Extensive Vegetated Roofs in Sweden

Establishment, Development and Environmental Quality

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Abstract

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This thesis discusses extensive vegetated roofs, *i.e.* vegetation systems placed on top of buildings as an aesthetical and/or ecological cover. Specific objectives was to (1) quantify how establishment techniques, substrates and plant mixes influence establishment and development of extensive vegetated roofs, (2) investigate effect of vegetated roofs on stormwater quality, and quantify how maintenance and starting fertilisation influences stormwater quality, and (4) investigate the role of vegetated roofs in planning tools for urban green space. The studies on vegetation establishment and development was carried out at the Augustenborg Botanical Roofgarden, Malmö (55°34'34''N, 13°1'42''E), the nutrient runoff was investigated on commercially installed systems in the Malmö-Lund region and in a greenhouse study. The role of vegetated roofs in planning of green areas was performed as a literature study. Vegetation establishment and development was investigated in relation to substrate, species and establishment method. Nutrient runoff was in the greenhouse study investigated in relation to fertiliser type, vegetation type and fertiliser amount.

Prefabricated vegetation mats had an advantage in establishment in creating high plant cover during the first year, which can be important on exposed sites. Establishment was similar for plug plants and cuttings. The commercial substrate was beneficial for establishment. The advantage in succulent cover of vegetation mats had disappeared after 3.5 years. All establishment techniques achieve the same long-term succulent cover. Moss cover increased over time and was at the end of the study dominating the system with approx 50-80% cover. Maintenance fertilisation can cause degradation of stormwater quality if conventional fertilisers are used. Conventionally installed vegetated roofs were found to be a source of potassium and phosphorous, and a sink for nitrogen. Vegetated roofs had a minor influence on heavy metal runoff. Spontaneous establishment on extensive vegetated roofs was low, which is beneficial from a maintenance perspective but unfavourable from a biodiversity perspective. The Green Space Factor tool was found to overestimate the environmental functions of thin vegetated roofs.

Keywords: green roof, *Sedum* spp., establishment, fertilisation, stormwater quality, planning tools, prefabricated vegetation mats, cuttings, plug plants

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Contents

Appendix

Papers I–V

The thesis is based on the following papers, which are referred to by their Roman numerals in the text. Papers are due to copyright not included in the Epsilonversion.

I. Emilsson, T. & Rolf, K. 2005. Comparison of establishment methods for extensive green roofs in southern Sweden. *Urban Forestry & Urban Greening* 3:2, 103-111.

II. Emilsson, T. Vegetation development on extensive vegetated roofs – Influence of substrate composition, establishment method and species mix. *Manuscript*

III. Czemiel Berndtsson, J., Emilsson, T. & Bengtsson, L. 2006. The influence of extensive vegetated roofs on runoff water quality, *Science of The Total Environment* 355:1-3, 48-63.

IV. Emilsson, T., Czemiel Berndtsson, J., Mattsson, J.E. & Rolf, K. 2006. Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. *Ecological Engineering (accepted for publication)*.

V. Emilsson, T., Persson, J. & Mattsson, J.E. Evaluation of ecological surface values of vegetated roofs in two biotope focused planning tools. *Manuscript*.

Contribution to papers:
As first author I contributed with the major part of experimental design, fieldwork, lab work, data analysis and writing of the paper. In paper I, Kaj Rolf was responsible for the experimental design and installation of the test sites. In paper III, Justyna Czemiel Berndtsson performed the sampling and analysis of stormwater data. Lars Bengtsson contributed with ideas and helped performing the rain simulation. In paper IV, Justyna Czemiel Berndtsson contributed with ideas and to the text, Jan Erik Mattson contributed with ideas for the text and the conclusions, Kaj Rolf contributed with ideas for the planning of the experiment and helped performing the greenhouse experiment. In paper V, Jesper Persson and Jan Erik Mattsson contributed with ideas for the analysis and to text.

Introduction

An aerial photograph of a modern Western city would soon reveal that large areas of our urban landscape are covered with unused surfaces in the form of dark-coloured rooftops. These dark hard surfaces are not only under-utilised, but also add to the problems connected to urbanisation, such as the urban heat island effect and increased stormwater runoff. These roof surfaces can be made more valuable and instead perhaps improve the local environment, if converted to carefully designed vegetated areas. This thesis deals with the establishment, development and environmental quality of thin vegetation systems used on roofs.

These thin roof-based vegetation systems are often termed green roofs, ecoroofs or, depending on their design, sometimes even brown roofs. All systems share some common characteristics: Vegetation is grown on top of buildings, the roof areas have a deliberately installed growth medium, consisting of either natural soil or artificial substrate, and are planted or spontaneously colonised by plants from the surroundings. The vegetation is also intended to be installed as a surface cover and not as individual specimen plants in containers or planters. The particular vegetation systems investigated in this thesis have a substrate layer of approximately 3-5 cm.

Figure 1. View of a typical extensive vegetated roofs established with vegetation mats. The roof is located on the Augustenborg Botanical Roofgarden

In this thesis, the term *vegetated roofs* is used, as opposed to the more commonly used term *green roofs* ('gröna tak'). In my opinion, the term *vegetated roofs* is a more precise but at the same time less restrictive description of the system, as it focuses on the fact that the system includes vegetation and that it is installed on buildings. It does not include values about how the system is intended to be designed or used, or its functions. The term *green roofs* relates more to the visual appearance of the system, where the focus on green can result in a perceived need for maintenance in the form of fertilisation and watering. The particular type of roof vegetation discussed in this thesis is in general more red than green, due to the stressful environment on the roof. The prefix 'green' also implies a degree of permanence and a reluctance to allow for vegetation change over time. It also adds a layer of environmental friendliness to the system, something that is scrutinised in this thesis (Anonymous, 2004). It is also possible that a *green roof* can be confused for other green-coloured roofs, such as oxidised copper roofs or painted metal roofs. I also believe that the term *vegetated roofs* is superior to the terms *ecoroofs* or *brown roofs*, even if they can be useful in some respect. The term *ecoroofs* has primarily been used in North America to describe similar types of thin vegetated roofs to those discussed in this thesis (Liptan, 2003). The term directly implies ecological performance, something that is not always the case. However, the term *ecoroofs* is understandable from the urban hydrology perspective where it was developed, as annual stormwater reduction was one of the first recognised beneficial effects of vegetated roofs (Liptan, 2003). The term *brown roofs* was developed as the opposite to the term *green roofs* to describe a vegetation system similar to that normally found on brownfield sites (Gedge, 2003). It is similar to the German term '*Naturdach*' (Paill *et al.*, 2004) and as it is used to describe roofs designed for biodiversity reasons with vegetation systems resembling ruderal or rubble areas, it is not applicable to the systems investigated in this work. An alternative scientific term, *plant-based surface systems* (PBSS), has been proposed by Tapia Silva *et al.* (2006). The term is neutral but is primarily focused on urban hydrology and the climatic effects of the vegetation, making it less relevant to the present thesis. The terms *green roof* and *roof greening* are used occasionally in this thesis, in instances where reference is made to previously defined expressions.

