System Interactions of Green Roofs in Blue-Green Cities

Lan HOANG, Richard A. FENNER*

Centre for Sustainable Development, Department of Engineering, University of Cambridge, CB2 1PZ, United Kingdom
**Corresponding author*
Email: raf37@cam.ac.uk

ABSTRACT
A blue-green city aims to integrate water management with green infrastructure, therefore recreating a naturally-oriented water cycle contributing to the amenity of the city. Amongst Blue Green solutions, green roofs have emerged as multifunctional components to reduce runoff by storing rainwater in leaves and soil and restoring urban ecology without taking valuable urban space. This paper reviews studies assessing the functional processes of extensive green roofs and highlights the parameters linking those processes. It is argued that substrate depth, soil moisture and plant coverage characteristics represented by the leaf area index (LAI) are important parameters simultaneously influencing soil water balance, thermal exchange, building thermal insulation, pollutant trapping and green roof ecosystem. Implications for green roof management are then drawn from a hypothetical case based on UK conditions.

KEYWORDS
Blue-green cities, flood risk management, multiple benefits, green infrastructure, green roofs

INTRODUCTION
A Blue-Green City aims to recreate a naturally-oriented water cycle while contributing to the amenity of the city by bringing water management and green infrastructure together. The Blue-Green approach is more than a stormwater management strategy and can also provide important ecosystem services and socio-cultural benefits when the urban system is in a non-flood condition. However, quantitative evaluation of benefits and the appraisal of the relative significance of each benefit in a given location are not well understood. The Blue-Green Cities Research Project is developing procedures for the robust evaluation of the multiple functionalities of Blue-Green Infrastructure/ Green Infrastructure (BGI/GI) components within flood risk management (FRM) strategies.

Green roofs are an important component of both water sensitive urban design and green infrastructure. In areas of diminishing green spaces, they have emerged as a solution to restore urban ecology without taking valuable urban space; in areas of flood risks, they could reduce runoff by storing rainwater in leaves and soil. Within the urban fabric, they could offer other multiple functions, such as urban cooling and serve as pollutant traps (Berndtsson, 2010; Speak *et al.*, 2014). Various studies have analysed each of these functions and some have provided quantification of their impacts. Yet, there are few studies that consider these multiple functions in a connected manner through analysis of the linking interactions and interdependencies of these benefits. This paper summarises the main functions of green roofs as reported in the literature and highlights the key parameters for the quantification of each function. The magnitude of these functions and the interactions across the functions are then demonstrated under a hypothetical case study set in the UK.

REVIEWING GREEN ROOF FUNCTIONS

The multiple functions of green roofs

A meta-analysis of the literature on green roofs reveals multiple methodologies to estimate a range of potential functions and benefits, which are:

- *Hydological performance regarding runoff retention and storage*: as a bucket model/storage that stores water in leaves and soil
- *Carbon sequestration*: as layers of plants, top soil and sub soil that store carbon in plants and soil
- *Noise reduction:* as porous media that can absorb sound propagation from engines and tyres
- *Building and urban cooling:* as high albedo surfaces that can reduce solar energy passing through the roof
- *Pollutant trap:* as a filter system which can trap particulates in soil and leaf surfaces
- *Food production:* as photosynthesis systems that takes in carbon dioxide, water, solar radiation to stimulate plant growth and reproduction
- *Biodiversity:* as a host for various species enhancing ecosystem services
- *Social benefits:* as a visibly green component and a place for social/physical activities

These benefits from green roofs can be classified into physical impacts, ecological impacts and socio-economic impacts (Figure 1). For physical impacts such as modifying building insulation and attenuating noise levels, the accounting methods often involve physical models of radiation being reflected off the roof or sound propagation through media (Berardi *et al.*, 2014). For ecological impacts, green roofs are often seen as one component of urban ecology which supports different functional species (Madre *et al.*, 2014). For socio-economic impacts, the estimation methods often rely on interviews and surveys of urban residents. These approaches tend to characterise green roofs solely by a specific function and ignore the potential interactions with other functions.

