International Journal of Sustainable Built Environment (2014) 3, 127–134

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International Journal of Sustainable Built Environment
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Review Article

A comprehensive study of green roof performance from environmental perspective

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Received 27 February 2014; accepted 20 May 2014

Abstract

Green roofs have been established for over 100 years and they have been become one of the key elements in urban area in the past few decades. Many scientific researches focus on its cooling performance, efficiency and survival rates of plants. This article provides an overview mainly from two aspects, the vegetation on the green roofs and its benefits toward the surrounding environments. Vegetation is the key element in installing green roofs. It also provides some factors in choosing suitable plants on rooftops, factors including species that are drought tolerant, solar radiation tolerant, and cooling ability of plants. In addition, green roofs play a critical role in improving the urban environment by enriching the biodiversity, delaying the storm peak to the drainage system, diminishing the runoff quantity, purifying the air pollutants as well as the runoff quality.

Keywords: *Sedum*; CAM; Albedo effect; Biodiversity

Contents

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Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2014.05.001

1. Introduction

Green roofs can be traced back as far as the gardens of Babylon and the Roman Empire, i.e. they grew trees on top of buildings (Peck, 2002). During 19th and 20th century, rooftops in major cities of the United States were greened to replace the rising land costs of building parks in the inner city (Herman, 2003). Nowadays, the world leader in green roof technologies is Germany, where more than 10% of houses have installed green roofs (Köhler, 2006). Köhler (2006) reported that the first wave of constructing green roofs in Germany came at the end of 19th century. It only covered less than 1% of roofs in Germany during this boom. However, incentive programs launched from 1983 to 1996 which required the installation of extensive green roofs for buildings in central part of the city and it allowed reduction of the additional costs of installation (Dunnett and Kingsbury, 2004). Nowadays, green roofs are also widespread in other European countries, for instance France and Switzerland. In addition, Portland government organized a few incentive programs to encourage the installation of green roofs on buildings. In Canada, Toronto also promoted wider construction of green roofs with sustainable alternatives to meet the urban environmental challenges (Banting et al., 2005). Green roofs are usually built in the inner city. Green roofs in the United Kingdom are also used in build-up areas, so that it can replace the gardens or local parks at ground level (Herman, 2003).

Generally, there are three types of green roofs: namely intensive green roof, semi-intensive green roof and extensive green roof. Different types of green roofs require different vegetations, and thus require different depths for growing medium (Banting et al., 2005). Researchers suggested few characteristics of extensive green roof plants: (1) they establish fast and reproduce efficiently; (2) they are short in height and cushion-forming or mat-forming; (3) their roots are shallow but spreading; and (4) their leaves are succulent or able to store water (Snodgrass and Snodgrass, 2006; Maclvor and Lundholm, 2011). Four types of vegetation have these characteristics: namely Moss-*Sedum*, *Sedum*-moss-herbaceous plants, *Sedum*-herbaceous-grass plants and grass-herbaceous plants; these types of vegetations require 2–20 cm depth of medium for growing (Banting et al., 2005). *Sedum* species are the most common choice of plant for extensive green roof because of their unique characteristics: grow with relatively shallow roots, able to store water, have crassulacean acid metabolism (CAM) to reduce water loss (Van Woert et al., 2005; Durhman et al., 2006; Maclvor and Lundholm, 2011). Another four types of vegetations can be applied in semi-intensive green roofs: grass-herbaceous plants, wild shrubs-coppices, coppices and shrubs and coppices; these types of vegetations require a deeper growing medium, i.e. 12–100 cm (Banting et al., 2005). Lastly, there are seven types of vegetations which can be planted on intensive green roofs: Lawn, low-lying shrubs and coppices, medium height shrubs and coppices, tall shrubs and coppices, large bushes and small trees, medium-size trees and large trees. They require even deeper growing medium, i.e. 15–200 cm (Banting et al., 2005). Extensive green roof is the least expensive among the three types of green roofs in terms of installation as well as maintenance, as it can be self-retained. Since the installation of extensive green roofs is easier and more flexible, most of the researches focused on the harsh environment on extensive green roofs provided. This article aims at summarizing the existing literature on the performance of intensive and extensive green roofs in subtropical maritime monsoon climate zone. Selection of plants is one of the essential components in resulting thermal benefits and storm water runoff, hence the energy savings follow.

