Ecological dynamics on old extensive green roofs: vegetation and substrates > twenty years since installation

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A thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

The University of Sheffield
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July 2015

Contents

Summary

Extensive green roof (EGR) technology has become a popular ecological intervention for towns and cities around the world in recent years. Much is known about EGR engineered performance, but little work has studied green roofs as “novel ecosystems” subject to the laws of nature. This research would not have been possible without the collaborative industry-academic partnership in which it was nested, in particular the arrangement of access to a number of old EGRs by the industry partner. Since roof access is typically difficult to attain, this was a unique opportunity to develop methods and gain preliminary insights into what will undoubtedly become an important field of work in the rapidly urbanizing future. With an interest in how the vegetation and substrates of commercial EGR systems develop over time, nine of the oldest EGRs in the world (at least twenty years since installation) were surveyed using methods of applied plant ecology in southwest Germany. The vegetation cover of old EGRs is dominated by succulents, which are tolerant of the environmental stress and disturbance to which these systems are subject. With reference to original lists, species- and functional diversity appear to decline over time in spite of colonization by other species, eventually to comprise assemblages defined by the adaptive strategies of stress tolerance and ruderal life cycles. The growing substrates increased in soil organic content and declined in soil pH, and it is conceivable that associated plant-soil feedbacks support the Sedum dominance observed. Having characterised the environmental conditions of the EGRs using Ellenberg Indicator Values, the vegetation was characterised into different types, which included variations of the “Sedum meadow” as well as “Species-poor Sedum roof”. To predict the processes directing EGR species assembly over time, these vegetation types together with the species’ functional traits were integrated with a hierarchical causal framework of natural succession. To illustrate the quantitative and qualitative aspects of these time-based processes, the twin-filter model was adapted from universal adaptive strategies theory. Given the obvious decline in floristic diversity, this research challenges the assumption that commercial EGRs can support biodiversity over the long term, and proposes some ways by which these technologies can be improved to respond to the pressing issues of urbanisation and global biodiversity decline.

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List of Abbreviations

The following table lists the various abbreviations and acronyms used throughout the thesis, and gives the page number on which each is defined and/ or first used.

Abbreviation	Meaning	Page
TPG	tar-paper gravel roof	2
EGR	extensive green roof	4
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau	10
FBB	Fachvereinigung Bauwerksbegrünung e.V.	12
IGRA	International Green Roof Association	12
UHI	Urban Heat Island	14
ibid	Latin: *ibidem* means "in the same place"	14
MEA	Millennium Ecosystem Assessment	15
ICLEI	Local Governments for Sustainability	17
CSR	adaptive strategies: Competition (C), Stress (S), Ruderality (R)	26
CSD	Competition (C), Stress (S), Disturbance (D)	26
UAST	Universal Adaptive Strategy Theory	26
PGE	Park Grass Experiment	29
LTER	Long-Term Ecological Research	30
AM	arbuscular mycorrhizae	43
VB (A1, A2)	Verkehrsbetrieb (Areas 1 and 2)	57
DIN	Deutsches Institut für Normung	75
ASTM	American Society for Testing and Materials	75
MWC	maximum water capacity	75
C_{org}	soil organic content	87
CAM	Crassulacean Acid Metabolism	90
LECA	Lightweight Expanded Clay	140
EIV	Ellenberg Indicator Value	180
CEC	cation exchange capacity	202

Acknowledgements

This work would not have been possible without the generous support, help and conditions imparted by a network of lovely people.

Many thanks to my supervisor, Dr. Nigel Dunnett, for inviting me onto this project. In addition to learning to write with “boring, dry style”, I’m grateful for the opportunities to teach and to work as a studio tutor on ecological design.

Many thanks to my examiners, James Hitchmough and Martin Hermy, for their committed efforts towards the improvement of this work. Huge thanks to everyone who helped with field work and other nitty gritty bits (e.g., discussions on data), especially Gianni Vesuviano, Claire Cannon, Tobias Emilsson, Elisa Olivares, Dan Richards, and Oliver Pescott.

I’m indebted to Dr. Reinhard Böcker, now Professor Emeritus with the Department of Landscape Ecology and Vegetation Science at the University of Hohenheim. When I appeared “out of the blue” in 2010, independent of any institutional arrangements, he happily helped me identify grass and bryophyte species and even arranged for me to use the facility’s drying ovens to process my biomass data, which involved several weeks’ worth of after-hours access. This recalls the biological term “commensalism”, whereby two organisms interact but only one benefits while the other is unaffected; I benefited massively and am grateful to have experienced such a supportive and friendly academic relationship.

Jean Russell holds a special place to the heart of this work, as her *beautiful mind* was able to make statistical sense of the multivariate and inadequate data. Jean’s ability to remember important trends or relationships months (years!) later, in relation to a new analysis, was astounding, particularly since ecology did not fall within her domain of expertise.

To all the colleagues who have accompanied me on this journey, whether at ZinCo GmbH (especially Ralf Walker, Wolfgang Ansel, Roland Appl, Heike Schäfer, Inge Wüppen), or from the Sheffield Green Roof Team (Nigel Dunnett, Virginia Stovin, Jeff Sorrill, Jörg Werdin, Rosie Mohoroko, Christian Berretta, Zoe Dunsiger, Gianni Vesuviano, Elisa Olivares, Maria Elena Provenzano). Thanks also must go to other colleagues in Landscape for the professional and intellectual stimulation shared, in particular studio tutors (especially Marian Tylecote, Fiona

McQuaid, Tim Blundell-Jones), faculty members (Ross Cameron, Mel Burton, Olaf Schroth, James Hitchmough) and the many students I've been fortunate to interface with.

To the global family of PhD researchers on 9th floor, for their friendly, supportive and enriching accompaniment of this unique journey, especially Jemima Unwin, Vera Hale, Elisa Olivares, Gloria Vargas, Chomchon Fusinpaiboon, Hae-Joon Jung, HyunJu Yang, Ziyad Jameel Frances, Bev Nadin, Maša Šorn, Mike Livingstone, Behdad Alizadeh, Xiang Ren Robert, Adrien L'homme-Duchadeuil, Daiwei Li, Jia Yuan, and so many more.

Beyond the Univeristy, I'm grateful for the professional colleagues who have supported me and this work. Ever encouraging and positive, Gary Grant has been a great colleague and friend; I'm particularly indebted to him for reading drafts of my thesis. Further thanks are owed to other colleagues for fruitful conversations and stimulating discussions, especially Dusty Gedge, Stephan Brenneisen, Nathalie Baumann, Maureen Connelly, Kerly Acosta, Genevieve Noell, Ken Thompson, and the late Mark Simmons (RIP, metta mate).

To family members who have been supportive in so many ways, including my wonderful parents, gorgeous sisters, lovely in-laws and beautiful nieces/ nephews in Canada; my sweet Swiss relatives; and my gentle and loving British kin, especially Giles and Jean Watts.

An mein Bruder, Walter Wild, for his boundless generosity and friendship. In addition to his gifts of a cosy home, inspired excursions in art and botany, cuddly cats and village goodness, this work would literally not have been possible without Walter. The blue Volkswagen Golf ('s *Rägätröpfli*) is an obvious case in point, as was his brotherly care after the surprise incident that put me in hospital for 4 days, 1 L short of blood, and bedridden for 4 weeks.

For the music, for keeping me buoyant and joyful: Sheffield Samba Band, Barba Gianni, Tom Carpenter, Heather Lonie, George Moran, Simon V, Storm, and the Tübingen Pressure crew. For the Dharma and all my Buddhist friends, for keeping me grounded, healthy, and happy.

And to all the friends who have shared food, laughs and tears, during both good and difficult times, including FF foodie enthusiasts: Sara Fischer, Itcha, Simi Stählin, Rachel Littelford, Claire McDade, Michael Haylett, Giles Watts, and many more.

1 Introduction

However urbanised Earth is due to become by 2050, with an ecologically primed roofscape its 6.3 billion urban residents may still have direct access to the natural world and its experiences. Appreciation for biodiversity and green infrastructure instilled in the first decades of the new millennium helped to foster support for regenerative urban design strategies, such as green roofs. An archipelago of verdant rooftops in a hard urban matrix can soften the impacts of the built environment, while also reducing greenhouse gas emissions, supporting pollinators and providing other ecosystem services, like cooler, fresher and cleaner air. In temperate climates, lightweight green roofs provide seasonal displays of colours and texture throughout the seasons, offering intrinsic benefits to human well-being. Having brought together the effectiveness of trans-disciplinary collaborations and industry-policy partnerships for the advancement of intelligent and applicable urban ecological design, green roofs became endowed with greater purpose and with more benefits than ever before.

With its goal of understanding how green roof vegetation and substrates develop over time, this dissertation takes reference from the science of ecology, using the methods and theories of applied vegetation science as well as recent developments in urban ecology. The ecological potential of vegetated roofs to serve as green infrastructure for enhancing ecosystem services is especially timely considering that we have entered a period of unprecedented urbanisation and population growth (UNFPA, 2011) concurrent with the greatest extinction cascade since the dinosaurs (CBD, 2006). Recognising also that we are currently in the UN Decade on Biodiversity (2010-2020) (CBD, 2010a), and that plants and soil form the basis of terrestrial biodiversity (trophic levels and food webs) (Wardle, 2002, De Ruiter et al., 2005), this dissertation examines how vegetation and soil on some of the oldest extensive green roofs have developed after 20-30 years. With all the knowledge acquired from centuries of experience, research and development, what role can lightweight green roofs play for an urbanising and biologically depleting planet? This work therefore identifies and bridges the gaps between past and future, and between ecology and culture.

1.1 What are green roofs?

Growing plants on roofs is a concept common to many cultures and climates, ranging from prehistory to modern times. Just as their range of appearances and constructions varied across time and space, vegetated roofs embody an equally broad scope of intent and purpose. Grass (or sod) roofs have a long lineage from around the world, and were generally used as a response to lacking building materials. Ancient examples of such roofs, often a simple construction of cut turf laid over a bark waterproofing (Grützmacher, 1993) (**Figure 1.1**), can be found in Central Asia, East Africa, and North and Central America (Dunnett and Kingsbury, 2004, Adler, 2005, Grant, 2006). The rich cultures of ancient Egypt and Greece are known to have used "hanging gardens" as personal sanctuaries to honour the gods, while in ancient Rome such roof gardens demonstrated wealth and luxury (Adler, 2005, Arhendt, 2007). By medieval times, the roof gardens of Islam were designed to recall paradise, while those in Aztec America were for urban agriculture and amenity (Adler, 2005, Arhendt, 2007, Grant, 2006).

