The use of greenroofs for the mitigation of environmental problems in urban areas

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Abstract

Greenroofs are new technology that can be applied in areas such as present-day cities, where less and less green space is available. Greenroofs have many benefits: they make buildings more thermally efficient, prolong the life of a roof, ameliorate extremes of temperature and humidity, reduce surface water runoff, help to reduce the urban heat island effect, air pollution and noise, and provide green space for people and wildlife. Greenroofs have been studied in many countries, from the point of view of thermal performance, protection of the roof membrane, stormwater retention and runoff quality. Although the results are site-specific, it is necessary to review these studies. Greenroofs were found to be effective in helping to keep buildings cool in summer and also to reduce building energy consumption. Research showed that planted roofs reduce the temperature fluctuation in the roof membrane. Greenroofs delay rainfall runoff and reduce runoff rate and volume. The results of greenroof runoff water quality showed that they behave as a sink or as source of contaminants in runoff water. The results of the investigation of Light Weight Aggregates (LWA)-based greenroofs in Estonia showed that an extensive greenroof is sufficiently capable of protecting the layers of the base roof from extreme temperatures. Typically, light rain is retained, whereas heavy rain penetrates the greenroof media. The quality of the runoff water varies depending on runoff character and the pollutants accumulated on the roof.
Keywords: energy saving, evapotranspiration, greenroof, rooftop garden, runoff quality, thermal performance, water retention.

1 Introduction

The main objective of this study is to give a sufficient review of the results of research that has been performed to find out how greenroofs work in reality. We also present the results of the first research into greenroofs in Estonia.

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1.1 Greenroof term and types

Greenroofs or rooftop gardens are a specialized roofing system that supports vegetation growth on rooftops. ‘Greenroof’ is the most common term, but other terms such as ‘planted roof’, ‘vegetated roof’, ‘grassed roof’ or ‘eco-roof’ are also used. Greenroofs are not a new concept. They have a long history, but today it is rapidly advancing technology that has the potential to improve the quality of urban life. Greenroofs are usually divided into two general categories: extensive and intensive, although mixed types and natural sod roofs [1] are also possible.

‘Extensive greenroofs’ have a thin substrate layer, low weight, low capital cost and can be installed over the flat roofs of existing buildings. This roof type is not usually designed to be accessible, except for maintenance. Vegetation normally consists of sedums, mosses, succulents, herbs or grasses and is self-sustaining. The thickness of an extensive greenroof’s substrate is <50–200 mm, and its weight can be <50–220 kg/m^2.

‘Intensive roof gardens’ have a deep soil layer and because of their great weight, need a stronger building structure. They are usually accessible, and may include lawns, shrubs and tree plantings. The roof garden needs regular maintenance including irrigation, fertilizing and weeding, and is very expensive to build and maintain. The thickness of an intensive roof garden’s soil layer is >200 mm, and its weight can be 200–1000 kg/m^2.

1.2 Greenroof construction

Greenroof systems are established mainly on top of an existing roof structure, and consist of certain specific layers [1, 2]:

– waterproofing membrane, typically made of polyvinyl chloride (PVC), high-density polypropylene or bituminous fabrics. If waterproof materials are not root resistant, they must be protected from root penetration;

– a drainage layer is needed to remove excess water from the growing medium and also to retain some water for irrigating the plants; a purpose-made fibrous plastic mat or a layer of gravel is often used for this;

– a filter membrane prevents fine particles in the substrate layer from clogging the drainage layer, which is usually a geo-textile filter fabric;

– a substrate layer (growing medium) is selected on the basis of water retention, water permeability, suitability for root growth and plant anchoring properties; the substrate layer usually consists of a mixture of soil, sand, gravel, organic matter and crushed brick; in Estonia a Light Weight Aggregate (LWA), which is lightweight, well-drained and silt-free, is mostly used in the substrate layer; if the roof’s slope is more than 20 degrees, supporting baffles are needed;

– plants must be resistant to extreme temperatures, solar exposure, scarce water, as well as an excess of water and stronger winds; plants for extensive greenroofs must be low-growing and shallow-rooted.