Vegetated roofs have historically been used on buildings in Scandinavia as an important part of the building envelope, aimed at maintaining a comfortable indoor climate by preventing heat from exiting and water from entering the building. Vegetated roofs were quite common in areas where sod was available. The base for the waterproofing of the roofs was several layers of birch bark or straw, which was covered with sods, mainly to keep the bark in place (Andersson, 1998). In one of his journals, Carl Linnæus describes sod-covered roofs planted with house-leek, *Sempervivum tectorum*, as a way to stabilise the soil and states that roofs that were overgrown with such plants could last for centuries (Hallenborg, 1913). The use of house-leek was also connected to beliefs that this plant could protect against evil and lightning (Fries, 1904). The use of traditional vegetated roofs as part of the building envelope started to decline in the middle of the Nineteenth Century, primarily due to the introduction of more convenient roofing materials such as wooden planks, tiles, wood shingles and later, bitumen layers (Werne, 1993).

The modern development of vegetated roofs was spurred by an advancement of building techniques and of concrete as a building material, which made it easier to build more large, flat roofs that could be used for garden-like installations (Dunnett & Kingsbury, 2004). Le Corbusier, who in his manifesto for modern architecture in 1926 declared roof gardens to be an essential part of the future city, was a strong advocate of incorporating vegetation onto buildings (Le Corbusier & Jeanneret, 1926). According to this concept, the roofs of buildings should not be left as unused space but should be turned into a place for relaxation and interaction, for the benefit of the inhabitants. The building envelope was meant to be secured by modern building materials and the roofs could instead take on the role of the private garden. Thus, the purpose of these roofs was quite different from that of the sod and birch bark-sealed roofs on Scandinavian cottages, but so were the cost of installation and maintenance. The use of trees and ornamental perennials required thick soil layers and intensive maintenance, which in combination with their location made them expensive to build. These roofs actually have a lot in common with the antique hanging gardens of Babylon or the ancient villas of Rome, which were designed for recreation and as a display of power and wealth (Osmundson, 1999). Today, one of the most common contemporary types of these thick systems is vegetated roof of underground parking garages. These high-maintenance vegetation systems, with a substrate layer of 15 cm or more, are defined as intensive green roofs by the German Landscape Research, Development & Construction Society, and are designed in a similar way to ground-based vegetation systems (FLL, 2002). A particular type of intensive green roof, 'simple intensive green roofs', has been defined by the same organisation as vegetation systems with 12 cm substrate or more, but requiring less maintenance due to a more nature-like design and use of plants adapted to extreme environments (Köhler, 1993; FLL, 2002).

The use and development of intensive roof gardens was accompanied by the development of thin vegetation systems, so-called extensive green roofs, which are the topic of this thesis. Extensive vegetated roofs have many things in common with intensive vegetated roofs, but differ by definition in respect to substrate thickness and maintenance requirements. An extensive roof is defined as having a substrate thickness between a few centimetres up to 25 cm, having a limited maintenance requirement and vegetation that resembles naturally occurring habitats (FLL, 2002). Dunnett & Kingsbury (2004) describe an additional important difference between intensive and extensive vegetated roofs as being related to the way individual plants or the vegetation is viewed. In an intensive design, the individual plants are managed, organised and cared for just as in a normal garden. In an extensive green roof, the individual plants are not viewed in isolation but more as components of a plant system, as in the case of *e.g.* lawn turf (Dunnett & Kingsbury, 2004). The goal is mainly vegetation cover and the combined appearance of all plants. This view is also apparent in the German guidelines, where the measurement of success is set in relation to plant cover, with the lowest acceptable ground cover following the establishment phase being 60% (FLL, 2002). However, plant cover is not the only measurement of success of extensive roofs, *e.g.* the plants still have to show a typical growth form not achieved by excessive use of fertiliser and water (FLL, 2002).

The most important and driving characteristic in extensive vegetated roofs is substrate thickness, which both imposes restrictions and opens up possibilities in the design of the systems. First, thin substrates are advantageous from a building perspective. The use of thin substrates drastically reduces the weight of the system, which means that extensive vegetated roofs can be applied to existing buildings without expensive reconstruction. The extensive roofs can also be installed on newly built houses without requiring installation of reinforcements. On the other hand, thin substrates are problematic from a design and plant perspective, since they can only hold limited amounts of water and can dry out quickly during summer.

Modern extensive roofs can be linked to the historical roof types used in the Scandinavian countries but even more to the spontaneously established gravel roofs used in Germany during the beginning of the last century (Liesecke, 1993; Liesecke, 1998b). One of the first investigations of a system similar to the modern extensive vegetated roofs was carried out as early as 1959, on 1- to 94-year-old spontaneously vegetated sand and gravel covered roofs, so-called *holzzement* (wood-concrete) roofs (Bornkamm, 1959). The gravel was placed on the roof to protect the tarpaper sealing membrane from degradation by UV-light, wind, rain and fluctuating temperatures. The unwashed clay-sand-gravel mix that was used was rapidly colonised and developed into several different stable vegetation systems ranging from *Poa compressa* communities on thicker sites to *Sedum* spp. and bryophyte-dominated systems on thinner eroded edges (Bornkamm, 1959). As the *holzzement* roofs were a quite common roof type in Germany, more studies of the vegetation development and substrate characters followed (Darius & Drepper, 1984; Bossler & Suszka, 1998). The spontaneously-colonised *holzzement* roofs functioned well from a vegetation perspective and also from a technical perspective, as the tarpaper underlay used as sealing membrane contained toxic substances that efficiently prevented root penetration (Bossler & Suszka, 1998). However, the thick soil layers were heavy and consequently required heavy constructions to be installed. The extensive roofs that were developed subsequently were intended to achieve the same qualities at a lower weight and a lower cost. Development of systems for efficient installation of extensive vegetated roofs started already in the late 1960s (Krupka, 1992). Research into substrate composition and root protection layers intensified and there were numerous publications produced during the following 10-15 years (Liesecke, 1985; Liesecke, 1987; Liesecke, 1989c; Liesecke, 1989b; Roth-Kleyer, 1998; Köhler & Schmidt, 1999; Kolb, 2000). The German organisation for landscaping research (FLL) has been publishing first principles for roof greening and, subsequently guidelines for roof greening since 1984. The latest version of the detailed guidelines was published in 2002 (FLL, 2002). A specialised journal on the greening of roofs (Dach+Grün) was started in 1992. The FLL guidelines are currently the only available reference work that has been developed for components for vegetated roofs and consequently they are used as a standard reference for comparison throughout the present work.

The purpose of vegetated roofs is not only to improve the visual aspects of the actual roofs but also to contribute to a better urban environment. Extensive vegetated roofs were promoted at an early stage as a way to reclaim for vegetation surfaces that had been lost through development, with a focus on improving urban air quality, urban climate and oxygen production (Ernst, 1984). Exploration of vegetated roofs as a way to mitigate problems connected with increased surface sealing began during the early 1980s and this was to become one of the main arguments for their installation and one of the most thoroughly researched area in connection to roof vegetation (Mendel, 1985; Kolb, 1987; Liesecke, 1988; Liesecke, 2002). Some of the federal states in Germany have introduced financial incentives for the use of vegetated roofs, with the primary goal of reducing stormwater runoff (Ministerium für Umwelt und Naturschutz Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen, 2001). Vegetated roofs have their main effect on annual runoff, which for thin roofs is reduced by approximately 50% (Bengtsson, Grahn & Olsson, 2005). The function of a vegetated roof can be likened to a box, which collects water until the water has risen to the edges of the box and starts to flow over the sides (Bengtsson, 2002).

