DISSERTATIONES GEOGRAPHICAE UNIVERSITAS TARTUENSIS
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ALAR TEEMUSK

Temperature and water regime, and runoff water quality of planted roofs

TARTU UNIVERSITY
PRESS

Department of Geography, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia.

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Supervisor: Prof. Dr. Ülo Mander, Department of Geography, University of Tartu, Estonia.

Opponent: Dr. Oliver Dilly, CEO, School of Integrated Climate System Sciences, Klima Campus, University of Hamburg, Germany.

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ABSTRACT

Planted roofs are technology that can be applied in areas such as cities, where less and less green space is available. Vegetated roof covers have many benefits: they make buildings more thermally efficient, prolong the life of a base roof, reduce urban heat island effect, reduce surface water runoff, reduce the pollution of urban rainwater, and provide green space for people and wildlife. Green roofs have been studied in many countries, from the point of view of thermal performance, protection of the roof membrane, stormwater retention and runoff quality. In this PhD dissertation, three general benefits of planted roofs in Estonian climatic conditions are investigated. Temperature regime in a Light Weight Aggregates (LWA-) based green roof and sod roof, water retention capability in cases of rain events, and also runoff water quality from different planted roof types are the topics presented here.

The temperature regime is analyzed on an existing LWA-based green roof (100 mm) in comparison with a modified bituminous membrane roof from June 2004 to April 2005. The sod roof (150 mm) was investigated from January 2007 to December 2007 to determine the differences from typical green roofs. In addition, 1x1.5 m roof plots were constructed and studied from June 2006 to May 2007 to see how non-insulated planted roofs acted in a cooler period. Three rainfall events and snow cover melting were measured. The investigated extensive green roof was also compared with the modified bituminous membrane roof. The water regime of roof plots was also measured in the cases of different rain events. The runoff water quality of LWA-based green roofs and sod roofs was analyzed and compared with precipitation and conventional roofs. Samples were taken from August 2004 to April 2009 from different planted roofs to find at which scale water quality may appear.

The results of the temperature regime of the investigated planted roofs are given both seasonally and daily; indexes to characterize planted roofs' temperature effects are also proposed. In summer, temperatures under both the green roof and the sod roof showed a similar temperature run; undesirable higher temperatures on the surfaces did not cause a notable increase in temperature under the substrate layers. The difference between temperature amplitude under the substrate layers of the planted roofs and the surfaces of the conventional roofs averaged 20°C. In autumn and spring, the sod roof's soil layer showed higher temperatures and lower amplitude than the green roof's substrate layer, which cooled down more. In winter, temperatures under the substrate layers of the planted roofs were higher than the surfaces of the conventional roofs; average amplitude was 1°C and 7–8°C respectively. Temperatures under the planted roofs on the non-insulated simple buildings are similar to temperatures at the surface, and fell depending on the air temperature, because cool air got closer below the base roof. Both seasonal and daily results showed that in Estonian climatic conditions, planted roof systems are sufficiently capable of protecting the roof membrane from extreme

temperatures. In autumn and spring the substrate layer protected the base roof's membrane from rapid cooling and freezing. It also provided effective thermal insulation in winter.

The studied green roof effectively retained light rain – the retention for 2.1 mm rainfall was 85.7%. In the case of a heavy rainstorm (12.1 mm), the green roof delayed the runoff for up to half an hour, but cannot fully retain it – the runoff volume was the same as that of the reference roof. The observation of snow cover melting showed that there are two meltings of a green roof: the melting of the snow cover and the melting of the frozen water in the substrate layer. Snow cover melted fast, but the green roof nevertheless prolonged the runoff to a longer timescale than that of the reference roof. The results of the study of roof plots showed that in the case of light rain there was no runoff from the planted roof types; however, from the steel roof most of rainfall water ran off. When rain events occurred partially during the time and there were also rainfalls before measured rain events, planted roofs showed higher runoff results than flat SBS roof. While rainfalls were distributed over a longer time scale, planted roofs also distributed water runoff equally, and showed notable retention compared with the steel roof. It is also clearly visible that the slope of the roof influences the amount of runoff water, so a green and sod roof with a 20° slope showed higher results than a flat green roof, also in the same case as a flat SBS roof.

The comparison of the green roof and the bituminous roof showed that the quality of the runoff water varies depending on the character of the runoff and the pollutants accumulated on the roof. When rain and runoff were moderate, concentrations of COD, BOD_7, Total-N and Total-P were higher on the bituminous roof. In samples taken during a heavy rainstorm, the components were less concentrated, as the rain washed more phosphates and nitrates off the green roof. In snow melting water, the concentrations of all components were greater on the green roof. In addition, the green roof runoff always contained more sulphates and Ca-Mg salt because of their presence in the LWA material. The results of different roofs show that vegetated roofs influence water quality considerably. The runoff water of the LWA-based green roof generally had higher results of pH, BOD_7, Total-P and PO_4-P. In contrary, COD, Total-N, SO_4 and Ca-Mg salt were higher in the sod roofs. The results of NH_4-N and NO_3-N for both roof types were similar. According to the results, the character of the runoff and the contents in the substrate layer at the moment affected the runoff quality more than the age of the vegetated roof and the location of the roof. The use of nutrients in the substrate or in the soil caused much higher concentrations in runoff water except for pH, BOD_7, SO_4 and Ca-Mg salt. The results of samples taken from the Tartu LWA-based green roof each spring in 2005–2009 at the time when snow had almost melted showed that concentrations of compounds in the runoff water generally decreased gradually. However, pH and Ca-Mg salt were stable, and this was caused by the LWA material.

While the temperature regime of the planted roofs has been investigated sufficiently, further investigations in fields of water quantity and quality are required to draw definite conclusions regarding the capability of planted roofs to retain water and improve water quality in Estonian climatic conditions.

1. INTRODUCTION

Green roofs are not a new concept. They have a long history, but today this is a rapidly advancing technology that has the potential to improve the quality of urban life. The earliest documented roof gardens were the hanging gardens of Semiramis in present Syria (Lebeau, 1997), considered one of the seven wonders of the ancient world. At present, green roofs are a technology that can be applied in areas such as cities, where less and less green space is available.

Planted roof term and types

Planted roofs or rooftop gardens are a specialized roofing system that supports vegetation growth on rooftops. 'Green roof' is the most common term, but other terms such as 'planted roof', 'vegetated roof', 'grassed roof' or 'eco-roof' are also used. 'Planted roof' and 'vegetated roof' may also be used as general terms for extensive and intensive roof systems. It is more popular to write these terms, primarily 'green roof', separately than to write them together as a compound word. For example, in Estonian, the direct meaning of 'green roof' is a green-coloured roof, but actually it means a roof covered mainly by green-coloured plant species, and thus it may be called a 'haljas-' or 'rohekatus'. Therefore one can use this term as a compound word – greenroof – but there are few authors who use it this way. Because most people correctly understand the meaning of 'green roof', due to the worldwide spread of green roofs, the way it is written is not a big problem.

Green roofs are usually divided into two general categories: extensive and intensive, although mixed types and natural sod roofs are also possible.

'Extensive green roofs' 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 green roof'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, they 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, fertilization 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.

Planted roof construction

Planted roof systems are mainly established on top of an existing roof structure, and consist of certain specific layers:

- a 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 to irrigate 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), also referred to as Light Expanded Clay Aggregates or LECA, which is a lightweight and porous well-drained material, 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 green roofs must be low-growing and shallow-rooted.

Popularity of planted roofs

Green roofs are becoming popular throughout the world, but there are some leading countries in the field. Since the 1980s, there has been increasing interest in green roof systems in Germany, because of their environmental benefits. The first volume of technical guidelines was published in 1982 by the Landscape, Research, Development and Construction Society (Forschungsgesellschaft für Landschaftsentwicklung und Landschaftsbau) (FLL, 2002). Many German cities have introduced programs to promote green roof technology and improve environmental standards. Building law now requires the construction of green roofs in many urban centres (Köhler and Keeley, 2005). Thus green roof technology in Germany is very successful; there are many research institutes to investigate green roofs and there are also many companies that offer their own green roof systems. In the United States of America there is also a rapid increase in interest in green roofs, there are many research institutes investigating these and also national programs to take into consideration the best management practice. In Germany and other Central European countries, as well as in the USA, there are more popular extensive roof systems. Tropical countries investigate intensive greened roofs' surfaces because of their capability to reduce heat flow and energy use. The tradition of sod (turf) roofs springs from Norway, where these were established long ago, and birch-bark was used as the base layer.

Investigations of planted roofs

Planted roofs are investigated more and more often in order to analyze their potential to improve the quality of the urban environment. The most common topics are thermal properties and energy saving, water quantity and quality performance, as well as the choice of plants used on the roofs. There are many possibilities to demonstrate the studies' results and compare them to each other.

The best opportunity is to publish articles in a peer-reviewed science magazine that is also available in the Internet. It is also popular to publish results in local literature. In Germany there are several such magazines, for instance “Dach + Grün” and “Stadt + Grün”. In addition, there are specific conferences on greened roofs, for example in the USA; special books on green roof systems are also produced in many countries. If the results of studies are demonstrated more in local literature in a local language, they have too little importance for the rest of the world. Many articles are produced in German local literature by research institutes, but fewer of these are also published in international literature. Considering that the results from Germany are still available, it is necessary that investigations from countries like Sweden and Norway also be published in international literature. There are no published articles about such roofs from Norway, which is the country of origin of sod roofs and has a long history in the field.

Considering that most available and legible sources are peer-reviewed science magazines from Elsevier B.V. publications (Science Direct, ISI Web of Science), Figure 1 offers an overview of articles about planted roofs published from 1998–2008 in those magazines (for instance “Energy and Buildings”, “Building and Environment”, “Ecological Engineering”, “Horticultural Science”). As shown, until 2003 there were more articles about thermal properties than other topics, and since 2005 many research topics have been published. It is clear that the popularity of investigations of green roofs is increasing. Articles on thermal properties are more often produced by tropical countries (Greece, Singapore), articles on water regime by the USA and Central European countries and also Sweden.

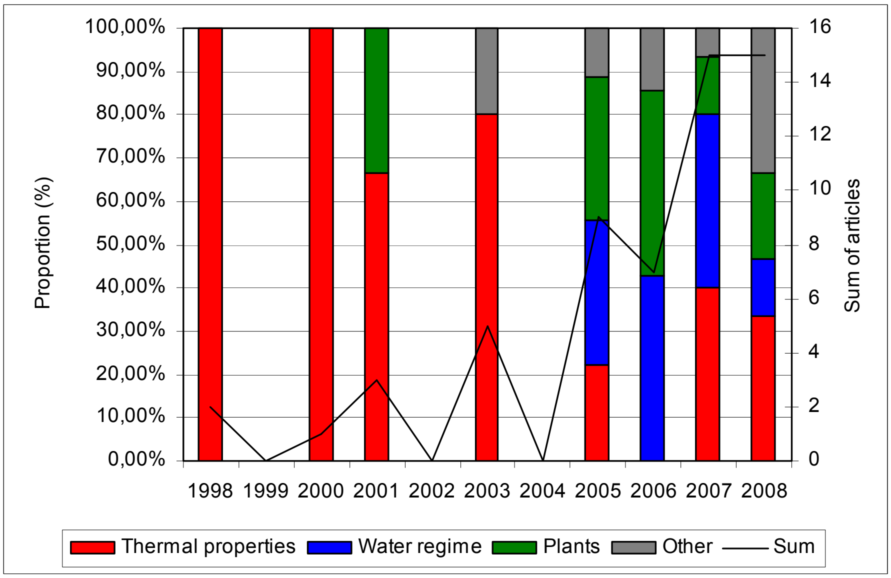

Figure 1. Articles about planted roofs published from 1998–2008 in peer-reviewed science-magazines from Elsevier B.V. publications.

Life cycle costs of planted roof types

The construction of green roofs costs about three times as much as that of conventional roofs. However, conventional roofs, like bitumen roofs, require replacement or major repairs after approximately 15 years, whereas green roofs will survive thirty or more years. In Germany, a comparison of life cycle costs during the lifespan of different types of roofs are worked out (90-year building life cycle with a 100 m^2 roof, costs are calculated per m^2) (Porsche and Köhler, 2003). Construction costs ($\$/m^2$) are 40, 50, 85 and 340 for bitumen, gravel, extensive green and intensive green roofs respectively. Whereas bitumen roofs need repairs every ten years and renovation after 15 years (the same figures are 15 years and 15–20 years for gravel roof), green roofs need only occasional renovation work. Renovation costs during the roofs' lifespan are 240, 200, 40 and 340 $ for bitumen, gravel, extensive green and intensive green roofs respectively. Summarily, also adding reconstruction and recycling costs, one obtains the final amounts of 320, 295, 185 and 820 $\$/m^2$ for bitumen, gravel, extensive green and intensive green roofs respectively. However, planted roofs need more maintenance than conventional roofs, for instance the removal of tree seedlings from extensive roofs, but intensive roof systems need many times more inspection than extensive roofs, which need low maintenance. Modern green roof systems in Germany are no more than 35 years old, and many researchers expect that these will last 50 years or more. The old green roofs in Berlin have a life span of more than 90 years before they require important repairs or replacement (Porsche and Köhler, 2003). Wong et al. (2003b) found similarly that although the initial cost of an extensive green roof is much higher (89 $\$/m^2$) than the cost of a flat conventional roof (49 $\$/m^2$), the life cycle cost is much less.

Temperature regime of planted roofs

One benefit of vegetated roofs which is effective in both temperate and tropical climates is the protection of the base roof membrane against solar radiation, thus lowering its temperature and also minimizing temperature fluctuations. 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 green roof blocks the solar radiation from reaching the membrane, thus lowering its temperature and also minimizing temperature fluctuations.

Some investigations have been performed concerning the temperature regime of green roofs, in which the main research topic was temperature fluctuations in green roofs and reference roofs. Thorough research has been done by Liu and Baskaran (2003) from the National Research Council in Ottawa, Canada. During the 22-month observation period (660 days), Liu and Baskaran demonstrated that the temperature fluctuation in the exposed membrane of the reference roof had a median of 42–47°C. The green roof reduced the temperature fluctuation in the roof membrane to a median fluctuation of 5–7°C throughout the year. Bass and Baskaran (2003) showed the results of the same roof temperature profile monitoring on typical days in different seasons. On a typical summer day the membrane temperature on the reference roof reached 70°C, but the membrane temperature on the green roof fluctuated by around 25°C. On a typical winter day without snow cover, the membrane temperature on the reference roof fluctuated from –15°C to 10°C depending on the air temperature, while at the same time the membrane temperature on the green roof remained relatively stable, between 1°C and 5°C.

DeNardo et al. (2005) found that maximum surface temperatures on green roofs averaged 6°C higher in the winter and more than 19°C lower in the summer. Wong et al. (2003a) from Singapore 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. Wanphen and Nagano (2009) from Japan investigated porous roofing materials which during daytime showed an average of 4.87°C and Sedum 9.08°C lower surface temperatures than conventional roof material mortar concrete (41.78°C).