2. Vegetation

2.1. Native, non-native and invasive plant

There are debates about using native plants on green roofs around the world (Currie and Bass, 2010). In Peck (2008)'s the book of award winning green roof designs, 45% of the award winning green roofs used native plants. Another book written by Cantor (2008) also recorded 59% of the green roofs used native plants. It shows the significance of using native plants on green roofs. Moreover, non-profit organizations, including the Ladybird Johnson Wildflower Center and the Peggy Notebaert Nature Museum in the United States, governmental organizations, namely the city of Toronto's Green Roof Pilot Program, and even commercial organizations, for example Rana Creek in the United States, also promoted the use of native plants on green roofs (Butler et al., 2012). Butler et al. (2012) also summarized the common reasons for choosing native plants in ground-level. First, Environmental Protection Agency (EPA) in the United States (2012) claimed that native plants were already adapted to the local conditions; once they are established, they do not need

Table 1
The survival rates of native and non-native plant species under different treatments in the United States and Canada (Butler et al., 2012).

Location	Full Sun				Shaded		References
	No Irrigation		Irrigation		No irrigation		
	Native	Non-native	Native	Non-native	Native	Non-native	
U.S.			100%	100%			Bousselot et al. (2009)
U.S.	100%	100%					Butler and Orians (2011)
U.S.	0%	31%					Carter and Butler (2008)
U.S.	0%	100%					Durhman et al. (2006)
U.S.	33%	100%			33%	67%	Getter et al. (2009)
U.S.	13%	100%			78%	100%	Licht and Lundholm (2006)
U.S.			14%	n/a			Martin and Hinckley (2007)
U.S.	22%	100%					Monterusso et al. (2005)
U.S.	33%	100%					Rowe et al. (2006)
U.S.	20%	100%	100%	100%			Schroll et al. (2009)
Canada	100%	n/a					Lundholm et al. (2009)
Canada	93%	n/a					Maclvor and Lundholm (2011)
Canada			67%	79%			Ngan (2010)
Canada	10%	75%	100%	100%			Wolf and Lundholm (2008)

watering, fertilizers or pesticides. Native plants can help restore the healthy ecosystem by attracting various animals, birds and butterflies (EPA, 2012). Currie and Bass (2010) also wrote that native plants have the potential to replicate local native species communities as well as benefit the ecology. In Alberta, Clark and MacArthur (2007) held a research of a semi-intensive green roof, which had a native mixed prairie community. They found that there was more biomass, in particular spiders and various species; they also found that the biodiversity in the semi-intensive roof was greater than an non-native extensive green roof (Clark and MacArthur, 2007).

Yet there are concerns about promoting native plants planting on green roofs. First, Sam Benvie (mentioned in Clark and MacArthur, 2007) suggested that native plant community can be threatened by other rare species and invasive species, so the cost of maintaining a native plant community on a green roof can be increased and challenging. Moreover, Dunnett (2006) stated the concern of whether the seeds of native plants from non-local source, i.e. local nursery, can survive during the establishment. Dunnett (2006) suggested rather than using seeds from other areas, using local plants as source of seeds. Dunevitz Texler and Lane (2007) cited reasons not to plant rare species or native plants because rare species or native plants, which are already in fragile populations, would be impacted by altering genes from similar plants. In addition to rare species, they often had various habitat requirements, so the process of planting and establishing could be unsuccessful in long term (Dunevitz Texler and Lane, 2007).

Opinions toward the use of native species on green roofs remain mixed. Butler et al. (2012) had also summarized different opinions toward their use. Quantitative data from 14 papers had been published regarding the rates of growth and survival of native plants on green roofs under different conditions. The data are summarized and shown in Table 1 (Butler et al., 2012). Nonetheless, unsuccessful establishment of native plants will influence the green roof performance, i.e. esthetics. Green roof performance will then influence the long-term acceptance by the public (Maclvor and Lundholm, 2011).

2.2. Drought tolerant and solar radiation tolerant

As mentioned above, green roof performance will influence the long-term acceptance by the public (Maclvor and Lundholm, 2011). Thus, choosing appropriate plants is important. This section summarized different researches about vegetation's performance as drought tolerant and solar radiation tolerant.

Sedum is often regarded as an ideal choice for planting on green roofs because of its properties (Van Woert et al., 2005). *Sedum* are succulents and regarded as crassulacean acid metabolism (CAM) plants in which the stomata opens in nighttime to allow carbon dioxide to enter and closes in daytime to avoid water loss from transpiration (Ting, 1985). Not only *Sedum* have such ability, but families of *Portulacaceae*, *Crassulaceae* and *Euphorbiaceae* are also CAM plants which can survive for a long period of time without watering (Liu et al., 2012). The research conducted by Farrell et al. (2012) showed that CAM plants, *Sedum pachyphyllum*, *Sedum spurium* and *Sedum clavatum* survived for about 113 days without watering, depending on the soil types. *S. spurium* was recorded to have a lower drought tolerance with only 19% of survival rate, under a low water regime of watering every 3 weeks (Nagase and Dunnett, 2010). Additionally, the report conducted by Liu et al. (2012) indicated that the temperature reduction effect increases with plant height: 10 cm < 15 cm < 35 cm. It was proved that even plants with high drought tolerance can help in regulating the temperature.