Thus, small rain events are completely absorbed by the system but the runoff during long-term continuous rain follow the mean precipitation over 20-30 minutes (Bengtsson, 2005). As Villarreal, Semadeni-Davies & Bengtsson (2004) and Mentens, Raes & Hermy (in press) point out, vegetated roofs can be a part of the solution to the urban runoff problem as they make use of otherwise unused space, but they cannot be the only solution as the their main effect is connected to annual runoff and not the peak runoff reduction which is the most important factor in the design of a stormwater system.

Vegetated roofs have also received attention for their influence on both the energy balances on an urban scale, *i.e.* the mitigating effect of vegetation on the urban heat island effect (Taha, 1997) but also on the energy balance of individual buildings (Eumorfopoulou & Aravantinos, 1998; Palomo del Barrio, 1998; Niachou *et al.*, 2001; Onmura, Matsumoto & Hokoi, 2001). Vegetation on roofs influences the urban climate positively by increased evaporation and increased surface reflection compared to a conventional black roof (Lazzarin, Castellotti & Busato, 2005). The main effect of a vegetated roof is achieved through evaporation as long as the vegetation system remains wet, but even dry roofs have a positive effect as compared to conventional roofs (Lazzarin, Castellotti & Busato, 2005). The interest for using vegetated roofs to combat increasing urban temperatures has mainly been manifested in countries that have higher temperatures than Sweden (Theodosiou, 2003; Wong *et al.*, 2003).

Another public benefit arising from the use of vegetated roofs is connected to biodiversity. Studies in Switzerland and Germany have shown that extensive vegetated roofs have a large potential for biological diversity and that they can support a rich invertebrate fauna, even including red-listed species, if they are installed with vertical and horizontal structures in the substrate layer and in the vegetation (Mecke & Grimm, 1997; Mann, 1998; Brenneisen, 2003). The diversity of soil-dwelling fauna is dependent on the vertical heterogeneity of the substrates but also on substrate composition and exposure level (Brenneisen, 2003). Patches with increased substrate thickness can increase the biological activity in the substrate compared to thinner substrates due to a more moderate climate (Buttschardt, 2001) but also allow for installation or colonisation of more tall growing vegetation compared to what is possible on thin substrates. A magnificent example of biological plant diversity on a vegetated roof can be found in Switzerland, on the roof of, the Lake water plant in Wollishofen, outside Zürich (Landolt, 2001). The roof vegetation was established in 1941, as a way to keep the building and the water below cool, by lifting local soil from adjacent to the building and seeding it with a local seed mix. The vegetation is managed by cutting the grass once or twice a year and by removing some of the cut biomass. This system has over time developed a remarkable biological diversity and it is now one of the largest sites of *Orchis moris* in the area. The fact that the vegetation on the roof has remained rather undisturbed compared to the soil in the surrounding landscape also means that the vegetation community on the roof can be seen as a remnant of a meadow type that was once quite common in Switzerland but that is currently under threat or completely gone (Landolt, 2001).

Vegetated roofs have also been proposed as having positive effects for building owners in respect to *e.g.* increased life-span of roofing materials (Björk, 2004) and reduction of noise from above (Ouis & Lagerström, 2004) but there are still very few studies available on these topics.

The first large modern-type vegetated roof in Sweden was constructed in 1990 on the SEB headquarters outside Stockholm. The use of vegetated roofs was controversial at this time and the landscape architect involved in the design was only given the permission to green 50% of the roof surface, resulting in stripes of vegetation covering the surface (Pär Söderblom, pers. comm.). The actual vegetation was applied as thin vegetation mats imported from Germany. Production of vegetation mats was started in Sweden a few years later and closely followed the technique developed in Germany. The market for extensive vegetated roofs grew rapidly during the late 1990s and in the beginning of the new millennium. The leading Swedish company for extensive vegetated roofs and other prefabricated vegetation systems had an increase in turnover of more than 600% during the period 1998-2001, mainly due to green roof sales which at the time accounted for two-thirds of the total sales (Anonymous, 2001; Dietl, 2002).

Vegetated roofs achieved their Swedish public breakthrough in connection with the European building exhibition Bo01, which took place in Malmö during 2001. The Bo01 development was promoted as the city of tomorrow and a range of new technologies was tested in the area. The use of thin vegetated roofs was greatly promoted by the use of a planning tool, the Green Space Factor, which was developed after a model previously used in Berlin. Thin vegetated roofs actually became one of the most common roof cover types in the neighbourhood (Jallow & Kruuse af Verchou, 2002). The enthusiasm in Sweden for new types of environmental friendly technologies and for vegetated roofs was high at this time and a botanical roof garden was opened in Malmö shortly after the housing expo, with the aim of researching, displaying and promoting different types of vegetated roofs.

At the time of the Bo01 expo, vegetated roofs were being promoted both for their ecological benefits and for their assumed financial benefits in terms of increased life span of the sealing membrane and reduced indoor temperatures during summer months. As described earlier, the ecological benefits include values such as increased biodiversity and reduced stormwater runoff. However, there were few investigations examining the actual design and how the systems primarily being used would function in the Swedish climate. There were also few investigations of how these new vegetation systems would actually fit into the urban environment.

Objectives

The main aim of this thesis was to increase current knowledge about how establishment factors and maintenance of thin extensive vegetated roofs influence technical performance of the system and how this relates to different aspects of urban environmental quality.

Specific objectives were to:

- Quantify how different establishment techniques, substrates and plant mixes influence the establishment and development of the vegetation on thin substrate layers
- Investigate the effect of extensive vegetative roofs on urban stormwater quality and in particular quantify how it is affected by maintenance and starting fertilisation of different types of extensive vegetated roofs
- Investigate the role of vegetated roofs in planning tools for urban green space.

The thesis is based on the 5 papers appended, which are reviewed and discussed in relation to other relevant literature in the first summarising part of the thesis. The second part comprised the individual papers.

The objectives of the thesis were achieved through: A series of investigations on an experimental roof garden in Malmö (Papers I & II); investigations of runoff water from commercially produced and installed extensive vegetated roofs in Malmö and Lund (Paper III); a laboratory study (Paper IV); and a literature investigation (Paper V). The experiments in Papers I-IV measured technical quality in terms of vegetation cover, biological diversity and stormwater nutrient content, while Paper V was an attempt to put these systems and design variables into context and to investigate how the use of vegetated roofs might influence the urban environment on a larger scale. This was done through an investigation of vegetated roofs as part of tools for planning urban green space.

The main focus of the thesis was to investigate the qualities deriving from vegetated roofs, *i.e.* the amount of nutrients released, the plant cover that can be achieved and the amount of biological diversity that the vegetation system can support. This thesis only touches upon questions related to how the design can be changed in order to be more responsive to public demand or interest in vegetated roofs.

Most people have only seen extensive vegetated roofs from a distance and are not familiar with how they are constructed. Therefore the construction of extensive vegetated roofs is explained before the results from the studies are presented and discussed.

Construction principles of extensive vegetated roofs

Substrates

The primary function of a growth medium is to function as a physical support for the vegetation and to supply the growing plants with sufficient access to nutrients, water and oxygen (Handreck & Black, 2002). Substrate design is also subject to a number of conditions in respect to stability, density, transportability, water conductivity and economy. This means that the final substrate design is a balance between sometimes contradictory functions or interests.