2 Materials and methods

In addition to a review of studies that have been performed throughout the world, this paper also briefly describes how an LWA-based greenroof works in the

Estonian climate, as the result of observing an existing greenroof in Tartu. The task was to assess the thermal performance, stormwater retention potential and runoff water quality of a greenroof, and to compare those with modified bituminous membrane roofs (roofs had the same area – 120 m^2). The studied greenroof consists of the following layers: modified bituminous base roof, plastic wave drainage layer (8 mm), rock wool for rainwater retention (80 mm) and substrate layer (100 mm) with LWA (66%), humus (30%) and clay (4%). The most common plant species are *Sedum acre, Thymus serpyllum, Dianthus carthusianorum* and *Cerastium tomentosium.*

The temperature was measured using sensors (Pt1000TG8/E) after every 15 minutes, and recorded with a data logger produced by Comet System. The measuring time was June 2004 to April 2005. As the bituminous membrane of the base roof was inaccessible, the temperature was measured on the surface of both the roof and above the roof at 1 m, and also at the depth of 50 and 100 mm in the substrate layer. Because the surface of the greenroof was mainly covered by LWA (plant cover was 45%), the surface temperature expresses the temperature of the LWA. It must also be noted that plant cover was thicker on one side of the roof than the other side, which influenced rainwater runoff results. Stormwater runoff was manually measured on an hourly basis with 20-litres canisters, or more frequently when necessary. The greenroof had two outflows, and there was one outflow for the reference roof. Runoff water samples were analyzed for pH, BOD_7, COD, totalN, NO_3^-, NH_4^+, totalP, PO_4^{3-}, SO_4^{2-}, Ca^{2+} and Mg^{2+} by AS Tartu Veevärk (Water Works of Tartu).

3 Mitigation of environmental problems in urban areas

3.1 Protection of roof membrane

An exposed roof membrane absorbs solar radiation during the day and its temperature rises, while in the evening its surface temperature drops. Daily temperature fluctuations create thermal stresses in the membrane and reduce its durability. The greenroof blocks the solar radiation from reaching the membrane, thus lowering its temperature and also minimizing temperature fluctuations. The life span of the membrane of a conventional roof is usually 20–25 years, but it is believed that a greenroof membrane may last twice as long.

During the 22-month observation period (660 days) in Ottawa, Canada, Liu [3] found that the membrane temperature of the reference bituminous roof exceeded 30°C for 342 days, was above 50°C for 219 days and above 60°C for89 days. In comparison, the membrane under the greenroof only exceeded 30°C for 18 days, and never reached 40°C. The temperature fluctuation in the exposed membrane of the reference roof had a median of 42–47°C. The greenroof reduced the temperature fluctuation in the roof membrane to a median fluctuation of 5–7°C throughout the year. Wong *et al* [4] found that surface temperatures measured under different kinds of vegetation were much lower than those measured on hard surfaces. The maximum temperature of the hard surface and under all kinds of plants was 57°C and 36°C respectively.

The Estonian study produced the following main results. In the summer months, from June to August, the LWA's surface heats and cools faster (amplitude 4.7°C to 54.8°C) on the sunny days than the surface of the bituminous roof (6.1°C to 52.7°C), remaining coolest at night. The temperature fluctuation at a depth of 100 mm was only 23.9°C (10.3°C to 34.2°C), and soil temperature was also more stable. Therefore the greenroof's substrate layer reduced summer temperature fluctuations by 22.7°C. The number of days on which the temperature exceeded 30°C was 63 for the bituminous roof, but only 9 at a depth of 100 mm of the greenroof's soil. Although LWA surface heating in the daytime and cooling in the evening involves corresponding changes in soil temperature, the latter fluctuates notably less, and thus the base roof is protected from large temperature fluctuations. The temperature at a depth of 100 mm rises slowly until afternoon, and then begins to fall just as slowly. At a depth of 50 mm the temperature runs in the same way, but is higher before noon and lower after noon. Since in summer the LWA's temperature fluctuates even a little more than the temperature of the bituminous membrane, the immediate establishment of vegetation is recommended. In the autumn months (September–November), temperatures did not change much, due to cool and cloudy weather.

