams of carbon per square meter of green roof is the dependent variable. Date harvested and species are independent variables. [b] Dates harvested were 30 June 2007, 23 August 2007, 17 October 2007, 15 April 2008, 12 June 2008, 15 August 2008, and 13 October 2008. [c] Species included *Sedum acre*, *Sedum album*, *Sedum kamtschaticum*, *Sedum spurium*, and a "substrate only" treatment.

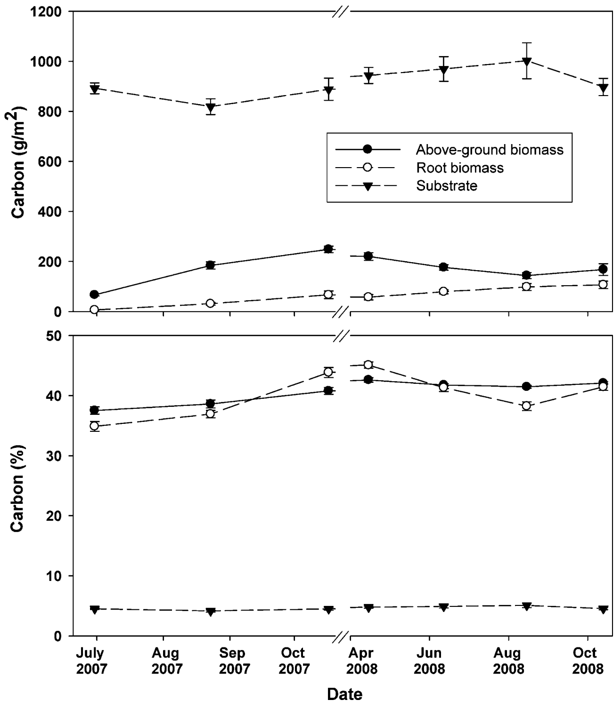

FIGURE 2. Carbon content ± standard errors for aboveground biomass, root biomass, and substrate across two growing seasons (April 2007 to October 2008).

carbon to roots. For substrate carbon over time, all species treatments remained steady throughout the study.

Application. This entire extensive green roof system sequestered 375 g C·m^{-2} (168 g C·m^{-2} in aboveground plant biomass, 107 g C·m^{-2} in belowground plant biomass, and 100 g C·m^{-2} in substrate carbon) beyond what was stored in the initial substrate (Table 2; Table 5). However, many components of a green roof have a carbon "cost" in terms of the manufacturing process. Embodied energy describes the total energy consumed, or carbon released, by a product over its life cycle. Typical components of a green roof include a root barrier installed on top of the normal roofing membrane (which protects the roof from root penetration damage), a drainage layer above the root barrier (which allows excess water to flow away from the roof), and a growing substrate. Many life cycle analysis studies ignore these unique components of a green roof by making the assumption that the root barrier, drainage layers, substrate, and plant material will all have a carbon cost similar to the traditional roofs' gravel ballast (*35, 8*), but this assumption may not be valid.

Hammond and Jones (*36*) analyzed building materials through the entire production process. Material consisting of low density polyethylene (LDPE) similar to a root barrier was found to average 78.1 MJ·kg^{-1} of embodied energy or 1.7 kg CO_2·kg^{-1} of embodied carbon. Assuming 0.51 mm thickness and a density of 925 kg·m^{-3} (Raven Industries, Sioux Falls, SD), there are 219 g C per m^2 in the root barrier. Drainage layers are commonly made from polypropylene (Colbond Inc., Enka, NC) which contains 5.0 kg CO_2 per kg of product (*36*). Assuming a weight of 0.39 kg·m^{-2} (Xero Flor America LLC, Durham, NC), there are 535 g C per m^2 in the