The main problem with installation of roof vegetation is the weight requirements of the building. This is addressed by limiting the amount of substrate required for the installation by using thin layers. The most obvious problem with thin substrate layers from a plant growth perspective is related to the reduced soil volume and consequently the low total water storage capacity. The second problem is related to oxygen deficiency of plant roots, which can arise as a consequence of the suspended water table that is formed above the drainage layer (Handreck & Black, 2002). A substrate with high content of clay or silt would be completely water saturated at the low suctions that can develop in a 3-5 cm substrate and thus, unable to support plant growth (Hillel, 1998). Large pores that are easily drained are need to allow oxygen transport to the roots.

The low total water storage capacity of thin substrates is addressed by using materials with as high a water-holding capacity as is practically and economically possible, *e.g.* scoria, pumice or different types of recycled inorganic materials (Roth-Kleyer, 2001). These materials have both surface and internal pores that increase the effective water-holding capacity of the material and allow a coarser and more easily drained material to be used, while at the same time generally maintaining water storage capacity. In addition to holding water, the surface pores play an important role in reducing the density of the material. Lightweight expanded clay aggregates (LECA) are sometimes referred to as a suitable material for use in substrates for vegetated roofs due to their low weight and high water-holding capacity, but it is not until they are crushed and the internal pores are exposed to the surrounding substrate that a high water-holding capacity is reached (Osmundson, 1999; Roth-Kleyer, 2001).

To achieve high water permeability and oxygen diffusion through the substrate, it is necessary to use coarse material and to limit the amount of fine particles in the substrate mix. German guidelines have used a maximum amount of particles <0.063mm of 15%-weight in layered extensive roofs and 7%-weight in single-layered roof systems (FLL, 2002). An investigation on the development of vegetated roofs over 9 years showed that there is actually a strong positive correlation between the amount of fine particles and the vegetation development within the range 0.5-10% particles <0.063mm (Fischer & Jauch, 2002). Thus, the final amount of fine particles in the mix should probably be as close to the upper limit as possible, especially as clay particles also have an important function for the nutrient exchange capacity of the substrate.

Substrates used in vegetated roofs have to be structurally stable and resist decomposition. Organic materials can only be used to a limited extent and should not constitute more than 8%-weight in layered vegetated roofs in order to avoid settlement of the substrate. Use of limestone in the substrate also ensures a stable pH level over time, which is demonstrated in some of the old spontaneously established holzzemment dächer (Bornkamm, 1959; Darius & Drepper, 1984; Bossler & Suszka, 1998). Substrate mixes entirely based on porous inorganic materials can result in significant acidification of the substrate over time (Fischer & Jauch, 2002).

The final aspect of substrate design is related to nutrient content, which is important both for the development of the vegetation and for the environmental quality of the system, *e.g.* the amount of $CaCl_2$ extractable nitrogen should not be more than 80 mg L^{-1} substrate and the total CAL extractable phosphorous should be below 200 mg L^{-1}. Recycled organic material such as compost or sludge has also been tested as a component for vegetated roof substrates (Kolb, 2001).

Species

The roof environment is an extreme growth habitat with high irradiation, high evaporation rates and some times high winds. Extensive vegetated roofs in Sweden are vegetated with drought-resistant succulent species, mainly from the genera *Sedum* spp., *Phedimus* spp. and *Hylotelephium* spp.. Grasses and drought-resistant herbaceous species are used more commonly in continental Europe as the market is more directed towards roofs with thicker roofs than in Sweden, something that is required for a positive development of herbs and grasses (Liesecke, 1989a; Krupka, 1992). However, use of grass is also restricted in Sweden due to fire regulations (Boverket, 2002). Some of the succulent plants used have been shown to be inducible CAM plants, *e.g. Sedum album*, *S. acre* and *S. rupestre* can switch their metabolism from the more common C_3 pathway to CAM when exposed to drought (Kluge, 1977; Sayed, Earnshaw & Cooper, 1994; Pilon-Smits, t' Hart & Van Brederode, 1996). CAM metabolism enables the plants to store CO_2 during the night and to keep their stomata closed during the day, which is one factor that can increase the water use efficiency of the plants (Gravatt & Martin, 1992). The succulent plants that are used on vegetated roofs are often described as having low nutrient requirements, but there is little systematic information on their actual response.

Establishment

Vegetated roofs can either be established onsite or installed as prefabricated vegetation. The use of vegetation mats for roofs was started more than 20 years ago in Germany but they are still a niche product with most of the vegetation being installed onsite (Krupka, 1987; Schade, 2002). Vegetation mats are composed of a substrate that is filled into or placed on top of some type of carrier material. The carrier material can either be organic material that is intended to be broken down or an inorganic cloth or textile that is intended to last as long as the vegetation system (Schade, 2002). Using organic material as the carrier might influence the available nutrients in the substrate and consequently also the vegetation development (Schade, 2002). There is also a risk that long vegetation mats composed of organic materials will shrink when they become dry (Schade, 2002). The main advantage, as previously discussed, is that by using a vegetation mat, a building contractor or developer can feel secure that the vegetation will fulfil the requirements at the final inspection of the building project (Kolb, 1999).

Onsite establishment is often carried out using shoots, cuttings or plug plants in different sizes. Cuttings of succulent species are well adapted for vegetative reproduction and investigations have shown that detached leaves can even survive more than 120 days and still have a high rate of propagule formation (Gravatt, 2003). Experiments have also shown that seeding can be a viable solution that is explored too seldom. It is the most economical establishment method but it also involves an increased risk in relation to climatic conditions during the establishment phase (Kolb, 1999).

Studies of extensive vegetated roofs in Sweden

Establishment and development

Background

Roof vegetation in Germany is primarily applied onsite, which means that substrate and plant material are brought to the roof separately. The substrate is often pumped onto the roof, levelled and vegetated by distributing cuttings from succulent species and seeds from drought-resistant herbs and grasses. Commercial installation in Sweden has almost exclusively been pursued through the use of thin extensive vegetation mats with a substrate thickness of around 3-5cm and a saturated weight of around 50-55 kg per m^2. The use of vegetation mats means that the vegetation can be installed rapidly. Vegetation mats have also been classified in accordance with Swedish Building Standard AMA, which is used to simplify the use of building materials (Svensk Byggtjänst, 1998). The possibility of specifying vegetated roofs in the same way as any other building material should have a positive effect on the acceptance of the system and its use. However, the cost of installation of vegetated roofs in Sweden is high in comparison with Germany and only a limited part the total roof surface is greened by onsite establishment.

In Germany, the substrates for green roofs have primarily been based on lightweight inorganic materials with high water-holding capacity, such as lava, pumice, or scoria. Recycled materials such as roof tiles, cinder or ash have also been used due to their low price (Roth-Kleyer, 2001). The market for vegetated roofs in Germany has been dominated by installation of roofs with substrate thicknesses around 10 cm. The substrates used in this thesis were chosen with particular focus on having a low environmental load and thus recycled materials was used a basis for the two generic substrates tested (Paper I and II).

There was no systematic investigation of how well different types of succulent species would survive on vegetated roofs in Sweden at the start of this investigation. A standard succulent mix was used but the outcome had never been monitored. It was natural to use the same commercial mix as the point of departure for the investigation of species mixes. A mix for more Northern conditions was also developed to test whether the current practice could be improved by having a mix with higher proportion of *Sedum acre*, a species with a known more northerly distribution (Hultén, 1971). Finally, a broad-leaved mix was used to test the performance of some horticultural succulents (Paper I and II).