Planted roofs' ability to reduce heat flow and energy cost

Green roofs 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 (Eumorfopoulou and Aravantinos, 1998). Many researches (Eumorfopoulou and Aravantinos, 1998; Palomo Del Barrio, 1998; Niachou et al., 2001; Wong et al., 2003c; Theodosiou, 2003) have demonstrated that green roofs reduce diurnal temperature variations in buildings by blocking solar radiation, which contributes to energy conservation. The green roof acted as a thermal mass that effectively dampened the thermal fluctuations going through the roofing system. In the summer period, a green roof's cooling effect is higher due to evapotranspiration from plants and the evaporation of retained moisture from the soil. In the winter period a green roof can help to reduce heat loss from buildings that act as an insulation membrane.

Palomo Del Barrio (1998) and Theodosiou (2003) demonstrated that vegetated roofs 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. Wong et al. (2003a) from Singapore detected that heat transfer through the bare roof was greater than that through planted roofs, and much less heat gain was observed on planted roofs. Liu (2003) from Ottawa, Canada, found that the green roof reduced the heat flow through the roofing system by over 75% in spring and summer. During the observation period (22 months), the green roof reduced 95% of the heat gain and 26% of the heat loss 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 green roof 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 green roof reduced it to less than 1.5 kWh/day. Liu and Baskaran (2004) from Toronto, Canada, found that green roofs 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 substrate layer (225 mm) provided a 10% potential energy savings in the winter and <5% in the summer than the shallow substrate layer (175 mm). The moisture availability for evapotranspiration was likely to be more important than the depth of the substrate.

Niachou et al. (2001) from Athens, Greece, found that surface temperatures of the outdoor spaces on the insulated buildings, both with and without the green roof, were 26–40°C. For non-insulated buildings, temperatures varied between 28–40°C and 42–48°C respectively. Green roofs had a significant thermal performance above non-insulated roofs, but for the well-insulated roofs, the role of the green roof was almost insignificant. Takakura et al. (2000) from Tokyo, Japan, 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. Kumar and Kaushik (2005) from India detected that green roof combined with solar thermal shading reduced average indoor air temperature by 5.1°C from the average indoor air temperature for the bare roof.

Onmura et al. (2001) from Japan demonstrated that the evaporative cooling effect of a rooftop lawn garden yielded a 50% reduction in heat flux in the rooms below the garden. Thus the evaporative component has an important role in reducing heat flux, depending 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. Wong et al. (2003c) from Singapore found that 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.

Planted roofs' ability to reduce 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, the absence of green space, month or season, time of day, and synoptic weather conditions (Oke, 1987). Vegetated roofs can reduce UHI effect by increasing evapotranspiration, which creates a cooling effect, thereby reducing the temperature of the surroundings. This effect only becomes more noticeable, however, when numerous green roofs are established side by side.

Gomez et al. (1998) 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 (2005) showed that urban irrigation reduced average urban temperatures by 1°C. The addition of irrigated green roofs 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, green roofs can reduce the UHI effect.

Water regime of planted roofs

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. Vegetated roofs 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 green roof, 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 (Mentens et al., 2006). The amount retained depends on many factors such as the volume and intensity of the rainfall, the amount of time since the previous rainfall event, the depth and wetting scale of the substrate layer and the slope of the roof. Beattie and Berghage (2004) worked out that for plant growth and water retention, the optimal porosity of the substrate layer is 60% and water holding capacity is 40% of soil capacity. Such a substrate layer can hold an average of 10 mm of rainwater for a 25-mm-thick substrate; thus for a more common 100-mm-thick green roof, optimal water holding capacity is 30–40 mm.

In Germany, the following stormwater runoff coefficients have been worked out according to roof type (Porsche and Köhler, 2003): a) roofs without greening: roof surface >3° slope – 1.0, <3° slope – 0.8, gravel roofs – 0.5; b) green roofs with a slope of up to 5°: dependent on structure thickness, <10 cm – 0.5, 10–25 cm – 0.3, 20–50 cm – 0.2, >50 cm – 0.1; c) green roofs with a slope over 5°: independent of structure thickness – 0.7.

The mean process by which a green roof reduces a roof's runoff is evapotranspiration. Kolb (2002) studied the evapotranspiration ability of green roof plots (substrate layer 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. Mentens et al. (2003) 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 greater on south-facing slopes than on north-facing ones.

Mentens et al. (2006) offers a review of the investigations of green roof runoff retention capability, which were mainly performed in Germany. For annual runoff, they found that runoff is mainly determined by roof type, and may be as low as 15% for an intensive green roof and as high as 91% for a traditional non-greened roof. For seasonal runoff, the results showed that green roof runoff was significantly higher during winter (80%) than during summer (52%). For the 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. Liesecke (1993; 1998) from Germany investigated two types of green roofs: one with a substrate depth of 20–40 mm with mosses and *Sedum* sp. and the other with 100–150 mm deep substrate with *Sedum* sp., grasses and herbs. Rainfall retention results showed that the shallow substrate retained 40–45%, and the 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 green roof can retain more rainwater in warm weather than it does during cold weather. Liptan (2003) from Portland, Oregon, USA, demonstrated the same result: between April and November, rainfall retention was 92%, and between December and March it was 59%. Total retention was 69% of the total rainfall in the 15-month monitoring period.

Liu (2003) from Ottawa, Canada, studied a green roof (150 mm) with grass that retained 54% of the total rainfall during the period April–September. During a light rain (19 mm in 6.5 h), the green roof delayed the runoff by 95 min, whereas during a heavy rain (21 mm in 21 min) the green roof delayed the runoff by only 4 min. Thus a green roof 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. The same conclusion was reached by Rowe et al. (2000) from Michigan, USA, investigating green roofs (25–60 mm deep) at 2–6.5% slopes. On average, 69–74% of the total rainfall was retained. During light rain events (<2 mm daily), up to 98% and during heavy rain events (>6 mm) 50% of rainfall was retained. Thus a green roof can retain rainfall more effectively during light rain events than during heavy rain events; a shallower substrate depth and steeper roof slope causes greater runoff.

Studies done by Carter and Rasmussen (2006) and Bliss et al. (2009) demonstrated similar results as the above-mentioned studies.

Moran et al. (2003) from North Carolina, USA, studied a green roof (50–100 mm) with *Sedum* sp and showed the following results: in the cases of three following rain events in April, the retained amount decreased from 75% in the first event to 32% in the last event. In the cases of three separate rain events in May on all occasions, an average of 90% of rainwater was retained. Thus the capability of green roof retention is dependent on the time between rain events and the volume and intensity of rainfall. A similar result was founded by Connelly and Liu (2005) from Vancouver, Canada, who investigated a green roof (75 mm deep) with mainly *Sedum* sp. Total retention was 67% of the total rainfall during 30 days in October. For rain events, retention was 95% of the first rainfall event (12.2 mm), 44% and 52% of the two medium events, and 17% and 20% of two long duration events (27.7 mm in 16.2 h and 10.4 mm in 18.17 h respectively). Thus the substrate layer of the green roof will be fully saturated with rainwater if rain events occur too soon after one another.

Villarreal and Bengtsson (2005) from Sweden investigated the retention ability of a green roof (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 62, 43, and 39% respectively; 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. Thus retention depended to a great extent on rainfall intensity and the slope of the green roof; the lower the intensity and slope, the greater the retention. DeNardo et al. (2005) from Pennsylvania, USA, studied a green roof (89 mm deep) with *Sedum* sp. and demonstrated retention averaging 45% (range 19–98%) of 7 rains during October and November. The green roof delayed the onset of runoff by an average of 5.7 h and delayed the peak runoff by 2 h. Kolb (2003) from Germany compared the gravel roof and the green roofs with 100 mm and 300 mm of substrate layer 15 min after simulated rainfall of 30 l/m^2 in summer, and the roofs' runoffs were 24 l/m^2 (80%), 7.5 (25%) and <1 l/m^2 respectively.

Runoff water quality of planted roofs

Planted roofs may reduce the pollution of urban rainwater runoff by absorbing and filtering pollutants, but they can also potentially contribute to pollutants released into water from soil, plants and fertilizers. The runoff quality from a green roof depends on the type of the roof (the thickness of the substrate layer, 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 (Berndtsson et al., 2006). For the majority of roof runoff water components, the results differ depending on the different green roof systems and the composition of the substrate layer.

Berndtsson et al. (2006) in Malmö and Lund, Sweden, studied different green roofs that behave as a sink of nitrate nitrogen; they reduced ammonium nitrogen and total nitrogen. They are sources of potassium, phosphate phosphorus and total phosphorus. Newly established green roofs behave as a greater source of total nitrogen 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 green roofs contributed lead, manganese and iron to runoff. However, green roofs 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. Comparing an intensive vegetated roof (in Japan) and an extensive green roof (in Sweden), Berndtsson et al. (2009) found that the intensive roof was a sink of Total-N and Total-P, whereas the extensive roof released those contaminants.

Moran et al. (2005) investigated an extensive green roof in North Carolina, USA, and showed that compost in the substrate layer may cause high concentrations of nitrogen and phosphorus in runoff water. Total nitrogen and total phosphorus concentrations in eleven green roof runoff samples were 0.8–6.9 mg/l and 0.6–1.5 mg/l, and in rainfall <1.0–2.1 mg/l and 0.05 mg/l respectively. In a study by Hathaway et al. (2008), also in North Carolina, USA, Total-N concentrations in the green roof outflow averaged 2.7 mg/l higher than in rainfall, and 1.3 mg/l higher than the control roof runoff. Total-P concentrations in the green roof outflow were 1 mg/l higher than the rainfall and 0.8 mg/l higher than the control roof runoff. Such differences in concentration were caused by the compost used in the green roof. Emilsson et al. (2007) investigated nutrient leaching from green roof systems and concluded that nutrient runoff from greened roofs is a problem that needs more attention. In their study, conventional fertiliser caused higher nutrient runoff than controlled release fertiliser; vegetation mats reduced the risk for nutrient runoff compared to the fertilization of newly established roofs.

Köhler and Schmidt (2003) in Berlin, Germany, found that the tested green roof substrates cause a rise in pH: in rainfall, the median pH was 6.2, in the runoff of the conventional roof it was 4.6, and in the runoff of substrates it was as much as 7.5. This was probably due to the high pH value of the substrates used (e.g., Ulopor). Green roof plots retained 94.7% of lead, 87.6% of cadmium, 80.2% of nitrates and 67.5% of phosphates over a three-year period. After the establishment of the vegetation, the efficiency of phosphate retention increased from 26% in the first year to 80% in the fourth year. In Bliss et al. (2009), the study values of phosphorus and COD were elevated by the green roof.

Other benefits of planted roofs

In addition to the above-mentioned benefits, planted roofs 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. Green roofs 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 green roof reduced sound by 41dB when dry, and 51dB when wet (Grant et al., 2003). Planted roofs also provide food, habitat and a safe place for many kinds of plants, animals and invertebrates (Brenneisen, 2003). In city centres, where access to green space is negligible, green roofs create space where people can rest and interact with friends or business colleagues. Green roofs provide a psychological benefit because of their appearance, which differs greatly from the ordinary. Therefore the aesthetic value is the most apparent benefit of green roofs.

Green roofs' investigations in Estonia

In addition to the authors' investigations (Papers I–V, Teemusk and Mander, 2006, 2007, 2009, 200Xa,b), several studies on green roofs have been performed in Estonia.

In the Koorberg study (2001) there are several general topics on the establishment of green roof systems in Estonia. The most important was the determination of the optimal composition of the substrate layer in Estonia, which consists 66% of LWA, 30% of soil and 4% of clay. Koorberg also found appropriate plants which are common to Estonian flora and are suitable for roof conditions. Estimating the economic benefits, the reduced amount of rainwater in Põlva (6500 inhabitants) due to potential green roofs can reduce the current costs for water pumping more than fourfold. On the contrary, the cost of establishing green roofs in Tartu (101,000 inhabitants) and the cost of cleaning water comparing with the water retention capacity are not equal.

Hallik (2004) constructed extensive green roof plots and a measuring system to analyze the radiation regime of green roofs. The initial results were from 56.5 W/m^2 in cloudy weather to 153.0 W/m^2 on a sunny day, but there is a need to make the measuring principle more effective. On the same green roof plots (50 and 100 mm), water regime was also investigated. Hallik (2005) found that the rainfall retention capacity of green roofs in spring was approximately 2 mm, and both substrates showed similar results. Thus evaporation rates in spring in Estonia are low and cause a situation where the majority of retained rainfall stays in the roof substrate, so that the green roof will be fully saturated and thereby the difference in soil thickness does not affect the additional amount of water that can be retained. Stormwater runoff was delayed approximately 45–75 minutes. The dynamics of stormwater runoff depended on substrate layer thickness: the roof with the thinner soil layer reacted fast to the beginning of precipitation, and runoff was intensive but short, while at the same time the thicker soil layer prolonged the duration of runoff. Conclusively, the effectiveness of using green roofs to reduce runoff is low in the spring period, but greater stormwater retention capacity can be expected in the summer period.

Hallik (2008) analyses the cooling potential of lightweight green roofs in Estonia. The results of the uninsulated roof showed that although different green roof configurations lowered the positive heat flux throughout the day, these functioned as an additional insulation layer at night and reduced the night-time cooling of the roof surface. The use of average and recommended normative insulation thickness in roof construction greatly diminished the variation and quantity of heat fluxes, so the differences in heat fluxes and room temperatures between bituminous roof and different green roof variations were very small. The calculated degree-hours over 25°C showed a 40 to 60% and a 7 to 14% increase in cooling demand for uninsulated and insulated roofs respectively, when green roof layers were applied to the roof construction instead of the bituminous roof cover. As in Estonia the main role in cooling the building is played by night-time cooling of the building enclosure (including the roof), the green roof decreases the thermal conductivity of the roof construction and causes heat accumulation inside the building. Thus the study shows that green roofs do not have a significant cooling potential of indoor conditions in the Estonian climate.

Kalbus (2007) investigated the effect of an individual component (LWA, soil and clay) of an extensive green roof substrate on overall water capacity and water retention capability. Results showed that evaporation from all of the test subjects was more or less the same, linear in time, but the water capacity differed greatly (LWA 0–2 mm had better holding capacity than LWA 4–8 mm). Thus the modification of the components in the substrate layer changes its hydrological characteristics through water capacity and therefore its water retention capability increases also, but none of the components is capable of making the substrate more resistant to evaporation. Optimal water holding capacity for plant growth and water retention is 40% of soil capacity (Beattie and Berghage, 2004). In the Kalbus (2007) study it was 15–27% (147–271 g/dm^3) and in the Koorberg (2001) study 20–22% (204–222 g/dm^3).