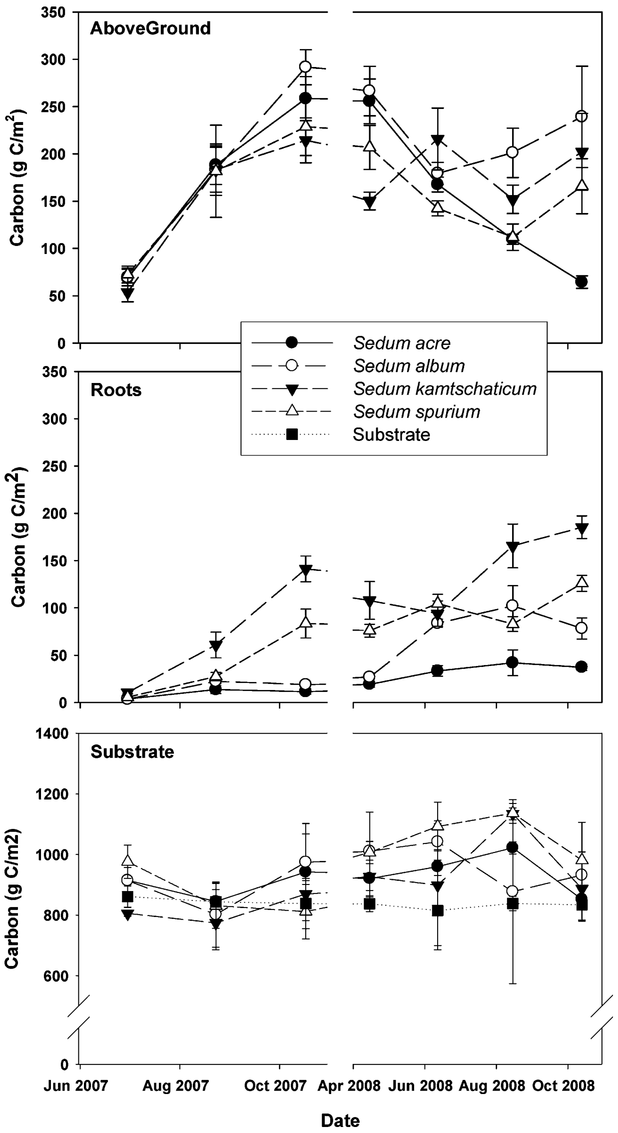

FIGURE 3. Carbon content ± standard errors for aboveground biomass, root biomass, and substrate across two growing seasons for four species and substrate only treatment (April 2007 to October 2008).

TABLE 5. Mean ± Standard Errors of Total Carbon and Carbon Concentrations of *Sedum* Based Green Roofs at the End of the Second Growing Season (13 October 2008) in East Lansing, MI[a]

	above ground		roots		substrate		
species	C·m^{-2} (g)	C (%)	C·m^{-2} (g)	C (%)	C·m^{-2} (g)	C (%)	total C·m^{-2}(g)
S. acre	64 ± 6.5 A	43.6 ± 0.2 A	37 ± 3.4 A	37.2 ± 1.5 A	852 ± 72.0 A	4.3 ± 0.4 A	953 ± 75.0 A
S. album	239 ± 53.6 B	42.7 ± 0.2 A	78 ± 11.3 B	40.9 ± 0.7 AB	932 ± 77.0 A	4.7 ± 0.4 A	1,249 ± 75.8 A
S. kamtschaticum	202 ± 40.5 B	40.5 ± 0.1 A	185 ± 12.0 D	43.8 ± 0.2 B	887 ± 98.1 A	4.5 ± 0.3 A	1,275 ± 183.7 A
S. spurium	166 ± 29.1 B	41.5 ± 0.3 A	126 ± 8.5 C	43.8 ± 0.2 B	981 ± 125.1 A	4.9 ± 0.5 A	1,272 ± 118.8 A
substrate only					834 ± 50.6 A	4.2 ± 0.3 A	
mean	168 ± 23.5	42.1 ± 0.2	107 ± 14.9	41.4 ± 0.6	913 ± 34.6[b]	4.6 ± 0.2	1,187 ± 58.8

[a] Mean separation in columns by LSD ($P \leq 0.05$). Uppercase letters in columns denote differences among species (n = 16). [b] Not including substrate only treatment. At establishment, substrate consisted of 810 g C·m^{-2} (Table 2).

drainage layer. The embodied energy for a substrate of sand and expanded slate is 0.005 and 0.44 kg $CO_2 \cdot kg^{-1}$, respectively (*36, 37*). A 6.0 cm substrate depth consisting of half sand and half expanded slate by volume with densities of 2240 and 1600 $kg \cdot m^{-3}$, respectively (*36, 38*), thus have 92 and 5769 g C per m^2 of substrate. These green roof components add up to an embodied carbon content of 6.6 kg C per m^2 of green roof.