Besides drought tolerance, solar radiation tolerance is also considered because most of the roofs are exposed to high solar radiation. Some plants are not favorable for strong sunlight while some are capable of withstanding it, e.g. *Parthenocissus quinquefolia* requires a site receiving less than three hours of direct sunlight (Fairfax County, 2007). On the contrary, some roofs might be shaded by nearby objects, for example buildings. According to the experiment conducted by Getter and Rowe (2006), *Sedum kamtschaticum*, *S. spurium* and *Allium cernuum* are good candidates for shaded locations; while *Sedum acre*, *Sedum album* and *Talinum calycinum* are suitable for both shaded and sunny locations on green roof.

2.3. Albedo effect

It is well known that there is a negative correlation between albedo effect and surface temperature: the greater the albedo, the lower the surface temperature. Gaffin et al. (2006) conducted a research comparing surface radiation reflectivity (albedo) of white roofs and green roofs. White paint recorded an albedo of 0.8 on average, but it is difficult to maintain high albedos on white surfaces without regular washing. It recorded an albedo decrease of 0.15 in a year (Gaffin et al., 2006). On the contrary, green roofs recorded an equivalent albedo of 0.7–0.85 (Gaffin et al., 2006). Gaffin et al. (2006) also made a comparison of temperatures of the subsurface (the conventional rooftop level) and the green roof surface. It is indicated that the subsurface temperature was significantly lower than the green roof surface temperature; it is because the green layer insulated heat (Gaffin et al., 2006). This proves that green roofs can reduce the thermal loading.

Moreover, albedo increases with higher peak cover and biomass on the green roof. A planted module of Maclvor and Lundholm (2011) reflected on average 0.22 of incoming solar radiation whereas growing medium only reflected 0.17 as control in the entire study period, from May to October. Lundholm et al. (2010) also reported that the average albedo of a conventional rooftop over the same period (from May to October) is only 0.066. By comparing the two sets of data, it was found that the best performing species from Maclvor and Lundholm (2011) increased the albedo effect by 22.2% over the growing medium alone and more than 200% of albedo effect over the conventional rooftop.

Blanusa et al. (2013) demonstrated that plants provide a cooling effect by transpiration of water through stomata and direct shading, as mentioned above. *Stachys* had a higher ability in regulating its own temperature and leaving its leaves cool (Blanusa et al., 2013). It had the lowest surface temperature even with limited soil moisture and closing stomata. One of the experiments compared the leaves with hairs trimmed indicating that hairs on the leaves of *Stachys* reduced the amount of infra-red radiation from leaf, thus making the leaves cooler. Such cooling mechanism may be due to the light hair color or its reflectivity of incoming irradiance, thus it provided higher albedo and avoided direct heat stress. Nevertheless, available moisture and water transpiring through *Stachys*' leaves strongly altered its air cooling ability (Blanusa et al., 2013).

Surface temperature was mainly related to solar radiation reflectivity (albedo). Solar radiation reflectivity is influenced by species richness and biomass variability, where greater biomass led to greater solar radiation reflectivity (Lundholm et al., 2010). Thus the thermal loadings in the daytime are decreased; the discomfort underneath the roof will be alleviated (Maclvor and Lundholm, 2011; Blanusa et al., 2013).

2.4. Growth substrate

According to Schrader and Boning (2006), soil formation takes place throughout the establishment of green roofs. They made a comparison of selected abiotic properties and collembolan densities between five old extensive green roofs and five young extensive green roofs (Schrader and Boning, 2006). Collembolans are typical pioneer microarthropods and transported by air during the primary succession, the pioneer period (Dunger, 1989). Schrader and Boning (2006) found that acidification and increasing contents of organic carbon took place in old green roofs. They concluded that the soil formation can improve the existing collembolans and promote urban biodiversity (Schrader and Boning, 2006).

Apart from improving urban biodiversity, soil is another important factor of cooling down the roof temperature as it holds water and heat (Getter et al., 2009; Maclvor and Lundholm, 2011). Growing medium which is more reflective can increase the overall albedo of the green roof, in turn raising the overall cooling ability of the roof (Maclvor and Lundholm, 2011). A shallower substrate held less moisture content (Getter et al., 2009). Getter et al. (2009) found that a 4 cm substrate depth held less moisture content than 7 or 10 cm depths, but the depths of 7 and 10 cm substrate are statistically the same. The depth of growth substrate controls the water retention, hence the runoff quantity and the runoff peaks.