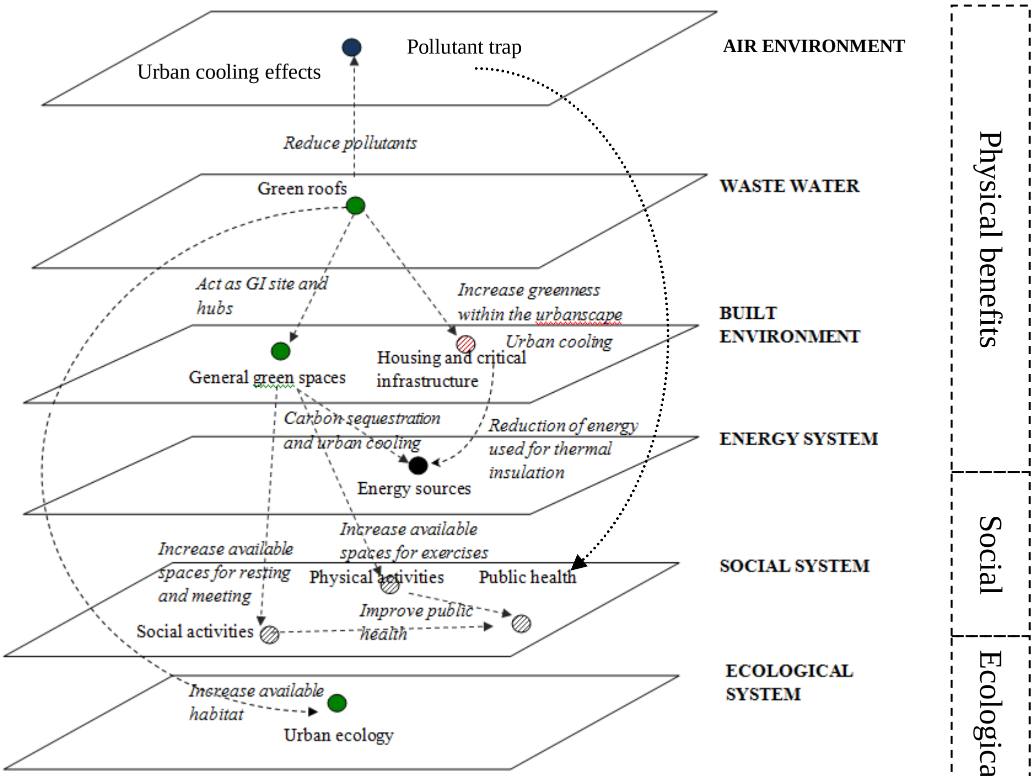

Figure 1 The inter-related impacts of green roofs across the urban system

Existing evidence on the linking functions

The linking processes between the hydrology and the ecology of green roofs are presented in Figure 2. Madre *et al.* (2014) demonstrated that the colonizing species can be influenced by roof characterization such as substrate depth, available area, building height, surrounding habitats and maintenance regime. Their analysis showed that higher building height can encourage light-affinity plants (due to more lighting) and wind-dispersal species (due to their seeds being continually carried at roof level) while maintenance by the building operators can encourage nutrient and moisture affinity plants (due to high soil moisture and soil nutrients). The composition of the plant coverage then affects canopy interception, the transpiration rate and subsequently, the hydrological processes of the roofs. Terri *et al.* (1986) noted that vegetation can affect the PET rate via transpiration and this is also linked to substrate depth, with deeper substrate tending to be able to accommodate higher plant growth and coverage, and subsequently more vegetation coverage and transpiration. Plant transpiration helps reduce soil moisture and thus maintains the water storage capacity of green roofs in the case of rainfall events (Villarreal and Bengtsson, 2005). Water retention is affected by substrate depth, available area, maintenance regime and additionally roof slope and orientation (Vanuytrecht *et al.*, 2014). Studies such as Nagase and Dunnett (2012) and Vanuytrecht *et al.* (2014) identified the important parameters on run off and water storage as plant heights, plant diameters and soil organic matter content, which can adhere more moisture to substrate. Nevertheless, Van Woert *et al.* (2005) and Wolf and Lundholm (2008) showed that the rate of water loss varies from species to species and depends on the interactions between transpiration, evaporation and water retention across the canopy and the soil layer. Some species like *Sedum acre* facilitate transpiration but also grows into a vegetation mat that restricts evaporation from the soil surface (Van Woert *et al.*, 2005). Examining the hydrological processes on green roofs, Stovin *et al.* (2013) and Berretta *et al.* (2014) provided hydrological models to analyse the influence of vegetation and substrate characteristics.