On the other hand, a traditional roof may also have a gravel ballast, which is no longer needed on a green roof. Assuming a density of 1800 $kg \cdot m^{-3}$ and a 2 cm depth, a gravel ballast has an embodied energy content of 0.017 kg $CO_2 \cdot kg^{-1}$ or 167 g C per m^2 of roof (*36*). When the unneeded ballast is subtracted out, total adjusted embodied carbon for the extensive green roof components above that of a traditional roof is then 6.5 kg C per m^2 of green roof.

While the embodied energy in the initial green roof system is greater than what is stored in the substrate and plant biomass at any given time, the emissions avoided due to energy savings should pay for those costs in time. Sailor (*6*) integrated the green roof energy balance into Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. His simulations found a 2% reduction in electricity consumption and a 9−11% reduction in natural gas consumption. Based on his model of a generic building with a 2000 m^2 green roof, the minimum annual savings were 27.2 GJ of electricity and 9.5 GJ of natural gas. When considering the greenhouse gas potential for generating electricity and burning natural gas (*16, 17*), these figures translate to 702 g C per m^2 of green roof in electricity and natural gas savings combined per year. Since the embodied cost is 6.5 kg $C \cdot m^{-2}$ (see above), nine years will be needed to offset the carbon debt of the green roof materials. After this time, the emissions avoided would simply add on to the sequestration potential of the roof. The carbon sequestered by growing biomass (375 g $C \cdot m^{-2}$ in this study) will shorten the carbon payback period in this scenario by two years.

Roofs are typically unused spaces; therefore, they provide a unique opportunity to sequester carbon. For example, in the Detroit metropolitan area, land area of rooftops is estimated to be 6335 and 8399 ha of commercial and industrial land use, respectively (*39*). If all of these roofs were covered with vegetation in a design similar to this study and, thus, were able to sequester 375 g $C \cdot m^{-2}$ of green roof, 55 252 t of carbon could be sequestered in the plants and substrates alone (not including avoided emissions). This is similar to removing more than 10 000 midsized SUV or trucks off the road for a year (*40*). While these figures depend on climate and green roof design, they nonetheless represent a small but significant potential for sequestering carbon in urban environments.

Acknowledgments

Funding for these studies was provided by Ford Motor Company, Dearborn, MI; XeroFlor America LLC, Durham, NC; Michigan Nursery and Landscape Association, Okemos, MI; and the Michigan Agricultural Experiment Station.

Literature Cited

(1) Carter, T.; Jackson, C. R. Vegetated roofs for stormwater management at multiple spatial scales. *Landscape and Urban Planning* **2007**, *80*, 84–94.

(2) Getter, K. L.; Rowe, D. B.; Andresen, J. A. Quantifying the effect of slope on extensive green roof stormwater retention. *Ecol. Eng.* **2007**, *31*, 225–231.

(3) Hilten, R. N.; Lawrence, T. M.; Tollner, E. W. Modeling stormwater runoff from green roofs with HYDRUS-1D. *J. Hydrol.* **2008**, *358*, 288–293.

(4) Jarrett, A. R.; Berghage, R. D. Annual and individual green roof stormwater response models. *Proceedings of the 6th North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Baltimore, MD, April 30, 2008−May 2, 2008; The Cardinal Group: Toronto, 2008.

(5) Santamouris, M.; Pavlou, C.; Doukas, P.; Mihalakakou, G.; Synnefa, A.; Hatzibiros, A.; Patargias, P. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. *Energy* **2007**, *32*, 1781–1788.