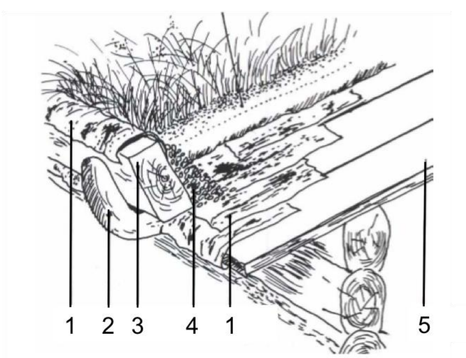


Figure 1.1. Build-up of traditional Scandinavian grass roof where 1=birch bark waterproofing; 2=bracket hook; 3= cullis hook; 4=gravel filter layer; 5=roof deck. Source: Grützmacher (1993).

Another early type of vegetated roof was the "*Holzzementdach*", or tar-paper gravel (TPG) roof in early 19th century Europe, which was favoured for its ability to inhibit the spread of fire (Arhendt, 2007, Köhler and Poll, 2010). By 1880, TPGs were prevalent on public and private homes, and on public, industrial and commercial buildings in many large continental European cities, though they were particularly popular in Germany (Arhendt, 2007). In addition to preventing fire, the upper sandy-gravel layers on TPG roofs helped to maintain the integrity of the roof membrane by shielding it from ultra violet light (Arhendt, 2007, Köhler and Poll, 2010). Various publications detailed the correct installation and construction of TPG roofs (e.g., Koch, 1894) (**Figure 1.2**). The exact substrate composition and depth of the gravel roofs varied somewhat per city, but the German standard apparently called for 50 mm each sand and gravel (Bornkamm, 1961). Standards were sometimes compromised, however; during Berlin's housing boom at the turn of the century, the sand layer was topped by 100-150 mm gravel amended with demolition waste (Darius and Drepper, 1983).

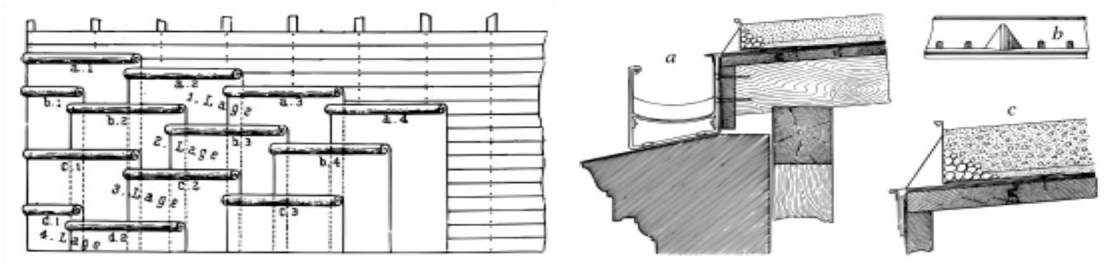


Figure 1.2. One German standard for TPG specified glue-brushing overlapping tarpaper (using "wood cement") onto a wooden roof deck, and layers of sand and gravel. Source: Koch (1894).

The early decades of the 20th century saw much experimentation with roof gardens by architects such as Henri Sauvage (Paris), Frank Lloyd Wright (Chicago) and Walter Gropis (Cologne) (Grant, 2006, Arhendt, 2007). One architect in particular, Le Corbusier (Swiss, 1887-1965) made perhaps the biggest contribution to the development of roof garden construction through his built examples, writings and teachings. Although most architects remained sceptical and conservative, Le Corbusier was generous with soil cover on his roof gardens. Convinced that soil and vegetation were the best protection for the waterproofing from weathering, and valuable insulation from solar gain, Le Corbusier installed almost one meter of earth on his parents' house near Lake Geneva in 1923. He didn't plant a formal garden but allowed colonisation and wild growth, preaching the benefits of a root network that very economically regulates building temperature and of a maintenance-free vegetation (Arhendt, 2007).

As the 20th century progressed, steel and reinforced concrete became more conventional building materials and the potential for integrating vegetation onto roofs moved from experimentation to widespread application. Countries that were less affected by World War II continued building and experimenting with roof gardens atop concrete buildings, with famous examples in England (e.g., Derry & Toms in London, opened 1938) and America (e.g., Rockefeller Centre in New York City, opened 1934) (Osmundson, 1999); Germany joined the movement in the 1960s. All of those early roof gardens created valuable green spaces in densely built-up districts, and also led to research and development to address problems of leaks and damage caused by roots. By 1971, the first purpose-made green roof products appeared on the market, alongside improved waterproofing and drainage systems; by the late 1970s 'extensive green roofs' had emerged (Krupka, 1992, Adler, 2005). Institutes in Germany, starting with polytechnic colleges like Fachhochschule (FH) Osnabrück, and followed by others in Berlin, Weihenstephan, Hannover, Veitshöchheim and Geisenheim, began to establish test facilities for the assessment and development of these new green roof systems (Krupka, 1992). A few decades experimenting with materials and vegetation has resulted in a global, burgeoning green roof industry (Thuring, 2009, GRHC, 2012, GRHC, 2014). This has led to knowledge of basic principles as well as progress in materials, particularly for vegetation technologies (Grant, 2006).

1.1.1 Extensive green roof systems

Extensive green roofs (EGRs) emerged in the 1970s as part of that era's greater Green Movement, which also included materialization of the Green Party, Greenpeace, etc. (Galtung, 1986). In the spirit of the times, vegetated roofs were seen as opportunities to reconnect urban dwellers with nature (Minke and Witter, 1983). Extensive roofs weigh between 60 and 240 kg/m^2, which means they can often be retrofitted in place of gravel ballast (used to prevent wind uplift) without the need for structural adjustments (Weiler and Scholz-Barth, 2009). The minimal loading capacity of EGRs means that these systems are designed for functional, rather than recreational, purposes. Similar to their precursors, modern green roof systems are basically layers on top of a building's waterproof membrane. Extensive green roofs comprise at least two layers – vegetation and growing substrate – but usually multiple layers are used (e.g., protection mat, drainage layer) (**Figure 1.3**). The drainage layer is designed to move excess water towards roof drains in order to minimise water logging and hydrostatic load (Kolb and Schwarz, 1999). Theoretically, drainage layers with storage cups can provide moisture to plants during periods of drought but, unless the cups are filled with granular infill, the substrate is effectively separated from the stored water by an air gap, which prevents capillary action. It appears the only way by which plants can access such moisture is if this stored water transfers to the substrate by evaporation (Vesuviano, 2013). Due to issues associated with poor drainage, single-layer systems should be limited to roofs with a minimum 2% slope (Krupka, 2006). Being intended as low-maintenance, self-sustaining systems, EGRs are typically not irrigated, except during establishment or during periods of extended drought (Dunnett and Kingsbury, 2004).

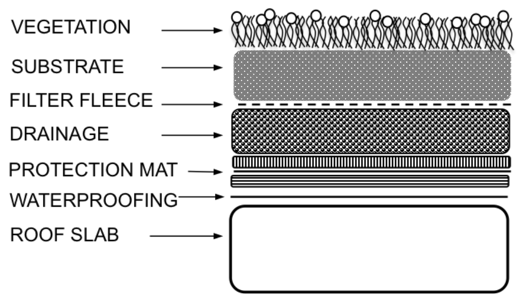


Figure 1.3. EGRs comprise a series of layers on top of the waterproofed roof deck.

Substrate depth is the primary constraint on EGR vegetation because the shallow profile offers limited provisions of rooting volume, moisture and mineral nutrition; water-logging, drought and heat have direct and immediate impacts on the vegetation; and conditions for humus formation, mineralisation and nutrient recycling are altered (Krupka, 1992). As part of the early research and development into these modern, lightweight systems, engineers determined the optimal depth and composition of growing substrates in order to minimize weight whilst maximizing stormwater retention (Li and Babcock, 2014), and horticulturalists have matched these substrates with the most reliable cultivars and varieties for shallow, drought-prone, and exposed environments (Dvorak and Volder, 2010). Given the limitations of substrate depth on plants, different types of vegetation can be confidently specified for certain depths; by definition EGRs have less than 200 mm substrate (FLL, 2008) (**Table 1.1).**

Table 1.1. Suitable vegetation for various EGR substrate depths. Modified from FLL (2008) (p. 43).

	Depth of vegetation support course (cm)							
Vegetation forms	4	6	8	10	12	15	18	20
Moss-Sedum								
Sedum-Moss-Herbaceous								
Sedum-Herbaceous-Grass								
Grass-Herbaceous								

1.1.1.1 EGR vegetation

Since EGRs are meant to be low-maintenance, EGR vegetation must guarantee a persistent, closed and stable cover with few inputs (e.g., moisture, fertilisation) (Kolb et al., 1983). Most EGR plants bear special attributes or adaptive strategies to store water and/ or to prevent water loss, and are able to regenerate after stressful periods (VanWoert et al., 2005b, Nagase and Dunnett, 2010, Schroll et al., 2011, Van Mechelen et al., 2014b). Prevailing climatic conditions will also direct the appropriate selection of plants; in northern latitudes (43 to 60° N), for example, at least 100 mm substrate is required to protect roots from freezing injury (Boivin et al., 2001). In accordance with the shallow depths, appropriate plants have shallow rooting systems able to acquire their requirements of moisture, air, and mineral nutrition within this limited root space. Since roofs are typically exposed without any protection, EGR vegetation must tolerate direct solar radiation, extreme temperature fluctuations, and emissions (Getter and Rowe, 2007, Getter et al., 2009a). Plants from xeric habitats with nutrient-poor soils perform well on extensive green roofs because of their adaptations to tolerate shallow, free-draining mineral soils, intense solar radiation, and regular occurrences of drought. In spite of a slow growth rate, xeric, stress-tolerant plants have a competitive edge on EGRs (Dunnett et al., 2008a).