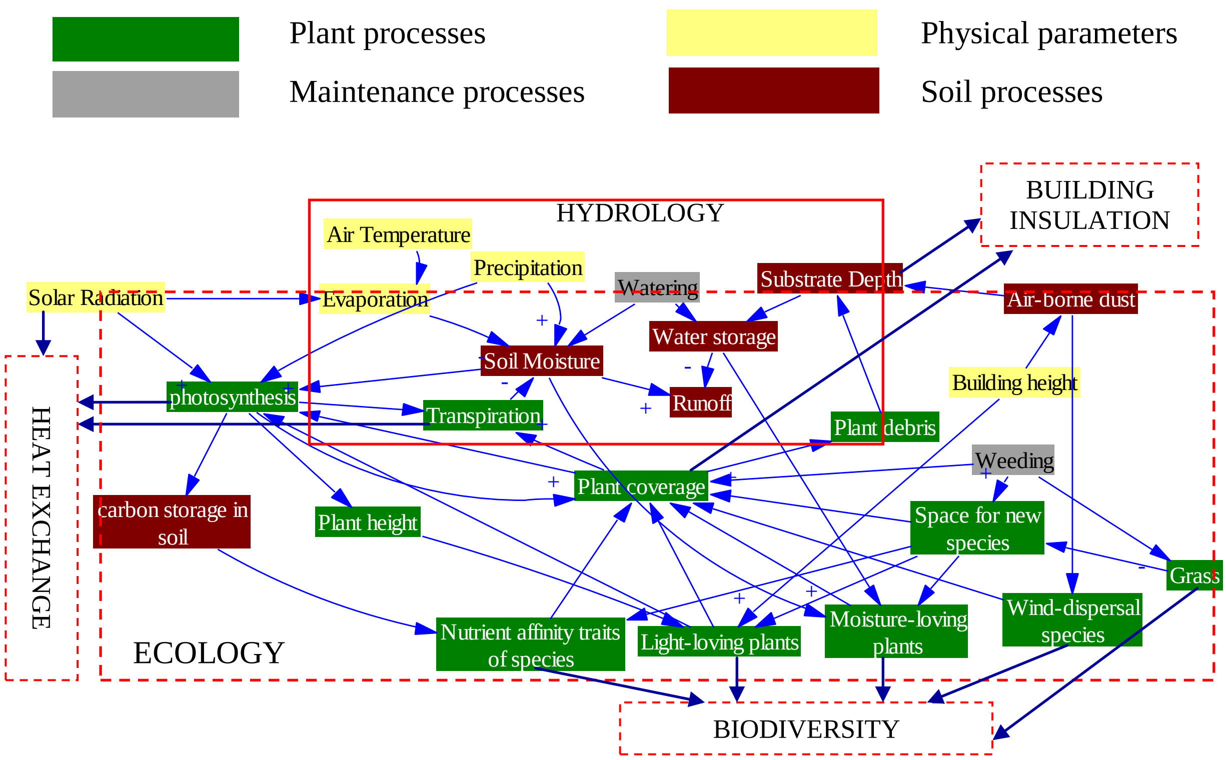

Figure 2 Inter-related hydrological and ecological processes. The same colour scheme for different proceeses is used in subsequent diagram in this paper.

The hydrological balance of the roof and the ecological processes in turn affect the photosynthesis process of plants, their growth rates and their spread across the green roofs (Figure 3). Photosynthesis also sequesters carbon from the atmosphere to store in soil and plant biomass (Getter *et al.*, 2009). Edmondson *et al.* (2012) noted that this organic carbon storage differs for different types of buildings, soil depth and types of soil. Plant leaves and air-borne dust could further contribute to soil nutrient and carbon storage. In addition to the physical properties of soil, the difference also exists between different building ownership categories, which may have different maintenance regime (Davies *et al.*, 2011). In essence, weeding may remove grass and thus create a niche for plants. Watering the roof also maintains soil moisture and as such encourages moisture-loving plants but also takes up storage for rainwater. During drought spells, the green roof ecosystem changes because water-dependent species wither while drought-resistant species remain. Therefore, the interactions of weather, watering and weeding can influence the composition of the roof ecosystem, which leads to different types of ecosystems, biodiversity of the roof and the potential for food production. The state of the roof could also infer different levels of visual amenity and their urban habitat values.