In winter (December–March) temperatures were low both on the surface of the greenroof (min –13.6°C) and in the soil (min –9.8°C), because the snow cover was thin due to ablation by snowstorms. The reference roof was covered by a 200 mm thick snow layer, which kept the surface temperature relatively stable (min –8°C). In the winter days, the insulating effect of the snow cover is apparent. In spite of the equal thickness of the snow cover, the greenroof's soil temperature is several degrees higher than the temperature of the surface of the reference roof. In spring the temperatures of roof surfaces fluctuated considerably due to daily sunshine and night frosts, whereas soil temperature was more stable. When the daytime sun heats and the night freezes it, the amplitude of the soil temperature (1.3°C) is remarkably less than that of the surface (20.1°C).

3.2 Reducing heat flow and energy cost

Greenroofs are recognized as providing thermal performance and roof insulation for buildings. Of the total solar radiation absorbed by the planted roof, 27% is reflected by the plants, 60% is absorbed by the plants and the soil, and 13% is transmitted into the soil [5]. Many researches [5–9] have demonstrated that greenroofs reduce diurnal temperature variations in buildings by blocking solar radiation, which contributes to energy conservation. The greenroof acted as a thermal mass that effectively dampened the thermal fluctuations going through the roofing system. In the summer period a greenroof's cooling effect is higher due to the evapotranspiration from plants and the evaporation of retained moisture from the soil. In the winter period a greenroof can help to reduce heat loss from buildings that act as an insulation membrane (Table 1).

Table 1: The key results and conclusions of the studies of thermal performance of greenroofs.

Study and location	Monitoring method	Results and conclusions
Palomo Del Barrio [6] and Theodosiou [7]; Mediterranean region	Mathematical model / combined computer model	Greenroofs act as insulation, reducing the heat flux through the roof. The main characteristics are: foliage density (the leaf area index), foliage height, soil layer thickness (apparent density and moisture content), canopy evapotranspiration, green roof type, insulation layer thickness, relative humidity and wind speed. Greenroof plants must have a large foliage development and/or mainly horizontal leaf distribution.
Takakura *et al* [10]; Tokyo, Japan	Field measurements and computer simulation	Measured results showed that the maximum difference between room air temperatures beneath the bare concrete roof and the ivy-covered roof was around 15°C. The simulation showed that for the soil covered, turf-covered and ivy-covered roofs, the heat flow was mostly from inside to outside, while for the bare concrete roof the heat flow was mostly from outside to inside.
Niachou *et al* [8]; Athens, Greece	Field measurements and mathematical approach	The surface temperatures of the outdoor spaces on the insulated buildings, both with and without the greenroof, was 26–40°C. For non-insulated buildings, temperatures vary between 28–40°C and 42–48°C respectively. Greenroofs have a significant thermal performance above non-insulated roofs, but for the well-insulated roofs, the role of the greenroof is almost inconsiderable.
Onmura *et al* [11]; Japan	Field measurements and wind tunnel experiment	The evaporative cooling effect of a rooftop lawn garden yielded a 50% reduction in heat flux in the rooms below the garden. The evaporative component is an important role in reducing heat flux. Evaporation depended on the moisture content in the lawn. In closed spaces with planted roofs, the air temperature beneath the plants is nearly 4–5°C lower than that of the air above.

Table 1: Continued.