(6) Sailor, D. J. A green roof model for building energy simulation programs. *Energy and Buildings* **2008**, *40*, 1466–1478.

(7) Takebayashi, H; Moriyama, M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Build. Environ.* **2007**, *42*, 2971–2979.

(8) Kosareo, L.; Ries, R. Comparative environmental life cycle assessment of green roofs. *Build. Environ.* **2007**, *42*, 2606–2613.

(9) Clark, C.; Adriaens, P.; Talbot, F. B. Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits. *Environ. Sci. Technol.* **2008**, *42*, 2155–2161.

(10) Van Renterghem, T.; Botteldooren, D. Numerical evaluation of sound propagating over green roofs. *J. Sound and Vibration* **2008**, *317*, 781–799.

(11) Yang, J.; Yu, Q.; Gong, P. Quantifying air pollution removal by green roofs in Chicago. *Atmos. Environ.* **2008**, *42*, 7266–7273.

(12) Baumann, N. Ground-Nesting Birds on Green Roofs in Switzerland: Preliminary Observations. *Urban Habitats* **2006**, *4*, 37–50.

(13) Brenneisen, S. Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland. *Urban Habitats* **2006**, *4*, 27–36.

(14) Getter, K. L.; Rowe, D. B. The role of extensive green roofs in sustainable development. *HortScience* **2006**, *41* (5), 1276–1285.

(15) Oberndorfer, E.; Lundholm, J.; Bass, B.; Coffman, R. R.; Doshi, H.; Dunnett, N.; Gaffin, S.; Köhler, M.; Liu, K. K. Y.; Rowe, D. B. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *BioScience* **2007**, *57* (10), 823–833.

(16) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: Fast Facts 1990−2005. Conversion Factors to Energy Units (Heat Equivalents) Heat Contents and Carbon Content Coefficients of Various Fuel Types*; EPA-430-R-07-002; U.S. Environmental Protection Agency: Washington, DC, 2007.

(17) *Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance: Indirect Emissions from Purchases/Sales of Electricity and Steam*; EPA-430-K-03-006; U.S. Environmental Protection Agency: Washington, DC, 2008.

(18) Akbari, H.; Konopacki, S. Calculating energy-saving potentials of heat island reduction strategies. *Energy Policy* **2005**, *33* (6), 721–56.

(19) Cushman, J. C. Crassulacean acid metabolism: A plastic photosynthetic adaptation to arid environments. *Plant Physiol.* **2001**, *127*, 1439–1448.

(20) Hopkins, W. G.; Hüner, N. P. A. *Introduction to Plant Physiology*, 3rd ed; John Wiley & Sons, New York, 2004.

(21) Durhman, A. K.; Rowe, D. B.; Rugh, C. L. Effect of substrate depth on initial coverage, and survival of 25 succulent green roof plant taxa. *HortScience* **2007**, *42* (3), 588–595.

(22) Getter, K. L.; Rowe, D. B. Media Depth Influences *Sedum* Green Roof Establishment. *Urban Ecosyst.* **2008**, *11*, 361–372.

(23) Vitousek, P. M.; Howarth, R. W. Nitrogen limitation on land and in the sea: How can it occur. *Biogeochemistry* **1991**, *13*, 87–115.

(24) Hunt, W. F.; Hathaway, A. M.; Smith, J. T.; Calabria, J. Choosing the right green roof media for water quality. *Proceedings of the 4th North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Boston, MA, May 11−12, 2006; The Cardinal Group: Toronto, 2006.

(25) Rowe, D. B.; Monterusso, M. A.; Rugh, C. L. Assessment of heat-expanded slate and fertility requirements in green roof substrates. *HortTechnology* **2006**, *16* (3), 471–477.

(26) Naeem, S.; Håkansson, K.; Lawton, J. H.; Crawley, M. J.; Thompson, L. J. Biodiversity and plant productivity in a model assemblage of plant species. *Oikos* **1996**, *76* (2), 259–264.

(27) Michigan State Climatologist's Office. Michigan Climatological Resources Program. Available at http://climate.geo.msu.edu/ (accessed 2008).