Almost every plant family has at least a few species that are adapted to colonize extreme and dry habitats, where conditions reflect those found on extensive green roofs. The influence of EGR substrate and depth on vegetation was demonstrated through a large plant screening trial in Heidelberg (Riedmüller, 1994). Compared to the deep profile of a natural soil, shallow EGRs constrain plant root architecture (**Figure 1.4**). That study concluded that EGR depth should never be less than 100 mm if species of dry meadows were to persist. Even then, the author added that provision for shade and water storage was still necessary. In addition to these, that study found that other key factors which determined EGR species composition included substrate properties and seed introduction (both seed bank and seed rain). Substrate depth and EGR vegetation will be reviewed more closely in later chapters.

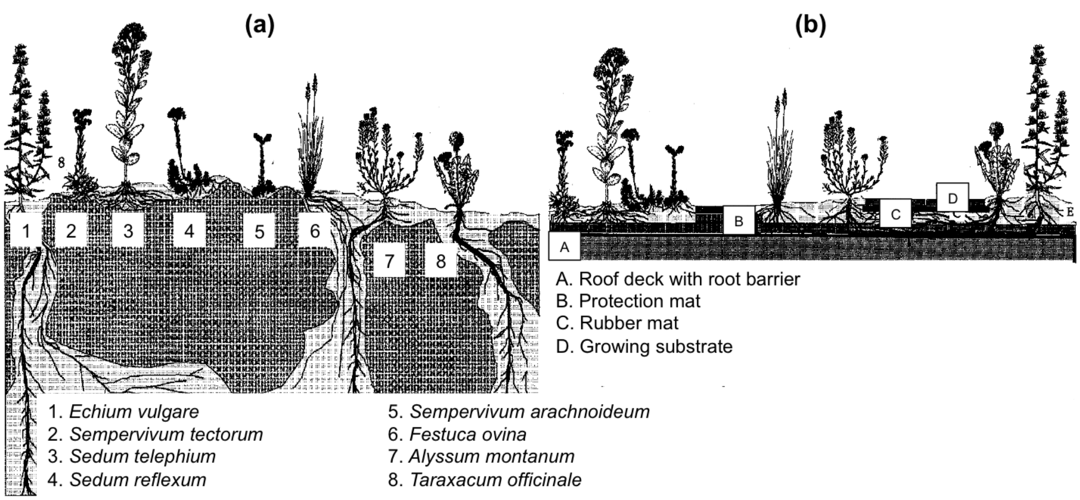


Figure 1.4. Plant habit and root architecture for eight species in **(a)** natural habitat and **(b)** extensive green roof system. Modified from Riedmüller, 1994 (p. 37-38).

1.1.1.1.1 Moss-Sedum vegetation

The Moss-Sedum vegetation type occurs as various forms in depths between 20 and 60 mm, and usually limited to boundaries and extreme habitat conditions (Krupka, 1992). Within this type, mosses comprise 60-95% cover. When the substrate becomes extremely shallow, mesophile mosses are replaced by xerophile species and the proportion of lichens (e.g., *Cladonia spp.*) increases. Sedum proportion varies considerably and depends on roof construction and roof location, occurring more frequently in zones with longer periods of moisture (e.g., near roof gutters), but falling away in zones prone to water-logging and becoming patchy in shaded and wind-sheltered areas. Moss-Sedum can form extensive, closed cover but it also occurs as smaller patches within other vegetation types. Key bryophyte species defining this vegetation form in Germany include *Barbula convoluta, B. hornschuchiana, Brachythecium rutabulum, Bryum spp., Ceratodon purpureus, Homalothecium sericeum, Polytrichum piliferum, Schistidium apocarpum, Cladonia spp.* (Krupka, 1992). As with the other vegetation forms, Moss-Sedum is changeable and will turn into or intersperse with other vegetation forms depending on conditions. Due to the shallow depths, Moss-Sedum vegetation is established by pre-cultivated mats, perhaps supplemented by the sowing of Sedum cuttings, while the moss component will colonise and develop in any bare patches (Krupka, 1992).

1.1.1.1.2 Sedum-Moss-Herbaceous vegetation

As a transition form, Sedum-Moss-Herbaceous vegetation is a common neighbour of the Sedum-Moss type and also occurs within the Sedum-Grass-Herbaceous form. Though it is difficult to define the boundaries between these three types, the Sedum-Moss-Herbaceous form occurs on depths between 60-100 mm (approximately 100 kg/ m^3), and is especially prominent in the early years after successful Sedum establishment, with between 70-95% Sedum cover (Krupka, 1992). In depths closer to 100 mm, grass and herbaceous taxa can dominate over Sedums, especially on flat roofs with damp patches. In addition, since most Sedums require high light and warm conditions, areas with variable light will tend to favour grasses and herbaceous taxa, while exceptionally wet years will benefit mosses. Sedum-Moss-Herbaceous vegetation can be established through the sowing of seed and Sedum cuttings, but also by pre-cultivated mats (Krupka, 1992).

1.1.1.1.3 Sedum-Grass-Herbaceous vegetation

This vegetation form is predominated by patches of Sedum with grasses evident as individual tufts, small groups or spreading swards (e.g., *Poa compressa*). As a rule, the herbaceous component is limited to small-statured, drought-tolerant, short-lived, and often spontaneous colonisers. Although inconspicuous, a distinctive moss layer is generally also present. The Sedum-Grass-Herbaceous form depends on the climatic conditions created by roof slope and aspect, and on substrate depths of 60-100 mm and 100-150 mm. On flat roofs, greater depths promote grasses and herbaceous taxa with Sedums limited to edges and other extreme areas. On exposed pitched roofs, this vegetation form is only possible in depths of 100-150 mm, with Sedums dominating the sun-exposed areas while grasses and herbaceous taxa occur in shade (Krupka, 1992). The small-scale dominance of herbaceous species like *Hieracium pillosella, Thymus spp.* or *Dianthus deltoides* is striking on flat roofs of 100-150 mm, and wet years can lead to a ruderal component of spontaneous colonisers, including legumes (e.g., *Trifolium repens*). Sedum-Grass-Herbaceous vegetation is established primarily through sowing of seed, but also by pre-cultivated mats (Krupka, 1992).

1.1.1.1.4 Grass-Herbaceous vegetation

Grasses form an extensive component of this vegetation form, but generally in patches of varied density since exposed and drought-prone areas create favourable conditions for mosses, herbs and succulents to colonise (Krupka, 1992). With its preponderance of xeromorphic species and relatively drought-tolerant mesomorphs, the Grass-Herbaceous form is comparable with semi-natural dry grassland (Krupka, 1992). On flat roofs with sheltered areas, this vegetation occurs upwards of 100 mm substrate; however, resilient grass-herbaceous assemblages can only persist in depths greater than 150 mm. As water supply improves, the grass component becomes denser, and strongly xeromorphic species like *Poa compressa* are replaced by pronounced swards of *Festuca* species and typical meadow grasses, like *Dactylis glomerata*. The herbaceous component can be distinguished between small, creeping, or rosette-forming taxa and tall-growing species whose flowering heads are visible within or above the grasses. Smaller-statured forbs require open spaces and will occupy extreme areas, like gravel edges, but also serve as regeneration for patches in which taller taxa have died out. Pitched and exposed roofs support a lean Grass-

Herbaceous variant, with grass covering about 50% and the conspicuous patches filled in with succulents and herbs (Krupka, 1992).

1.1.1.2 EGR substrates

Green roof substrates need to be water-absorbent, in order to ensure that soil moisture levels are maintained at adequate levels and to delay and reduce runoff, but they also need to be free-draining in order to minimize water logging and associated structural loading. These characteristics are achieved in shallow substrates and through the use of granular and porous minerals (70-90%) (FLL, 2008). Low organic content is a requirement for fire protection purposes (FLL, 2008) but can also be advantageous for vegetation growing in drought-prone habitats because moderately stressed plants are hardier and stand a better chance of survival when resources become suddenly limited (Rowe et al., 2006, Handreck and Black, 2010, Nagase and Dunnett, 2011). This also reduces maintenance because the vegetation is limited to low growing, hardy, drought-tolerant taxa. Taken together, these conditions pose challenges for plants and other organisms, and are responsible for the attributes that characterize successful green roof taxa, such as small leaf area, specific leaf area and whole leaf dry mass, needle-like or scale-like leaves, (facultative) CAM metabolism, stress-tolerance, dispersal through fragmentation or runners and storage of reserves through succulence (Durhman et al., 2006, Getter et al., 2009a, Lundholm et al., 2010, MacIvor and Lundholm, 2011b, Van Mechelen et al., 2014b).

Typical EGRs don’t use natural soils so terms like ‘substrate’ or ‘growing medium’ are more appropriately used. Due to the unique soil-air-water dynamics on green roofs and their disconnect from a greater soil profile, EGRs can be considered analogous to very large, shallow containers filled with horticultural growing media (Beattie and Berghage, 2004). This being the case, a major distinction lies in the longevity of horticultural media versus EGR substrates; while potting soils need only be stable for a short duration (a few months to 1 or 2 years), EGR substrates will remain on the roof for many years. In this light, good EGR substrates must continuously supply plant roots with balanced proportions of water, air, and nutrients, with little to any maintenance or inputs. Idealistic green roof installations specifying the use of natural soils to enhance or re-create locally distinctive biodiversity must recognise that a soil’s chemical, physical and biological characteristics will change as soon as it is disturbed or removed from a site; unless it is cut as part of a very deep turf, a “local soil” will not have the same properties and characteristics once placed on a roof (Dunnett, 2006).

The disconnect of EGR systems from a greater soil profile has major impacts on the vegetation (Krupka, 1992), including (but not limited to) limited rooting space; constrained nutrient, water and air provisions; large variations in soil moisture; and weaker buffering capacity for pH and temperature (Rumble and Gange, 2013). Soil ecological processes are presumably also influenced by these conditions. Most of the research and development for EGR substrates have been explicitly more interested in long-term stability (Kolb and Schwarz, 1999, Roth-Kleyer, 2002) and engineered drainage performance (Liesecke, 1979, Liesecke, 1995, Kolb et al., 1982). Rightfully so, as the harsh conditions of EGR habitats lead to double-edged requirements: while water retention is one of their most important functions, excess water must concurrently be drained quickly to prevent any ponding or surface water (Henneberg and Mann, 2010). EGR substrates play meaningful roles to stormwater retention, evaporation and biodiversity, but less so to fertility and carbon sequestration (Getter et al., 2009b). The chapter focused on substrates will introduce the physical and chemical aspects of EGR substrates in closer detail.