3. Environmental benefits

3.1. Enriching biodiversity in urban area

Green roofs in urban and suburban areas act as green corridor, which are the stepping stones for wildlife to enter the nearby habitats (Kim, 2004). They can connect the fragmented habitats with each other so as to promote the urban biodiversity (Kim, 2004). A total number of 30 species or even more of organisms were observed in the green roof (Fountain and Hopkin, 2004; Schrader and Boning, 2006). Species like *Isotoma viridis* and *Parisotoma notabilis* were observed and they are classified as cosmopolitan pioneer in urban soils (Dunger et al., 2004; Fountain and Hopkin, 2004). The distributions of organisms in soil were diverged from young and old roofs (Schrader and Boning, 2006). Schrader and Boning (2006) revealed that there are three factors contributing to the biodiversity in the green roof. First is the type of growing substrate; second is the process of soil formation during the maturation of substrate; and the last is the increasing biological activity as well as increasing organic matter from dead leaves or organisms. Nonetheless, it is suggested that green roof could not be a justification for destroying the natural nor replace the nature.

3.2. Cooling performance on the building and surroundings

The cooling performance of the green roof depends on the plant species chosen (MacIvor and Lundholm, 2011; Blanusa et al., 2013). Green roofs cool down the temperature because of the direct coverage of plants and the opening of stomata that allows transpiration during daytime (Santamouris, 2012). The textures of leaf surface and albedo effect also take place. The vegetation stores the heat and cools down the air (Santamouris, 2012). The daily maximum temperature on the vegetated rooftops was reduced and dampens diurnal temperature fluctuations. Researches in US indicated that vegetated rooftops decreased the peak temperature from 0.5 K to 3.5 K; along with dropping of temperature, the albedo increased from 0.05 up to 0.61 (Santamouris, 2012). Susca et al. (2011) compared the albedos of the white-painted roof and green roof, its influence toward the surface temperatures, and the energy consumption for controlling the indoor temperature below the green roofs. The white and green roofs substituted the black-painted roof and reduced the energy consumption. Moreover, a green roof rather than a white roof can further reduce the energy saving from 40% to 110%.

3.3. Managing runoff quantity

First of all, the definition of water retention means the water storage capacity of a green roof. Green roof characteristics including the growing medium and the drainage layer influence the water retention capacity as well as the runoff dynamics (Banting et al., 2005). In between different types of vegetation in extensive green roofs, their water retention ability varied from 40% to 60% of total rainfall. Water retention for semi-intensive and intensive green roofs depends on area coverage (Banting et al., 2005). The size of rain event as well as the rain intensity affects the water retention. Green roofs retained all small rain events that were less than 10 mm. The retention of green roofs differed from 88% to 26% when the rain events were 12 mm. Such retention was depended on the substrate and the type of drainage (Simmons et al., 2008). The peak discharge of small storms from vegetated roof was lower than that from conventional roof; however, such effect was reduced for larger storms. On a vegetated roof, 57% of peaks were delayed up to 10 min comparing with a conventional roof (Carter and Rasmussen, 2006). According to DeNardo et al. (2005), the rainfall intensity reduced from 4.3 mm/h to average green roof runoff rate of 2.4 mm/h. Therefore, green roofs reduced the peak intensities.

Age of green roof also affects the storm water discharge (Getter et al., 2007). By comparing the organic matter content and physical properties of soil after five years of time, the organic matter content was increased from 2% to 4% and the pore space was also increased from 41% to 82%. Along with these two factors, the water holding capacity also increased from 17% to 67% (Getter et al., 2007). However, the vegetation plays a minor role in water retention when comparing with the substrate. Van Woert et al. (2005) proved that roofs with media alone retained 50.4% of rainfall while vegetated roofs retained 60.6%. On the contrary, MacIvor and Lundholm (2011) showed that some plant species can evapo-transpire more water, so they create more space for water storage capacity of media. In addition, warmer seasons lead to higher evapo-transpiration, thus the water storage regenerates faster. There were seasonal variations toward the runoff reduction (Bengtsson et al., 2005). During September to February, the runoff reduction was 34% while during the period between March and August, the runoff reduction was 67%. The slope has impacts on water retention too. The lower the slope, the higher the water retention on the green roofs (Villarreal and Bengtsson, 2005).