(28) Ovington, J. D. The volatile matter, organic carbon and nitrogen contents of tree species grown in close stands. *The New Physiologist* **1957**, *56*, 1–11.

(29) Pettersen, R. C. The Chemical composition of wood. In *The chemistry of solid wood; Advances in chemistry*; Rowell, R. M., Ed.; Series 207; American Chemical Society: Washington, DC, 1984.

(30) Schlesinger, W. H. *Biogeochemistry: An Analysis of Global Change*; Academic Press: San Diego, CA, 1997.

(31) Lindsay, E. A.; French, K. *Chrysanthemoides monilifera* ssp. *rotundata* invasion alters decomposition rates in coastal areas of south-eastern Australia. *For. Ecol. Manage.* **2004**, *198*, 387–399.
(32) Jones, R. J. A.; Hiederer, R.; Rusco, E.; Montanarella, L. Estimating organic carbon in the soils of Europe for policy support. *Eur. J. Soil Sci.* **2005**, *56*, 655–671.
(33) Harte, J.; Saleska, S.; Shih, T. Shifts in plant dominance control carbon-cycle responses to experimental warming and widespread drought. *Environ. Res. Lett.* **2006**, *1*, 014001.
(34) Snodgrass, E.; Snodgrass, L. *Green Roof Plants: A Resource and Planting Guide*; Timber Press, Inc.: Portland, OR, 2006.
(35) Alcázar, S. S.; Bass, B. Life cycle assessment of green roofs—case study of an eight-story residential building in Madrid and implications for green roof benefits. *Proceedings of the 4th North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Boston, MA, May 11−12, 2006; The Cardinal Group: Toronto, 2006.
(36) Hammond, G. P.; Jones, C. I. Embodied energy and carbon in construction materials. *Proc. Inst. Civ. Eng.: Energy* **2008**, *161* (2), 87–98.
(37) GBC. The Green Building Challenge Handbook of the D-A-C-H clay brick industry. Available at http://www.ziegel.at/gbc-ziegelhandbuch/Default-eng.htm (accessed 2008).
(38) Expanded Shale, Clay and Slate Institute. Lightweight Expanded Shale, Clay and Slate Aggregate for Geotechnical Applications Information Sheet 6001. Available at http://www.escsi.org/pdfdoc1/Geotech_Info_Sheet__6001-June_2008.pdf (accessed 2008).
(39) Clark, C.; Talbot, B.; Bulkley, J.; Adriaens, P. Optimization of green roofs for air pollution mitigation. *Proceedings of the 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Washington, DC, May 4−6, 2005; The Cardinal Group: Toronto, 2005.
(40) U.S. Environmental Protection Agency. Office of Transportation and Air Quality. *Emission Facts: Greenhouse Gas Emissions from a Typical Passenger Vehicle*; EPA420-F-05-004; U.S. Environmental Protection Agency: Washington, DC, 2005.
(41) Gee, G. W.; Bauder, J. W. Particle-size Analysis. In *Methods of soil analysis: Part 1. Physical and mineralogical methods*; Klute, A., Ed.; ASA Monograph Number 9; American Society of Agronomy: Madison, WI, 1986; pp 383−411.
(42) Bouyoucos, G. J. Hydrometer method improved for making particle size analysis of soils. *Agron. J.* **1962**, *54*, 464–465.
(43) Ferguson, M. H.; Howard, L.; Bloodworth, M. E. Laboratory methods for evaluation of putting green soil mixtures. *USGA J. Turf Manage.* **1960**, *13* (5), 30–32.
(44) NCR-13. *Recommended chemical soil test procedures for the North Central Region*; North Central Regional Publ. 221; Missouri Agricultural Experiment Station: Columbia, MO, 1998.
(45) Jolivet, C.; Arrouays, D.; Bernoux, M. Comparison between analytical methods for organic carbon and organic matter determination in sandy spodosols of France. *Commun. Soil Sci. Plant Anal.* **1998**, *29*, 2227–2233.

ES901539X