1.1.1.3 FLL guidelines

In order to ensure reliable and high quality green roofs in Germany, the not-for-profit association FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, or The Landscape Development and Landscaping Research Society), has developed guidelines since the inception of the green roof market there. A body within the Federation of German Industries, the FLL has defined technical guidelines for the planning, construction and maintenance of green roofs since 1982. The first edition, “Principles for roof greening”, has progressed through seven editions named “Guidelines for roof greening” since 1990. The FLL guidelines have served for respected quality specifications and, having published numerous versions, reflect the most current state-of-the-technology and best practices with reference to standards that apply to the green roof disciplines (e.g., DIN, ISO) (Lösken, 2004). Since it is itself not a standard, the FLL guideline contains content and information with few degrees of liability or obligation. For instance, while it refers to research, the guidance does not claim to be scientifically accurate (Lösken, 2004).

Based upon years of research and supported by existing laboratory standards, the FLL has developed precise guidelines and requirements for green roof substrate properties and composition in order to optimise conditions for plant performance and runoff retention (Lösken, 2004). According to the guidelines, “the materials and dimensions chosen for [the substrate layer] are determined by local construction requirements and by objectives for the vegetation” (FLL, 2008, p. 56). Construction requirements relate to the drainage function of the substrate, as well as its design load and protection to the building envelope, while the vegetation-based objectives relate to the demands imposed by the desired greening type, to the longevity of plant-oriented functions, and to limiting maintenance and costs relating to plant development (FLL, 2008). For the substrate, or “vegetation support course,” the FLL provides detailed guidance on granulometric distribution and water storage capacity, but also includes information on frost-resistance, pore volume, structural stability, pH, nutrient and salt content.

As stated by the FLL (2008), “the essential effects of roof-greening are: a reduction of drainage water from precipitation, the retention of rain water to meet the water needs of the roof vegetation and the delay in the runoff water into the drains. These features are of economic, ecological and technical significance” (p. 44). The technical requirements for EGR performance consequently overshadow most aspects of soil science. It is important to recall that these standards were developed in the continental climate of central Europe, and that EGRs in other climates may have different criteria (Williams et al., 2010, Razzaghmanesh et al., 2014, Van Mechelen et al., 2014a, Farrell et al., 2012).

1.1.2 Policies and standards supporting EGR development and implementation

The financial incentives that different municipal and state governments around the world provide for green roofs have helped their widespread implementation. By the 1990s, EGRs had become quite popular in many places in Europe, especially in Germany. By 2006, some 130 km^2 had been installed, at a rate of approximately 13 km^2/ year (Grant, 2006). Germany’s unmatched progress in both continual development and widespread implementation can also be attributed the creation of industry associations, and to supportive policies (often with financial incentives). In 2005, nearly 120 cities offered incentives, with support ranging from 25% to 100% of installation cost (Grant, 2006). Taken together, these various levels of organisation have been key to the development and sustained growth of the German green roof industry and market (Ansel et al., 2011).

Extensive green roofs consistently cover more area per year than intensive green roofs in Germany. According to a member survey from 2011, the FBB (Fachvereinigung Bauwerksbegrünung e.V.) (professional association for the greening of buildings under the Federation of German industries) estimates that between eight and ten million square meters of roof surface are covered by vegetation every year in Germany. In proportion with intensive green roofs, 89% of green roof installations in 2008 were extensive; 83% in 2010 and 87% in 2011 (FBB, 2012). In 1997, the European Federation of Green Roof Associations (EFB) formed in order to unite Europe's green roof associations; the EFB currently has 10 member countries (EFB, 2013).

Green roof coverage in other parts of the world has also been growing dramatically since the late 1990s, particularly the USA and UK (Oberndorfer et al., 2007) but also in tropical and Mediterranean climates (Williams et al., 2010). From its corporate members' survey, the North American industry association, Green Roofs for Healthy Cities, reported an increase by 115% (in m^2 coverage) in the year from 2010 to 2011 (Peck, 2012). The leading North American cities for green roof coverage also have incentives in place, whether in the form of direct incentives (e.g., Portland, 2005; Toronto, 2009) and green improvement programs (e.g., Chicago, 2006; Philadelphia, 2007; Washington DC, 2007; Syracuse, 2010), utility and/ or stormwater fee credits (e.g., Minneapolis, 2005; Milwaukee, 2010), or density bonuses (e.g., Austin, 2011) (GRHC, 2012). In 2007, Green Roofs Australasia was incorporated as a not-for-profit association (Green Roofs Australasia, 2012).

The widespread use of extensive green roofs, starting globally in the 1990s, is owing to their simplicity and versatility. Being shallow and drought-prone not only minimises roof loading but also reduces green roof maintenance since only the hardiest of taxa will survive. Deeper substrates, by contrast, offer more rooting depth and greater stores of moisture to permit more complex vegetation, including grasses, which require maintenance like mowing and biomass removal. Since building owners want as little maintenance as possible (especially when they are required by law to include a green roof), Sedum roofs are the most popular export on the global green roof market [personal communications: January 2013, Ansel (IGRA), Breuning (Green Roof Service LLC), Küsters (Optigrün), Roth-Kleyer (FH Geisenheim), Walker (ZinCo)]. Perhaps related to the minimal input from ecologists or biologists, and most certainly to the commercial success of the industry, the EGR systems most widely implemented today are uniform and homogeneous by design.

1.1.3 The function and benefits of extensive green roofs

Of all the reasons people over the ages have installed vegetation on roofs, green roofs have always evolved to reflect the interests and capacities of every culture, from material availability to contemporary trends, through to policies and social issues. In this light, EGRs are a modern expression of a biophilic tradition whose progress is deeply rooted in human innovation and ingenuity to improve the urban environment, reduce the impacts of the built environment and improve human quality of life. A study of the perception of people overlooking naturalistic versus simple Sedum vegetation on green roofs in Toronto and Chicago reported a great variety of responses, and concluded that vegetated roofs agree with the biophilia hypothesis, namely that humans possess biological inclinations to affiliate with natural systems and that this is instrumental to our health and productivity (Kellert et al., 2008). That study commented that the installation of naturalistic and diverse EGRs, rather than Sedum-dominated systems, present an opportunity to shift human preferences from scenic or tourist aesthetics to ecological inclinations (Loder, 2014). Modern green roofs can clearly offer more than just technological solutions to urban residents.

In addition to the availability of commercially manufactured systems, extensive green roofs have become increasingly popular since the 1990s because of the many benefits they provide. The original driver for modern green roofs in the 1970s was to improve conditions for urban dwellers; psychological and health benefits were promised through more exposure to nature, improvements to air quality and better thermal insulation (Minke and Witter, 1983, Weiler and Scholz-Barth, 2009). Since then, green roofs have been promoted and recognized for their capacity to reduce the volume and delay peak flows of storm water runoff, to mitigate the urban heat island effect, for cooling and insulation, to extend the lifespan of waterproofing, to provide habitat for wildlife, and combinations of all of these benefits (Oberndorfer et al., 2007).

The amount of rainfall retained by green roofs is of particular interest to cities with aging stormwater infrastructure because green roofs can retain and detain runoff. Depth strongly influences stormwater performance, as deeper substrates have greater storage capacity (Mentens et al., 2006, VanWoert et al., 2005a). In spite of their shallow substrates (< 200 mm), EGRs have measured cumulative annual retentions of 70% in northern Germany (Liesecke, 1995, Liesecke, 1998), 60% in North Carolina (Moran et al., 2004) and 50% in northern England (Stovin et al., 2012b). In addition to depth, retention values depend on the intensity and duration of a rain event, local climate, vegetation, and roof slope (Villarreal and Bengtsson, 2005, VanWoert et al., 2005a, DeNardo et al., 2005, Dunnett et al., 2008b, Yio et al., 2013, Getter et al., 2007, Stovin et al., 2012a). Most hydrologic models are based on relatively young green roofs or test facilities; other than one company's proprietary research station (Uhl et al., 2003), the evaluation of green roof hydrological performance over time is largely unknown (Li and Babcock, 2014).

Extensive green roofs are also promoted for improving air quality (Speak et al., 2012). Like any leafy vegetation, green roof plants can trap dust and airborne particles (Dimoudi and Nikolopoulou, 2003), while moderating ambient temperatures to mitigate the urban heat island (UHI) effect (Köhler et al., 2002, Dimoudi and Nikolopoulou, 2003, Wong et al., 2003a, Takebayashi and Moriyama, 2007, Hunter-Block et al., 2012). Vegetated rooftops can reduce the demand for air conditioning by reducing heat entering the building (Wong et al., 2003a, Wong et al., 2003b, Niachou et al., 2001, Connelly et al., 2006, Simmons et al., 2008) and therefore also help to reduce greenhouse gas emissions (Getter and Rowe, 2006, Takebayashi and Moriyama, 2007). Further to thermal insulation, green roofs can mitigate low frequency noise and attenuate sound (Connelly and Hodgson, 2013).

The functions provided by green roofs are bolstered by cost-savings. Building owners may reduce their roofing or replacement costs, since the shade and protection from temperature fluctuations by green roofs can double or triple the roof membrane's life expectancy (Weiler and Scholz-Barth, 2009, Kosareo and Ries, 2007). Municipalities can save costs by installing (relatively inexpensive) green roofs on new developments instead of expanding stormwater infrastructure. Home owners can increase their property values by investing in green roofs (Peck et al., 1999). Green roofs enhance photovoltaic function, and buffer heat flux entering buildings in summer, for which the decreased demand on air conditioning means fewer greenhouse gas emissions (Cantor, 2008). Visual aesthetics of vegetated versus concrete roofs can improve cognitive functioning, such as boosting attention spans (Lee et al., 2015), which aligns with psychophysiological accounts of the beneficial effects of natural views on hospital patients (Ulrich, 1984)).