Hallik et al. (2007) investigated the possibility of covering Tartu flat roofs with 100 or 150 mm thick green roofs to retain rainwater. Taking into consideration the results of water retention of green roofs demonstrated in the literature and the average monthly rainfall in Tartu, Hallik et al. determined the estimated rainfall retention capability values of a green roof in Tartu. In summer (rainfall 281 mm) is expected retention is 44.1–80 mm (70–100%), in autumn (rainfall 103 mm) 19.2–27.5 mm (40–50%), in winter (rainfall 95 mm) 0 mm and in spring (rainfall 114 mm) 11.2–26.5 mm (40–50%). Thus green roofs may, on average, reduce total rainfall (593 mm) runoff to 283.5–389.5 mm per year. Considering that average heat conductivity coefficients for wet substrate, LWA components and rock wool are 0.55, 0.19 and 0.035 W/mK respectively, heat transfer coefficients for these are therefore 5.5 (substrate layer 100 mm) or 3.66 (150 mm), 6.3 and 0.7 W/m^{2}K respectively. Heat transfer coefficients for the whole green roof with or without the rock wool layer are 0.56 or 2.94 W/m^{2}K for the 100 mm thick substrate layer and 0.54 or 2.33 W/m^{2}K for the 150 mm. Hallik et al. also calculated that in Tartu there are 858,000 m^2 flat roof surfaces that could potentially be covered with green roof systems. The estimated costs of the two types of green roofs with common layers (area

1000 m^2) are 450,000 EEK and 535,000 EEK for a 100 and 150 mm roof respectively. The cost of materials alone is 255,000 EEK and 300,000 EEK for a 100 and a 150 mm roof respectively.

Planted roof popularity in Estonia

Before the year 2000 there were a few man-made sod roofs in Estonia, but since the year 2000 interest in and knowledge about vegetated roofs has increased. Figure 2 shows the numbers of definitely existing LWA-based green roofs and sod roofs and also the estimated area of those planted roof types. In addition, there are certain data about some intensive roof systems, (covering 500 m^2). In 2003 and 2007 sod roofs were built at the Tallinn Zoo (16 buildings) and at the Piusa holiday centre (14 buildings) respectively. As no sufficient reviews of planted roofs in Estonia have been performed, the estimated area in Figure 2 is very approximate. It may generally be supposed that at the beginning of 2009 there were about 9000 m^2 of roofs covered with LWA-based green roof systems and 10 000 m^2 with sod in Estonia.

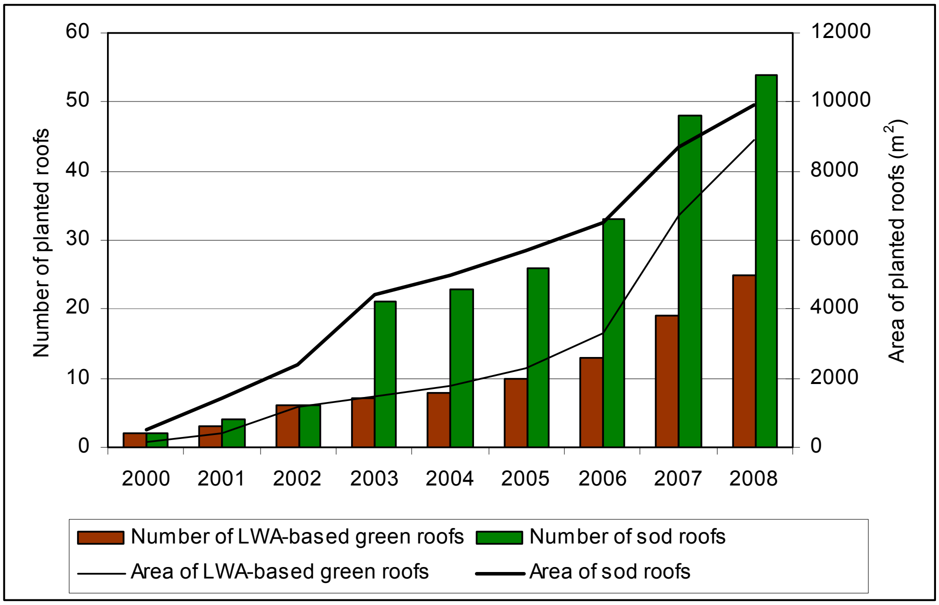

Figure 2. Numbers of definitely existing LWA-based green roofs and sod roofs and the estimated area of these planted roof types in Estonia, 2000–2008.

It should be mentioned that the popularity of planted roofs is growing slowly but consistently in Estonia. The following reasons inhibit the progress of green roofs: in cities there are enough green areas, knowledge of possibilities for using green roofs is still too low, there are few companies that can build these roofs and thus few advertisements, the costs are too high and there are no benefits and subsidies from higher levels. Nevertheless, there is an increasing trend of the construction of planted roofs – those who are interested in this environmentally friendly and exclusive possibility will get it anyway. Also, it is always possible to build the roof oneself, like most sod roofs were built. Thus it may be expected that planted roof systems will become more and more popular in Estonia in coming years.

Objectives

(1) To find out how LWA-based green roofs and sod roofs, two popular types of planted roofs in the temperate zone, function in local weather conditions. The task is to compare the temperature regime under the substrate layers of the planted roofs and on the surfaces of the conventional roofs, and also to compare green roofs with sod roofs (Paper III and IV).
(2) To analyse the stormwater retention potential of a green roof compared with the modified bituminous membrane roof. Three different rain events and also snow cover melting were observed, and different rain events in the roof plots were measured (Paper II).
(3) To determine runoff water quality scale from different planted roof types in Estonia, and also to analyse the influence on runoff water of a LWA-based green roof over a six-year period (Paper V).

2. MATERIALS AND METHODS

2.1. Site description

The studied green roof was established in May 2003 and is situated near the city centre of Tartu, Estonia (58°22'40''N, 26°44'07''E). It consists of the following layers: a modified bituminous base roof, a plastic wave drainage layer, rock wool for rainwater retention (80 mm) and a substrate layer (100 mm) with LWA (66%), humus (30%) and clay (4%). The green roof has an area of 120 m^2 and no slope. During the measurement period, the amount of plant cover was 45% of the whole roof area. The most common plant species were *Sedum acre* (planted and seeded; covers 55%), *Thymus serpyllum* (20%), *Dianthus carthusianorum* (5%), *Cerastium tomentosum* (all seeded; 3%); and also *Veronica filiformis* (occasional species; 7%). The brick building covered by the green roof is a one-storey printing plant annex to a three-storey office building. There was also a reference modified bituminous membrane roof (called an SBS roof) near the green roof, which was used for the comparison of temperature measurement and runoff water samples.

The studied sod roof was established in summer 2003 and is situated to the west of Tallinn, Estonia (59°25'00''N, 24°39'30''E). On the base flooring there is a modified bituminous membrane layer, a plastic wave drainage layer and a soil layer (120 mm) with a transplant layer (20–30 mm). Thus the roof is a 150-mm-thick turf roof, more often referred to as a sod roof, as in this article. The sod roof has a 20° slope, with the area of one slope-side being 100 m^2. Grass plants were from the *Gramineae* species, and cover 90% of the whole roof area. The building with the sod roof is one of 16 similar buildings at Tallinn Zoological Gardens, and has two sides: a heatable workers' side and non-heatable barn for Transcaspian Urial. In summer 2008 a similar roof to the older one was built, and so runoff water from that roof was investigated to compare it with the older roof.

The experimental platforms of simple buildings' roofs (for example a shelter) situated in Tartu, Estonia (58°22'35''N, 26°45'00''E) were established in May 2006. The place where the roof plots in one row existed was the modified bituminous membrane roof of the five-storey building, to guarantee no disturbed sunshine and conditions appropriate to roofs. There were three 20° slope sod roofs, three 20° slope green roofs, three flat green roofs, a flat SBS roof and a 20° slope steel sheet roof. Temperature measurements took place at one of three identical types of roofs. The sod roofs consist of the following layers: a wood base roof, a membrane, a plastic drainage layer, a filter fabric layer and a soil layer (80–100 mm). The green roofs consist of a wood base roof, a membrane, a plastic drainage layer, a filter fabric layer, rock wool for rainwater retention (40 mm) and a substrate layer (~70 mm) with LWA (66%), humus (30%) and clay (4%). The flat modified bituminous membrane roof (called an SBS roof) and the red steel sheet roof with tiled profile is situated next to the planted roof plots. The size of each roof plot is 1x1.5 m; height from the base of the roof is 0.8 m. During the measurement period, the amount of plant cover on each green roof plot differs between 20–40% of the whole roof area. There are difficulties creating sufficient plant cover with *Sedum* species, one reason being the jackdaws that devastated the planted roof plots. Finally, there was an average of 35% plant cover, and the most common plant species was *Sedum acre*. On the sod roofs there was initially, in summer 2006, turf with *Achillea millefolium*, but it disappeared, probably due to the thin soil layer, and was involuntarily replaced with *Thlaspi arvense* in summer 2007.

There are also some existing planted roofs that are used for the investigation of roof runoff water quality to see how the roofs of different type, age and place influenced the quality of the runoff water. The Viimsi LWA-based green roof was established in autumn 2002 and is situated near five-storey buildings in the small town of Viimsi. There are three green roofs which are shelters above entries to the nursery school; these have a 15° slope and an area of 35 m^2. The second additionally studied LWA-based green roof was established in spring 2007 and is situated near the Luunja settlement, which is practically in the countryside compared with the Tartu green roof. The investigated green roof on the private residence has an area of 50 m^2 and a 15° slope. The layers and plants used on both roofs are the same as those of the Tartu green roof.

There are also three additionally studied sod roofs. The Kuusalu sod roof was established in summer 2007 and is situated in the countryside, a couple of kilometres from Kuusalu settlement. The roof on the private residence has a 200 mm thick soil layer, a 20° slope, and the area of one slope-side is 50 m^2. The roof is similar to the Tallinn Zoo sod roof, but in the Kuusalu roof, an LWA-based drainage layer was used. The Otepää sod roof was established in summer 2004 and is situated in the countryside, a couple of kilometres from the town of Otepää. The roof on the bath-house has a 200 mm thick soil layer, a 30° slope, and the area of one slope-side is 70 m^2. The turfs and soil descend from the grassland near the house. The Ihaste sod roof was established in summer 2004 and is situated in a district of private residences in Tartu. The flat grass roof has a 200-mm-thick soil layer with an LWA-based drainage layer, and an area of 35 m^2. For all three sod roofs, grass plants species used on the roofs were from the *Gramineae* species, and cover most of the whole roof area. Photographs of studied planted roofs are presented in Figure 3.

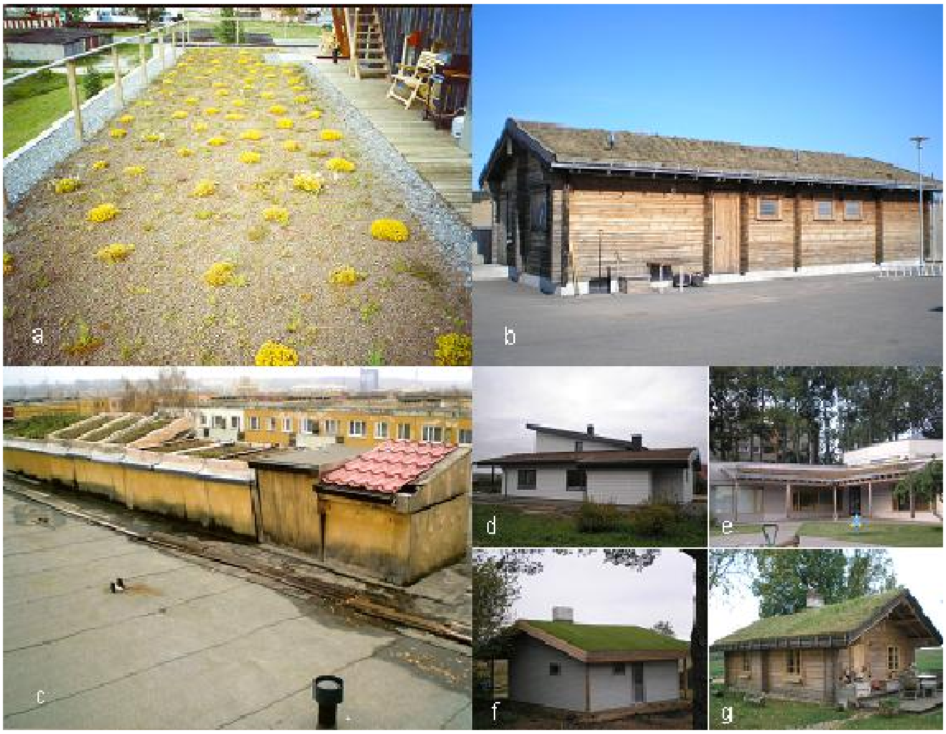

Figure 3. Studied planted roofs: a – Tartu green roof; b – Tallinn Zoo sod roof; c – simple buildings' roof plots; d – Luunja green roof; e – Viimsi green roof; f – Kuusalu sod roof; g – Otepää sod roof.

2.2. Sampling and analysis

2.2.1. Temperature measurement

On the studied green roof the measuring period was 10.06.04–25.04.05. The temperature was measured every 15 minutes using Pt1000TG8/E sensors produced by Evikon MCI (Estonia), and recorded with data logger R0141, produced by Comet System Ltd (Czech Republic). Data processing was performed using MS Excel. On the green roof the temperature was measured in two places: on the eastern and western sides of the roof. The temperature was measured on the surface of the roof, at a depth of 50 mm in the substrate layer and under the substrate layer (100 mm), and also at 1 m above the roof. As the green roof's surface was mainly covered by LWA (plant cover was only 45%), the surface temperature expresses the temperature of the LWA. As the temperatures of both sides of the green roof were similar, therefore only the results of the eastern side are used for comparison.

On the studied sod roof, the measurement period was 1.01.07–31.12.07. The temperature was measured every 15 minutes using Pt1000TG8/E sensors produced by Evikon MCI (Estonia), and recorded with data logger R0141 produced by Comet System Ltd (Czech Republic). Data processing was performed using MS Excel. The temperature was measured in two places: at the heatable side and non-heatable side of the roof. The temperature was measured on the surface of the roof, at a depth of 70 mm in the soil layer and 150 mm under the soil layer, and also in the air beside the roof. The temperatures measured on the heatable side were on average 2°C higher than on the non-heatable side. Considering that more buildings with sod roofs have a heating system, and the room under the compared green roof is heatable, the results of the heatable side are used in comparisons. From 1.01.08–31.03.08 there was also additional measurement to compare the sod roof with the steel roof that is situated in the vicinity of the sod roof.

On the studied simple buildings' roof plots, the measurement period was 1.06.06–31.05.07. The temperature was measured every 15 minutes using Pt1000A and T3111 sensors produced by Evikon MCI (Estonia) and recorded with data logger MS3+ produced by Comet System Ltd (Czech Republic). Data processing was performed using MS Excel. On the sod roof and the green roof with a slope of 20°, the temperature was measured in two places: on the upper and lower side of the roof. Considering that the results were very similar, in comparisons the results of the upper side measurement are used. The temperature was measured on the following locations on the green roofs: on the surface, at a depth of 40 mm in the substrate layer, between the substrate layer and the rock wool layer, between the rock wool layer and the drainage layer, and on the membrane. Measuring places on the sod roof were: on the surface, at a depth of 40 mm in the soil layer, between soil layer and drainage layer, and on the membrane. As the green roof's surface was mainly covered by LWA (plant cover was only 20–40%), the surface temperature expresses the temperature of the LWA. On the SBS roof and the steel roof, the temperature was measured on the surfaces.