3.4. Prevent and reduce pollution

Green roofs act as a sink for nitrogen, lead and zinc (Gregoire and Clausen, 2011); it is also the source of phosphorus (Köhler et al., 2002; Berndtsson et al., 2009; Gregoire and Clausen, 2011). On the thin soil of extensive green roofs which does not affect the concentrations of heavy metals in runoff water, i.e. the concentrations of heavy metals in runoff water were the same as that in precipitation (Köhler et al., 2002). Nonetheless, the green roof retained over 65% of the zinc from precipitation (Gregoire and Clausen, 2011). In addition, Gregoire and Clausen (2011) found that more than 90% of the copper and zinc concentrations from green roof runoff were in the dissolved form. Moreover, taking account into the reduced runoff volume, the amount of water reduction affected the reduction of nitrogen in runoff (Köhler et al., 2002). Similarly, the green roofs reduced the loads of pollutants due to runoff reduction (Köhler et al., 2002; Gregoire and Clausen, 2011).

As mentioned above, green roofs were the source of phosphorus (Köhler et al., 2002; Gregoire and Clausen, 2011) and copper (Gregoire and Clausen, 2011). Green roof fertilization contributes to the increase in phosphorus (Köhler et al., 2002; Berndtsson et al., 2009; Gregoire and Clausen, 2011). Besides the concentration of phosphorus, Gregoire and Clausen (2011) also found that the concentration of copper was from Harrell's fertilizer, which contained water soluble copper, used on the green roof.

Green roofs can also reduce the effects of acid rain by raising the pH value from 5 to 6 in rain water to over 7

Table 2
Summary of optional barriers for applying extensive green roof systems for existing buildings.

Barriers	References
• Increase of maintenance cost	Peck and Callaghan (1999) and Ngan (2004)
• Increase of design and construction cost	Ngan (2004)
• Lack of incentive from the government toward developers	Getter and Rowe (2006)
• Lack of incentive from the government toward owners of the existing buildings	Peck and Callaghan (1999) and Getter and Rowe (2006)
• Technical difficulty during the design and construction process	Peck and Callaghan (1999) and Getter and Rowe (2006)
• The old age of existing building	Townshend (2007)
• The weak affordability of extensive roof to withstand wind load	Peck and Callaghan (1999) Townshend (2007)
• Weak structural loading for applying extensive green roof system	Townshend (2007)
• Poor utilities arrangement	Townshend (2007)
• Lack of awareness on extensive green roof system in public and private sectors	Hui (2006)
• Lack of promotion from the government and social communities among the public and private sectors	Townshend (2007)

to 8 in runoff water. Plants can also absorb air pollutants such as carbon dioxide and generate oxygen. In addition, Yang et al. (2008) demonstrated that green roofs in Chicago reduced the air pollution through the uptake of ozone by plants. In addition, the uptake of NO_2, PM_{10} and SO_2 by plant was 27%, 14% and 7% respectively. The maximum average uptake is in May while the minimum average uptake is in February.

4. Cost and Barriers of installing green roofs

Environmental Protection Agency (2009) compared the costs of extensive green roofs and intensive green roofs installation. The costs of constructing green roofs depended on the components, including the growing medium, type of roofing membrane, quantity of plants and drainage system. As indicated in the report conducted by Environmental Protection Agency (2009), it was estimated that the initial costs were varied from US$ 10 per square foot for a simple extensive roof to US$ 270 per square meter for an intensive roof. Maintenance costs for either extensive or intensive green roofs range from US$ 8 to US$ 11 per square meter. The maintenance costs of extensive green roofs drop when plants cover the roof entirely, whereas such costs for intensive green roofs remain constant. Architectural Services Department (2006) in Hong Kong also conducted a study on green roof application in Hong Kong. It is indicated that the costs vary depending on the sources of materials, either international or local. Local supplier's claimed using reputable imported product cost from US$ 90 to US$ 130 per square meter; while they claimed using local materials would cost from US$ 50 to US$ 80 per square meter. Maintenance costs of local intensive green roof range from US$ 1 to US$ 6 per square meter each year; while that of extensive green roof ranges from US$ 0.1 to US$ 0.3 per square meter each year.

Table 2 shows a list of barriers of installing extensive green roofs on existing buildings. According to the survey done by Zhang et al. (2012), "Lack of promotion from the government and social communities among the public and private sectors", "Lack of incentive from the government toward the owners of the existing buildings", "Increase of maintenance cost" and "Technical difficulty during the design and construction process" were the major barriers during the stage of planning and designing. It is suggested that the government should play the leading role in the stage of planning and designing for implementation of extensive green roof systems. During the stage of construction and operation as well as management stages, barriers including "Increase of maintenance cost" and "Technical difficulty during the design and construction process" were more essential.