1.2 Green roofs and urbanisation

At the global level, urban populations grew very rapidly over the 20th century, from 220 million in 1900 to 2.8 billion in 2000, but "the next few decades will see an unprecedented scale of urban growth” especially in the developing world, with almost 5 billion projected for 2030 (UNFPA, 2007). For the first time in history, 2008 marked the year at which more than half the world’s human population (3.3 billion) was living in urban areas (UNFPA, 2011). At the same time, losses in biodiversity due to human activities have occurred more rapidly in the past 50 years than at any time in human history (Millennium Ecosystem Assessment, 2005a). Considering that green roof markets continue to grow in Germany (FBB, 2012) and in other parts of the world [e.g., (Peck, 2012)], and that the original EGR systems developed in the 1970s are currently being re-evaluated (Green Roof Systems Project, 2013), vegetated roofs could serve as important biophilic technologies for this extraordinary point in history in which human population growth and urbanisation are negatively correlated with plummeting biodiversity. By elucidating the capacity of EGRs for ecosystem function over the long-term, this dissertation hopes to clarify the role they may play for the future ahead.

1.2.1 Ecosystem services and biodiversity: current knowledge

Life on this planet would not be possible without functioning natural ecosystems. Potable water and breathable air, fertile soils, the pollination of food crops, the decomposition and processing of wastes and countless other processes are all manifestations of the workings of life on Earth. The concept of ecosystem services was formalised and made popular by the Millennium Ecosystem Assessment (MEA) and helps to explain how humans are supported by, and reliant upon, the natural environment (Grant, 2012). On the first page of this massive report, which took 1360 scientists from 95 countries four years to create, the MEA states simply: “Everyone in the world depends completely on Earth’s ecosystems and the services they provide” (Millennium Ecosystem Assessment, 2005b). Ecosystem services are grouped into four broad categories including 1) *provisioning* (e.g., production of food and water); 2) *regulating*, (e.g., control of climate and disease); 3) *supporting* (e.g., nutrient cycles, crop pollination); and 4) *cultural* (e.g., spiritual and recreational benefits). The MEA emphasises that biodiversity underpins ecosystem services, so the two terms can be considered synonymous (*ibid*).

Plants and soil are the foundation for terrestrial ecosystems (Cilliers and Siebert, 2011), and are important for biodiversity due to their position underscoring trophic foodwebs. Species diversity has functional consequences because the number and kinds of species present determine the organismal traits that influence ecosystem processes (Chapin et al., 2000). Experiments have revealed correlations between species richness and rates of ecosystem processes for low species numbers (Tilman et al., 1996, Hector et al., 1999), but less is known about the impact of species richness in species-rich, natural ecosystems (Chapin et al., 2000) and even less so for urban ecosystems (Pickett et al., 2008). Still, although the mechanisms and circumstances under which species diversity influences ecosystem properties are uncertain, incorporating diversity effects into policy and management is essential in order to reduced restrictions on future management options (Hooper et al., 2005).

The most dramatic changes in ecosystem services will likely come from altered functional compositions of communities and the resulting effects on genetic and taxonomic species diversity (Millennium Ecosystem Assessment, 2005a). The loss of species within the same trophic level of locally abundant species may have greater impacts rather than the loss of already rare species (Diaz et al., 2006). This concern partly explains why attention has shifted to consider the ecosystem services delivered by towns, cities and urban areas (Gomez-Baggethun and Barton, 2013, McDonald et al., 2013). Land conversion for purposes of human settlement is the most direct driver of biodiversity decline (McDonald et al., 2013), since growing populations require more built infrastructure while consuming ever more ecosystem services. With over 60% of this projected urbanisation yet to be built (CBD, 2012), proponents of urban ecology must coordinate ranks if they hope to meet the opportunities embedded in this challenge (Elmqvist et al., 2013, Pickett et al., 2014, Steiner et al., 2013). It's evocative to consider that, by 2050, global population is projected to reach 8.1 - 9.6 billion (Millennium Ecosystem Assessment, 2005a), of which 6.3 billion will be urban, nearly twice the urban dwellers worldwide in 2010 (CBD, 2012).

While green roofs and other forms of green infrastructure may contribute to urban ecosystem services, they may also contribute to "ecosystem disservices" (Honey-Roses et al., 2014), too. Whether they facilitate the spread and increase of allergens, invasive species, pathogens and pests, or obstruct mobility or compromise human security and safety, informing social perceptions and knowledge must complement the collaborative urban planning of green infrastructure (Lyytimaki, 2014). As it is, the concept of ecosystem services is not without criticism [e.g., Bull et al. (2013)] for being too abstract, for compromising knowledge of ecological complexity for the sake of static economic models and, especially, for claiming the ability of quantifying the benefits of functioning ecosystems towards the values implicit to financial currency, as was recently completed for the United Kingdom (UK National Ecosystem Assessment, 2014).

The direct drivers of declining biodiversity are either remaining steady, showing no evidence of decline over time, or are increasing in intensity over time (CBD, 2012). In effect, we are currently witnessing the sixth major extinction event in the history of the Earth; the greatest since the dinosaurs disappeared 65 million years ago (CBD, 2006). It is not surprising that geologists refer to this industrialised era as the Anthropocene (Steffen et al., 2007, Zalasiewicz et al., 2010). We are approaching the threshold limits of freshwater, land use, ocean acidification and interference with global nutrient cycles (Millennium Ecosystem Assessment, 2005b) and may already have transgressed the threshold boundaries of three Earth-system processes: climate change, rate of biodiversity loss, and interference with the nitrogen cycle (Rockstrom et al., 2009). Ultimately, "the choice of biodiversity levels must be determined by society" (p. 16), as the interaction of human health, security, social relations, freedom, and human well-being have direct impacts on biodiversity (Millennium Ecosystem Assessment, 2005a). For context:

In 2008-09, the world's governments rapidly mobilised hundreds of millions of dollars to prevent collapse of a financial system whose flimsy foundations took the markets by surprise. Now we have clear warnings of the potential breaking points towards which we are pushing the ecosystems that have shaped our civilisations. For a fraction of the money summoned up instantly to avoid economic meltdown, we can avoid a much more serious and fundamental breakdown in the Earth's life support systems. (CBD, 2010b) (p. 87)

1.2.2 Green roofs as green infrastructure

Ecological design using green infrastructure and living architecture integrates science and design with culture and nature, following the principles of biomimicry and ecological restoration (Grant, 2012, Orr, 1999, Lundholm and Richardson, 2010). Cities are considered essential to meeting the global environmental challenges described above, and there are many local government and municipal leaders who are engaged in action. Since the 1990s, "Local Governments for Sustainability" (ICLEI) have united cities from around the world to build more sustainable communities through numerous initiatives (ICLEI, 2011). However grim, the increase in natural disasters, extreme weather events, and socio-economic crises have unequivocally softened humanity's sensibility to its vulnerability, and to the profound truth of interconnectedness. A sign of the times, policies have begun emerging which support trans-disciplinary collaborations that demonstrate ecologically informed approaches to designing and managing the environment. Of the four potential development paths for reducing poverty and hunger in fifty years (Millennium Ecosystem Assessment, 2005a), the two scenarios with the most balanced impacts on human well-being and the least biodiversity loss, *Adapting Mosaic* and *TechnoGarden,* refer to green roofs.

Green infrastructure takes green space planning beyond the preservation of a few selected sites and places emphasis on large-scale, forward planning of restored, interconnected landscapes. Multi-functionality is emphasised such that a wide range of ecosystem services is afforded by all sites (Grant, 2012). In the United States, the unparalleled extreme weather events of 2012, coupled with Superstorm Sandy (the largest Atlantic hurricane on record) have led to an unprecedented promotion for the widespread financing and implementation of green infrastructure (Natural Resources Defense Council, 2013). Whether roadside plantings, green roofs, vegetated parks, or porous pavement, the combination of vegetation and soil allows green infrastructure to manage and clean stormwater by capturing rain on or near where it falls and either storing the water or allowing it to naturally filter back into the ground (U.S. Environmental Protection Agency, 2011).

Ecological urbanism is a comprehensive design approach which reflects the complexity of the urban situation through a language which integrates ecological principles into the urban matrix (Mostavi and Doherty, 2010). In terms of landscape, this ecologically informed approach replaces horticulture-based design practices for the benefit of urban remediation. It involves the development of trans-disciplinary collaboration and enhanced professional awareness about the relationship of vegetation, soil and ecology by both design and management. This approach can also help to change public attitudes to more naturalistic planting styles in the public realm, which is culturally beneficial as funding for green and open spaces becomes increasingly constricted, as in the UK (Heritage Lottery Fund, 2014). Cities have traditionally been built to operate in exclusion of ecology, and in ways that promote the widespread ignorance of it (Grant, 2012), so using the ecological approach is a social tool to turn this around.

1.3 Ecology and green roofs

If cities create environmental problems, they also contain the solutions. The potential benefits of urbanisation far outweigh the disadvantages. The challenge is learning how to exploit its possibilities. (UNFPA, 2007)

This research directs ecological interest to the roofscape, so the relevant ecological theories, sub-disciplines and approaches shall be introduced here and may be expanded upon in the chapters that follow. To start with, a brief history of ecology as a science and discipline will be reviewed since it has evolved tremendously over the years. The parts of ecological theory and methods that are relevant to this work were formed during different points in history, sometimes under varying cultural beliefs, so their foundations will be introduced here.

1.3.1 A brief history of ecology

Ecology is the science of relationships of living organisms with each other and with the environment (Greek: *oikos* means "house"; *-ology* means "study of"). In the period from Aristotle until Darwin, humanity's world view beheld the natural world as static and unchanging, made of closed and self-regulating systems that excluded humans (Pickett et al., 1992). Studies of the natural world up until the early 20th century therefore used coarse scales to examine bits and pieces of its material and phenomena (McDonnell, 2011). While the positivist scientific tradition that prevailed at that time allowed classic disciplines like physics, astronomy and chemistry to make great strides, its methods precluded the study of the dynamic and reciprocal relations between organisms, their adaptations, and the environment (Pickett et al., 1994). This explains why the diligent naturalists of the 18th century so avidly collected (and pickled) specimens: their goal was to study individual organisms; little regard was given for the conditions in which those organisms existed.

The assertion that nature maintains an innate balance which includes all influences from the organic and inorganic world (i.e., geologic causes, biota) – with clear exception of "cultured man" (Marsh, 1864) – has been interpreted as a metaphor which ecologists have referred to as the "equilibrium paradigm" (McDonnell, 2011). This classical paradigm emphasises that all ecosystems have stable points of equilibrium, and that ecological systems are closed (Pickett et al., 1992). Consonant with the metaphor of the "balance of nature", the equilibrium paradigm has had widespread repercussions to the development of Western culture and science (Pickett et al., 1994). Beyond tangible outcomes, like the overexploitation of natural resources and the unequal distribution of wealth, the psychological effects of alienation of humans from nature has had subtle but profound consequences, which persist through negative feedbacks (Chiesura, 2004, Turner et al., 2004, Dallimer et al., 2012).

