Chapter 1
Introduction to Green Roof Ecosystems

Richard K. Sutton

Abstract Green roofs have been heralded as a “sustainable building practice” in cities throughout the world as one response to mounting environmental stresses. A range of stressors plus erosion of aesthetics and human well being in urban areas have initiated policies and practices often with incentives to develop green infrastructure such as green roofs. They provide a suite of public and private benefits most of which map onto services generally provided by the ecosystem. Green roof development imbeds in environmental design processes and is constrained by both human and environmental factors.

As relatively small, simple, anthropogenic ecosystems, green roofs relate to several existing conceptual and applied ecological ideas. Understanding and applying from ecology and ecosystem studies, ecological engineering, managed ecosystems, construction ecology, urban ecology, landscape ecology, restoration ecology, reconciliation ecology, soil ecology and community ecology show green roof ecosystems can be created to cycle energy and nutrients. Furthermore, green roofs can be constructed to model an ecosystem and may provide a setting for testing ecological concepts. This book takes an ecosystems approach to describing a large number of interactions on green roofs placing them in the total human ecosystem.

Keywords Novel ecosystems · Ecosystem benefits · Ecosystem services · Design

1.1 Structure and Purview of this Book and Chapter

It has been nearly a decade since the seminal article, Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services (Oberndorfer et al. 2007), reviewed green roofs’ impacts on ecosystem services (benefits) and suggested a modest applied research agenda. That agenda focused on an ecosystem approach to

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R. Sutton (ed.), *Green Roof Ecosystems,* Ecological Studies 223,
DOI 10.1007/978-3-319-14983-7_1

diversifying plant assemblages, experimental studies of belowground and aboveground communities (both plant and animal) quantification and qualification of local stormwater outputs (especially roof leachate), energy, and air quality, reductions and social benefit models linked to economics and governmental policy. Meanwhile, there have been many more acres of green roofs created and research has continued apace. The following pages of this volume survey some of what has been accomplished and suggest more that should be done.

This book was assembled and written with three, somewhat overlapping yet distinct groups in mind: policy makers interested in urban sustainability and livability, designers who specify and layout green roofs to meet a wide range of stakeholder needs, and environmental professionals, researchers, and students wanting a primer on the ecological foundations and interactions occurring on and between green roofs and other living systems. While this target audience is broad, we have assumed that an interest in sustainable, ecologically prudent design connects them. Each chapter will review, examine, and analyze current knowledge about a specific area, propose unanswered questions, and suggest future research directions and applications from the perspective of the author(s).

This introductory chapter will place green roofs in the realm of policy and urban sustainability (especially its ecological underpinnings), requisite support services and resultant public and private benefits. Next, it will briefly describe green roof technology and components; then it will tie green roofs to a wide variety of ecosystem approaches studies, concepts and applications; finally it will give a brief preview of each chapter.

1.2 What is a Green Roof?

Modern green roofs, also known as vegetated green roofs (Enright 2013) or ecoroofs, are nascent, somewhat isolated, novel, anthropogenic patches consisting of membranes, engineered substrate (the growing medium), and assemblages of plants placed atop buildings or other structures. Their shallow profiles and usual detachment from the earth's surface produce strong wind exposure creating an unusual niche with few potential natural analogues (Lundholm and Richardson 2010; Sutton et al. 2012). They receive intense solar input and varied precipitation and may or may not be irrigated. Green roofs have appeared because of advanced building materials, evolving design techniques, and emerging ideas about how to make our built environment more sustainable and humane (Getter and Rowe 2006; Weiler and Scholz-Barth 2009). The modern green roof movement began in Europe in the 1980's (Köhler and Keeley 2005), and spread to North America and the rest of the world after the new Millennium. Thousands of green roofs now lay atop buildings in most urban metropolises worldwide.

1.3 Green Roof Policy as a Sustainable Practice

Normative policies describe, explain, and advocate how humans should act in organizing ourselves. Policies promote features or actions that ought to occur and thus are future-oriented. An often-quoted example of sustainable development policy comes from the World Commission on Economic Development (Brundtland Commission) (WCED 1987): “development that meets the needs of current generations without compromising the ability of future generations to meet their own needs.”