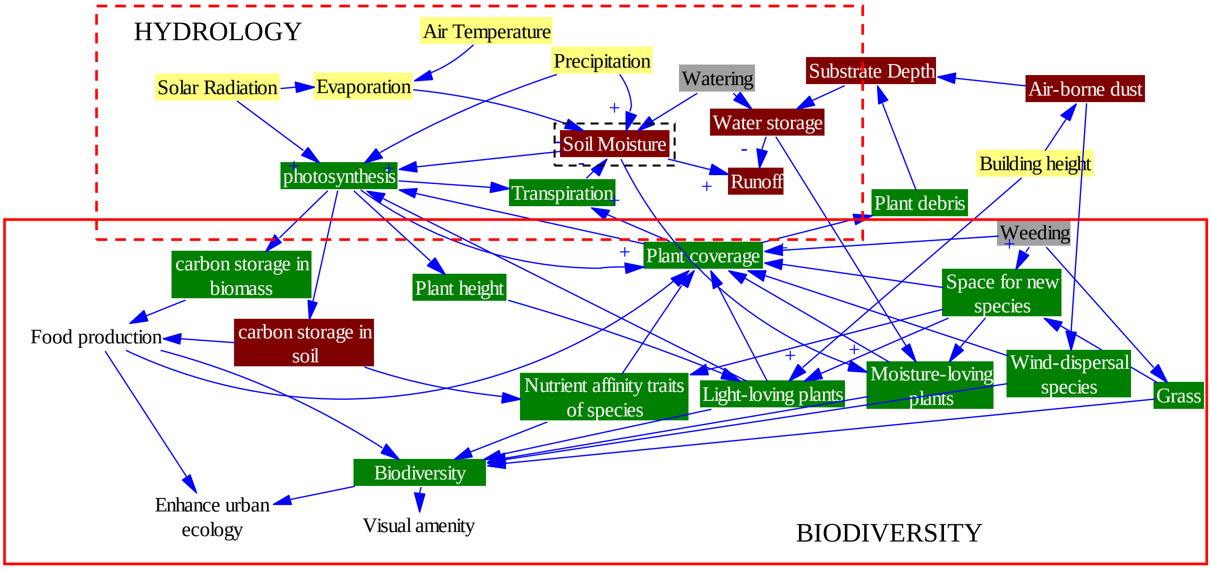

Figure 3 Inter-related processes of photosynthesis, plant growth, roof maintenance and roof ecosystems

The ecological and hydrological processes of the roof also affect its ability to absorb and scatter noise (Figure 4). One major source of noise in the urban landscape is road traffic (Van Renterghem and Botteldooren, 2009). With increasing building height, the green roof is further away from the noise source and therefore can attenuate less noise. The sound absorption capacity of green roofs comes from two effects: reduced sound propagation in porous media (soil substrate) and the damping effect of foliages (mainly to sound of high frequencies). The effect of sound propagation of the soil substrate depends on substrate depth and substrate sound impedance while that of the foliages depends on types of plants and the design of the vegetation layer (Yang *et al.*, 2012; Horoshenkov *et al.*, 2013). Yang *et al.* (2013) further demonstrated that soil moisture content can reduce the sound absorption capacity of green roofs. This is further confirmed by Connelly (2011), who found that plants can reduce the sound absorption capacity of the roof due to their water retention. The sound absorption capacity of green roofs therefore is linked to characters of the vegetation and soil cover.

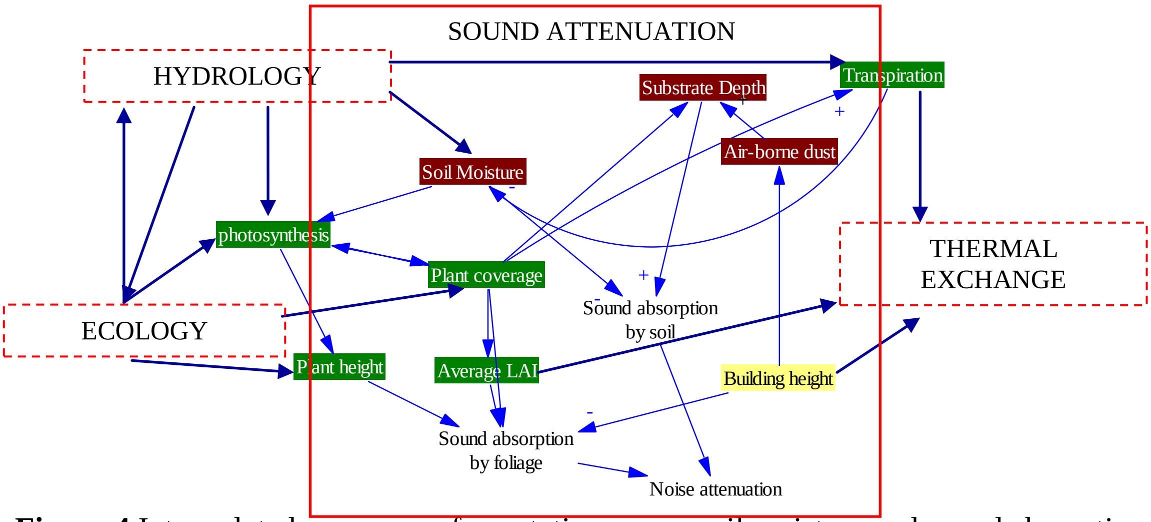

Figure 4 Inter-related processes of vegetation cover, soil moisture and sound absorption