The distribution of measurement time in different seasons used in studies presented here is the following: winter – 16.12–15.03; spring – 16.03–31.05; summer – 1.06–15.09; autumn – 16.09–15.12. Such partition is sufficiently comparable to the principle of seasonal distribution, and it is simple to make comparisons between different years, and it follows typical weather changing time in Estonia.

2.2.2. Runoff water measurement

Rainfall runoff was measured from the Tartu green roof and compared with the reference modified bituminous roof. Runoff volume was measured until runoff ended. Therefore, when the runoff of the first rain event had not finished before the next rain event occurred, it was also measured. Rainfall runoff was manually measured on an hourly basis with 20-litre canisters. If the canister filled with water in less than one hour, then water volumes were added. The green roof had two outflows, and there was one outflow for the reference roof. Some rain events roof runoff was also measured from the roof platforms in autumn 2007. Rainfall runoff was manually measured on an hourly basis with 10-litre canisters from one roof plot of each roof type. Runoff volume was measured until runoff finished, so there might be many rain events during one measurement period.

2.2.3. Runoff water quality analysis

Samples from outflows were collected in a sample bottle. Rainwater samples were taken during heavy rain and collected in a bowl. In the melting period, snow was collected from the roof and melted in a bowl. Most of samples are shown in Table 1. Samples on the existing SBS roof were taken on 31.08.04 during heavy and on 21.09.04 during moderate rainfall, and also on 26.03.05 after the melting of the snow cover. Samples of the Tartu green roof runoff water from the years 2004–2009 were taken on 21.09.04 (during moderate rainfall), 26.03.05, 30.03.06, 12.03.07, 31.03.08 and 02.04.09 (all after the melting of the snow cover). The reference number was snow water quality (26.03.05).

All water samples were analysed for pH, BOD_7, COD, Total-P, PO_4^{3-}, Total-N, NO_3^-, NH_4^+, SO_4^{2-}, Ca^{2+}-Mg^{2+} salt (total hardness). Analyses were performed by the laboratory of Tartu Veevärk Ltd. (Water Works of Tartu) for the samples taken in the Tartu area and by the Central Laboratory of the Estonian Environmental Research Centre for the samples taken in the Tallinn area. These water quality parameters were chosen because they are the core indicators of runoff water quality from catchments, and they also indicate groundwater quality. Five replicate samples of LWA from five different places in the Tartu green roof were taken for the chemical analysis of this material (April 2006). In the Plant Biochemistry Laboratory of the Estonian University of Life Sciences, the concentration of phosphorus, potassium, calcium, magnesium and organic matter in four fractions of LWA (<2, 2–4, 4–10, 10–20 mm) was analysed. The chemical analysis of the soil material from the sod roof at Tallinn Zoo was performed by Tartu Environmental Research Ltd. (29.04.09). The structure analysis of the soil material from the Tallinn Zoo sod roof was performed by the

Geotechnical Laboratory of the Estonian Environmental Research Centre Ltd. (18.05.09).

Table 1. Overview of roof runoff samples and explanations of abbreviations used in Tables 5 and 6, Paper V (Teemusk and Mander, 200Xb).

Abbreviation	Explanation of the roof runoff sample	Time the sample was taken
Rainwater	Rainwater taken during heavy rain with a bowl beside the Tartu roof plots	12.10.2007
Steelroof	Runoff sample from the Tartu steel roof plot taken during moderate rain	19.09.2007
Snow Tartu	Snow sample taken from the Tartu LWA-based green roof and melted in a bowl	12.03.2009
Snow Luunja	Snow sample taken from the Luunja LWA-based green roof and melted in a bowl	12.03.2009
Tartu GRP-a	Runoff sample from the Tartu LWA-based green roof plot taken during moderate rain	19.09.2007
Tartu GRP-b	Runoff sample from the Tartu LWA-based green roof plot taken during heavy rain	12.10.2007
Tartu SRP-a	Runoff sample from the Tartu sod roof plot taken during moderate rain	19.09.2007
Tartu SRP-b	Runoff sample from the Tartu sod roof plot taken during heavy rain	12.10.2007
Tartu-melt08	Runoff sample from the Tartu LWA-based green roof taken after melting of the snow cover	31.03.2008
Tartu-melt09	Runoff sample from the Tartu LWA-based green roof taken after melting of the snow cover	02.04.2009
Luunja-rain	Runoff sample from the Luunja LWA-based green roof taken during moderate rain	09.09.2008
Luunja-melt08	Runoff sample from the Luunja LWA-based green roof taken after melting of the snow cover	31.03.2008
Luunja-melt09	Runoff sample from the Luunja LWA-based green roof taken after melting of the snow cover	02.04.2009
Viimsi-melt08	Runoff sample from the Viimsi LWA-based green roof taken after melting of the snow cover	01.04.2008
Viimsi-rain	Runoff sample from the Viimsi LWA-based green roof taken during moderate rain	28.08.2008
Tallinn-melt08-1	Runoff sample from the Tallinn Zoo sod roof taken after melting of the snow cover	24.03.2008
Tallinn-melt08-2	Runoff sample from the Tallinn Zoo sod roof taken after melting of the snow cover	27.11.2008
Tallinn-new08	Runoff sample from the newer Tallinn Zoo sod roof (built in summer 2008) taken after melting of the snow cover	27.11.2008
Ihaste-rain	Runoff sample from the Ihaste sod roof taken during moderate rain	15.10.2007
Otepää-melt08	Runoff sample from the Otepää sod roof taken after melting of the snow cover	30.03.2008
Kuusalu-melt08	Runoff sample from the Kuusalu sod roof taken after melting of the snow cover	01.04.2008

2.2.4. Statistical analysis

The data were analysed using MS Excel and STATISTICA 7.0 software. The normality of data was checked using the Lilliefors and Shapiro-Wilk tests. Most of the temperature values (except for the surface temperatures measured on the conventional roofs in summer) were not normally distributed. For the analysis of these data, non-parametric statistics (e.g. the Spearman Rank Order Correlation) are used. For significance level, a Mann-Whitney U Test was used to analyze the data. The results of pH, BOD_7, COD and Ca-Mg salt concentrations in runoff water were normally distributed, and for significance level the T-test was used, and for other components a non-parametric Mann-Whitney U Test was used to analyze the data.

2.3. Background information

Monthly average temperature and precipitation at Tartu-Tõravere meteorology station for Tartu study periods are shown in Figure 1 in Paper V (Teemusk and Mander, 200Xb). The same information at Tallinn-Harku aerologic station for Tallinn study periods is shown in Figure 2 in Paper V.

Because the chemical composition of precipitation also had an influence on the quality of runoff water from roofs, the results of precipitation chemistry monitoring of Estonia at Harku station (59°23’52’’N, 24°36’09’’E) in 2007 are shown here. We found the following averages: pH unit 5.74, NH_4-N 0.29 mg/l, NO_3-N 0.44 mg/l, SO_4 0.70 mg/l and K 0.11 mg/l (National…, 2009).

The soil used in the sod roofs’ roof plots, referred to as Biolan black soil, consisted of horticultural peat, composted soil mix, sand, composted chicken dung (90 l/m^3) and dolomite lime (8 kg/m^3). The soil contained the following nutrients: nitrogen (100 mg/l), phosphorus (80 mg/l) and potassium (400 mg/l); the soil pH unit was 6.5.

3. RESULTS AND DISCUSSION

3.1. Temperature regime

3.1.1. Temperature regime on LWA-based green roof

On the studied green roof the measuring period was 10.06.04–25.04.05. There are the following main results, which are published in Paper III. In the summer months, the LWA's surface heats and cooled faster (amplitude 4.7°C to 54.8°C) on 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 green roof's substrate layer reduced summer temperature fluctuations by 22.7°C (Figure 2 and Figure 4 in Paper III, Teemusk and Mander, 2009). 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 green roof's soil. Although LWA surface heating in the daytime and cooling in the evening involves corresponding changes in soil temperature, the latter fluctuates considerably less, and thus the base roof is protected from great temperature fluctuations. The temperature at a depth of 100 mm rises slowly until the 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 (Figure 7 in III). 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, temperatures did not change much, due to cool and cloudy weather (Figure 9 in III).

In winter, temperatures were low both on the surface of the green roof (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). On the winter days, the insulating effect of the snow cover is apparent. In spite of the equal thickness of the snow cover, the green roof's soil temperature is several degrees higher than the temperature of the surface of the reference roof (Figure 10 in III). In spring the temperatures of roof surfaces fluctuated considerably due to daily sunshine and night frosts, whereas soil temperature was more stable (Figure 11 in III). When the daytime sun heats it 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).

3.1.2. Temperature regime on sod roof

On the studied sod roof, the measurement period was 1.01.07–31.12.07. The way results are analyzed is similar to that in the Teemusk (2005) study, but considering the similar principle of these results of the study of the LWA-based green roof, only the main results are demonstrated here. The temperature scale throughout the year is shown in Figure 4. Average temperatures over the whole year were 9.5°C under the soil layer, 9.3°C in the soil layer (70 mm) and 9.1°C on the surface above the heatable side. The same temperatures were 9.0°C, 8.9°C and 9.4°C above the non-heatable side of the roof respectively. The average air temperature was the lowest, –8.1°C. The maximum daily temperatures over the whole year were 26.0°C under the soil layer, 26.2°C in the soil layer (70 mm) and 29.6°C on the surface above the heatable side. The same temperatures were 25.2°C, 25.4°C and 29.5°C above the non-heatable side of the roof respectively. The maximum air temperature was 26.0°C. The minimum daily temperatures over the whole year were –9.9°C under the soil layer, –10.0°C in the soil layer (70 mm) and –11.4°C on the surface above the heatable side. The same temperatures were –11.1°C, –11.4°C and –11.5°C above the non-heatable side of the roof respectively. The minimum air temperature was –14.0°C.

Amplitudes at different measuring locations are shown in Figure 5. In all seasons, temperature fluctuation in the soil layer above the non-heatable side of the roof was 0.4–1.4°C higher, caused probably by the different soil structure around the sensors. However, in winter the effect of heating is also important. In addition, the couple of degrees higher results of surface temperatures on the non-heatable side are caused by the different plant foliage density around the sensor. In winter, the average temperature fluctuation was 1.0°C in the soil layer above the heatable side and 1.4°C above the non-heatable side of the roof. The surface temperature fluctuated by an average of 3.5°C and the air temperature 7.1°C. In spring the average temperature fluctuation was 3.4°C in the soil layer above the heatable side and 4.8°C above the non-heatable side of the roof. The surface temperature fluctuated by 22.7°C and the air temperature 13.7°C. In summer, as in spring, the average temperature fluctuation was 3.1°C in the soil layer above the heatable side and 4.5°C above the non-heatable side of the roof. The surface temperature fluctuated by 19.5°C above the heatable side and 23.7°C above the non-heatable side of the roof; the air temperature amplitude was 12.6°C. In autumn the average temperature fluctuation was 1.0°C in the soil layer above the heatable side and 1.3°C above the non-heatable side of the roof. The surface temperature fluctuated by an average of 4.4°C and the air temperature 6.2°C.

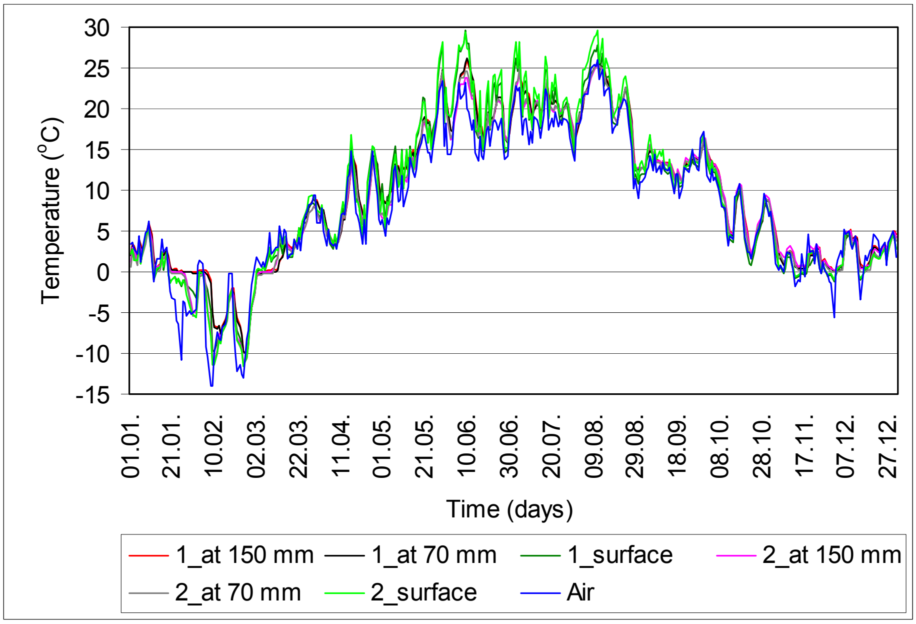

Figure 4. Daily average temperature values above the heatable side (1) and the non-heatable side (2) of the Tallinn Zoo sod roof during the entire measurement period (1.01.07–31.12.07).

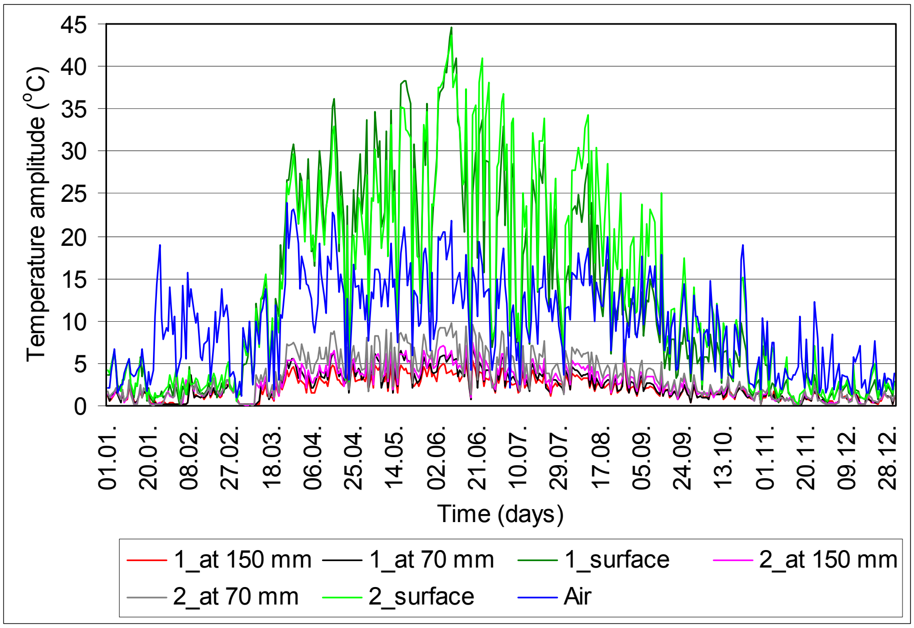

Figure 5. Variation of the amplitudes (difference between the maximum and minimum values) of daily average temperatures above the heatable side (1) and the non-heatable side (2) of the Tallinn Zoo sod roof.