5. Conclusion

The installations of green roofs have been promoted worldwide, especially in European countries and United States. Extensive green roofs are often the target of scientific research since it costs less than intensive green roof. In addition, its weight adding to the building is less than intensive green roof; hence extensive green roofs are more common. Nevertheless, extensive green roofs face harsh climate, for instance high solar radiation, limited precipitation and shallow growing substrate; therefore it limits the choices of plants. These factors become obstacles in constructing extensive green roof; whereas comprehensive watering system can be installed on intensive green roofs. Therefore, water efficiency is not the major problem for intensive green roofs. Different types of green roof require different nature of plants; nonetheless, three common criteria of selecting plants using on extensive green roofs are their drought tolerance, albedo ability and native or non-native. Typical plant species used on it is *Sedum* because of its feature of CAM which helps it to survive during harsh climate. Due to the harsh climate faced by the extensive green roofs, research usually focuses on the survival rates of plants. The survival rates of plants directly influence the esthetic of the green roofs; hence influence the acceptance of the general public. Other scopes of green roof studies are including the temperature reduction caused by green roofs, runoff quantity control as well as reduction of pollution. A research recently showed that broad leaves performed better than *Sedum* on rooftop, i.e., cooling efficiency. There are also arguments about whether native species or non-native species should be introduced for green roofs. Native plants can provide homes and food for the native animals; however, one research claimed that non-native plants also provide same function for the native animals. Nevertheless, it is uncertain whether non-native species become invasive or not; thus using native plants is still the first priority.

From soil formation on green roofs, it improves the urban biodiversity, for underground animals in the growth substrate, for the inserts in the canopy. Green roofs not only clean the air, but also the runoff. Plants on the rooftops can purify the air; plants and soil can purify the runoff as well as delay the storm peak. Green roofs act as a sink for nitrogen, lead and zinc from precipitation, but it also increases the concentration of phosphorus, which came from fertilizer used on green roofs. After reviewing research from mainly environmental perspectives, from the installation of green roofs, to its benefits to environment, with respect to urban area, it has been concluded that green roofs are good for rebuilding green areas in urban area; however, it should not be an excuse to destroy the outskirt green belts as green roofs cannot replace the role of natural habitat.

Acknowledgments

The author would like to thank Mr. Chan Yung Hau for the manuscript preparation and improvement. Financial support from the Department of Science and Environmental Studies of The Hong Kong Institute of Education is gratefully acknowledged.

References

Architectural Services Department., 2006. Study on green roof application in Hong Kong. Retrieved Aug 8, 2013, from http://www.archsd.gov.hk/media/11630/green_roof_study_final_report.pdf.

Banting, D., Doshi, H.H., Li, J., Missios, P., 2005. Report on the Environmental Benefits and Costs of Green roof technology for the city of Toronto. City of Toronto and Ontario Centres for Excellence—Earth and Environmental Technologies, Toronto.

Bengtsson, L., Grahn, L., Olsson, J., 2005. Hydrological function of a thin extensive green roof in southern Sweden. Nord. Hydrol. 36 (3), 259–268.

Berndtsson, J.C., Bengtsson, L., Jinno, K., 2009. Runoff water quality from intensive and extensive vegetated roofs. Ecol. Eng. 35, 369–380.

Blanusa, T., Vaz Monteiro, M.M., Fantozzi, F., Vysini, E., Li, Y., Cameron, R.W., 2013. Alternatives to sedum on green roofs: can broad leaf perennial plants offer better 'cooling service'? Build. Environ. 59, 99–106.

Bousselot, J.M., Klett, J.E., Koski, R.D., 2009. High elevation semi-arid taxa: evaluations on an extensive green roof. Paper Presented at the Annual Greening Rooftops for Sustainable Communities Conference, Atlanta, GA.

Butler, C., Orians, C.M., 2011. *Sedum* cools soil and can improve neighboring plant performance during water deficit on a green roof. Ecol. Eng. 37 (11), 1796–1803.

Butler, C., Butler, E., Orians, C.M., 2012. Native plant enthusiasm reaches new heights: perceptions, evidence, and the future of green roofs. Urban Forestry and Urban Greening 11, 1–10.

Cantor, S.L., 2008. Green Roofs in Sustainable Landscape Design. W. W. Norton & Company, New York.

Carter, T., Butler, C., 2008. Ecological impacts of replacing traditional roofs with green roofs in two urban areas. Cities and the Environment 1, Article 9.

Carter, T.L., Rasmussen, T.C., 2006. Hydrologic behavior of vegetated roofs. J. Am. Water Resour. Assoc. 42 (5), 1261–1274.