Until the present investigation, no tests had been performed on establishment of vegetated roofs in Sweden. There were no previous systematic tests where generic substrate mixes were compared to commercial substrates in combination with both different establishment techniques and species mixes. This research is important in allowing establishment success to be improved and in finding new ways to decrease costs connected with green roof installation, which can be seen as a barrier to their more wide-spread use.

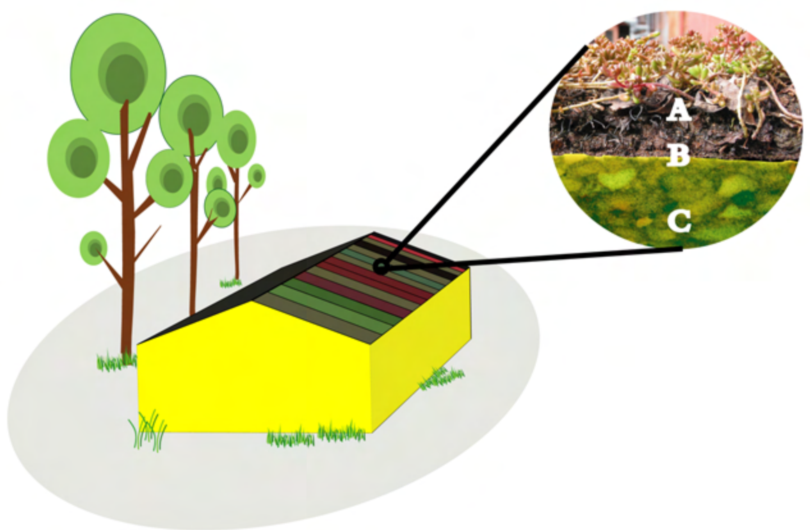

Fig 2. The investigated roofs were located on a roof at the Augustenborg Botanical Roofgarden, in Malmö. A total of 21 treatments were replicated 5 times yielding 105 plots that were randomly distributed over the roof. All roof were 3-layered vegetated roofs including A) a substrate/vegetation layer, B) a filter layer and C) a drainage layer.

Establishment of extensive vegetated roofs (Paper I)

The objectives of this study were to investigate:

- o Two types of onsite establishment compared with installation of vegetation mats
- o Use of different substrates, including recycled material, and their influence on establishment
- o Species mixes and their influence on vegetation cover
- o Spontaneous establishment in relation to plant diversity and maintenance

The study was carried out in Malmö, southern Sweden, in a completely randomised 3-way factorial experiment investigating establishment method, *i.e.* prefabricated vegetation mats, shoots and plug plants; substrate design, *i.e.* two substrates based on recycled roof tiles and a commercial alternative; and species mix, *i.e.* a standard succulent mix, a mix for Northern conditions and a mix with more deciduous species with big leaves. The experiment was carried out on actual vegetated roof surfaces (fig. 2).

We found that the vegetation mats produced a higher succulent cover than the other establishment techniques. The cover following onsite establishment was lower but still acceptable for most treatment combinations. We also found that there was no difference in the cover of succulents between planting a roof with plugs and establishing it using succulent shoots. This means that an establishment with shoots would be the preferred strategy, as it is a cheaper method. The shoot-established sites also allowed establishment of bryophytes to a larger extent than the other establishment methods. Moss is a natural part of extensive vegetated roofs but can be a problem if it becomes the dominant ground cover, due to problems with feed-seeking birds.

Our generic substrates containing recycled material differed from the commercial substrate for a range of variables. The most striking differences were found between the total nitrogen concentrations, which were close to 300% higher in the commercial substrate than in the generic. It was also clear that the commercial substrate produced higher succulent cover than the substrates containing recycled roof tiles. The initial difference between the two generic substrates tested decreased as the organic material decomposed and did not have any effect on plant cover.

It was also clear that the standard mix containing the highest proportion of the ground-covering *S. album* was the most successful in producing a fast high cover. Some of the additional big-leaved species did not have any great influence on cover but might be important for the aesthetics through flowering and foliage during the growing season. Spontaneous establishment occurred but was low on the roof surfaces during the first year. This can have several implications. First, it questions statements about extensive thin roofs having an important function for plant biodiversity. Secondly, the fact that establishment of woody perennials did take place even on these thin roofs highlights the importance of yearly maintenance in order to reduce the risk of root penetration of sealing membranes. Thirdly, many of the spontaneously established species were probably brought from the production site.

Development of vegetated roofs over time (Paper II)

Extensive vegetated roofs have been installed in Sweden during the last 15 years as an aesthetic and ecological cover and they are, as previously described, claimed to have low maintenance requirements once installed. Their development should be guided by natural processes, with limited interference from Man. The system should be easy to maintain and have a low lifetime cost.

Part of the reason for installing the roofs is aesthetics and part ecological, and it is therefore important to investigate how these functions might change over time, *e.g.* how the species cover will change as the surfaces get older and how much spontaneous establishment, *i.e.* biodiversity, will develop over time. The development of the vegetation over time becomes increasingly important for two reasons: (1) the development and visual characters will determine how and when the surfaces are maintained, and (2) several municipalities are using or thinking about testing subsidies or financial tools to encourage the use of vegetated roofs. Thus, it is important to increase our knowledge of what they are subsidising.

This investigation was a continuation on the establishment study and thus included the same factorial design and treatments investigating three substrates, three establishment methods and three species mixes. The surfaces were investigated every spring and autumn until the roofs were 3.5 years old.

The objectives of the study were to investigate:

- How vegetated roofs develop over time
- The influence of establishment, substrate and species mix on development

The advantage of vegetation mats during the establishment gradually diminished over time. There was no significant difference in total succulent cover or biomass for any of the establishment techniques at the end of the experiment.

The most striking result was the increase in moss cover during the course of the experiment, which reached close to 80% cover in some treatments (fig. 3). The development of moss in the onsite established plots was affected by substrate design and the same was true for the succulent cover. The moss cover was reduced on the commercial roof soil and the succulent cover showed an opposite pattern with increasing cover on roof soil. The moss biomass, on the other hand, was not dependent on any of the treatments and reached more than 500g/m^2. The substrates investigated were found to differ in all measurable variables. The roof soil was then found to have a rather high organic content of 8%. The total nitrogen content in the commercial roof soil was almost seven times as high as the total nitrogen in the generic substrate.

The total cover of succulent vegetation was dominated by the ground-covering species *S. album*. *S. acre* was found to decrease in most treatments but it was still present and had increased cover in many of the treatments involving the Northern mix, which was the treatment where *S. acre* was the main component of the mix.

There was a difference in the species that managed to establish in the different sampling seasons. More plots were colonised by spontaneously established plants during the spring.