Finally, vegetation cover can influence the roof's capacity for pollutant trapping, building thermal insulation and general thermal exchange with the atmosphere (Figure 5). The pollutant trapping capacity comes from the deposition of air-born particulate matter on leaves in dry conditions and from pollutant washout during rainfall events, termed as dry and wet deposition, respectively (Speak *et al.*, 2014). Plants additionally indirectly reduce air pollutants via lowering surface temperature and therefore reduce photochemical reactions forming ozone (Akbari *et al.*, 2001). Regarding green roof capacity in building thermal insulation, Theodosiou (2009) reported the cooling capacity of green roofs and highlighted existing roof insulation, foliage density, soil moisture content and soil thickness as determining factors. Barrio (1998) found that green roof, particularly extensive green roofs, do offer limited passive cooling and mainly cool buildings via insulation. Similar to Theodosiou (2009), Barrio (1998) found that the leaf area index, soil thickness, soil density, soil moisture content and the foliage geometrical characteristics are relevant parameters characterizing the cooling potential. Ouldboukhitine *et al.* (2011) further coupled the heat and mass transfer process to look at the thermal exchange between the canopy and the soil layer. Within that model, vegetation coverage, leaf canopy height and soil moisture remained the important parameters.

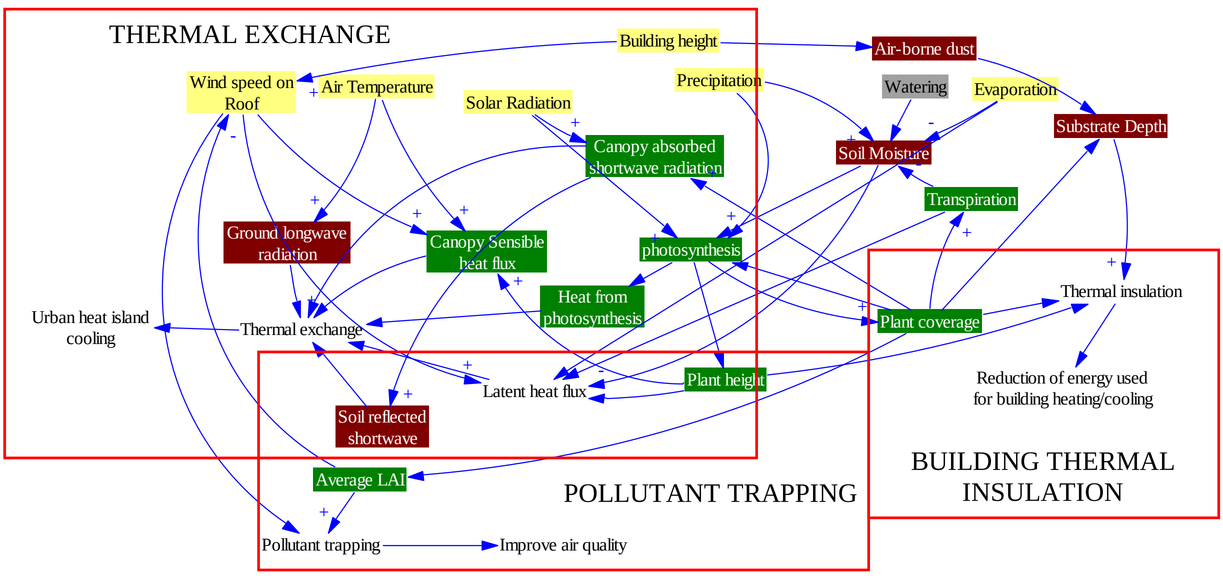

Figure 5 Inter-related processes of plant state, thermal insulation, urban cooling and pollutant trapping

KEY PARAMETERS AND A HYPOTHETICAL EXAMPLE

Methodology

Overall evidence in the literature has highlighted the interdependent natures of green roof functions. In essence, parameters representing the vegetation cover and the soil substrate have been found to be highly relevant to water retention, green roof ecosystems and thermal exchange. Additionally, maintenance regarding watering and the weeding regime can affect a green roof ecosystem and its soil moisture, which further influences thermal exchange, sound propagation and plant growth.