Clark, M., MacArthur, S., 2007. In Proceedings from the Fifth Annual International Green Roofs Conference. Greening Rooftops for Sustainable Communities, Minneapolis, April 29 to May 30th. Toronto: The Cardinal Group.

Currie, B.A., Bass, B., 2010. Using Green Roofs to Enhance Biodiversity in the City of Toronto. Retrieved March 16, 2014 from http://www1.toronto.ca/city_of_toronto/city_planning/zoning__environment/files/pdf/greenroofs_biodiversity.pdf.

DeNardo, J.C., Jarrett, A.B., Manbeck, H.B., Beattie, D.J., Berghage, R.D., 2005. Stormwater mitigation and surface temperature reduction by green roofs. Trans. ASAE 48 (4), 1491–1496.

Dunevitz Texler, H., Lane, C., 2007. Species Lists for Terrestrial and Palustrine Native Plant Communities in East-central Minnesota. Minnesota Department of Natural Resources and Great River Greening Ecological Strategies, LLC. Retrieved March 15 2014 from http://www.greatrivergreening.org/plant_communities.asp.

Dunger, W., 1989. The return of the soil fauna to coal mined areas in the German Democratic Republic. In: Majer, J.D. (Ed.), Animals in Primary Succession. The Role of Fauna in Reclaimed Land. Cambridge University Press, Cambridge, pp. 307–337.

Dunger, W., Schulz, H.-J., Zimdars, B., Hohberg, K., 2004. Changes in collembolan species composition in Eastern German mine sites over fifty years of primary succession. Pedobiologia 48, 503–517.

Dunnett, N., 2006. Green Roofs for Biodiversity: Reconciling Aesthetics with Ecology. In Proceedings of the Fourth Annual International Green Roofs Conference. Greening Rooftops for Sustainable Communities, Boston, May 11–12 2006. Toronto: The Cardinal Group.

Dunnett, N.P., Kingsbury, N., 2004. Planting Green Roofs and Living Walls. Timber Press, Oregon, USA, p. 254.

Durhman, A.K., Rowe, D.B., Rugh, C.L., 2006. Effect of watering regimen on chlorophyll fluorescence and growth of selected green roof plant taxa. HortScience 41, 1623–1628.

Environmental Protection Agency, United States, 2009. Reducing urban heat islands: compendium of strategies.

Environmental Protection Agency, United States, 2012. Greenacres: Landscaping with Native Plants. Retrieved March 3, 2014, from http://www.epa.gov/greenacres/.

Fairfax County, Virginia, 2007. Recommended Plant List for Intensive vegetated roofs. Retrieved Aug 8, 2013, from http://www.fairfaxcounty.gov/dpwes/publications/lti/07-03attach1.pdf.

Farrell, C., Mitchell, R.E., Szota, C., Rayner, J.P., Williams, N.S.G., 2012. Green roofs for hot and dry climates: interacting effects of plant water use, succulence and substrate. Ecol. Eng. 49, 270–276.

Fountain, M.T., Hopkin, S.P., 2004. Biodiversity of Collembola in urban soils and the use of Folsomia candida to assess soil 'quality'. Ecotoxicology 13, 555–572.

Gaffin, S., Parshall, L., O'Keeffe, G., Braman, D., Beattie, D., Berghage, R, 2006. Energy balance modeling applied to a comparison of white and green roof cooling efficiency. Green roofs in the New York Metropolitan region research report. Retrieved March 19 2014 from http://www.statisticstutors.com/articles/debrat-green-roofs.pdf#page=17.

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

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

Getter, K.L., Rowe, D.B., Cregg, B.M., 2009. Solar radiation intensity influences extensive green roof plant communities. Urban Forestry and Urban Greening 8 (4), 269–281.

Gregoire, B.G., Clausen, J.C., 2011. Effect of a modular extensive green roof on stormwater runoff and water quality. Ecol. Eng. 37, 963–969.

Herman, R., 2003. Green roofs in Germany: yesterday, today and tomorrow. In: *Proc. 1st N. Amer. Green Roof Conf.: greening rooftops for sustainable communities 1*, pp. 41–45.

Hui, S.C.M., 2006. Benefits and potential applications of green roof systems in Hong Kong. In: Proceedings of the 2nd Megacities International Conference 2006, 1–2 December. 351–60.

Kim, K.G., 2004. The application of the biosphere reserve concept to urban areas: the case of green rooftops for habitat network in Seoul. Ann. N. Y. Acad. Sci. 1023, 187–214.

Köhler, M., 2006. Long-term Vegetation Research on Two Extensive Green roofs in Berlin. J. Urban Habitats 4 (1), 3–26.