Policies often become the method by which discussion about the allocation of public resources are focused, formulated and ratified. In the United States at the Federal level the Clean Water Act provides an impetus to local subdivisions for improving storm water discharges (Carter and Fowler 2008). Ratified locally, policies are crafted into laws, ordinances, and finally reflected in building codes or other types of standards (GRHC 2006b). Local policies and codes can hinder or facilitate green roofs as a sustainable building practice (Dvorak 2011).

Places where green roofs have been promoted include cities with pressing environmental problems and/or compelling visions about creating more resilient and beautiful infrastructure. Sustainable urban environments vary in the suite of issues (Tables 1.1 and 1.2) and their importance underlying policies and the ways those policies are implemented. Urban stormwater controls or ordinances mandating green roof coverage on new development often involve fees or trade offs for impermeable surfaces. Revised building codes that simplify structure weight-loading requirements, tax incentives, rebates on fees, fast-tracking the development process, density bonuses, and outright grants have all been used to encourage green development and in some cases have been specifially directed at promoting green roof implementation (Carter and Fowler 2008; Simons et al. 2009).

1.4 Benefits

Looking at the various reasons posited to promote public policies that include green roofs as a part of sustainable building development (Getter and Rowe 2006), we see many overlapping benefits. These benefits can further be subdivided into those for private and/or public green roofs (Table 1.2) (Green Roofs for Healthy Cities 2006a; Berardi et al. 2013):

Green roofs can be considered a category of a stormwater best management practice (BMP). In comparison to conventional impervious rooftops, green roofs retain greater amounts of precipitation (that eventually return to the atmosphere through evapotranspiration) and also detain precipitation allowing it to drain more slowly (Bates et al. 2009; Berndtsson 2010; Morgan et al. 2012). Retarding and holding runoff water depends the type of roof vegetation, the total volume of the substrate, its composition and the nature of the storm event (Schroll et al. 2011; Gregoire and Clausen 2011).

Table 1.1 Key issues specified for green roof adoption in twenty-five world metropolises

City	Stormwater quality	Stormwater quantity	Heat Island	Green space	Energy savings	Air quality	Bio-diversity	Urban Agr
Toronto	√	√	√	√		√		
Chicago	√	√	√		√			
New York	√	√	√		√			
Baltimore	√	√	√		√			
Berlin	√	√	√				√	
Atlanta	√	√	√			√		
Singapore			√	√	√	√		
Washington		√	√			√		
Tokyo			√		√	√		
Austin		√	√		√			
Cologne	√	√						
Seattle	√	√						
Philadelphia	√	√						
S Francisco	√			√				
Waterloo		√				√		
Munster		√		√				
Stuttgart				√		√		
London				√			√	
Montreal					√			√
Pittsburgh	√							
Seattle	√							
Minneapolis	√							
Vancouver	√							
Basel							√	

Because green roofs intercept and detain rainwater, they can initiate a train of stormwater treatments and be designed to direct the slowed runoff into cisterns, rainwater gardens, bio-swales or detention ponds. Green roofs filter out many atmospheric pollutants and nutrients borne in precipitation before they reach streams or lakes (Berndtsson et al. 2009).

Green roofs by themselves and in aggregate affect a building's and a city's energy budget. In summer, a city with enough green roofs will have its overall ambient temperature reduced (Smith and Roebber 2011; Solecki and Leichenko 2006; Gaffin et al. 2008). An individual building similarly can reduce its need for summer cooling and winter heating since green roofs act as an insulator (He and Jim 2010; Jim and He 2010; Teemusk and Mander 2010; Feng et al. 2010). Additionally, some of the retained stormwater will be transpired during the growing season to further cool a building. In the winter, dormant green roof vegetation captures additional

Table 1.2 Green roof benefits derive from their existence as functional, living ecosystems and map onto a suite of ecosystem services described by the Millennium Ecosystem Assessment (MEA 2005)