Liu [3]; Ottawa, Canada	Field measurements	The greenroof reduced the heat flow through the roofing system by over 75% in spring and summer. During the observation period (22 months), the greenroof reduced 95% of the heat gain and 26% of the heat loss as compared to the reference roof. In the autumn and early winter the growing medium acted as an insulation layer. On the other hand, as the growing medium froze, its insulation value was greatly diminished, but then snow coverage provided insulation to the roofing system. The greenroof effectively improved the energy efficiency of the roofing system in spring and summer. The average daily energy demand for space conditioning due to the heat flow through the reference bituminous roof was 6.0–7.5 kWh/day, and the greenroof reduced it to less than 1.5 kWh/day.
Wong *et al* [9]; Singapore	Energy simulation program	The installation of a rooftop garden on a five-story commercial building can result in a 0.6–14.5% saving in annual energy consumption. A rooftop garden with shrubs (300 mm thick soil and shrubs) was found to be most effective in reducing building energy consumption.
Wong *et al* [4]; Singapore	Field measurements	Heat transfer through the bare roof was greater than that through planted roofs, and much less heat gain was observed on planted roofs. Both the soil layer and planted vegetation play a role in the thermal benefits of the greenroof. Wet soil can provide an additional insulation effect to the roof. The 'cooling effect' of plants lasted from afternoon to sunrise the next day.
Kumar and Kaushik [12]; India	Mathematical model	A greenroof combined with solar thermal shading reduced averaged indoor air temperature by 5.1°C, from the average indoor air temperature for the bare roof. The greenroof provided a cooling potential of 3.02 kWh/day to maintain an average room air temperature of 25.7°C. A larger leaf area index reduces the canopy air temperature, stabilizing the fluctuating values and reducing the penetrating flux by nearly 4 W/m^2.
Liu and Baskaran [13]; Toronto, Canada	Field measurements	Greenroofs reduced heat flow by 70–90% in summer and 10-30% in winter. The potential energy saving was 19–26 $kWh/m^2/year$. The deeper growing medium (225 mm) provided a 10% potential energy savings in the winter and <5% in the summer than the shallow growing medium (175 mm). The moisture availability for evapotranspiration was likely to be more important than the depth of the growing medium.

3.3 Reducing the urban heat island effect

The 'urban heat island effect' (UHI) is the difference in temperature between urban areas and the surrounding undeveloped areas. It is caused by changes in the natural water and energy balance. Cities have large areas of dark materials such as roofs that absorb solar radiation and reflect this heat back into the atmosphere at night. The result of the UHI effect is that urban areas have higher air temperatures and lower air humidity than in the surrounding undeveloped areas. The intensity of a UHI depends on many factors, such as the size of the city and its energy consumption, geographical location, heat emission, absence of green space, month or season, time of day, and synoptic weather conditions [14]. Greenroofs can reduce UHI effect by increasing evapotranspiration, which creates a cooling effect, thereby reducing the temperature of the surroundings. But this effect is only more noticeable when numerous greenroofs are established side by side.

Gomez *et al* [15] found that there was a heat difference of over 5°C between the city centre and the rural areas. The difference in temperatures between the city and the rural areas was 1.3°C. In green areas the temperature was about 2.5°C below the city's maximum temperature. Using the Mesoscale Compressible Community Model, Liu and Bass [16] showed that urban irrigation reduced average urban temperatures by 1°C. The addition of irrigated greenroofs located in the downtown area increased the cooling effect to 2°C and extended the 1°C cooling region over a larger geographic area. The simulation showed that with sufficient moisture for evapotranspiration, greenroofs can reduce the UHI effect.

3.4 Reducing rainwater runoff problems

Rainfall in urban areas is typically more problematic than in rural areas, because of impervious surfaces such as roofs, parking-lots and roads. These collect the flow and direct it into the urban drainage system, causing rapid runoff and higher peak flows. Greenroofs reduce rainwater runoff and thereby mitigate this problem. The reduction consists in delaying the initial time of runoff due to the absorption of water in the greenroof, reducing the total runoff by retaining part of the rainfall and distributing the runoff over a long time period through a relatively slow release of the excess water that is stored in the substrate layer [17]. The amount retained depends on many factors such as the volume and intensity of rainfall, the amount of time since the previous rainfall event, the depth and wetting scale of the growing medium and the roof slope. The main results and conclusions are presented in table 2.

The mean process by which a greenroof reduces a roof's runoff is evapotranspiration. Kolb [18] studied the evapotranspiration ability of greenroof plots (growing medium 50–140 mm) in Veitshöchheim, Germany, and found that, with an average monthly rainfall of 47 mm, evaporation was 21 mm (45%) during the year. Between May and August almost all rainfall evaporated, and between November and February evaporation was insignificant.