Since the 1970s, a mounting body of scientific evidence has grown to indicate flaws in the classical paradigm (Botkin, 1990, Pickett et al., 1992). The "flux of nature" paradigm expresses a human-inclusive world view and, with reference to empirical evidence, observes that ecological systems are driven by process rather than endpoint (Vitousek and White, 1981), as open systems potentially regulated by external forces (Whittaker and Levin, 1977). In effect, this means that humans are explicitly included as components of ecosystem processes and functions that regulate the structure and function of ecosystems as much as any external force (e.g., fires, floods) (McDonnell, 2011). While the coarse-scale studies from classical ecology have helped to develop methods and establish preliminary ecological theories, the fine-scale emphasis of the contemporary "flux of nature" paradigm has delivered important ideas about natural systems. In the new paradigm, a landscape may be in compositional equilibrium even while individual patches are in a variety of states, distributed through space and time (Pickett et al., 1992). As shall be shown, most of the ecological approaches that are relevant to this work reflect this latter paradigm, though some have only reached this point after considerable transformation from the original conceptual form.

1.3.1.1 Phytosociology: plant community ecology

Early ecologists agreed that plant species tend to occur together in consistent combinations (e.g., forests, grasslands, and heathlands), but the methods for describing them developed somewhat in Europe. While American and British schools of ecology pursued methods of ordination to describe and predict vegetation change over time, European plant ecologists focused on classifying vegetation into communities. Since both approaches are based on their own systems of values, interests, assumptions and concepts, which consequently interlink to inform practices and serve underlying interests, divergent scientific cultures emerged (Whittaker, 1972). As such, the European approach of classification is not widely known or used by the English-speaking schools of ecology (Goodall, 2014). As shall be reviewed later, this approach was used to classify spontaneous rooftop vegetation so it will be introduced here.

In the 1920s, Josias Braun-Blanquet (1884-1980) coined the term "plant sociology" and established methods that are still used today for recognizing and defining plant communities. Owing to his affiliations, this approach became known as the Zürich-Montpellier school of plant sociology. The main construct of phytosociology [the study (-*ology*) of plant (*phyto*-) communities (*socio*-)] is that distinct species assemblages repeat over space and time, and can therefore be identified as communities or associations. This concept, also described by Clements (1916), was developed by numerous plant ecologists over time, in some cases with strongly differing opinions [e.g., Gleason (1939), Tansley (1920, 1935)]. From the basis that vegetation falls into discrete categories ('associations'), of which a certain assemblage of 'characteristic' species are normally present, European botanists set out sampling plots from as many ecosystems as possible, with the goal of classifying all the major plant communities and their constituent species. According to this conceptual framework, the species assemblage of a plant community is determined by specific endogenous and exogenous factors, i.e., dynamics caused by the organisms themselves or by forces directing dynamics from outside the system. From a practical standpoint, this implies that some species will have strong relationships to particular habitats, and also to certain accompanying species. The tighter a species' relationships ('fidelity'), the more characteristic it is to a designated community. Still, though "fidelity is of supreme diagnostic importance", a decisive classification is ultimately the summation of all the floristic, ecologic, syngenetic, and synchorologic characteristics, as well as spatial factors and precise geographic location (Braun-Blanquet, 1932) (p. 365).

1.3.2 Natural succession and vegetation dynamics

To the discipline of ecology, the theoretical model of natural succession occupies the same role as evolution does for biology (Anderson, 1986, Margalef, 1968, Dawkins, 2004). Natural succession has commanded much of the attention of plant ecologists since the inception of the discipline in the late 19th century, with the aim of describing or predicting patterns of vegetation change through time (Pickett et al., 1987, Luken, 1990) All plant assemblages change their species composition and structure over time, and natural succession is a very complex conceptual model due to the temporal and spatial scales over which it occurs (not to mention the logistical difficulties of studying natural communities across these scales) (Barbour et al., 1999). Unsurprisingly, the mechanisms and processes driving successional change have been disputed since the theory first emerged. **Figure 1.5** presents a summary of seven major interpretations, of which all bear merit to our understanding of natural succession.

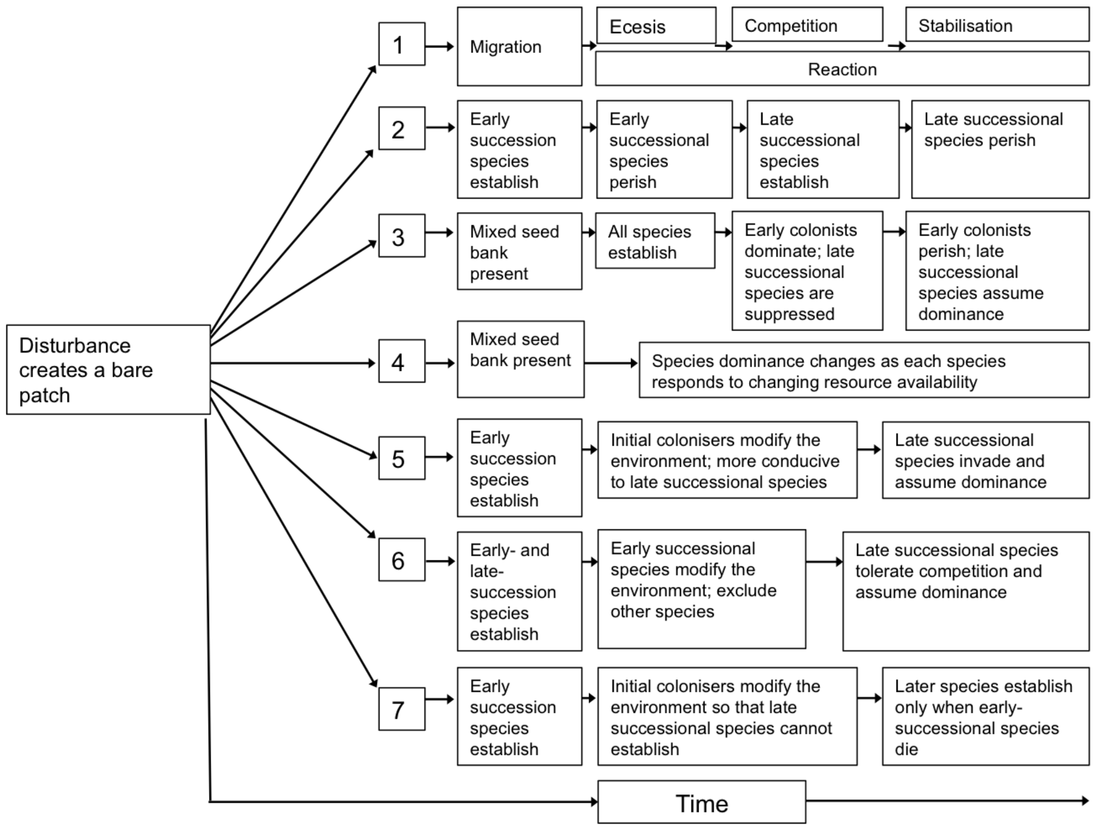


Figure 1.5. Various interpretations of succession. 1. Clementsian view. 2. Relay floristics. 3. Initial floristics. 4. Changing resource availability. 5. Facilitation. 6. Tolerance. 7. Inhibition. Modified from Luken (1990).

Though the need for simplicity is at least partly to blame, the straight arrows in the figure above imply that change over time is directional, with an end point where change ceases. This was the first and biggest point of contention when ecologists first began the quest for understanding the vegetation dynamics of abandoned arable fields. The first and strongest explanation (**Box 1 in Figure 1.5**) suggested that natural succession occurs in five basic steps after a site has been denuded, eventually reaching a stable "climax community" endpoint (Clements, 1916). Doubts to the predictability and certainty of this model were raised from the onset, with contrary suggestions that plant succession is directed by chaos, individualism, competition and a blur of continuous change and complexity (Gleason, 1939). The theory was continually developed further as alternative perspectives arose, like consideration for and emphasis on pattern and process (Watt, 1947) or the pattern climax concept that emerged from new methods of gradient analysis (Whittaker, 1967).

The concept of “plagioclimax” was another early refinement to succession theory that may be useful for describing EGR vegetation development. Although still assuming directional change, this model implies deflected succession, as derived from the Greek *plagios* which means slanting or sideways (**Figure 1.6**). Observations of chalk grassland led British ecologists to suggest that this species-rich vegetation was maintained, even produced, by grazing and would not persist without this continuous disturbance (Hope-Simpson, 1940, Tansley, 1965). Plagioclimax communities, like chalk grassland, are floristically stable, but only when provided with appropriate grazing regimes that “deflect” the vegetation from changing into species-poor, coarse grassland dominated by competitive grasses (Bakker et al., 1984, Gibson and Brown, 1992, van der Maarel, 1971, Bardgett et al., 1996). The deflecting disturbances associated with plagioclimax communities can also be the product of local environment and soil conditions (e.g., extremely shallow soil which prevents higher plants from establishing) (Tansley, 1958). Certainly, shallow soils inhibit competitive species with deep root architecture (Graham and Hutchings, 1988). If the vegetation of such conditions attains a stable or steady state, then it may qualify as an *edaphic* (soil-caused) plagioclimax.

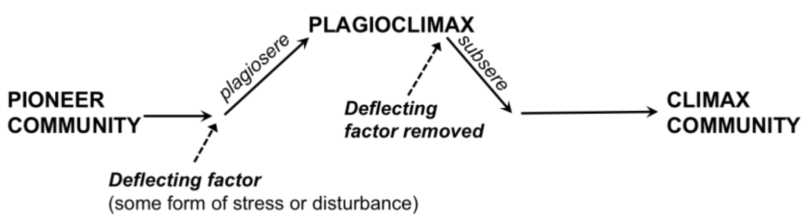


Figure 1.6. When natural succession is deflected by continuous disturbance, such as grazing, the vegetation develops into and is maintained as a plagioclimax community. Modified from Tansley (1965).