	Green roof benefits		Ecosystem services			
	Public	Private	Provision	Regulate	Cultural	Support
Stormwater quantity	√	√		Water		
Stormwater quality	√		Water	Purification		Nutr. cycling
Heat island	√			Climate		
Membrane life		√				Resilience
Building energy		√		Climate		
Noise reduction		√		Sound	Aesthetic	
Air quality	√			Air		Nutr. cycling
Biodiversity	√			Pollination	Knowledge	Nutr. cycling
Retard fire		√			Well-being	
Views; marketing	√	√			Aesthetic	
Rooftop agriculture		√	Food		Educational	Soil formation
Education opportunity		√			Educational	
Local employment		√			Well-being	
Carbon sequestration	√			Air		

precipitation and enables snow to stay on the roof, thus adding an additional layer of insulation.

Typically, most roof membranes have a lifespan of about 20 years largely because of ultraviolet light degradation and micro-tears caused by diurnal heating and cooling cycles. Green roofs protect a membrane from those deleterious effects and may double membrane life thus reducing life cycle costs and delaying worn out membranes from entering the landfill (Carter and Keeler 2008; Bianchini and Hewage 2012).

Because green roofs have a porous mass, they serve as noise attenuators (Connelly and Hodgson 2008). Depending on depth and composition they can lower the noise impact from an overhead source such as an airliner up to 10 decibels.

Buildings and their urban conglomerations reduce space for other living things such as plants (Cook-Patton and Bauerle 2012; Madre et al. 2014) insects (MacIvor and Lundholm 2011), and birds (Coffman and Waite 2011). Green roofs allow some reestablishment of habitat for a few of those organisms. Flowering plants on vegetated roofs allow the introduction of bees and support other pollinators. While green roofs can never completely replace the biodiversity and complexity of intact ecosystems, they mitigate some of those changes and may supply living corridors for insect and bird movement in cities. They vastly improve the lack of biodiversity found on white and black roofs dominating a city's impervious surfaces. Hotels with green roofs easily charge more for rooms that open on to garden terraces. Chefs seek the herbs and vegetables grown nearby to their restaurants for the reduced cost and high quality freshness. Green roofs offer such a venue. Office workers gazing onto a green roof fatigue less easily and produce more under stress-reduced workloads. Green roof aesthetics, however, go beyond the mere pleasure than might be experienced in view the surface feature of any garden (Sutton 2014). All such connections help people value the natural world, become calmer, more alert and involved as humans (Kaplan and Kaplan 1989; Kahn 1999; Louv 2012).

1.5 Green Roof Design and Technology

Most often green roofs sit atop nearly flat roofs of commercial or public buildings. Occasionally they can be found on sloping or residential roofs though they are most likely to be part of new building project when extra weight loading can be considered and accounted for in structural design. Retrofitting the structure of existing building is a difficult and expensive proposition. Weight limitations become paramount because green roofs capture and hold a portion of the precipitation that falls on them. Based on the substrate depth, green roofs are classified as extensive (<15 cm) (<6 in.), semi-intensive (>10 and <20 cm) (>4 and <8 in.), or intensive (>15 cm) (6 in.) (GRHC 2006a). This general nomenclature applied above to depth classifications actually refers to the amount of maintenance expected for shallow, moderate, and deep substrate. Deeper substrate means that a wider array of plantings that include herbaceous perennials, shrubs and trees could be grown creating more of a rooftop garden, whereas, shallow substrate depths support fewer and lower-growing plant types. Most roof decks allow only minimal weight loads and so limit adoption of even extensive green roofs with shallower substrate depths. Where more weight loading can be supported, a semi-intensive or intensive roof can be used. The term extensive comes from a German to English translation of these concepts in the 2002 English translation of the FLL Guidelines for Green Roofing. It is a green roof system that “involves cultivation of vegetation in forms which create a ‘Virtual Nature’ landscape and requires little if any external input for either maintenance or development” (FLL 2002, p. 12). Its intention is to be extensive or wide spread in its application because of low cost, low-maintenance and ease in population with local flora (FLL 2002).