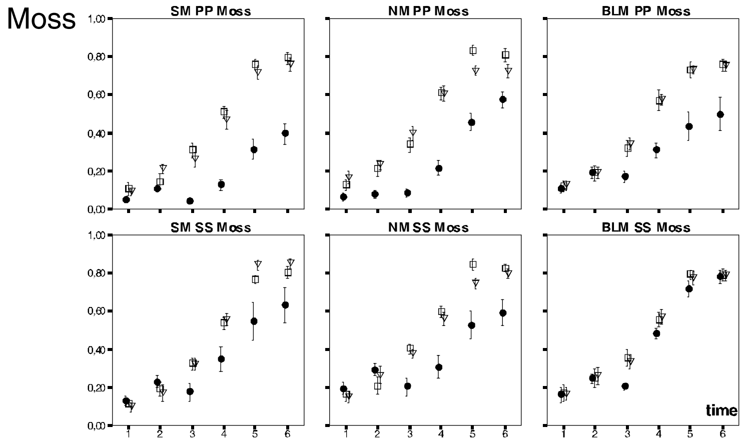

Fig 3. Three-year development of moss cover on plots established on-site. Filled circles = roof soil (RS), open boxes = substrate A (SA) , open triangles = substrate B (SB).

Vegetated roofs and stormwater runoff quality

One of the most important functions of vegetated roofs is their ability to reduce stormwater runoff volume, and to delay and reduce peak flows. Even thin extensive roofs have been shown to reduce the annual runoff by approximately 50% and reduce the peak flow to the average of rain intensity over 20-30 minutes (Bengtsson, 2005; Bengtsson, Grahn & Olsson, 2005). Vegetated roofs have also been linked to positive effects on stormwater quality for both nutrients and heavy metals, mainly depending on the retention capacity of the roofs (Steusloff, 1998; Köhler *et al.*, 2002). If vegetated roofs are to be seen as beneficial to stormwater quality, then the runoff water should be as good as, or better than, the runoff from conventional roofs. In Malmö, vegetated roofs have been used in combination with an open stormwater system with ponds and open canals. Some of the ponds exhibited poor visual water quality due to algae bloom and it was deemed important to investigate whether and how much nutrients were leaving the system.

Impact of installation factors on stormwater quality (Paper III)

The aim of this study was to investigate whether vegetated roofs can be seen as beneficial to stormwater quality. The specific objectives were to investigate:

- o Nutrient runoff from different types of vegetated roofs installed in the Malmö or Lund area
- o Whether vegetated roofs can influence the runoff of heavy metals from urban areas

The investigation was carried out on commercially installed extensive vegetated roofs of different types, ages and locations. The investigation involved an extended sampling campaign during 2001-2003 on vegetated and unvegetated roofs installed at Augustenborg in Malmö; four sampling events on vegetated roofs in the Malmö-

Lund area during the autumn of 2003; and a rain simulation of vegetated roofs at Augustenborg, using tapwater.

We did not find any clear beneficial effect of vegetated roofs on the nutrient or heavy metal loads to the stormwater recipient. Given the 51% reduction in stormwater runoff, the roof functioned as a sink for nitrogen but as a source for potassium and phosphorus. The roofs had almost no influence on cumulative metal runoff.

There are no clear regulations on nutrient concentrations in roof runoff but a comparison to water quality classes used for natural waters in Sweden showed that the concentrations from vegetated roofs corresponded to high or in some instances very high phosphorous concentrations. This might be related to input from bird droppings but more likely to input from fertilisers added as maintenance or during the production stage. New or newly maintained roofs seemed to release the highest concentrations.

Lead, copper and zinc concentrations in runoff water from the vegetated roofs were low, but the design of the total system is important, given the large impact of copper flashing on one roof. The influence of a first flush effect as commonly experienced on hard surface areas has to be investigated more thoroughly in respect to vegetated roofs.

Influence of maintenance fertilisation on stormwater quality (Paper IV)

The investigation of nutrient runoff from constructed vegetated roofs revealed that newly constructed roofs and maintenance in the form of fertilisation might have a disproportionately large impact on the nutrient runoff (Paper III). Substrates for vegetated roofs have primarily been designed in relation to building weight requirements and the success of the desired vegetation. The outcome has been substrates with low density, low organic content, low content of fine particles and high permeability for water and air. The combination of thin vegetation layers and the inherent design of the substrates has to be investigated more closely in respect to stormwater quality.

Extensive vegetated roofs are installed both as a visual and an ecological cover. As described earlier, the systems are intended to have low maintenance requirements but are still fertilised at installation and in the following year. There are examples of extensive vegetated roofs that are fertilised for as many as 9 consecutive years to increase plant cover (Fischer & Jauch, 2002). Fertilisers can also be added for revitalisation of older systems that do not conform to the demands for plant cover or flowering. Vegetated roofs are in Sweden commonly fertilised with a combination of controlled release fertiliser and conventional fertiliser. The controlled release fertiliser is added to reduce the need for repeated applications and to supply nutrients at a rate similar to plant demand. Conventional fertilisers are used for their direct effect on the vegetation and their lower price.

Investigations and guidelines have been developed for the German market for roof vegetation but it is hard to directly translate them to the systems used in Sweden. The vegetation mats that are used in Sweden are of a very thin type never investigated in relation to nutrient runoff. The substrate used in these vegetation mats also differs slightly from the German FLL standards by incorporating natural soil and a larger fine particle fraction.

The objectives of the study described in Paper IV were to:

- o Test the influence of different fertiliser types and levels on nutrient runoff of N, P and K from extensive vegetated roofs
- o Test how a starting fertilisation of a newly constructed vegetated roof relates to a maintenance fertilisation of an older roof
- o Investigate how temporary storage in substrate and plants influences runoff

The study was carried out in a controlled laboratory environment during a 6-week period in which old vegetation mats and newly established vegetated and unvegetated roof systems were fertilised with conventional and controlled release fertilisers and subsequently irrigated with simulated rainfall.

The use of conventional fertilisers clearly increased the nutrient runoff, primarily in the first weeks following fertilisation. The thin roofs, the small amount of substrate and the high permeability meant that the excessive nutrients were rapidly lost from the system. The total cation exchange capacity of the substrates is usually low due to low organic content, low clay content and limited rooting volume (Marx & Kolb, 2002). The main nutrient loss problem was found in the first weeks, but there was also sustained leaching of all the substances investigated except ammonium.

The release pattern of nutrients from the plots differed both for the different substances and for the different treatments (fig 4). The runoff of nitrogen from plots fertilised with conventional fertiliser was probably the result of both over-saturation of exchange sites and transformation between different forms of nitrogen, which was favoured by high ammonium concentrations, high temperatures and the coarse air-filled substrate (Brady & Weil, 1999)

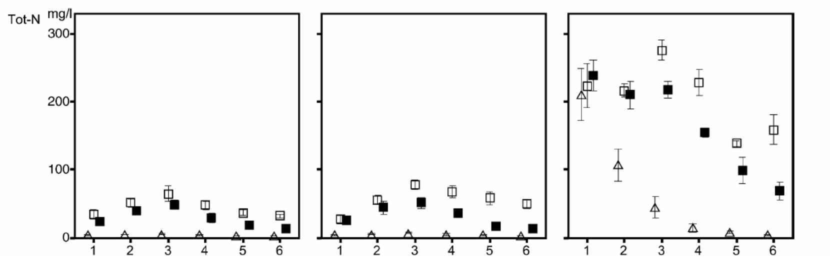

Fig 4. Concentration (mg L^{-1}) of Tot-N in runoff water from three types of experimental vegetated roof plots (vegetation mat, open triangle; shoot-established, black box; unvegetated substrate, open box) fertilised with three different fertilisation levels (from left to right: low, mid, high) during a 6-week simulated fertilisation experiment.