This paper uses a hypothetical example of an extensive green roof with Sedum species. In this initial analysis, the functions are limited to water retention, carbon sequestration, pollutant trapping and noise reduction. The paper uses observed rainfall and temperature data of Wiggoholt (UK) from 2004 to 2007 to demonstrate the linkages and non-linearity of green roof processes. The extensive green roof function is calculated based on a unit area of 1 m^2, with a substrate depth of 40 cm, soil moisture field capacity of 30 cm, wilting point of 15 cm and an initial moisture content of 10 mm. Soil porosity is assumed to be 0.63, with no soil compaction occurring and has 15% soil organic matter. The sustainable coverage of the vegetation (the minimum level of coverage to ensure survival) is 35% and the maximum vegetation coverage is 100%. PET is calculated from the Thornthwaite PET equation (with an exponential decay rate representing the effect of a plant species) and rainfall input. Substrate moisture content and runoff is calculated based on Stovin et al. (2012) as follows

Substrate moisture content

$$S_t = \max\left(0, \min\left(S_{t-1} + Rain_t - ET_t, S\_\max\right)\right)$$

With $Rain_t$, S_t, ET_t being the soil moisture content at time t and S_{max} the maximum soil moisture

Equation1

Run off

$$R_t = \begin{cases} 0 & if\ S_{t-1} + P_t - ET_t \leq S\_\max \\ P_t - (S\_\max - S_{t-1}) - ET_t & if\ S_{t-1} + P_t - ET_t > S\_\max \end{cases}$$

Equation 2

Note that sedum cannot grow under temperature <10^0 C; we construct a simple population dynamic model of vegetation cover as follows

$$P_{t+1} = \begin{cases} P_t\ if\ T < 10^0C \\ P_t - \alpha P_{t-1}^2 (L - P_t)(K - P_{t-1})\ otherwise \end{cases}$$

With P_t being the plant coverage at time t;
L is the carrying capacity;
K being the minimum sustainable population
α a constant, set to be 0.03

Equation 3

The pollutant trapping rate is assumed to be constant and based on Speak et al. (2012)'s measurement for Sheffield (UK), which is 0.42 ± 0.01 g m^{-2} $year^{-1}$. The actual trapping is a function of this rate and the plant coverage.

Also assuming that the constant rate of 0.14 kg C $m^{-2}year^{-1}$ or 0.384 g C $m^{-2}day^{-1}$ (Davies *et al.*, 2011) of carbon sequestration applies when there is growth (e.g. temperature >10^0 C)

$$Sequestration_t = \begin{cases} 0\ if\ T < 10 \\ 0.384 * Coverage\ otherwise \end{cases}$$

Equation 4

The absorption coefficient of the roof to sound at 1000 Hz frequency is calculated based on a regression by Connelly (2011) as an illustration of soil moisture impacts. The regression concerns the percentage of organic matter (OM), soil porosity (Ψ), soil compaction (C) and whether soil moisture (ω) is at wilting point or field capacity as follows:

Sound Absorption Coefficient=-0.0423 +0.85OM+0.8151 Ψ-0.1331(if soil moisture=Wilting)-0.2357(if soil moisture= Field Capacity)-0.097C *Equation 5*

Results and discussion

The runoff model from Stovin et al. (2012) has been used to simulate the hypothetical runoff and soil moisture from 2004-2007 (Figure 5). The results show relatively drier periods over the summer time. In other periods, run off occurs once the soil moisture storage is saturated.

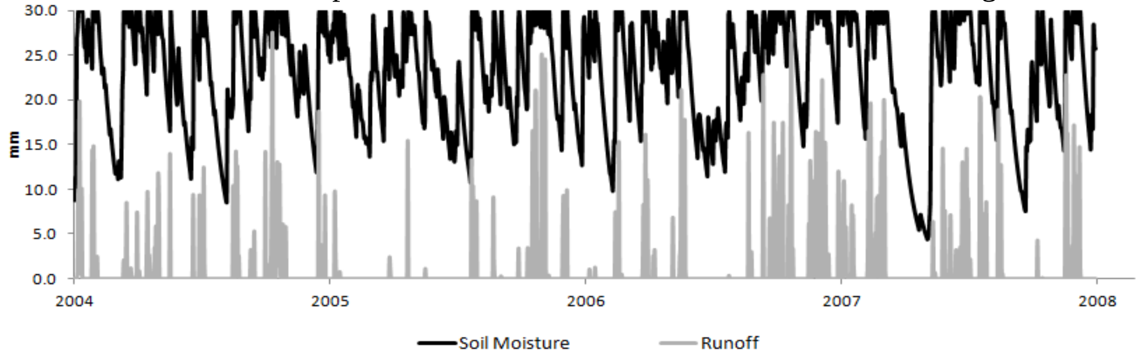

Figure 5 Simulated runoff (mm) and soil moisture storage (mm) for a unit area of 1 m^2 of the hypothetical green roof