A typical green roof cross-section begins at the bottom with the building’s structural system, moving up through its decking, insulation, waterproof membrane, root barrier, drainage layer, drain filter, growing substrate, and finally a living layer of plants (Fig. 1.1).

Each layer plays a role in protecting the membrane, buffering and filtering rainfall and, with plant coverage, guarding against wind and rain-caused erosion of the growing substrate. Because substrate ballasts the building’s membrane and insulation, it must possess some weight, yet it must be well drained with large pore spaces to quickly allow percolation of excessive rain and lessen weight loading. Plants must be selected to withstand drought, wind, heat, and cold. If plantings fail then the substrate, becomes exposed to loss due to wind scour. Three key factors must

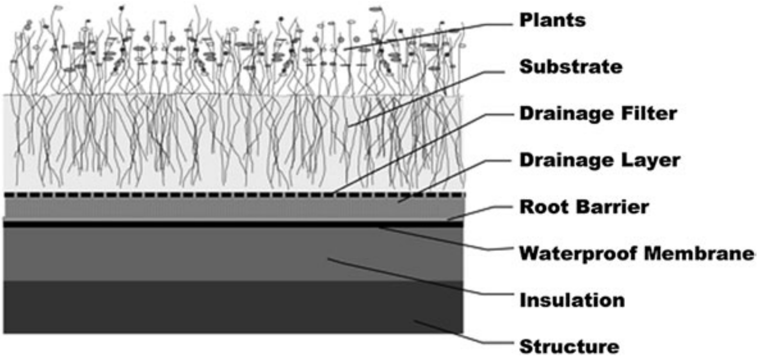

Fig. 1.1 A typical green roof cross-section shown above with its multiple layers

always be kept in mind when designing and maintaining green roofs: (1) stay with in structural loading limit, (2) protect the integrity of the waterproofing membrane, and (3) keep plants alive to protect and hold substrate in place.

A green roof design must account for horizontal as well as vertical forces. Daily wind pressure and especially wind action during storm events can cause scouring of substrate and dislodging of plantings. As the height of a green roof from the ground increases, so do ambient and storm winds, particularly if the green roof is unprotected by other building mass. Placement of membrane ballasting and scour protection may be dictated by local building codes (SPRI 2010). The height and location of parapet and building walls can create turbulent, chaotic, unpredictable, and increased speeds for wind flows (Suaris and Irwin 2010) but also reduce wind speeds. Wall and parapet height and location can also affect sun and shade patterns that should be acknowledged in layout of any designed planting.

Substrate can be layered and embedded in several different ways. The simplest is monolithic placement in a bed at the specified depth. Placement could also be built-up with layers of two or three substrates with differing drainage characteristics. The next method consists of modular tray systems either with pre-grown plants or filled with substrate and planted after placement. Trays can be made of plastic or a degradable material. One advantage of plastic material is that the tray can be picked up and moved for roof repair. A third method involves a thin, integrated, pre-planted, flexible, rubberized or plastic rug-like structure embedded with substrate and plants. It can be laid as a mat or rolled for transport and unrolled upon installation.

The plants may or may not be irrigated and supplemental water beyond rainfall may be applied by hand as needed, or by automatic spray or drip systems on the surface or embedded in the substrate. Excessive use of water for irrigation runs counter to the intent of a sustainable building.

Where green roofs have been designed for physical access other landscape amenities can be added such as paving, decking, seating, water features, arbors, and trellises. Green roof landscape design per se is beyond the scope of this book. It is suggested that readers wishing to know more about the design and construction process consult books by Osmundson (1999), Weiler and Scholz-Barth (2009), Luckett (2009), Snodgrass and MacIntyre (2010), or Daykin et al. (2013).