Table 2: The key results and conclusions of the studies of greenroofs' rainwater retention capability.

Study and location	Depth of the substrate	Rainfall retain results	Conclusions
Liesecke [20], Liesecke [21]; Germany	20–40 mm with mosses and *Sedum* sp.; 100–150 mm with *Sedum* sp., grasses and herbs.	Shallow substrate 40–45% of the annual rainfall, deeper substrate up to 60% of the annual rainfall. In warm weather a shallow substrate can retain 11% and a deeper substrate 20% more rainwater.	A greenroof can retain more rainwater in warm weather than it does during cold weather.
Kolb [22]; Veitshöchheim, Germany	100 mm.	15 minutes after simulated rainfall of 27.2 l/m^2 greenroofs with slopes 1.4°…40° showed very similar runoff results.	The influence of the slope of a greenroof on runoff rate and volume is almost insignificant.
Kolb [23]; Veitshöchheim, Germany	100 and 300 mm.	Comparing the gravel roof and the greenroofs with 100 mm and 300 mm of growing medium 15 min after simulated rainfall of 30 l/m^2 in summer, the roofs' runoffs were 24 l/m^2 (80%), 7.5 (25%) and <1 l/m^2, respectively.	
Liptan [24]; Portland, Oregon, USA		69% of the total rainfall in the 15-month monitoring period; between April and November rainfall retention was 92%, between December and March it was 59%.	A greenroof can retain more rainwater in warm weather than it does during cold weather.
Liu [3]; Ottawa, Canada	150 mm with grass.	54% of the total rainfall during Apr.–Sept. During a light rain (19 mm in 6.5 h) the greenroof delayed the runoff by 95 min, during a heavy rain (21 mm in 21 min) the greenroof delayed the runoff by only 4 min.	A greenroof cannot delay a heavy rain runoff. If rain falls steadily, the growing medium will become saturated with water and will not have enough time to dry out between rainfalls.

Table 2: Continued.

Moran *et al* [25]; North Carolina, USA	50–100 mm with *Sedum* sp.	Three following rain events in April: the retained amount decreased 75% in the first event to 32% in the last event. Three separate rain events in May: on all occasions, an average of 90% of rainwater was retained.	The capability of greenroof retention is dependent on the time between rain events and the volume and intensity of rainfall.
Rowe *et al* [26]; Michigan, USA	25–60 mm at 2–6.5% slope.	On average, 69–74% of the total rainfall during light rain events (< 2 mm daily) up to 98% and heavy rain events (> 6 mm) 50% of rainfall was retained.	A greenroof can retain rainfall more effectively during light rain events than during heavy rain events; a shallower substrate depth and steeper roof slope caused greater runoff.
Connelly and Liu [27]; Vancouver, Canada	75 mm with mainly *Sedum* sp.	67% of the total rainfall during 30 days in October. 95% of the first rainfall event (12.2 mm), 44% and 52% of the two medium events; 17% and 20% of two long duration events (27.7 mm in 16.2 h and 10.4 mm in 18.17 h respectively).	The growing medium of the greenroof will be fully saturated with rainwater if rain events occur too soon after one another.
DeNardo *et al* [28]; Pennsylvania, USA	89 mm with *Sedum* sp.	An average 45% (range 19–98%) of 7 rains during Oct. and Nov. The greenroof delayed the start of runoff by an average of 5.7 h and delayed the peak runoff by 2 h.	
Villarreal and Bengtsson [29]; Lund, Sweden	40 mm with *Sedum* sp.	For roof slopes of 2°, 8°, and 14°, the retention of the total precipitation for a rainfall with an intensity of 0.4 mm/min was respectively 62, 43, and 39%; for a rainfall of 0.8 mm/min it was 54, 30, and 21%; and for a rainfall of 1.3 mm/min 21 and 10% were retained for 2° and 14° slopes, all for dry initial conditions.	Retention depended to a great extent on rainfall intensity and the slope of the greenroof; the lower the intensity and slope, the greater the retention.