Köhler, M., Schmidt, M., Grimme, F.W., Laa, M., de Assunção Paiva, V.L., Tavares, S., 2002. Green roofs in temperate climates and in the hot-humid tropics – far beyond the aesthetics. Environ. Manage. Health 13 (4), 382–391.

Licht, J., Lundholm, J., 2006. Native coastal plants for northeastern extensive and semi-extensive green roof trays: substrates, fabrics, and plant selection. Paper presented at the Annual Greening Rooftops for Sustainable Communities Conference, Boston, MA.

Liu, T.C., Shyu, G.S., Fang, W.T., 2012. Drought tolerance and thermal effect measurements for plants suitable for extensive green roof planting in humid subtropical climate. Energy Buildings 47, 180–188.

Lundholm, J.T., MacIvor, J.S., Ranalli, M.A., 2009,). Benefits of green roofs on Canada's east coast. Paper presented at the Annual Greening Rooftops for Sustainable Communities Conference, Atlanta, GA.

Lundholm, J.T., MacIvor, J.S., MacDougall, J.Z., Ranalli, M.A., 2010. Plant species and functional group combination affect green roof ecosystem functions. PLoS ONE 5 (3), e9677.

Maclvor, J.S., Lundholm, J., 2011. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. Ecol. Eng. 37, 407–417.

Martin, M.A., Hinckley, T.M., 2007. Native plant performance on a Seattle green roof. Paper presented at the Annual Greening Rooftops for Sustainable Communities Conference, Minneapolis, MN.

Monterusso, M.A., Rowe, D.B., Rugh, C.L., 2005. Establishment and persistence of *Sedum* spp. and native taxa for green roof applications. HortScience 40, 391–396.

Nagase, Ayako, Dunnett, Nigel, 2010. Drought tolerance in different vegetation types for extensive green roofs, effects of watering and diversity. Landsc. Urban Plan. 97, 318–327.

Ngan, G., 2004. Green roof policies: tools for encouraging sustainable design. Retrieved 10 August 2013 from http://www.gnla.ca/assets/Policy%20report.pdf.

Ngan, G., 2010. Vegetation monitoring of a green roof in Saskatoon. Paper presented at the Annual Cities Alive Conference, Vancouver, Canada.

Peck, S.W., 2002. Green Roofs: Infrastructure for the 21st Century. 1st Annual Urban Heat Island Summit 2002, Toronto.

Peck, S.W., 2008. Award Winning Green Roof Designs. Schiffer Publishing Ltd, Pennsylvania.

Peck, S.W., Callaghan, C., 1999. Greenbacks from green roofs: forging a new industry in Canada, Research report for Canada Mortgage and Housing Corporation.

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

Santamouris, M., 2012. Cooling the cities-a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy. http://dx.doi.org/10.1016/j.solener.2012.07.003.

Schrader, S., Boning, M., 2006. Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans. Pedobiologia 50, 347–356.

Schroll, E., Lambrinos, J., Sandrock, D., 2009. Irrigation requirements and plant survival on northwest green roofs. Paper presented at the Annual Greening Rooftops for Sustainable Communities Conference, Atlanta, GA.

Simmons, M.T., Gardiner, B., Windhager, S., Tinsley, J., 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems 11, 339–348.

Snodgrass, E.C., Snodgrass, L.L., 2006. Green Roof Plants: A resource and Planting Guide. Timber Press, Oregon.

Susca, T., Gaffin, S.R., Dell'Osso, G.R., 2011. Positive effects of vegetation: urban heat island and green roofs. Environ. Pollut. 159, 2119–2126.

Ting, I.P., 1985. Crassulacean acid metabolism. Annu. Rev. Plant Physiol. 36, 595–622.

Townshend, D. (2007). Study on green roof application in Hong Kong. Architectural Services Department, Urbris Limited 2007. Retrieved 10 August 2013 from http://www.archsd.gov.hk/media/11630/green_roof_study_final_report.pdf.

Van Woert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Xiao, L., 2005. Watering regime and green roof substrate design affect *Sedum* plant growth. HortScience 40 (3), 659–664.

Villarreal, E.L., Bengtsson, L., 2005. Response of a *Sedum* green-roof to individual rain events. Ecol. Eng. 25, 1–7.

Wolf, D., Lundholm, J.T., 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecol. Eng. 33, 179–186.

Yang, J., Qian, Y., Peng, G., 2008. Quantifying air pollution removal by green roofs in Chicago. Atmos. Environ. 42, 7266–7273.

Zhang, X.L., Shen, L.Y., Tam, W.Y., Lee, W.Y., 2012. Barriers to implement extensive green roof systems: a Hong Kong study. Renew. Sustain. Energy Rev. 16, 314–319.