1.6 Design and Use

To gain public and private benefits from green roofs means adding another layer of complexity to design of buildings. It requires a design team that includes an owner, engineer, architect and landscape architect to establish parameters and oversee specification and installation of green roof materials to meet desired outcomes. Green Roof Professional (GRP) is a special certification by the Green Roofs for Healthy Cities group in North America given after completion of an exam and requiring yearly continuing education. These design professionals also rely upon a group of craftsmen and suppliers to help create a green roof. Designers must understand local policies and codes, the building's needs, location, and whether a roof will be accessible and by whom. Weight loading and roof slopes must be acknowledged and understood very early in the process. Building codes for green roofs apply not only to building envelope integrity and public health, safety and welfare during and after construction including fall safety, emergency egress, and wind and fire impacts. The development of code and performance specification requirements for green roof construction is most advanced in Europe. North America is beginning to make advances in development of codes, guidelines and other legal documents for public and private green roof construction, but many green roof elements lack guidance (Dvorak 2011).

Integrity and lifespan of the waterproofing membrane represents the second most important condition of a green roof. Everyone accessing a roof from designers to installers, maintainers, and visitors must do so in a way that protects the membrane. Improper access and use impact a membrane and can, at best, void any warranty and at worst cause roof leakage.

On green roofs, the substrate composition for physically supporting plants and supplying water and nutrients varies widely. Some designers recommend highly organic admixtures with up to twenty percent compost or peat moss, while others opt for lower amounts of organic matter in the five percent range (Friedrich 2008; Buist 2008). Many of the large-scale commercial providers of growing media in Europe and North America use an engineered media based upon the German FLL Guidelines (FLL 2002) for Green Roofs. The FLL-based guide suggests a range of materials and performance characteristics for media assuming use of a xeric plant palette. The organic fraction holds water, microbial populations and supplies nutrients and structure that while the inorganic fraction brings needed internal structure and adds overall ballasting weight. Importantly, the inorganic substrate fraction provides structure that allows rapid permeability and resists freeze-thaw cycles, and compaction. Inorganic material must be near neutral in pH, size-graded to allow rapid percolation and have very little substrate in the clay particle size range. Types of inorganic substrate material typically include heat expanded slate, shale and clay;

crushed brick or tile; volcanic ash; pumice; lava rock; perlite; sand and admixtures of these. Compost or worm castings supply the initial organic fraction with its critical complement of nutrients.

Plant selection for green roofs must consider its microclimate (Metselaar 2012), the well-drained growing substrate, plants, ecological relationships amongst themselves and fauna (Brenneisen 2006; MacIvor and Lundholm 2011), as well as aesthetic intent and use. Plants must be able to withstand wind, heat, cold, and drought (Sutton et al. 2012). For low profile, extensive green roofs, plants also need to be able to self-sow and/or fill in gaps by creeping rootstocks or stems. Effort should be taken to use locally sourced materials with minimal emergy (embodied energy).

All human-occupied landscapes require maintenance, especially carefully designed green roofs. Roof top environments can be harsh and cause stress on plants. Detailed inspections of plants for insects and diseases must occur frequently during the first 3–5 years, and continue beyond in subsequent years. During and after heat or drought spells and at the beginning and end of the growing season, plant health must be assessed and water added (as needed) and repairs made to scoured substrate, faulty irrigation and the pavements, drains, and other life-safety features. If flower displays become critical to the objectives of the green roof's design, then yearly, spring soil tests are required to reveal need for supplemental nutrients. When applying nutrients, small amounts in a slow release form should be used. Nutrients easily leach from the substrate so it is important to guard against over-fertilizing (Morgan et al. 2012).

1.7 Green Roof Ecosystems Concepts and Applications

While some readers may question juxtaposing the terms, green roof with ecosystem as we have done in this volume's title, the expansion of ecological study into a plethora of sub-disciplines suggests a wider view of what constitutes the study of ecology and displays a broad suite of compatible ecological concepts underlying a green or living roof. Below we review some of the varied ecosystem-oriented, ecological approaches that may have facility and add understanding to the practice of green roof design and assembly.

Ecology as a subject has matured to the point where it is no longer ensconced wholly in biology (Odum 1992). Broadly defined, ecology is the science of relationships between, living things and their environment. The ecosystem model explicates system inputs and outputs powered by the flow of energy (Odum 1971). Even the term, energy, has evolved into emergy (Odum and Nilsson 1996; Odum 2002) (embodied energy) and exergy (Jorgensen et al. 2004; Kibert 2002) (the useful applicable part of energy driving ecosystem processes). Feedback occurs in systems that tend to be self-organizing and hierarchical (Berryman 1989; Allen 2002; Kay 2002).