The role and use of vegetated roofs in planning tools for urban greening (Paper V)

Several Swedish municipalities and public companies have started to view vegetated roofs as a vegetation system that can influence the urban environment or their operations in a positive way. The greatest interest has been found among people working with stormwater management, an area where the effect of vegetated roofs has been quantified (Bengtsson, 2005; Bengtsson, Grahn & Olsson, 2005; Mentens, Raes & Hermy, in press).

The issue of stimulating an increased use of vegetated roofs has been approached from different perspectives, *e.g.* Stockholm Water has decided to reduce or remove the annual stormwater fee of 1.55 – 3.20 SEK·m^{-2}·year^{-1} for individuals or organisations that reduce or disconnect themselves from the stormwater system (StockholmVatten, 2004). Other cities such as Malmö have adopted a different approach towards the planning of green space and vegetated roofs and are instead testing a planning tool, the Green Space Factor (GSF) designed as a Swedish version of the Biotope Flächen Faktor that has been used in Berlin since the 1970s (Senatsverwaltung für Stadtentwicklung, 2003). Vegetated roofs are also used to compensate for ecological functions lost during urban development in the German compensation system (Henz, 1998; Köppel *et al.*, 1998)

The study in Paper V investigates how vegetated roofs fit into these planning tools, what values that are assigned to them and how this is related both to the aim of the tool and to empirical data on ecological effect of vegetated roofs.

The objectives of the study were to investigate how:

- Vegetated roofs are valued in the two models and how this relates to the goal of the tool and to available data on environmental function of the systems

The study was performed as a literature study on available data for functions of vegetated roofs, and on descriptions of the used tools. Our investigation was a comparison between the tool, the Green Space Factor (GSF) which was actually used in the well-documented Bo01 expo project, and an alternative German planning tool, the Karlsruhe model (KM) which is based on a compensational approach. The Bo01 expo area in Malmö was used as a framework for the discussion about the two different planning tools.

Our analysis showed that there was a discrepancy between both (1) the explicit goals of the GSF tool and the environmental functions actually needed in the area where it was implemented, and (2) the values assigned to the thin extensive vegetated roofs in respect to available empirical data on the ecological functions of vegetated roofs.

The GSF tool rated stormwater management as a primary goal, a value that we found to be less important given the seaside location of the test neighbourhood. Thin vegetated roofs were also rated as being as valuable as, or more valuable than, thicker intensive vegetated roofs in respect to stormwater management and vegetation community or even stormwater management, biodiversity and human experience, something that is not in line with empirical data. The values of vegetated roofs were found to be dependent on design variables such as vegetation structure and substrate design and not only on substrate thickness.

The high surface value of extensive vegetated roofs assigned in GSF also means that these systems were selected at the expense of thicker roof systems and ground-based vegetation. As extensive vegetated roofs cannot be used for recreation, this changes the function of the green space provided.

The surface values in the other tool investigated (KM) were more closely based on empirical data than those in GSF. On the other hand, KM put a strong emphasis on the natural characteristics of the vegetation and the surfaces. In our opinion this can be problematic, since it is hard to determine what is natural and since there is also no real reason for an all-natural policy in relation to *e.g.* plant selection in an urban area. The KM is based on a compensational approach, where environmental qualities should be maintained even after development. We think that this is a good starting point but also believe that the post-development values should be open to discussion in a democratic process.

Discussion

Establishment and development of vegetated roofs in Sweden

The use of vegetation mats is popular in Sweden as they fit into modern building practices, but the same total succulent cover was achieved within the first 3.5 years with on-site establishment by shoots or plug plants. Vegetation mats were superior in the establishment phase and have an important role in establishing vegetation on exposed sites or in particular projects that has to be rapidly greened. If this is not a requirement, it might be a good idea to use plug plants or cuttings instead. The use of plug plants offered little advantage as compared to cuttings, neither in the establishment phase nor in the long-term. The use of plug plants is a slightly more labour intensive and expensive establishment technique, making the use of succulent cuttings a viable option for vegetated roofs in Sweden. The plug plant establishment in particular was problematic as the plugs contained insects and other animals that attracted birds. Additional effort should be made to produce plants that do not attract birds or that can be secured in the substrate. However, the plants managed to root even when located on top of the substrate.

The initial high cover of ground-covering species that was seen after establishment was found to be unstable, primarily due to inferior performance of *S. acre*. *S. acre* is not commonly used in mixes in German research installations and it has not reached the same high cover as *S. album* or *S. sexangulare* in studies where it has been used (Liesecke, 1998a; Schade, 2002). *S. acre* remained in slightly higher amounts in plots where it was the dominating species in the applied species mix, but even those plots showed decreasing cover (Paper II). The cover of succulents was 3.5 years after installation, despite its downward trend, 55% on the commercial substrate and approximately 30% on the other substrates. The reduction in succulent cover was paralleled by an even stronger increase in moss cover, reaching close to 80% cover in some treatments. The increase in moss was most pronounced on the generic substrate.

The increase in moss and decrease in succulent cover seemed to be accompanied by a reduction in substrate nutrient content, particularly on the generic substrates but the data has to be improved in order to make clear predictions about the relationship between substrate nutrient content and plant performance (Paper I & II).

In Sweden, installation of vegetated roofs follows the German tradition and the only measurements against which establishment success in Sweden has been compared have been German data. This was the first Swedish study of extensive vegetated roofs. Vegetated roofs are in the German tradition supposed to have a nature-like appearance (on plant cover, typical stature of plants, *etc.*) but the vegetation is at the same time often maintained by fertilisation as often as every year (Fischer & Jauch, 2002; FLL, 2002). This supports the unstable nature of the system that was shown in our investigation on unfertilised plots. The investigated vegetation has not yet reached its final stature and it is likely that the cover of succulent species will continue to decrease.

The dynamic nature of the vegetation and the likely reduction in succulent cover and large increase in moss over time should be communicated to purchasers of these systems. Marketing of flowering vegetated roofs with dense cover of succulents can be problematic as it is hard to maintain on these extremely thin systems. The maintenance requirements would be reduced by changing the perception of the vegetated roofs, towards a greater focus on the natural characters of the system and for the beauty of moss cover.

The value of vegetated roofs for biological diversity can be high if properly designed (Brenneisen, 2003), but the very thin uniform extensive systems used in our investigation did not show any greater value for plant biodiversity. This thin extensive vegetation system can make buildings more beautiful and reduce their stormwater runoff, but describing the conventional installed system as beneficial to urban plant biodiversity would be an over exaggeration. There are of course more plants than on a conventional roof but special characteristics have to be incorporated during the design phase in order to create systems with high potential for diversity. The low survival of colonising plants is on the other hand beneficial from a maintenance perspective. The extreme dry environment reduces long-term survival, but as establishment of *e.g.* Field Maple (*Acer campestre*) takes place quite easily it is important to have yearly inspections.

Maintenance fertilisation and stormwater quality

The growth of succulent plants can be improved by fertilisation, but fertilisation can also have detrimental effects on stormwater quality if not performed properly (Paper IV). Revitalising fertilisation of old vegetation mats where the succulent cover has decreased and where bryophytes are the dominant organisms should not cause problems if performed with controlled release fertilisers or if the runoff is treated during the first months following fertilisation. Fertilising with conventional fertilisers gives a greater plant regrowth effect but reduces the quality of the stormwater. The key question is whether revitalising fertilisation is necessary or whether mossy vegetated roofs can be accepted as this is the likely outcome given the results from our experiments (Paper II). The positive effect on heavy metal runoff reported by Köhler *et al.* (2002) and Steusloff (1998) could not be repeated in our study (Paper III).