Mentens *et al* [19] studied in Belgium how evaporation is influenced by orientation of the slope. They found that there is a significant interaction with period, day and orientation. Evaporation is significantly different between all orientations except for east and west, being bigger in south-facing slopes than north-facing ones.

Mentens *et al* [17] offers a review of the investigations of greenroof runoff retention capability, which were mainly performed in Germany. For annual runoff, they found that runoff is mainly determined by the roof type, and may be as low as 15% for an intensive greenroof and as high as 91% for a traditional non-greened roof. For seasonal runoff, the results showed that greenroof runoff was significantly higher during winter (80%) than during summer (52%). For three seasons runoff is 30% for the warm, 51% for the cool and 67% for the cold season; substrate depth was significantly important for the warm season.

The water retention capability results of the Estonian study are similar to the results of the studies presented in Table 2. In the Estonian study three rain events were investigated. Two light rains were measured: rainfall of 2.1 mm (2.08.04) and rainfall of 2.6 mm (1.4 + 1.2 mm; 14.–15.09.04). The greenroof retained these rainfalls well – runoff was 32.6 and 19.3 l respectively, while the runoff from the reference roof was 290 and 340 l respectively. For the first rainfall, runoff from the greenroof ceased 10 hours later than runoff from the reference roof. Therefore the retention was 88.8 and 94.3% respectively. Exceptionally in the course of 4 days, a 18.2 mm rainfall took place (31.08.04–06.09.04). 12.1 mm fell during the first 5 hours. It appeared that in the case of a heavy rainstorm, a greenroof can delay the runoff for up to half an hour, but cannot fully retain it. From both roofs an estimated 2850 l water ran off during those days. 1240 l ran off from the first outflow of the greenroof (gr1), which collected water from the more heavily plant-covered side, and 1650 l ran off from the second (gr2), less plant-covered side. Gr1 runoff finished later than the others, but still 40 hours after the other outflows.

The melting of the snow cover with an average thickness of 220 mm of the greenroof was also observed over 17 days (22.03.05–07.04.05). It was to be expected that water came off less and more slowly from the more plant-covered side of the greenroof, and more rapidly from the less plant-covered side (by 995 l). When the snow on the greenroof melted within one day, the runoff was about to cease, but started again after a couple of days, as the lower part of the substrate layer only began to melt then. The total runoff from the greenroof was 3195 l, and 4066 l from the reference roof, because of the thicker layer (average thickness 290 mm) of snow.

3.5 Reducing urban rainwater runoff quality problems

Greenroofs may reduce the pollution of urban rainwater runoff by absorbing and filtering the pollutants, but they can also potentially contribute to pollutants released into water from the soil, plants and fertilizers. The runoff quality from a greenroof depends on the type of the roof (the thickness of the growing medium, its composition, vegetation and the type of drainage), the age of the roof, its maintenance; and also on the type of the surrounding area and the local pollution sources [30]. For the majority of roof runoff water components, the results differ depending on the different greenroof systems and the composition of the growing medium. The main results and conclusions are presented in Table 3.

Table 3: The key results and conclusions of the studies of greenroofs' runoff water quality.