In winter one can note the influence of heating or the absence of heating in the room under the sod roof. Above the heatable side the temperature was a couple of degrees higher than above the non-heatable side, whereby when weather became cooler, the difference increased. The temperature on the surface of the roof is influenced more by weather and the thickness of snow cover on the roof than by heating. For example, a 10-day period from February is shown in Figure 6-I. On 9 February the air temperature decreased to –20°C, while at the same time temperatures in the soil layer were –4°C and –11°C above the heatable and non-heatable side respectively.

In April, a typical spring month, the temperatures under the soil layer fluctuated averagely not more than three degrees in day. There was not notable difference between the temperatures of both sides of the roof, nevertheless the temperature was averagely one degree higher above the heatable side. Surface temperatures were averagely 7°C higher than air temperatures; it shows influence of solar radiation on the surface. Although the surface warmed up in daytime rapidly, there was not big influence to soil layer temperatures (Figure 6-II).

In the summer season, the temperatures under the soil layer fluctuated on average by no more than four or five degrees a day. At the same time, the temperature on the surface fluctuated 20°C (Figure 6-III). In autumn, on cloudy and rainy days the amplitudes of each measured point were trivial; at the same time, sunrise and bright night caused greater amplitude on the surfaces, where the temperature also decreased below zero (Figure 6-IV).

Comparing the difference between the sod roof and the steel roof in March 2008, it is clearly visible that the steel surface heated up in daytime and cooled down at night more than the surface of the sod roof (Figure 7). The difference is probably caused by the fact that there was snow cover on the sod roof, but the steel roof with 20° slope was slippery, and snow could easily slip off. Thus the surface was open to the influence of solar radiation. Comparing the temperatures under the soil layer of the sod roof and on the surface of the steel roof, the soil layer had an important positive influence on temperature fluctuation.

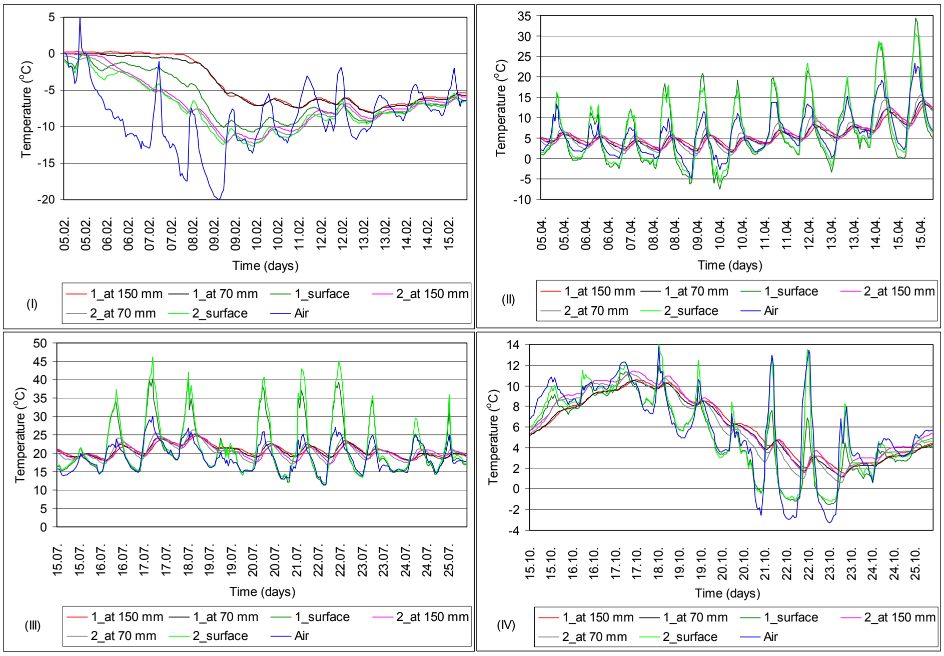

Figure 6. Temperatures above the heatable side (1) and the non-heatable side (2) of the Tallinn Zoo sod roof in 10-day periods in February (I), April (II), July (III) and October (IV) 2007.

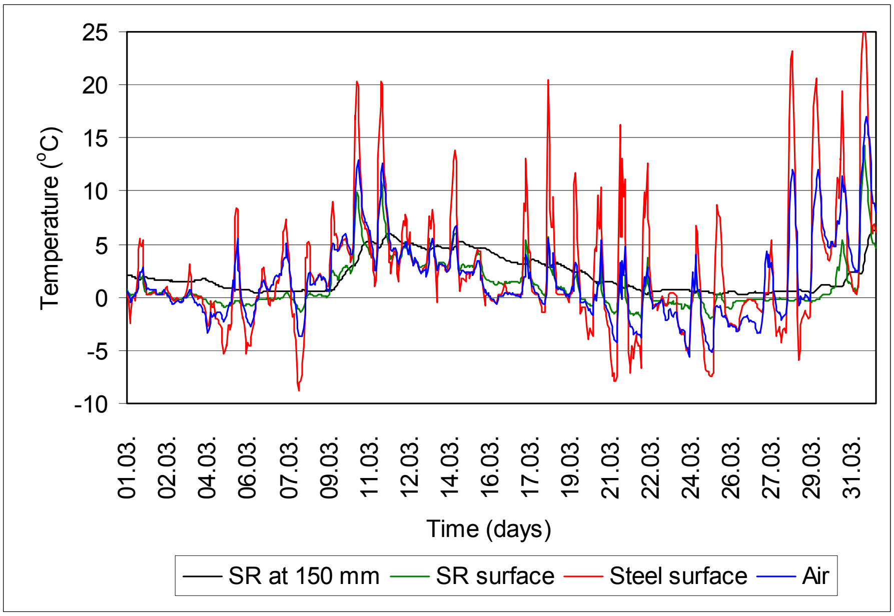

Figure 7. Temperatures on the sod roof (SR) and steel roof in March 2008.

3.1.3. Temperature regime on roof plots of simple buildings

The measuring period in the simple buildings' roof plots was 1.06.06–31.05.07. The scale of temperatures of the whole measurement period is presented in Figure 8. The results in the warm period showed the same temperature pattern as in previous studies, and thus the principle of results in cool season are only shown here. As demonstrated in Figure 9, the influence of cool air temperature is faster for the surfaces of the conventional roofs, which cooled down more rapidly than the planted roofs' membranes, which cooled down slower, but still faster and more than would occur on insulated roofs. The main conclusion is that planted roofs on non-insulated simple buildings freeze completely in winter, so they do not act as additional insulation.

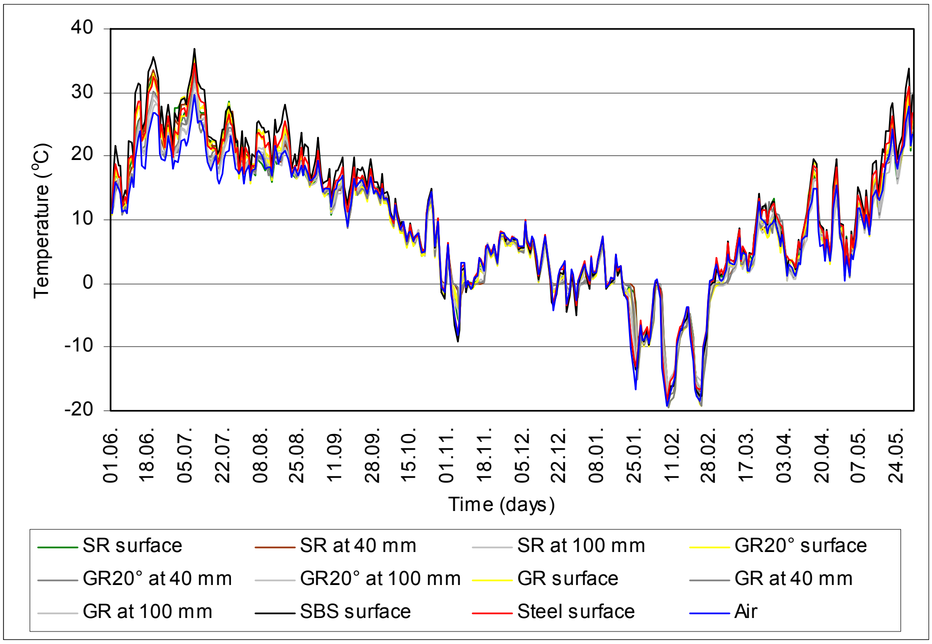

Figure 8. Daily average temperature values on simple buildings' roof plots during the entire measurement period (1.06.06–31.05.07). The roof plots: sod roof with 20° slope (SR), green roof with 20° slope (GR20°), flat green roof (GR), flat SBS roof, steel roof with 20° slope.

Figure 3-I–IV in Paper IV (Teemusk and Mander, 200Xa) illustrates daily average temperature values in different seasons. In the summer period, measurements showed that temperatures under the substrate layers of the planted roofs were a couple of degrees lower than on the surfaces, which were similarly high and demonstrated great amplitude. Thus the substrate layer was sufficiently able to reduce the temperature fluctuation effect (Figure 3-I in IV).

The highest temperature results were demonstrated by the surface of the SBS roof; the difference with the surface of the green roof was significant (p=0.005), with the temperature under the green roof being highly significant (p<0.0001). The results for the autumn period were similar, and the temperatures under the planted roofs remained warmer than on the surfaces (Figure 3-II in IV). There were no significance differences in the autumn period.

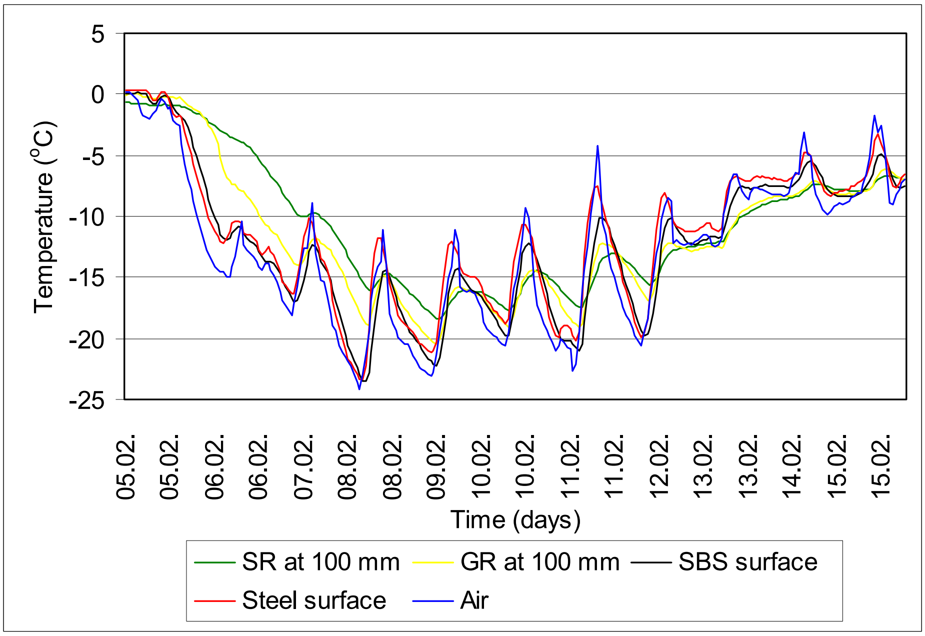

Figure 9. The principle of results on non-insulated simple-buildings' roof plots in the cool season (10-day period from 5.02–15.02.07) (SR – sod roof; GR – green roof).

In the winter season, the temperatures under the planted roof's substrate layers were similar to the temperatures on the surface, because there was no insulation under the base roof, and cool air also came from the underside (Figure 3-III in IV). In the spring season, the temperatures under the planted roof's substrate layers were lower than on the surface, probably due to the substrate layer's temperature reduction effect and also the cool air at night (Figure 3-IV in IV). The conventional roofs had higher temperatures than the planted roofs; the differences between the temperature under the sod roof and on the surfaces of the conventional roofs were significant.

3.1.4. Daily average temperature values on the mean roof types

Figures 1-I–IV in Paper IV illustrates results, measured in different time periods, which describe daily average temperature values on the four compared mean roof types. the above-mentioned figures show the green roof (100 mm) and the sod roof (150 mm) temperatures at the depth of 100 mm and 150 mm respectively, as well as the surface temperatures of the SBS roof and the steel sheet roof. In the summer period, measurements showed that the temperatures under the substrate layers of the planted roofs were significantly lower ($p<0.0001$) than on the surfaces of the conventional roofs (Figure 1-I in IV). The temperature under the green roof's substrate layer cooled down more than under the sod roof, so daily averages were higher for the sod roof ($p=0.04$). It is also noticeable that the SBS roof heats up more than the steel roof in the summer period ($p=0.02$). In the autumn period the sod roof remained warmer than the green roof, because it has a dense soil layer (Figure 1-II in IV). The temperature results of the conventional roofs were very similar, and higher than temperatures under the planted roof's substrate layers because of warming in daytime. However, the conventional roofs cooled down at night, but the temperatures in the substrate layers of the planted roofs did not generally fall below zero. The difference between the average temperatures measured on the surfaces of the conventional roofs and under the green roof was more significant ($p=0.001$) than the difference with the sod roof ($p=0.03$).

In the winter season the temperatures in the planted roof's substrate layers were much higher than on the surfaces of the conventional roofs (Figure 1-III in IV). However, the thicker sod roof was warmer (average –0.1°C) than the thinner green roof (average –1.1°C), which may freeze more easily, and the difference was significant ($p=0.002$). Comparing the planted roofs and the conventional roofs, only the difference between the sod roof and the SBS roof was significant ($p=0.01$). In the spring season, there is once again the same effect as in autumn, and the thicker sod roof was warmer than the green roof, which cooled down more at night (Figure 1-IV in IV). Comparing the planted roofs and the conventional roofs, only the difference between the green roof and the SBS roof was significant ($p=0.004$). The conventional roofs acted as they did in summer.

3.1.5. Temperature amplitudes on the mean roof types

Figure 2-I–IV in Paper IV illustrates the results measured in different time periods, which describes the variation in the amplitudes (the difference between the maximum and minimum values) of daily average temperature values on the same four compared mean roof types. In the summer period, measurements showed that temperature amplitudes on the surfaces of the conventional roofs

were on average 20°C higher than under the substrate layers of the planted roofs (Figure 2-I in IV). The temperature under the thicker sod roof was more stable than under the green roof's substrate layer, which depends more on temperature fluctuation on the surface. All differences were highly significant ($p<0.0001$), except between the conventional roofs. In the autumn period the principle of the results was similar to the summer period, and the difference in amplitudes was on average 10°C (Figure 2-II in IV). The difference between the planted roofs was significant ($p=0.0003$), although the conventional roofs were once again similar.