Ecosystem diagrams (Fig. 1.2) use symbols to describe flows of energy, materials and information to, from and within an ecosystem. Ecosystems are very open to

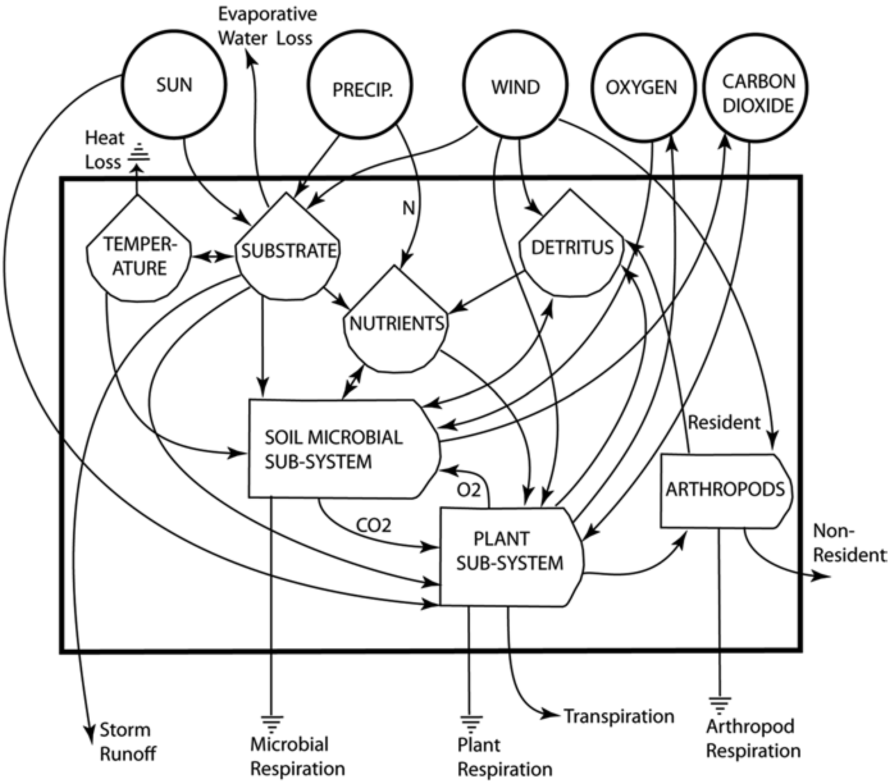

Fig. 1.2 A green roof ecosystem showing flows of energy, water, nutrients, and organisms

inputs and outputs, though a green roof ecosystem has spatial boundaries that are relatively easy to define. Within it, physical materials, like substrate or plants, become objects to, through, and from which flows occur. The usefulness of ecosystem diagrams using Odum's emergese language shows and brings invisible interactions to our attention.

These activities are rather like a transitive verb: they display action on and between physical objects. Allen (2002, p. 118) describes the design of systems processes thusly: "A critical distinction between design, embodied in mechanisms, and system dynamics, is the notion of rate dependence as opposed to rate independence. Dynamics is described as a series of rates of processes that are interrelated. Dynamics depends on rates, and a description of dynamics has to rely on rates for adequate description." A sedum plant on a green roof is not a sedum plant at a rate. It is simply a locus of activity that absorbs energy, stores it in complex biochemical compounds for later to use with water and carbon dioxide in Crassulacean acid metabolism (CAM). It does so to reduce the loss of internal water caused by opening stomata, though some *Sedum* species may switch between C3 and CAM (Sayed 1994; Cushman and Boland 2002). In the relatively cool, higher humidity found at night less

Springer
http://www.springer.com/978-3-319-14982-0

Green Roof Ecosystems
Sutton, R. (Ed.)
2015, XII, 447 p. 101 illus., 78 illus. in color., Hardcover
ISBN: 978-3-319-14982-0