The installation of vegetated roof is the most problematic phase from a stormwater quality perspective, as starting fertiliser is added and the substrate has a high initial nutrient content. The investigation of nutrient runoff from installed roofs confirmed this notion (Paper III). The main problem was related to phosphorous and potassium runoff and not to nitrogen that was found to be absorbed by some roofs. The problem with phosphorus runoff seems on the other hand to be decreasing as the roofs gets older. However, it has to be investigated on a greater number of roofs to be able to quantify how long time this reduction will take. There is a current lack of rules or guidelines regarding the nutrient runoff from urban surfaces and also regarding the use of nutrient-rich substrates for vegetated roofs in Sweden. The problem with nutrient concentration in the substrates is, however not only related to the stormwater problem but also for plants growth as excessive fertilisation can lead to increased sensitivity to frost and drought, and also to increased establishment of undesirable faster growing species at those times of the year when there is available water (Kolb & Schwarz, 2002)

In Sweden in recent years, there has been increased interest in open stormwater systems and ponds as a measure to solve local flooding. Vegetated roofs are often seen as an integral part of such systems (Villarreal, Semadeni-Davies & Bengtsson, 2004). The nutrient runoff from vegetated roofs has to be controlled if they are to function in combination with open stormwater systems. Our investigations examined both nutrient concentrations in the runoff and the total nutrient load. The nutrient concentrations are important as a basis for modelling of nutrient loads from different watersheds or neighbourhoods. Looking at the effect on a single recipient or water body, it is often more useful to measure total nutrient load. Vegetated roofs are currently not used in a larger extent from a watershed perspective and the total effect from fertilised vegetated roofs should be negligible. However, problems might arise if they are becoming more popular, if they are heavily fertilised and particularly if they are used in combination with open stormwater systems.

The German FLL guidelines are the only structured detailed guidelines that are available for installation and design of vegetated roofs but they also have a rather horticultural approach on use and installation of vegetative roofs. The guidelines can be valuable for the general design of the systems but it is important to remember that they are not universal, as requirements might differ in respect to *e.g.* climates. It is also important to remember that the goals of a vegetated roof installation can differ and that a flowering, densely covered and succulent-dominated roof is not always the desired outcome.

Vegetated roofs as urban greening

Vegetated roofs have the potential to contribute to a better urban environment but several of the benefits of the system are highly dependent on the design of the system. A vegetated roof is simply not just a vegetated roof. As different types of roofs have different values and functions, it is important that this variance is reflected in a planning tool. The use of planning tools might improve the status of urban green space, but must at the same time rely on scientific data regarding prioritised goals of the tool.

There is also a greater need for local adaptation of the tool and that the values that are chosen as the primary functions in the area actually are important and that they are addressed in the ecological surfaces values used in the model. The planning tools should also be open and transparent, which is a problem in the Green Space Factor that uses an aggregated approach to the evaluation of surfaces. The German Karlsruhe model has greater complexity and use surface values that are based on available scientific information about the future of vegetated roofs, but at the same time puts a strong emphasis on the natural characters and the typical functions of the area. Stating what can be seen as the typical function or natural system is not trivial. Defining a desired system or outcome following a democratic process would be a preferred alternative.

Finally, it is possible to transfer some of the values and functions normally connected to ground based vegetation to roofs, but not all. Vegetated roofs make use of unused roof space and they should be more frequently used as a complement to ground based vegetation but not as an absolute substitute. Several aspects of the urban environment would be improved by vegetated roofs and primarily by the installation of a range of different roof vegetation systems.

Reflections on materials and methods and experimental setup

The establishment and development study was originally intended as a repeated full factorial experiment with 27 treatments, but problems with some of the building components for the installation meant that the combination of vegetation mats on generic substrates had to be abandoned. Thus, the establishment with vegetation mats was only used in combination with the commercial RS substrate, yielding an incomplete experimental design. This was handled by dividing the analysis into two parts, the first focusing on the development of plots established onsite and the second focusing on vegetation development on the commercial RS substrate. The lack of vegetation mats in combination with the generic substrates was most apparent in the establishment study, where the question of how much effort has to be put in to a substrate for vegetation mats could not be answered.

The two substrates that were used in the installation were similar to each other in chemical and physical character but at the same time rather different from the commercial substrate. The two substrates were designed to test how recycled materials could be incorporated into substrates but also the role of organic material in establishment and development. Peat was chosen as the organic material but this material was too easily decomposed. A larger difference between the two generic substrates and a more resistant organic material would have given greater insights into the response of the established species to substrate characteristics and not just substrate type.

The vegetation community was not investigated with any multivariate techniques during this study. The use of univariate approaches can be problematic when dealing with a large number of species, as there is a greatly increased risk of type I errors. Reducing the risk of type I errors in the analysis of community data by adjusting the significance levels for the multiple comparison is the options that was chosen in this study.

The investigation of nutrient runoff from installed vegetated roofs was started as a screening project after it was discovered that ponds that were receiving stormwater from vegetated roofs were exhibiting reduced water quality. The project was intended to get some rough numbers of nutrient runoff. The laboratory investigations of nutrient runoff were designed to study the particular effect of different fertilisation regimes regularly used on vegetated roofs. The greenhouse approach was chosen to be sure that we had control of both the water flow through the system and all nutrient inputs. The experiment was designed without any true control of the system, as all plots received some type of fertiliser. This means that the effect of fertilisation can not be completely separated from the effect of leaching from the substrate.

The investigation of the Green Space Factor and its use as planning tool was spurred by the attention directed towards the frequent use of vegetated roofs in the Bo01 area in Malmö. Vegetated roofs were in the area the most common type of roof cover, which was largely due to the use of the GSF planning tool and the high surfaces values attributed to extensive vegetated roofs. The choice of the Bo01 area was also motivated by the good documentation from the area. Investigating a tool that has been developed for an expo can also be problematic as the area is different from what can be described as a normal development. New ideas that will never be used in practice can be tested in an Expo to stimulate thought, to market the involved companies and organisations or to demonstrate new techniques. However, the Green Space Factor is not such an example as it is currently being developed to be used in other areas in Malmö.

Conclusions

- Establishing vegetated roofs by onsite construction is clearly a viable alternative to the use of vegetation mats in Sweden. The advantage in respect to plant cover for vegetation mats diminished after only 3.5 years.
- Extensive vegetated roofs will if they are not fertilised develop into systems dominated by moss.
- Not all vegetated roofs can be described as beneficial for the environment. The value of the vegetation system is dependent on design characteristics such as substrate components but also on maintenance.
- There might be an increased risk of nutrient leaching soon after the installation of vegetated roof but also from the use of conventional fertilisers. Conventional fertilisers should not be used unless the water is recycled or reused.
- Planning tools have to address the real problems of the area where it is applied. The values of individual surfaces in the model should be based on available scientific data. More green areas are generally beneficial for the urban environment, but there is a risk of ground-based accessible vegetated being traded for inaccessible roof systems.

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