In the winter season, the average temperature amplitude in the planted roof's substrate layers was only 1°C, while at the same time the temperature fluctuated on average 7–8°C on the surfaces of the conventional roofs (Figure 2-III in IV); therefore the difference was highly significant ($p<0.0001$). As the planted roofs were frozen, they showed similar results, and the green roof was also more comparable to the sod roof due to the thicker snow cover, which provides additional thermal insulation. In the spring season, the green roof's temperature fluctuated much more than the temperature of the sod roof, which retained coolness ($p=0.0004$); the planted roofs also remained noticeably cooler than the conventional roofs (Figure 2-IV in IV). The difference was more than 20°C ($p<0.0001$), and thus the surface temperatures of the conventional roofs respond rapidly to the intensive sunshine.

3.1.6. Temperature regime in typical days on different roof types

Below are present the temperature regime results of the temperature measurement in simple buildings' roof plots on typical days and also the results of the comparison of the green roof and the sod roof, which was measured in different investigation periods, but in the daytime are used as similar weather conditions as possible.

One important ability of planted roofs is to reduce temperature fluctuation near the base roof throughout the substrate layer. The surface temperatures of the SBS roof (amplitude 50.4°C) and the steel roof (amplitude 42.4°C) rose with the sun, fluctuated according to cloudiness and fell in the evening (Figure 4 in IV). At the same time, all measured temperatures under the planted roofs (average amplitude 18.7°C) rose slowly to a maximum in the afternoon, and then began to fall just as slowly, remaining warmer at night. Comparing the green roof and the sod roof on a typical summer day, their temperature run was similar (Figure 5 in IV). The air temperatures rise at the same level, but the temperature under the 150 mm thick sod roof is more stable than under the 100 mm thick green roof. Thus the thicker substrate is better able to protect the base roof against higher temperatures.

Consecutive falls in air temperature over several days in the winter period have a greater influence on the surface temperature of the steel roof and the green roof than on that of the sod roof (Figure 6 in IV). It is clearly evident that temperatures under the planted roofs on the non-insulated simple buildings fell depending on the air temperature. The reason why temperature fell more slowly under the sod roof than under the green roof may be due to the different snow cover thickness and substrate freezing stage. The initial fall in air temperature on the existing planted roofs did not cause the temperature to fall under the substrate layers (Figure 7 in IV). After the fourth day the temperature under the sod roof fell 5°C more than under the green roof. This was probably due to the thicker snow cover on the green roof, which provided additional insulation, and to the fact that during the investigation of the sod roof, the air temperature was lower on the days after those shown in the graph.

On a typical early spring day on non-insulated simple buildings, the temperatures on the surfaces rose to a maximum before air temperature, but the temperatures under the planted roofs were more stable (Figure 8 in IV). Temperature amplitude under the planted roofs (12.2°C) was three times lower than on the surfaces of the conventional roofs (38°C). The early spring temperature run in the existing planted roofs followed the same principle as in the previously demonstrated example (Figure 9 in IV). The temperature under the sod roof was a couple of degrees higher than under the green roof because of the influence of the previous day, but the rise and fall in temperature was similar.

3.1.7. Indexes characterizing temperature effects of planted roofs

Mean seasonal temperatures of the studied roofs at different measuring sites are shown in Table 2. Mean air temperature describes the average air temperature of three different investigation periods.

Table 2. Mean seasonal temperatures (°C) of the studied roofs at different measuring sites.

Seasons	Measuring sites						
	1	2	3	4	5	6	7
Summer	18.79	19.14	19.61	19.84	23.45	21.66	17.88
Autumn	4.93	4.27	6.09	5.08	7.54	7.44	5.63
Winter	–1.13	–2.24	–0.12	–0.98	–3.14	–2.57	–2.75
Spring	8.41	9.03	10.57	10.73	12.75	12.09	8.93

Seasons: summer: 1.06–15.09; autumn: 16.09–15.12; winter: 16.12–15.03; spring: 16.03–31.05. Measuring sites: 1–GR at 100 mm; 2–GR surface; 3–SR at 150 mm; 4–SR surface; 5–SBS surface; 6–steel surface; 7–air beside the roofs, (approximation), for three measurements.

Indexes for the characterization of planted roofs' temperature effects are shown in Table 3. These are based on a comparison of the mean seasonal temperatures of the measuring sites of the planted roofs with the average air temperature and conventional roofs. The closer the index is to one, the more similar the compared temperatures are. Indexes I and II compare the temperatures under the planted roofs' substrate layer with air temperature. Indexes below one show the desired effect, and accordingly average temperature under the planted roof is better (cooler in summer and warmer in winter). The sod roof shows the best result in comparison with winter air. Indexes III and IV compare the surface temperatures of the planted roofs with air temperature. Results in spring and summer are greater than one, and thus worse (excessive heating); results in winter are better, especially on the sod roof.

Table 3. Main proposed indexes for the characterization of the temperature effect of planted roofs in different seasons.

Seasons	Indexes									
	I	II	III	IV	V	VI	VII	VIII	IX	X
Summer	1.05	1.10	1.07	1.11	0.98	0.99	0.80	0.91	0.82	0.92
Autumn	0.88	1.08	0.76	0.90	1.15	1.20	0.65	0.82	0.57	0.68
Winter	0.41	0.04	0.81	0.36	0.50	0.12	0.36	0.04	0.71	0.38
Spring	0.94	1.18	1.01	1.20	0.93	0.98	0.66	0.87	0.71	0.89

Seasons: summer: 1.06–15.09; autumn: 16.09–15.12; winter: 16.12–15.03; spring: 16.03–31.05. Indexes: I–GR at 100 mm/air beside the roofs (1:7); II–SR at 150 mm/air beside the roofs (3:7); III–GR surface/air beside the roofs (2:7); IV–SR surface/air beside the roofs (4:7); V–GR at 100 mm/GR surface (1:2); VI–SR at 150 mm/SR surface (3:4); VII–GR at 100 mm/SBS surface (1:5); VIII–SR at 150 mm/steel surface (3:6); IX–GR surface/SBS surface (2:5); X–SR surface/steel surface (4:6).

Indexes V and VI compare the surface temperatures of the planted roofs with the temperatures under the planted roofs' substrate layer. Indexes in winter show insulation effect, and in spring and summer indexes are only slightly better. In autumn the indexes are greater than one, but this is a good result considering that it describes a warming effect in a cool time. Indexes VII and VIII compare the temperatures under the planted roofs' substrate layer with the surface temperatures of the conventional roofs; thus it is a most important comparison. All indexes are below one, and therefore planted roofs' substrate layers have a considerable effect in each season, also in winter, offering additional insulation. Indexes IX and X compare the surface temperatures of the planted roofs with those of the conventional roofs. All indexes are below one because average air temperature for all three measurement periods is used. Taking into consideration the different sunshine conditions in different measurement periods, the indexes for spring and summer must be somewhat higher than shown. That is the only case where different conditions are more important. The other comparisons are sufficiently accurate.

3.2. Stormwater runoff retention of planted roofs

The investigation of rainwater runoff retention on the existing green roof in Estonia showed the following results (Paper II, Teemusk and Mander, 2007). In the case of light rain, the total runoff from the reference modified bituminous roof was 1.9 mm, while the runoff of the green roof was only 0.3 mm (Table 1 in II). Retention was 85.7%. The green roof was able to retain rainfall efficiently because of the previous days on which no rain fell, although the result was also similar in the case when previous runoff ended the day before. The runoff from the green roof began one hour later than from the reference roof, but it was only dripping. The runoff of the reference roof ceased nine hours before the runoff of the green roof. For almost every rainfall, runoff from the two outflows was different. The reason for this is probably that on one side of the roof (gr1 outflow side) the plant cover was thicker than on the other side (gr2 outflow side), where plant cover was thinner. The roots of plants in the substrate layer held water and slowed water release from the substrate layer. The estimated water holding capacity of the 100 mm substrate layer of the green roof was 30–40 mm.

The results in the case of a heavy rainstorm showed that the green roof could delay runoff for up to half an hour, but not fully retain it. The runoff began 20 minutes after rainfall from the reference roof; the green roof was able to retain water up to 15 minutes longer. Initially the runoff intensity from the reference roof was noticeably higher than from the green roof, while in the third hour of rainfall the intensity was similar for both roofs. 12.1 mm fell during 5 hours; the runoff from the reference and green roofs was 11.9 and 11.2 mm respectively. Taking into account the rainfalls that occurred on the next days, finally a total of 17.5 mm of water ran off the reference roof, and 17.8 mm of water ran off the green roof (Table 1 in II). The results show that the green roof can effectively retain light rain events, but in the case of a heavy rainstorm, rainwater runs off relatively rapidly.

The melting of snow cover with an average thickness of 220 mm on the green roof was observed over a period of 17 days (22.03.05–07.04.05), during which there was no precipitation. According to the results, we may distinguish two melting periods on the green roof: the melting of the snow cover and the melting of the frozen water in the substrate layer. The total runoff from the green roof was 26.6 mm, and 32.8 mm from the reference roof (Table 2 in II). Due to the difference in the amount of sunshine that fell on the roofs, the runoff of the reference roof began later than that of the green roof. It is clear that the runoff from the reference roof was more intensive than that of the green roof, which distributed the runoff over a longer period. The snow cover of the green roof, however, melted too quickly, and the substrate layer of the green roof was unable to retain it effectively.

In autumn 2007, runoff rates from different 1.5 m^2 roof plots (flat green roof, green roof with 20° slope, sod roof with 20° slope, flat SBS roof, steel roof with 20° slope) were studied. The results showed that in the case of light rain there was no runoff from the planted roof types; however, from the steel roof most of the rainfall water ran off (Table 4). When rain events occurred partially during the period and there were also rainfalls before measured rain events, planted roofs showed higher runoff results than the flat SBS roof. When rainfalls were distributed over a longer time period, planted roofs also distributed water runoff equally, and showed notable retention compared with the steel roof. It is also clear that the slope of the roof influences the amount of runoff water, so a green and sod roof with a 20° slope showed higher results than a flat green roof, as was the case with flat SBS roof.

Table 4. The key parameters of measured rain events and roof runoff results from the 1.5 m^2 roof plots (flat green roof, green roof with 20° slope, sod roof with 20° slope, flat SBS roof, steel roof with 20° slope).

Runoff measurement time	Rain (mm)	Rain duration (h)*	Runoff volume (mm)				
			flat gr	gr 20°	sod roof 20°	flat SBS roof	steel roof 20°
8 October, 10.00 h to 8 October, 11.00 h	0.7	1	nr	nr	nr	0.2	0.6
5 October, 19.45 h to 5 October, 20.45 h	1.7	1	nr	nr	0.1	0.7	1.6
15 October, 00.30 h to 15 October, 12.30 h	5.0	12	2.0	3.5	2.7	1.8	4.8
6 October, 15.00 h to 6 October, 18.00 h	6.2	3	1.4	2.6	1.8	2.8	6.0
18 September, 15.00 h to 19 September, 12.00 h	8.0	21	0.5	3.0	2.5	4.3	7.8
17 October, 10.00 h to 18 October, 14.00 h	11.7	28	5.3	6.8	7.4	6.7	11.4
11 October, 22.00 h to 13 October, 10.00 h	25.0	36	7.5	9.9	14.5	16.7	24.6

* – rain events occurred partially during the time
nr – no runoff

3.3. Runoff water quality of planted roofs

3.3.1. Runoff water quality of LWA-based green roof compared with SBS roof

Comparing a typical extensive green roof and a conventional bituminous roof in Tartu, the main conclusions are the following. The character of the runoff influence the quality of the runoff water: the slower the runoff rate, the higher the concentrations of Total-N, NH_4-N and organic material (after BOD_7 and COD). Total-P concentration did not vary significantly in relation to water discharge. Heavy rain washed more phosphates and also nitrates out of the green roof. In snow melting water, the concentrations of all components were greater on the green roof due to the accumulation of atmospheric pollutants in snow (Table 3 in Paper II). It is also clear that the material used in the substrate layer has an important influence on runoff quality. As the measurements showed, the green roof runoff always contained more sulphates and Ca-Mg salt, because of their presence in the LWA material. The concentrations of Total-P and Total-N, and also COD and BOD_7, were higher in the runoff water of the bituminous roof in the case of moderate runoff (Paper II).

3.3.2. Runoff water quality of LWA-based green roofs

The results of the water quality indicators of LWA-based green roofs are presented in Table 5. The values of pH in the green roofs' outflows rose by several units compared with the precipitation, i.e. from 6.2–6.6 to 8.1–8.5. The higher level of the values of the pH of the outflow water from each roof occurred in the case of melting water in 2008. The reason for the higher values of the outflow water from the green roofs compared with the steel roof is the carbonate contents of the LWA component.

The BOD_7 describes the organic compounds released (e.g. from the decomposition of plant remnants) from the substrate layer of the green roof. The concentrations of BOD_7 rose from 1.4–4.5 mg O/l in the precipitation to 1.1–4.8 mg O/l in the outflows of the green roofs. More organic compounds were added to the runoff water in the melting water samples than in the rainfall water samples. Comparing the results of the Luunja green roof, there was a much lower concentration of BOD_7 in the rainfall sample in September 2008 than in the melting water sample in April 2009, which is probably due to the rainy summer in 2008, and thus organic compounds were washed out with frequently occurring outflow. On the green roof plot there was a higher result in the case of heavy runoff, when more organic compounds in the LWA-substrate were washed out.

COD describes the dust components accumulated in the substrate layer and the chemical components of the precipitation. The concentrations of COD rose from 4–8 mg O/l in the precipitation to 12–49 mg O/l in the green roofs' outflows. Comparing the rainfall samples, there was a much higher COD concentration in the sample of the Viimsi green roof than of the Luunja green roof, probably due to the dust components which may partly be caused by traffic near the house, but one must also consider the effect of the different amount of precipitation. Although the Tartu green roof is situated near the city centre and intensive traffic, the COD values are not as high as may be expected, but they are still higher than others in some sample cases. On the green roof plot there was a higher result in the case of moderate runoff, because the runoff was slow and collected much more dust than in the rapid runoff.

Total phosphorus is a plant nutrient that entered into the roof through precipitation and fertilization. Concentrations of Total-P rose from 0.012–0.035 mg/l in the precipitation to 0.008–0.69 mg/l in the outflows of the green roofs. For the green roof plot in the case of moderate runoff, the substrate layer retained phosphorus well, but in the case of heavy runoff, more phosphorus was washed out. Higher concentrations than in the green roof plots were found in the runoff water from the Viimsi green roof. There must be some steady source for this, probably fertilization. The results of total phosphorus were similar on the same roof despite the time the sample was taken. Thus in the samples of the Luunja green roof there were higher concentrations than those of the Tartu green roof, probably due to the different age of the roof and the phosphorus content. The principle of the results for phosphates (PO_4-P) was similar to the results for Total-P. The concentrations of PO_4-P rose from 0.003–0.015 mg/l in the precipitation to 0.004–0.64 mg/l in the outflows of the green roofs.

Table 5. Water quality indicators of different outflow samples from the studied LWA-based green roofs. The explanation of samples is described in Table 1.