Study and location	Results and conclusions
Kolb [31]; Bayern, Germany	Metal roofs with greenery cover reduced copper and zinc concentrations in roof runoff. For three year measurements, the copper concentration in the percolating water of a non-greened copper-sheet roof increased from 0.9 to 2 g, and in a greened roof it only increased from 0.8 to 1.1 g. The zinc concentration in percolating water of non-greened zinc-sheet roof increased from 3.5 to 4.8 g, whereas in greened roof it decreased from 5 to 1.9 g.
Köhler and Schmidt [32]; Berlin, Germany	The tested greenroof substrates cause a rise in pH: in rainfall, median pH was 6.2, in the runoff of the conventional roof it was 4.6, and in the runoff of substrates it was up to 7.5. Greenroof plots retained 94.7% of lead, 87.6% of cadmium, 80.2% of nitrates and 67.5% of phosphates over a three-year period. The efficiency of phosphate retention increased after the establishment of the vegetation from 26% in the first year to 80% in the fourth year.
Liptan and Strecker [33]; Portland, Oregon, USA	There was a decreasing trend in the total phosphorous concentrations measured in greenroof runoff. Phosphorous concentrations varied between 0.24–1.11 mg/l. The copper concentration in greenroof runoff was 4.8–10.5 μg/l, caused by the materials to be used on the roof, for example drainage materials. However, the copper loading would be much reduced in comparison to a traditional roof.
Moran *et al* [25]; North-Carolina, USA	The results showed that compost in the growing medium may cause high concentrations of nitrogen and phosphorus in greenroof runoff. Total nitrogen and total phosphorus concentrations in four greenroof runoff samples was 2.1–5.4 mg/l and 1.2–1.5 mg/l, and in rainfall 0.3–0.7 mg/l and 0.05 mg/l respectively.
Berndtsson *et al* [30]; Malmö and Lund, Sweden	The studied greenroofs behave as a sink of nitrate nitrogen; they reduced ammonium nitrogen and total nitrogen. They are sources of potassium, phosphate phosphorus and total phosphorus. Young greenroofs behave as a source of total nitrogen, more than others. All of the heavy metals measured (Cd, Cr, Cu, Fe, Mn, Pb, Zn) were usually the same or lower than in the precipitation and reference roof runoff. Some studied greenroofs contributed lead, manganese and iron to runoff. However, greenroofs behave as a sink for copper and zinc. It should be noted that metals that are first retained by the roof can potentially be released from it when the roof ages.

In Estonia, water quality was studied at three runoff events. When the rain and runoff were moderate, concentrations of COD, BOD_7, TN and TP were higher on the bituminous roof; pH on both roofs increased by more than 2 units. In samples taken in case of a heavy rainstorm, the components were less concentrated, as the rain washed more phosphates and nitrates out of the greenroof. In snowmelt, the water concentrations of all components were greater on the greenroof, because the greenroof contained more wintertime pollutants. In addition, the greenroof runoff always contained more sulphates and Ca-Mg-salt because of their presence in the LWA-material.

In the Estonian study, the concentrations of total nitrogen and total phosphorus were much lower than that in the Moran *et al* [25] or Liptan and Strecker [33] studies, because the Estonian greenroof did not contain compost like the others. Therefore, in the Estonian study total phosphorous concentration was 0.03–0.09 mg/l, and total nitrogen concentration 1–2.1 mg/l. Thus the composition of the growing medium should be taken into consideration in selecting the soil mix.

3.6 Other greenroof benefits

In addition to the above-mentioned benefits, greenroofs also improve air quality, by catching a number of polluting air particles and gases, as well as smog. The evaporation and oxygen producing effect of vegetated roofs can contribute to the improvement of the microclimate. Greenroofs can also mitigate noise pollution. The substrate layer blocks lower sound frequencies and the plants block higher frequencies. In a standard test, an unvegetated roof reduced sound by 33dB. The greenroof reduced sound by 41dB when dry, and 51dB when wet [1]. In city centres, where access to green space is negligible, greenroofs create space where people can rest and interact with friends or business colleagues. Greenroofs provide a psychological benefit because of their appearance, which differs greatly from the ordinary. Therefore, aesthetic value is the most apparent benefit of greenroofs. Planted roofs also provide food, habitat and a safe place for many kinds of plants, animals and invertebrates.

4 Conclusion

This study showed that greenroofs can be effectively used in the mitigation of environmental problems in urban areas. Greenroofs are effective in helping to keep the building cool in summer and also to reduce building energy consumption. Their ability to effectively reduce the effect of urban heat islands was not sufficiently investigated, but it surely may be concluded that greenroofs are well able to do that. We may confirm that vegetated roofs reduce the temperature fluctuation in the roof membrane and prolong its lifespan. Greenroofs delay effectively rainfall runoff rate and volume, more in warm and less in cold period. The greenroofs' runoff water quality was not as good as may be expected. Further investigations of the benefits of greenroofs will definitely be necessary in order to obtain more exact results on all of these topics and to confirm their ability to reduce environmental problems.

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