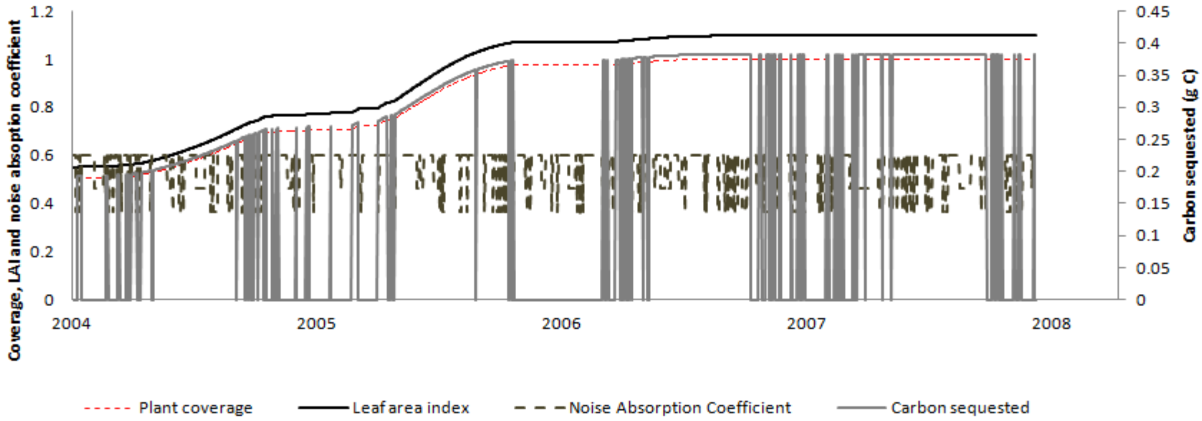

Figure 6 Simulated plant coverage, leaf area index, noise absorption coefficient and the amount of carbon sequestration in the canopy for a unit area of 1 m^2 of the hypothetical green roof

These periods nevertheless correspond to periods of high temperature which promotes vegetation growth and photosynthesis leading to carbon sequestration (Figure 6). Because *Sedum* is a drought-tolerant species, the limiting factor of soil moisture on plant growth is not likely to affect *Sedum*. Initial plant growth rate is high and then reduces once the vegetation cover approaches the carrying capacity of the roof. In response to increasing vegetation coverage, the average leaf area index also increases. Carbon sequestration, as such, occurs in phases when the temperature is above 10^0 C and also approaches the maximum capacity once the vegetation occupies the whole green roof. These are also the periods when green roof vegetation has higher capacity to attenuate noise, since they are not dampened by high soil moisture content. The periods of photosynthesis do not necessarily correspond to high transpiration since *Sedum* can switch the metabolism mechanism under different water availability: under abundant water availability, this is mostly C3 (water intensive) mode; under restricted water availability and high temperature, the plants switch to crassulacean acid metabolism (water efficient) mode and thus only open their stomata at night to reduce water loss (Borland, 1996). Therefore the green roof offers more transpiration under high temperature and high soil moisture condition (which could occur either due to precipitation or maintenance). Pollutant trapping is a function of vegetation coverage and increases with this coverage until reaching maximum capacity.

Therefore, the hypothetical example demonstrates that different functions of a green roof can prevail under different conditions. The main determining factors of these conditions are heat and water budget of the roof. A preliminary summary of green roof functions under different conditions is presented in Table 1. In particular, high soil moisture can diminish the functioning of noise attenuation, limits the capacity for stormwater uptake but could enhance photosynthesis, carbon sequestration and thermal exchange. Under high temperature, additional thermal exchange occurs via transpiration, which also reduces soil moisture and maintains capacity for rainwater uptake.

Table 1 Potential functions of green roofs under different conditions.
+, ++, +++ denote the potential level of functions from low to high; - denotes small or zero functioning

Soil Moisture	**Low**		**High**		**Saturation**	
Air temperature	*Low*	*High*	*Low*	*High*	*Low*	*High*
Water storage capacity	++	+++	+	++	-	-
Pollutant trap	++	++	+++	+++	+	+
Thermal building insulation	++	++	++	++	+	+
Thermal exchange	+	++	+	+++	-	+
Carbon sequestration	+	+	++	+++	-	-
Noise attenuation	+++	+++	++	++	+	+
Biodiversity	*Cold and drought resistant ecosystem*	*Drought resistant ecosystem*	*Cold resistant ecosystem*	*Multiple species*	-	-
Visual amenity	+	++	+++	+++	-	-

CONCLUSION

This paper shows that green roofs have inter-related functions that need to be considered conjunctively in benefit accounting and modelling. These functions have strong dependencies on soil moisture and characteristics of the vegetation and the soil cover. Via a simple hypothetical example, the paper has demonstrated that different green roof functions prevail under different temperature and soil moisture conditions. The paper further demonstrates that green roofs are likely to have a maximum capacity for each of their functions, and this capacity is often influenced by parameters reflecting initial roof design such as substrate depth, building height and the soil and vegetation types. Regarding the level of service, green roof functions can occur in discrete periods such as carbon sequestration or continuously such as pollutant trapping. In conclusion, integrated models need to be developed to link the hydrological, ecological and other physical processes of green roofs and evaluate the interdependencies of their functions across physical conditions, plant types and maintenance regime.