As a conceptual construct, the continual improvements to this model over the course of the 20th century reflect as much the methods used as well as the worldview and the vernacular culture of its proponents. As methods improved for monitoring and analysis, and more empirical evidence accumulated, ecologists began to accept a more dynamic “flux of nature” model (to the demise of the Aristotelian “balance of nature” myth). Important developments to community ecology and population dynamics have described succession through contributions from Pickett (1976), Connell and Slatyer (1977), Grime (1977), Tilman (1985), Huston and Smith (1987) and others.

1.3.2.1 Emergence in biotic communities

Concurrent with the earliest studies of succession, the concept of emergence arose from the same philosophical foundations upon which science and ecology are based. The term was coined during the age of positivist philosophy by G.H. Lewes (1891), who defined an emergent as "unlike its components insofar as these are incommensurable, and it cannot be reduced to their sum or their difference" (p. 412). A phenomenon is therefore emergent if it cannot be predicted by means of the accepted theories of the time and on the basis of the data available before its occurrence (Henle, 1942). From the perspective of ecology, biotic communities may exhibit emergent properties when the sum of their components (including interactions and patterns) are greater than their individual parts to that system, or when the collective exhibits more complex behavior than the individuals together can exert (Edson et al., 1981). The emergent property itself may be very predictable, such as secondary succession on old fields, or they may be entirely unpredictable and unprecedented, such as the assemblage of novel ecosystems in urban environments.

Though the debate over an organismal versus individualistic sort of natural succession eventually receded from centre stage, the notion of emergent community characteristics remained tacitly accepted (if not always philosophically endorsed) by community ecologists (Anderson and Kikkawa, 1986). In that context, any reference to perturbation or disturbance is seen to imply the operation of a selective force on that system, and it is the system, rather than its component individuals, which is expected to respond (Anderson and Kikkawa, 1986). The notion of emergence to ecology has not been without scorn (Salt, 1979, Edson et al., 1981); not only is it difficult (impossible?) to define, but any observation of phenomena is inescapably confined to the scope of knowledge at a given time, so suggestions of emergent characteristics are relative, not absolute, and their status may change when more knowledge is available (Hempel and Oppenheim, 1948). In addition, any ecologist aware of inter-connectivity will attest that interactions between components of a system will increase exponentially with the number of components, meaning that new and subtle types of behaviour may emerge (Edson et al., 1981). Lastly, large numbers of interactions can work against the emergence of interesting behaviour as they may generate too much noise to perceive an emerging signal (Beckner, 1968). Thus organization of components also plays a role in emergence, or of our ability to perceive it. Edson et al. (1981) argue that seeking emergent status of different ecological phenomena simply diverts time, attention and resources away from the real focus of ecological inquiry, namely the empirical study of ecological relationships. The main opposition to the concept of emergence was due to how it was being used rather than its merit, as some ecologists used it as an excuse to describe certain phenomena as mysterious and absolutely unexplainable rather than using conventional ecological measurements for explanation and prediction (Hempel and Oppenheim, 1948, Edson et al., 1981).

1.3.2.2 Succession according to plant functional traits and adaptive strategies

A major development in succession theory argued that most of the perceived phenomena of successional sequences could be ascribed to differences in species' ability to colonize, grow and survive in environments with different suites of resource combinations (Drury and Nisbet, 1973). This opinion that a comprehensive theory of succession should be sought at the level of the organism, and not in emergent properties of communities, led to studies of the ecophysiological attributes of species characterising different successional stages [e.g., Bazzaz (1979), Bazzaz and Pickett (1980)]. Some ecologists referred to the influence of species' life history strategies on the structure and composition of vegetation and successional processes. The popular concept of *r/K* continuum (MacArthur and Wilson, 1967) encapsulated many of the conditions necessary for evolution and diversity, whereby conditions of high mortality risk favoured short-lived organisms capable of early reproduction (*r*-selection) while conditions of low mortality selected for organisms with delayed reproduction, larger stature, longer lifespans, and the capacity to monopolize resource capture (*K*-selection) (Pianka, 1970). Still, some ecologists felt an important dimension was missing, namely the location within the model for tolerance (Grime, 1977, Southwood, 1977, Pugh, 1980, Greenslade, 1983) or for particular forms of competition for resources (Tilman, 1982, Tilman, 1988) and space (Bolker and Pacala, 1999).

These lacking aspects of *r*- and *K*- selection theory were resolved by empirical studies which revealed that there were three, rather than two, selective strategies and that these exist in nature as distinct, coherent phenomena (Taylor et al., 1990). Specifically, high and low levels of stress and disturbance were seen to have led to the evolution of three distinct types of strategies, which can be described by four permutations (**Table 2**). Competitive plants thrive in conditions of low stress and low disturbance; stress-tolerant plants thrive in conditions of high stress and low disturbance; and ruderal plants thrive in conditions of low stress and high disturbance. Few species are found in habitats subject to high intensities of disturbance and stress. Secondary and tertiary strategies result as adaptations to intermediate intensities of competition, stress and disturbance (Grime et al., 2007, Pierce et al., 2013, Hodgson et al., 1999).

Table 1.2. Suggested basis for the evolution of three strategies in vascular plants. Grime (1977)

	Intensity of stress	
Intensity of disturbance	Low	High
Low	Competitive strategy	Stress-tolerant strategy
High	Ruderal strategy	No viable strategy

The triangular CSR model is defined by a continuum where three life strategies – competition or growth (C), stress-tolerance or maintenance (S), and ruderality or regeneration (R) – emerge as a result of two environmental selection pressures, stress and disturbance (**Figure** 1.**7**). Since neighbouring organisms also exert pressure, three selection forces of a habitat – competition (C), stress (S) and disturbance (D) – may be considered a three-way equilibrium (Grime and Pierce, 2012). Just as CSR theory remains unfalsified, empirical studies continue to validate CSD equilibrium theory through collaborative research groups working from different countries (Diaz et al., 2004, Wright et al., 2004, Cerabolini et al., 2010, Freschet et al., 2012). In fact, the increasing validation that this three-way trade-off occurs throughout the tree of life (i.e., in addition to plants), CSR theory has recently been extended into **universal adaptive strategy theory** (UAST) (Grime and Pierce, 2012). With respect to natural succession, the CSD equilibrium is a mechanism that explains how and why adaptive different strategies may persist or get filtered out of habitats. Based on observations that all organisms have a limited potentiality with regard to their evolutionary response to CSD, the equilibrium is defined by trade-offs that dictate the assumption of predictable sets of core adaptive traits (Grime and Pierce, 2012). UAST will be reviewed more closely in Chapter 7.

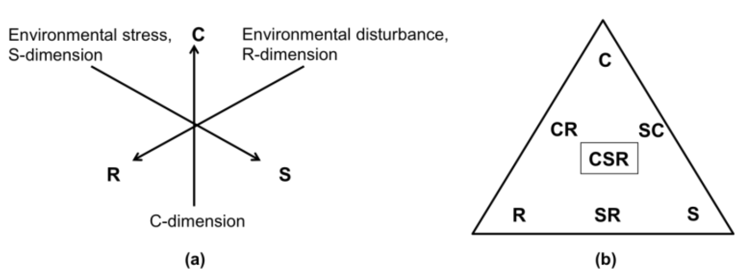


Figure 1.7. CSR space: **a)** the relations between the two environmental dimensions (stress and disturbance) and the three plant dimensions (C, S and R); **b)** the locations of three primary (C,S,R) and four secondary (CR, SC, CSR, SR) plant functional types within the entirety of CSR space. A further twelve tertiary intermediates exist between these seven. Modified from Hunt et al. (2004).

The predictive power offered by the CSR model to the study of succession (and to the practice of succession management) is illustrated in **Figure 1.8**, where trajectories and their locations within CSR space identify the sequence of dominant plant strategies likely to characterise secondary succession in varying conditions of potential productivity (Grime, 2001). Since secondary succession begins on disturbed ground, successional trajectories begin in the R-corner and proceed towards the S-corner with differing proximity to the apex of the triangle where C-strategists dominate. The circles superimposed on the curves represent the relative size of plant biomass at three stages of succession. Since conditions of fixed potential productivity as shown by S_1-S_3 (**Figure 1.8a**) are unlikely to occur in nature, the curves in **Figure 1.8b** show hypothetical pathways of succession under conditions of increasing (S_4) and decreasing (S_5) potential productivity.

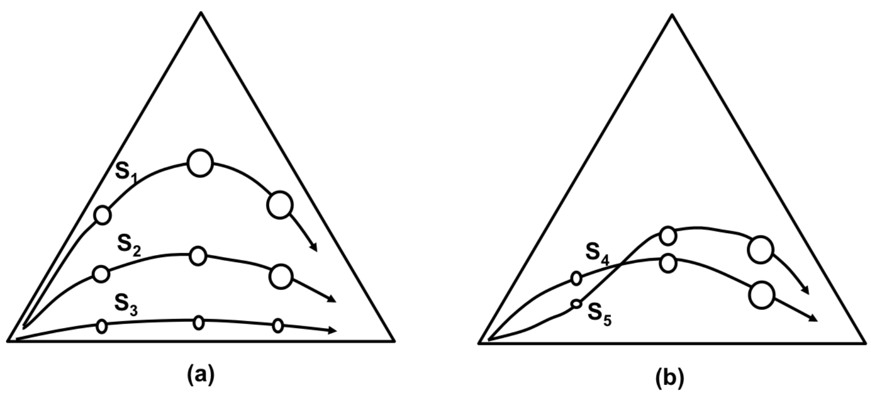


Figure 1.8. The CSR model of plant strategies can be used to illustrate pathways of natural succession under various degrees of disturbance and productivity: **(a)** succession under conditions of high (S_1); moderate (S_2), and low (S_3) potential productivity; **(b)** under conditions of increasing (S_4) and decreasing (S_5) potential productivity. Modified from Grime (2001).

In **Figure 1.8a,** the upper arc (S_1), representing exceptionally productive habitats, extends into the central CSR zone and then descends steeply into the S-corner. This succession can be characterised by a mid-point of intensive competition by competitive herbs followed by woody vegetation, and leading to a terminal phase where stress-tolerance becomes increasingly important because mineral nutrients become locked up in the biomass dominated by large, long-lived trees. When succession occurs in less productive habitats (S_2), the appearance of highly competitive species is prevented by the earlier onset of resource depletion and the stress-tolerant phase is associated with dominance by smaller slow-growing trees and shrubs in various vegetation types. Finally, the lower arc (S_3) represents unproductive habitats, where plant biomass remains low over the course of succession, and the vegetation shifts from ruderal directly to stress-tolerance. The CSR model “is perhaps the nearest approach to a coherent predictive theory of succession” (Burrows, 1990) (p. 273) with potential to reveal great insights into its driving mechanisms (Bazzaz, 1996).