Samples	Indicator									
	pH	BOD_7 (mg O/l)	COD (mg O/l)	Tot-P (mg/l)	PO_4-P (mg/l)	Tot-N (mg/l)	NH_4-N (mg/l)	NO_3-N (mg/l)	SO_4 (mg/l)	Ca-Mg salt (mg equiv/l)
Rainwater	6.57	<3.0	<10	0.020	0.004	0.4	0.10	0.10	<2	<0.02
Steelroof	7.01	1.9	10	0.010	0.003	1.1	0.45	0.30	<2	0.08
Tartu GRP-a	8.24	3.2	85	0.200	0.120	3.8	0.54	2.0	<2	1.88
Tartu GRP-b	8.06	4.0	40	0.300	0.170	6.4	2.40	1.10	<2	1.06
Luunja-rain	8.13	1.1	16	0.160	0.120	0.4	0.30	0.03	<2	2.06
Viimsi-rain	8.15	<3.0	49	0.640	0.630	4.9	0.01	0.005	<5	2.60
Tartu-melt08	8.32	4.7	23	0.008	0.004	0.4	0.25	0.03	<2	2.04
Luunja-melt08	8.44	4.2	30	0.193	0.143	1.1	0.20	0.85	16	2.88
Viimsi-melt08	8.52	<3.0	12	0.690	0.640	3.4	<0.01	0.009	<5	2.60
Snow Tartu	6.30	4.5	<10	0.019	0.011	0.4	0.14	0.25	<2	<0.1
Tartu-melt09	8.27	3.8	25	0.049	0.015	0.5	<0.10	0.025	7	1.99
Snow Luunja	6.21	1.5	<10	0.035	0.015	0.4	0.13	0.23	<2	<0.1
Luunja-melt09	8.12	4.8	14	0.174	0.086	1.1	<0.10	0.49	15	1.69

Nitrogen came to a roof either from the air or from bacterial activity, and also through fertilization. The concentrations of Total-N rose from 0.4–1.3 mg/l in the precipitation to 0.4–4.9 mg/l in the outflows of the green roofs. For the green roof plot in the case of heavy runoff, more nitrogen was washed out than in the case of moderate runoff, when the substrate layer retained nitrogen. This result is opposite to the result of the study on the Tartu green roof in 2004 (Paper II). As in the case of Total-P, for Total-N higher concentrations were also due to the soil used in the substrate layer, which contains NPK-nutrients. In the samples of the Luunja green roof there were higher concentrations of Total-N than in the Tartu green roof, due to the age of the roof and the soil contained in the substrate layer. The concentrations of ammonium nitrogen (NH_4-N) were 0.015–0.22 mg/l in the precipitation and 0.01–0.3 mg/l in the outflows of the green roofs. The results were higher again in the samples of the green roof plot; in the Viimsi green roof, however, there was no ammonium. The results for the Tartu and Luunja green roofs were low, and in 2009 were even lower than in the snow water. The concentrations of nitrate nitrogen (NO_3-N) were 0.09–0.25 mg/l in the precipitation and 0.005–0.85 mg/l in the outflows of the green roofs. The results, influenced by plants and the substrate layer, were higher in the samples of the Luunja green roof than that of the Tartu green roof, and the sample taken in 2009 contains even less than in snow water. In the samples of the green roof plot there were once again higher concentrations, but the result was higher in the case of moderate runoff.

The results for sulphates (SO_4) were lower than the minimum measurable amount (<2 mg/l and <5 mg/l accordingly the laboratory where sample was analysed), which is surprising considering the results of the study performed in 2004 (Paper II), where a green roof showed higher concentrations of sulphates. It may be expected that the concentration of the sulphates that is present in the LWA material decreased during that time. Thus the results of the older green roofs in Viimsi and Tartu are understood, compared with the results of newer green roof in Luunja, where concentration of sulphates was higher. The concentrations of Ca-Mg salt (total hardness), which is present in the LWA material, rose from 0.02–0.1 mg equiv/l in the precipitation to 1.69–2.88 mg equiv/l in the outflows of the green roofs. There were lower results for Tartu and Luunja green roofs than for the Viimsi green roof.

3.3.3. Runoff water quality of sod roofs

The results of the water quality indicators of sod roofs are presented in Table 6. The values of pH in the sod roofs' outflows generally rose more than one unit compared with precipitation, i.e. from 6.2–6.6 to 7.6–8.1. For the new sod roof of the Tallinn Zoo, the higher level of the values of the pH of the outflow water is probably due to the soil component. The outflow water from Ihaste sod roof also has a high pH value due to the LWA component used in the drain layer.

The concentrations of BOD$_7$ rose from 1.4–4.5 mg O/l in the precipitation to 1.8–5.3 mg O/l in the sod roofs' outflows. The highest concentration was in the runoff water from the Kuusalu sod roof, probably due to the fresh soil used in the roof. On the sod roof plot there are higher concentrations of BOD$_7$ in the case of moderate runoff, when more organic compounds are washed out. The concentrations of COD rose from 4–8 mg O/l in the precipitation to 18–70 mg O/l in the sod roofs' outflows. The highest concentration was in the runoff water from the Otepää sod roof, probably due to the soil used in the roof, which comes from the field near the roof. The COD value of the runoff water of the sod roof plot was very high in the case of moderate runoff. The reason for this is probably the contents of the soil mix, but also the soil tufts that were excavated from near a road with high traffic and may long before have contained compounds that caused a higher COD value.

Table 6. Water quality indicators of different outflow samples from the studied sod roofs. The explanation of samples is described in Table 1.

Samples	Indicator									
	pH	BOD$_7$ (mg O/l)	COD (mg O/l)	Tot-P (mg/l)	PO$_4$-P (mg/l)	Tot-N (mg/l)	NH$_4$-N (mg/l)	NO$_3$-N (mg/l)	SO$_4$ (mg/l)	Ca-Mg salt (mg equiv/l)
Rainwater	6.57	<3.0	<10	0.020	0.004	0.4	0.10	0.10	<2	<0.02
Steelroof	7.01	1.9	10	0.010	0.003	1.1	0.45	0.30	<2	0.08
Tartu SRP-a	7.63	6.1	245	1.600	1.300	51.0	1.30	36.0	<2	3.54
Tartu SRP-b	7.63	4.1	105	0.430	0.400	9.8	0.70	6.0	<2	1.20
Tallinn-melt08-1	7.64	3.3	30	0.099	0.055	3.3	0.01	<0.02	<5	3.70
Tallinn-melt08-2	8.11	<3.0	18	0.090	0.060	2.6	<0.01	0.005	12	2.90
Tallinn-new08	8.13	<3.0	44	0.130	0.070	2.6	0.01	0.005	274	7.30
Ihaste-rain	8.22	<3.0	58	0.070	0.040	1.3	0.10	0.30	76	5.86
Otepää-melt08	7.72	1.8	70	0.168	0.128	4.4	0.80	2.90	<2	0.89
Kuusalu-melt08	8.05	5.3	19	0.870	0.750	5.8	0.02	0.52	35	3.20

The concentrations of Total-P rose from 0.012–0.035 mg/l in the precipitation to 0.07–0.87 mg/l in the outflows of the sod roofs. The highest concentration was in the runoff water from the Kuusalu sod roof, probably due to the fresh soil used in the roof, which may also contain nutrients. Total-P concentration was high for the sod roof plot in the case of moderate runoff, caused by the P-nutrient used in the soil. The principle of the results for phosphates (PO$_4$-P) was similar to the results for Total-P. The concentrations of PO$_4$-P rose from 0.003–0.015 mg/l in the precipitation to 0.04–0.75 mg/l in the outflows of the sod roofs. The results for the Tallinn Zoo and Ihaste sod roofs were lower than those for the Kuusalu and Otepää sod roofs.

The concentrations of Total-N rose from 0.4–1.3 mg/l in the precipitation to 1.3–5.8 mg/l in the outflows of the sod roofs. Total-N concentration was much higher than for other roofs for the sod roof plot in the case of moderate runoff, due to the N-nutrient used in the soil. Due to the fresh soil used in the roof, the concentration is again also high in the runoff water from the Kuusalu sod roof. There were less nutrients for plants on the Ihaste sod roof than on the other roofs. The concentrations of ammonium nitrogen (NH_4-N) were 0.015–0.22 mg/l in the precipitation and 0.01–0.8 mg/l in the outflows of the sod roofs. The concentrations of nitrate nitrogen (NO_3-N) were 0.09–0.25 mg/l in the precipitation and 0.005–2.9 mg/l in the outflows of the sod roofs. Only in the Otepää sod roof was there a high concentration of both NH_4-N and NO_3-N due to the soil and plants.

The concentrations of sulphates (SO_4) rose from <1 mg/l in the precipitation to 1.7–76 mg/l in the sod roofs' outflows. Exceptionally, there was a very high concentration in the runoff water from the newer Tallinn Zoo sod roof, which was probably due to the derivation of the fresh soil used. The high concentration of sulphates in the Ihaste sod roof was caused by the LWA material used in the drain layer. Results of Ca-Mg salt were also high in the same roofs. The concentrations of Ca-Mg salt rose from 0.02–0.1 mg equiv/l in precipitation to 0.89–7.3 mg equiv/l in the sod roofs' outflows.

3.3.4. Runoff water quality comparison between green roofs and sod roofs

Comparing the results of studied LWA-based green roofs and sod roofs, one may conclude that the runoff water of the LWA-based green roofs generally had higher results of pH, BOD_7, Total-P and PO_4-P. However, COD, Total-N, SO_4 and Ca-Mg salt were higher in the sod roofs. The results of NH_4-N and NO_3-N for both roofs were similar. According to the results of roof plots, the use of NPK-nutrients in the substrate layer and soil layer caused much higher concentrations of COD, Total-P, PO_4-P, Total-N, NH_4-N and NO_3-N, but there was no difference between the other roofs' results of pH, BOD_7, SO_4 and Ca-Mg salt (Figure 3 in Paper V, Teemusk and Mander, 200Xb).

3.3.5. Change in LWA-based green roof runoff water quality over time

Results of samples taken from the Tartu LWA-based green roof each spring in 2005–2009 at the time when the snow had almost melted, and one sample taken in 2004 from moderate rainfall runoff, demonstrated that concentrations of compounds in the runoff water generally decreased over time. There is no steady trend for Total-P, PO_4-P and NH_4-N. There was an increasing trend until 2006, and a decreasing trend since then for BOD_7 and COD. The falling concentration and subsequent stabilizing trend is proper for Total-N and NO_3-N.

SO_4 showed a clearly decreasing trend. There is a stable content pattern for pH and Ca-Mg salt (Figure 4 in Paper V).

3.3.6. Additional analysis and comparisons

The results of the chemical analysis of the Tartu green roof's LWA material showed that the finest fraction (<2 mm) of LWA had the largest proportion of organic matter, P, K, and Ca, whereas Mg was more equally distributed (Table 1 in Paper V). The results of the chemical analysis of the Tallinn Zoo sod roof's soil showed high concentrations of Ca and Mg, which caused a higher Ca-Mg salt result. The amount of organic matter was similar to the LWA material. The results of the soil texture analysis of the Tallinn Zoo sod roof's soil showed that there was 10.3% of gravel (2–20 mm), 77.5% of sand (0.06–2 mm), 11.2% of silt (0.002–0.06 mm) and 1.0% of clay (<0.002 mm) fraction. The porosity of the turf was 58.5%.

Comparing extensive green roof runoff quality data and marginal rates in Estonia, the results of green roofs did not exceed the values of drinking water for pH, BOD_7, NO_3-N, SO_4 and Ca-Mg salt, although there was higher COD, Total-P, Total-N, and NH_4-N in the green roofs' outflows. All results of the green roofs' outflows were lower than the limit values for effluent. A comparison of the average results of studied green roofs and the results of studies by Berndtsson et al. (2009) and Moran et al. (2005) showed that there is no clear difference between results. The scale of results was similar, but there are some lower results for phosphorus and nitrogen in this study than in the Swedish study; phosphorus concentrations are higher in the studied extensive green roof in North Carolina (Table 2 in Paper V).

4. CONCLUSIONS

The results presented in this dissertation showed that planted roofs may alleviate problems in urban areas, and they are sufficiently capable in Estonian climatic conditions. At the same time, there are some issues, especially in the area of runoff water quality, which need further investigation.

The results of the green and the sod roof were similar; the thicker sod roof had better results than the thinner green roof. In warmer times, the surface of the planted roof heats up too much, however, such high and rapid heating of the surfaces does not cause a considerable temperature rise under the substrate layers. The difference between temperature amplitude under the planted roofs and the surfaces of the conventional roofs averaged 20°C. Thus a green roof can provide a base roof with effective protection against the influence of intensive solar radiation. In autumn and spring, the sod roof's soil layer showed higher temperature and lower amplitude than the green roof's substrate layer, which cooled down more (Paper III; Paper IV; Teemusk and Mander, 2009, 200Xa).

In winter temperatures under the planted roofs were higher than the surfaces of the conventional roofs; average amplitude was 1°C and 7–8°C respectively. Consecutive days of falling air temperature in winter did not influence planted roofs immediately, but in about four days the temperature under the soil layer fell a few degrees depending on the air temperature and snow cover thickness on the roof. Temperatures under the planted roofs on the non-insulated simple buildings were similar to temperatures on the surface, and fell depending on the air temperature, because cool air got closer below the base roof (Paper III; Paper IV).

A green roof can effectively retain light rain events that do not occur too soon after one another, if the substrate layer is not fully saturated. The green roof can retain rainfall more efficiently if the preceding days are rainless and the substrate layer is dry. The green roof can also retain a moderate rain even when the substrate layer is wet from previously fallen rain. It is also clear that the slope of the roof influences the amount of runoff water. In the case of a heavy rainstorm, the LWA green roof cannot retain it, and rainwater runs off relatively rapidly. The green roof can distribute the runoff over a longer period. The snow cover of the green roof melted in one day, while the melting of the substrate layer lasted 12 days (Paper II, Teemusk and Mander, 2007).

The LWA green roof has a considerable effect – both positive and negative – on the quality of runoff water. This clearly depends on the character of the runoff: the slower the runoff rate, the higher the concentrations of Total-N, NH_4-N and organic material (after BOD_7 and COD) in the runoff water. Total-P concentration did not vary significantly in relation to water discharge. Heavy rain washed more phosphates and also nitrates out of the green roof. In snow melting water, the concentrations of all components were greater on the green roof due to the accumulation of atmospheric pollutants in snow. The LWA green roof generally acts as a storage device: pollutants are accumulated in the substrate layer and released when intensive rainwater washes them out. The green roof runoff always contained more sulphates and Ca-Mg salt, because of their presence in the LWA material. On the other hand, the concentrations of Total-P and Total-N, and also COD and BOD_7, were higher in the runoff water of the bituminous roof in the case of moderate runoff (Paper II).