ACKNOWLEDGEMENT

This work is part of the Blue Green Cities project funded by the UK Engineering and Physical Sciences Research Council, grant EP/K013661/1.

List of references

Akbari, H., Pomerantz, M. & Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy,* 70 (3), 295-310.

Barrio, E.P.D., 1998. Analysis of the green roofs cooling potential in buildings. *Energy and Buildings,* 27 (2), 179-193.

Berardi, U., Ghaffarianhoseini, A. & Ghaffarianhoseini, A., 2014. State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy,* 115 (0), 411-428.

Berndtsson, J.C., 2010. Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering,* 36 (4), 351-360.

Berretta, C., Poë, S. & Stovin, V., 2014. Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics. *Journal of Hydrology,* 511 (0), 374-386.

Borland, A.M., 1996. A model for the partitioning of photosynthetically fixed carbon during the c3-cam transition in sedum telephium. *New Phytologist,* 134 (3), 433-444.

Connelly, M., 2011. *Acoustical characteristics of vegetated roofs's contributions to the ecological performance of buildings and the urban soundscape*. University of British Columbi.

Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R. & Gaston, K.J., 2011. Mapping an urban ecosystem service: Quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecology,* 48 (5), 1125-1134.

Edmondson, J.L., Davies, Z.G., Mchugh, N., Gaston, K.J. & Leake, J.R., 2012. Organic carbon hidden in urban ecosystems. *Scientific reports,* 2.

Getter, K.L., Rowe, D.B., Robertson, G.P., Cregg, B.M. & Andresen, J.A., 2009. Carbon sequestration potential of extensive green roofs. *Environmental Science & Technology,* 43 (19), 7564-7570.

Horoshenkov, K.V., Khan, A. & Benkreira, H., 2013. Acoustic properties of low growing plants. *The Journal of the Acoustical Society of America,* 133 (5), 2554-2565.

Madre, F., Vergnes, A., Machon, N. & Clergeau, P., 2014. Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. *Landscape and Urban Planning,* 122, 100-107.

Nagase, A. & Dunnett, N., 2012. Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure. *Landscape and Urban Planning,* 104 (3–4), 356-363.

Ouldboukhitine, S.-E., Belarbi, R., Jaffal, I. & Trabelsi, A., 2011. Assessment of green roof thermal behavior: A coupled heat and mass transfer model. *Building and Environment,* 46 (12), 2624-2631.

Speak, A., Rothwell, J., Lindley, S. & Smith, C., 2014. Metal and nutrient dynamics on an aged intensive green roof. *Environmental Pollution,* 184, 33-43.

Stovin, V., Poë, S. & Berretta, C., 2013. A modelling study of long term green roof retention performance. *Journal of Environmental Management,* 131 (0), 206-215.

Terri, J.A., Turner, M. & Gurevitch, J., 1986. The response of leaf water potential and crassulacean acid metabolism to prolonged drought in sedum rubrotinctum. *Plant physiology,* 81 (2), 678-680.

Theodosiou, T., 2009. Green roofs in buildings: Thermal and environmental behaviour. *Advances in building energy research,* 3 (1), 271-288.

Van Renterghem, T. & Botteldooren, D., 2009. Reducing the acoustical façade load from road traffic with green roofs. *Building and Environment,* 44 (5), 1081-1087.

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.

Vanuytrecht, E., Van Mechelen, C., Van Meerbeek, K., Willems, P., Hermy, M. & Raes, D., 2014. Runoff and vegetation stress of green roofs under different climate change scenarios. *Landscape and Urban Planning,* 122 (2), 68-77.

Villarreal, E.L. & Bengtsson, L., 2005. Response of a sedum green-roof to individual rain events. *Ecological Engineering,* 25 (1), 1-7.

Wolf, D. & Lundholm, J.T., 2008. Water uptake in green roof microcosms: Effects of plant species and water availability. *Ecological Engineering,* 33 (2), 179-186.

Yang, H.-S., Kang, J. & Cheal, C., 2013. Random-incidence absorption and scattering coefficients of vegetation. *Acta Acustica united with Acustica,* 99 (3), 379-388.

Yang, H.S., Kang, J. & Choi, M.S., 2012. Acoustic effects of green roof systems on a low-profiled structure at street level. *Building and Environment,* 50, 44-55.