Both the LWA-based extensive green roof and the sod roof have a considerable effect on the quality of runoff water. This depends on the character of the runoff: the slower the runoff rate, the higher the concentrations of all studied components in the sod roof runoff water. The same effect was found in the green roof for pH, COD, NO_3-N and Ca-Mg salt, but in the case of heavy runoff there was more BOD_7, Total-P, PO_4-P, Total-N and NH_4-N. The use of nutrients in the substrate or soil caused much higher concentrations in runoff water except for pH, BOD_7, SO_4 and Ca-Mg salt. As the measurements showed, the runoff water of the LWA-based green roof generally had higher results for pH, BOD_7, Total-P and PO_4-P. In contrary, COD, Total-N, SO_4 and Ca-Mg salt were higher in the sod roofs. The results of NH_4-N and NO_3-N for both roofs were similar. The results of samples taken from the Tartu LWA-based green roof showed that concentrations of compounds in the runoff water generally decreased over time. However, pH and Ca-Mg salt were stable, being caused by LWA material (Paper V, Teemusk and Mander, 200Xb).

Altogether, we may conclude that even with a low percentage of plant cover, green roofs can reduce the overheating of air in cities and reduce water runoff volume, and also delay peak flow. This is in contrast to the modified bituminous roof, which is completely covered by a heat-absorbing coat and also directs all water into sewer systems. Although most contaminants were higher in runoff water than in precipitation, comparisons of marginal rates showed that the situation is not as bad as may be expected. In the countryside, it is possible to use runoff water for the irrigation of plants, which thereby obtain the necessary nutrients. Nevertheless, the fertilization of planted roofs and also the composition of the soil layer must be taken into consideration to decrease the amount of some contaminants runoff water.

The investigations showed that planted roofs are sufficiently effective in Estonian climatic conditions which are somewhat intermediate between Mid-European (e.g. Germany, where sedum-based green roofs dominate) and North-European (e.g. Norway, where sod roof is popular) conditions. In Estonia, there occur both sunny and hot summer season and cold winter season, also cool and wet autumn. Thus in Estonia there are good facilities to research different types of planted roofs. Several brief studies on green roofs have been performed in Estonia by other researchers; study presented in this dissertation was the first embedding large-scale investigation. Surely there are needed further proper investigations to find clearly out all possible effects of planted roofs in Estonian climate.

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SUMMARY IN ESTONIAN

Haljaskatuste temperatuuri- ja veerežiim ning nõrgvee kvaliteet

Käesoleva doktoritöö eesmärk on analüüsida katusehaljastuse kolme põhilist kasutegurit Eesti kliimas. Selleks on teostatud uuringud, mis hõlmavad haljaskatuste temperatuurirežiimi eesmärgiga hinnata temperatuuri kõikumist alandavat mõju, veerežiimi eesmärgiga vaadelda rohekatuste vee äravoolu hulka vähendavat ja algust edasilükkavat võimet ning veekvaliteeti eesmärgiga leida, millisel moel mõjutab katusehaljastus äravoolu vee kvaliteeti.

Katusehaljastus on tehnoloogia, mida saab muuhulgas rakendada linnakeskkonnas, kus leidub aina vähem rohealasid. Kindlate kihistiku osadega, kuid erineva paksusega haljaskatused on jõudsalt arenenud Saksamaal, kus on välja töötatud vastavad reeglid katusehaljastuse rajamiseks, mida ka riiklikult soositakse. Peale Saksamaa, kus tehtud uuringuid on avaldatud enamjaolt kohalikes ajakirjades, on rohekatuste uuringud ette võetud Ameerika Ühendriikides, Kanadas ja mujal. Kuigi haljaskatuste uuringutes on välja kujunenud juhtivad maad, avastatakse nende võimalusi paljudes riikides üle maailma. Oma uurimustulemuste avaldamiseks kasutatakse üha enam ka rahvusvahelisi eelretsenseeritavaid teadusajakirju.

Uuringud on näidanud, et haljaskatused vähendavad temperatuurikõikumiste mõju aluskatusele (Liu and Baskaran, 2003; Bass and Baskaran, 2003); jahutavad katusealuseid ruume ning omavad muid positiivseid soojuslikke omadusi (Palomo Del Barrio, 1998; Theodosiou, 2003; Wong et al., 2003c; Liu, 2003); vähendavad kuuma saare efekti (Gomez et al., 1998); vähendavad katuselt äravoolava vee hulka ja pikendavad äravoolu algust, samas suurte sajuhulkade puhul on näha selle võime vähenemist (Rowe et al., 2000; Liu, 2003; Villarreal and Bengtsson, 2005; Mentens et al., 2006); osalt vähendavad saasteainete kandumist äravooluvette, kuid samas võivad ise suurendada toitainete hulka vees sõltuvalt substraadi mõjust (Moran et al., 2005; Berndtsson et al., 2006; Hathaway et al., 2008); vähendavad müra ja õhusaastust ning omavad suurt esteetilist väärtust. Uuringud Eestis on näidanud, et haljaskatused ei seo kevadperioodil nii hästi vett kui suveperioodil (Hallik, 2005), kuid aasta jooksul on võimelised kinni hoidma keskeltläbi 55% sademetest (Hallik et al., 2005). Katusehaljastus ei oma Eestis tähtsust katusealuste ruumide jahutajana, vaid pigem katusemembraani kaitsjana (Hallik, 2008).

Temperatuuriuuringud on teostatud kergkruusapõhisel murukatusel (100 mm paksuse substraadiga) võrreldes tulemusi bituumenkatusega (juuni 2004 kuni aprill 2005). Mätaskatust (150 mm) uuriti jaanuarist detsembrini 2007, et võrrelda kahte peamist Eestis levinud katusehaljastuse tüüpi. Samuti teostati temperatuuriuuringud 1x1.5 m suurustel katseplatvormidel, mis imiteerisid soojustamata lihtehitiste katuseid, nägemaks haljaskatuste temperatuurirežiimi alt soojustamata katustel. Kergmurukatusel ja bituumenkatusel mõõdeti kolme vihmajuhtu ning lume sulaperioodi. Erinevate intensiivsustega vihmasadude mõju äravoolule uuriti ka katseplatvormidel. Veekvaliteedi analüüse võeti kergmurukatustelt ning mätaskatustelt erinevatel aegadel, võrreldes neid sademete ning võrdluskatuste tulemustega. Proove võeti vahemikus august 2004 kuni aprill 2009, et leida, millises skaalas võib vee kvaliteet varieeruda.

Vaatamata erinevatel ajaperioodidel teostatud uuringutele näitasid võrdlused piisavalt selgelt, et nii kergmuru- kui mätaskatus on võimelised vähendama temperatuurikõikumiste mõju aluskatusele. Tulemused olid üldiselt sarnased, arvestades uuritud mätaskatuse paksust, oli see paremate tulemustega kui õhem kergmurukatus. Mõlema haljaskatuse pinnad aga soojenesid sarnaselt soojadel päevadel liialt, mida saaks vähendada tihedama haljastusega. Samas pindade liigne soojenemine ei toonud kaasa alumise kihiosa suurt soojenemist, seega säilis kihistiku temperatuuri alandav mõju. Suvised uuringutulemused näitasid, et kergmuru- ja mätaskatuse pinnasealused temperatuurid on samasuguse temperatuurikäiguga, kuid mätaskatuse pinnasealune püsib õhtuti kauem soojem, sest õhem kergmurukatus on rohkem mõjutatud pinnal toimuvast temperatuurikõikumisest. Haljaskatuste pinnasealuste ja tavakatuste pindade temperatuuriamplituudide vahe oli suveajal keskmiselt 20°C. Sügisperioodil oli kergmurukatuse pinnasealune pisut jahedam kui mätaskatusel viimase tihkuse tõttu, hoides rohkem sooja, ka oli mätaskatusel keskmine amplituud paksusest tulenevalt minimaalne.

Talveperioodil olid kõrgemad temperatuurid haljaskatuste kihistike all kui tavakatuste pinnal, seejuures paksem mätaskatus püsis soojem kui õhem kergmurukatus, mille põhja jõudis jahedus varem. Keskmine amplituud haljaskatuste kihistiku all oli sarnaselt vaid 1°C võrreldes tavakatuste pindadega, kus see oli 7–8°C. Talvised tulemused näitasid, et mõnepäevane külmenemine kohest mõju pinnasealustele temperatuuridele ei avalda, kuid pikema külmenemise korral langeb ka pinnasealune temperatuur sõltuvalt õhutemperatuurist ja katuse lumekatte paksusest. Tavakatuste pinnatemperatuurid langesid ka –20°C lähedale, kuid haljaskatuste all ei langenud temperatuur alla –10°C. Kergehitiste alt soojustamata haljaskatused olid sarnaste tulemustega kui tavakatuste pinnad, sest külm pääses ligi ka altpoolt. Kevadperioodil oli tõenäoliselt öiste jahtumiste tõttu madalam keskmine temperatuur kergmurukatuse all, mätaskatus hoidis sooja paremini. Kergehitiste haljaskatuste pinnasekihi all oli temperatuuriamplituud (12°C) kolm korda väiksem kui mõõdetud tavakatuste pinnatemperatuuridel (38°C), seega vähendaks selliste katusepindade haljastamine tunduvalt temperatuurimõjusid katusekattele.

Vee kinnipidamisvõime tulemused näitasid, et haljaskatus suudab kinni pidada nõrga vihma, kui ei järgne mitu vihma üksteisele ning ei toimu substraadi veega küllastumist. Mida kuivem substraat ja pikem vahe vihmadel, seda paremini suudab katus vett siduda. Siiski suudab substraat hoida teatud määral vett kinni ka järjest toimuvate vihmavalingute korral. Mõõtmised näitasid, et paduvihma haljaskatuse substraat kinni hoida ei suuda, vaatamata pooletunnisele äravoolu alguse viivitusele oli äravool pea sama mis võrdluskatuselt. Sulaperioodi mõõtmised näitasid, et lumi sulab päikeselise ilma korral kergmurukatuselt paari päevaga, sellele järgneb üle nädala kestev substraadikihi sulamine. Katseplatvormidel teostatud mõõtmised näitasid, et kaldega haljaskatuste puhul on äravool mõnevõrra suurem kui kaldeta haljaskatustelt.

Kergmurukatuse ja bituumenkatuse nõrgvee kvaliteeti võrreldes leiti, et äravoolu intensiivsus mõjutab suuresti äravoolu vee kvaliteeti. Mida aeglasem on äravool, seda enam sisaldab see lämmastikku, ammooniumi ja orgaanilist materjali (BHT_7 ja KHT). Hõreda vihma ja rahuliku äravooluga olid KHT, BHT_7, fosfori ja lämmastiku sisaldus bituumenkatuse nõrgvees kõrgemad kui murukatusel, pH suurenes mõlemal katusel üle kahe ühiku. Paduvihm uhtus murukatuse kasvusubstraadist välja fosfaate ja nitraate. Tõenäoliselt saasteainete tõttu lumes ja substraadis olid kõikide komponentide sisaldused suuremad murukatuse lumesulavees. Kergmurukatuse äravool sisaldas alati rohkem Ca-Mg soolasid nende esinemise tõttu kergkruusas.

Võrreldes kergmurukatuse ja mätaskatuse mõju nõrgvee kvaliteedile, on selge, et mõlemal juhul on see märkimisväärne. Oluline on äravoolu intensiivsus: mida väiksem see oli antud uurimuses, seda kõrgemad olid kõikide komponentide sisaldused mätaskatuse äravooluvees. Sama efekt oli kergmurukatusel pH, KHT, NO_3-N ja Ca-Mg soolade sisalduse osas, kuid intensiivsema äravooluga kasvas BHT_7, P, PO_4-P, N ja NH_4-N sisaldus äravoolus. Toitainetesisaldusega kasvumulla kasutamine mätaskatuse pinnases ja kergmurukatuse substraadis põhjustas mitmete komponentide kõrgema sisalduse äravoolus, välja arvatud pH, BHT_7, SO_4 ja Ca-Mg soolad. Tulemused näitasid, et kergmurukatuse äravooluvesi sisaldas üldiselt rohkem pH, BHT_7, P ja PO_4-P, samas KHT, N, SO_4 ja Ca-Mg soolad olid kõrgemad mätaskatuse äravoolus. NH_4-N ja NO_3-N tulemused olid sarnased. Tulemused näitasid, et äravoolu iseloom ja substraadi koostis ajahetkel omavad äravoolu vee kvaliteedile suuremat mõju kui katuse vanus ja asukoht. Igakevadised veeproovid Tartu kergmurukatuselt, võetuna peale lumekatte sulamist aastatel 2005–2009, näitasid, et üldiselt oli komponentide osas näha langevat trendi, kuid pH ja Ca-Mg soolade tase püsis stabiilne, põhjustatuna kergkruusast.

Nagu uurimused näitasid, on haljaskatused Eesti kliimatingimustes piisavalt efektiivsed. Eesti paikneb vahepealse kliimaga tsoonis, jäädes Kesk-Euroopa ja Põhja-Euroopa vahele, kus vastavalt on rohkem levinud kas kergmurukatused (näiteks Saksamaal) või mätaskatused (Norras). Seega on Eesti soodsa asukohaga piirkond, kus saab uurida erinevaid haljaskatuste tüüpe, sest siin esinevad nii kuumad suveperioodid kui ka külmad talveperioodid, lisaks jahe ja vihmane sügis. Mitmeid lühiajalisi kergmurukatuste töid on Eestis tehtud varemgi, käesolev uuring oli esimene laiema haardega teostatud uurimustöö üldise ülevaate saamiseks. Kindlamate järelduste tegemiseks haljaskatuste efektiivsuse kohta Eesti tingimustes on vajalik teostada põhjalikumaid uuringuid igas valdkonnas, eeskätt aga nõrgvee kvantiteedi ning kvaliteedi osas.

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PUBLICATIONS

CURRICULUM VITAE

ALAR TEEMUSK

Date of birth: 27.01.1981
Address: Department of Geography, Vanemuise 46, 51014 Tartu, Estonia
Contact: Phone: +372 53 966 232; E-mail: alar.teemusk@ut.ee

Education

1999 – Lasnamäe General Gymnasium
2003 – University of Tartu, Faculty of Biology and Geography, Institute of Geography, Environmental technology. *BSc.*
2005 – University of Tartu, Faculty of Biology and Geography, Institute of Geography, Environmental technology. *MSc.* (master's thesis topic "Temperature control and water retention capability of greenroof in climatic conditions of Estonia")

Publications

Teemusk, A. and Mander, Ü. 2006. The use of greenroofs for the mitigation of environmental problems in urban areas. In: Mander, Ü., Brebbia, C.A. and Tiezzi, E. (Eds) The Sustainable City IV, WIT Press, Southampton and Boston, pp. 3–17.

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ELULOOKIRJELDUS

ALAR TEEMUSK

Sünniaeg: 27.01.1981
Aadress: Geograafia osakond, Vanemuise 46, 51014 Tartu, Eesti
Kontakt: Tel: +372 53 966 232; E-post: alar.teemusk@ut.ee

Haridus

1999 – Lasnamäe Üldgümnaasium
2003 – Tartu Ülikool, Bioloogia-geograafia teaduskond, Keskkonnatehnoloogia. *BSc*.
2005 – Tartu Ülikool, Bioloogia-geograafia teaduskond, Keskkonnatehnoloogia. *MSc*. (magistritöö "Murukatuse temperatuuri reguleerimise ja vee kinnipidamise võime Eesti kliimatingimustes")

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