1.3.2.3 LTER for understanding succession

Temporal study is clearly essential to understanding succession and ecological change, but this is not easily accomplished. Short-term research can be misleading as it can offer neither “definitive bases for addressing societal concerns related to environmental biology nor … the substantial advancement of a science that deals with processes occurring over long periods of time” (Callahan, 1984)(p. 363). With respect to natural succession, Luken (1990) states three methods for accumulating a database for a particular area or plant community: (1) published research, (2) cooperative research agreements, and (3) on-site research. Historical records are usually inadequate (Callahan, 1984), if only because the time scales of many ecological phenomena occur over the course of generations, which results in discontinuous records as methods and practitioners change over time (Bakker et al., 1996, Dunnett et al., 1998). This affects the quality of baseline data, limiting its extent to recent work and current observations, which plainly inhibits long-term perspective. The development of a unified theoretical base for ecology has been severely impeded by the lack of comprehensive and comparable information across a diversity of ecosystems (Callahan, 1984). Many ecologists would also agree that “the traditional patterns and rules for the planning of research and competing for funding have often been counterproductive to a science that deals with many phenomena occurring over decades or centuries” (Callahan, 1984) (p. 367).

Long-term observations of ecological phenomena and biodiversity, and the consistent and reliable accumulation of long-term synoptic datasets, are crucial to understanding how natural systems work (Callahan, 1984, Likens, 1989, Franklin et al., 1990), including questions like ‘why’ (causes) and ‘how’ (mechanisms) (Bakker et al., 1996). Chronosequences (or 'space-for-time substitutes') which may result from such studies are useful for qualitative purposes and for hypothesis generation. Site history is of plain importance, but the implicit assumption that sites of different ages will have similar environments (i.e. same soil conditions, microclimate, and availability of propagules) is rarely met (Glenn-Lewin and van der Maarel, 1992). So, while they can provide invaluable perspective into plant community dynamics, unless the assumptions are met chronosequences are unreliable for gaining deeper insights into successional change (Pickett et al., 1987). Another reason that long-term ecological research is rare is due to the nature of scientific funding, which is never intended for decades, let alone centuries (Franklin et al., 1990). Although concern about the ecological effects of projected climate change underscores the importance of understanding of how plant communities change (Silvertown et al., 1994) – and how stable they are over 50 to 100 years (Pimm, 1991) – few research projects last longer than 10 years (Delcourt and Delcourt, 1988).

Despite the limitations, there are a number of examples of long-term research in grassland or heathland ecology. The Russian plant ecologist L.G. Ramenskii (1938) pioneered the use of permanent quadrats for describing meadow, fen and steppe vegetation over time, and implemented an early understanding of the necessity of objective methods for studying the complex relationship between vegetation and habitat. Ramenskii instigated the process of recognising the fundamental and inescapable constraints that are integral to the core functioning of plant communities (Grime et al., 2007). The use of permanent plots and long-term surveys can enhance our knowledge of the mechanisms of succession (Bakker et al., 1996). As one example, annual surveys (starting in 1958) of mesotrophic grassland along wide roadside verges in southern England granted perspectives into how species abundance can fluctuate within a single year, even within what may be thought of as relatively stable, non-successional vegetation (Hunt et al., 2004, Morecroft et al., 2004). The comparison of annual vegetation records with a time series of basic meteorological data (individual weather variables) and higher-level weather data (synoptic patterns) permitted that study to illustrate correlations between stress tolerant species with warm dry springs and summers, and between more productive species with wet growing seasons (Dunnett et al., 1998, Dunnett and Willis, 2000).

Perhaps the longest grassland monitoring program is the Park Grass Experiment (PGE) at Rothamsted (England), begun in 1856 with only a few time gaps (Bakker et al., 1996). The PGE features a series of contiguous meadow grassland communities within the same microclimate and soil type, divided into soil treatments (fertilizer, liming) in order to quantify the effects on species richness, floristic composition, annual net primary production, community stability, and more (Johnston, 1991, Silvertown et al., 1994, Dodd et al., 1995). A similar experiment was set up in northern England in 1993 (The Buxton Climate Change Impacts Lab) in order to determine how projected climate conditions in 2100 would affect species-rich calcareous grasslands (Grime et al., 2013). Six treatments (warming, summer drought, supplementary rain) are delivered through microcosm techniques and field manipulations in order to study the effects on dominant plant species on the trophic structure of herbaceous vegetation. 2013 marked twenty years of continuous climate manipulation in the main experiment at Buxton, and collaborative experiments have since extended to other Universities in Britain, Italy, Switzerland and the United States. These manipulations have revealed insights into how plant communities and agrarian systems may respond to climate change, e.g., dispersal (rather than biotic resistance) as main obstruction to species' northward migrations (Moser et al., 2011), and the importance of fine-scale soil heterogeneity as a buffer for community response (Fridley et al., 2011).

On a grand scale, the American National Science Foundation (NSF) initiated a Long-Term Ecological Research (LTER) program in 1980 which established 26 sites as "sample ecosystems" across the U.S. with several thousand associated scientists (Robertson et al., 2012). Comparability of data across LTER sites was of key importance (Callahan, 1984) and, after 40 years, they have indeed addressed some fundamental questions, many of which cannot be addressed by short-term funding cycles (e.g., How do populations change in response to long-term environmental changes, such as landscape and climate change? How do these changes affect biodiversity and trophic interactions and, in turn, primary productivity, element cycles, and other ecosystem processes? What are the lags in ecosystem responses to and the legacies of past human and natural disturbances? What precipitates ecological tipping points, and are such changes predictable?) (Robertson et al., 2012). In the 1990s, two urban metropolises were added to the LTER network: Phoenix (AZ) and Baltimore (MD) (Grimm et al., 2000). In Europe, a similar program has been assembled under the heading "Long-Term Socio-Ecological Research" (LTSER) (Mauz et al., 2012).

1.3.3 Urban ecology

Today's built environment is a perfect manifestation of the "equilibrium paradigm" that has dominated human thought for so long, of the worldview that humanity is separate from nature. For much of human history, buildings were integrated with the natural environment, whereby builders, artisans, and designers used local materials and adopted themes and patterns from nature in order to create beautiful, enduring and functional structures which connected culture and heritage with the natural world (Kellert et al., 2008). Modern accomplishments in architecture and engineering, however, have helped to foster the belief that humanity can transcend the dictates of natural systems. David Orr (1999) lamented that this dangerous illusion has led to an architectural practice which encourages overexploitation, environmental degradation, and separation of people from natural systems and processes. Humanity's increasing alienation from the natural world is described by the biophilia hypothesis, which refers to an instinctive bond between human beings and other organisms and systems. Defined as "the urge to affiliate with other forms of life" (Wilson, 1984), the term biophilia literally means "love of life or living systems" (Greek: *bio* means "life"; -*philia* means "affiliation, love, or attraction to"). Biophilic design can be implemented at any scale, from buildings to cities, and reflects on the interactions between the natural environment and human experience (Kellert et al., 2008).

Very little traditional ecology research has contributed to our understanding of the ecology of human settlements (Grimm et al., 2008) because, under the spell of the 'equilibrium paradigm', any sites worthy of ecological study would explicitly exclude humans. Traditional ecologists therefore viewed any non-human organisms living in cities as being there by coincidence and, therefore, as uninteresting (McDonnell, 2011). It is also noteworthy that many of the early ecological theories and concepts were developed concurrent with the settlement of the New World and Oceania, meaning that traditional ecological studies focused on areas with low cultural impact or human population density (McDonnell, 2011). As such urban ecology is a relatively young applied science which intrinsically reflects a human-inclusive world view (McDonnell, 2011). Given its tremendous range of trans-disciplinary observations, it may be best to describe urban ecology as ecological research in the urban setting (Rebele, 1994, McDonnell et al., 2009, Niemela, 2011).

In fact, the human desire to understand vegetation that occurs naturally in cities has a long-standing tradition, certainly in Central Europe and the UK. The flora of the Coliseum of Rome was described by Panarolis in 1643, and vegetated walls in Palestine were documented in 1762 by Hasselquist (Sukopp, 2002). Since the 17th century, the flora of castle ruins and walls was studied and given the name "ruderata" (Buxbaum 1721, Linnaeus 1751) from the Latin *rudus* for rubble or ruins (Sukopp, 2002). Disturbance has always held a central role to urban ecological theories because cities have generally always been considered disturbed environments (McKinney, 2006). As a discipline, urban ecology traces its origins to post-war Europe, as the spontaneous colonization of exotic vegetation in bombed demolition sites issued dramatic social responses (Salisbury, 1943). In northern regions, these rubble sites were warmer and drier than the natural habitats, allowing species from warmer climates to expand their ranges through dispersal and colonisation (Sukopp, 2002, Millard, 2004, Thompson and McCarthy, 2008).

Modern cities may actually be less disturbed than is sometimes thought, however, particularly if they were not recently bombed (Thompson and McCarthy, 2008). Urban habitats classified as ''disturbed'' can equally be termed ''novel'' or ''anthropogenic'' (McKinney, 2006), as it is those features, rather than disturbance, which create the observed effects. In any case, descriptions of nature of the city as a whole, rather than as individual biotopes, began in the 1970s (Sukopp, 2002); Berlin (Germany) was one of the first cities to be studied comprehensively (Breuste et al., 2008). Some of the long-term processes explored include natural succession of different urban soils (Rebele, 1992), urban woodlands (Bornkamm, 2007) and grasslands (Fischer et al., 2013, Kowarik, 1990), as well as green roof vegetation (Köhler, 1990). Interestingly, the German research has also led to design concepts for low-input urban landscapes using spontaneous urban vegetation (Kühn, 2000). As ever more cities are surveyed and studied, a new understanding has begun to accrue, predominantly for cities in the northern hemisphere (Cilliers and Siebert, 2011).

On the basis that cities present both the problems and solutions to the challenges of an increasingly urbanized world (UNFPA, 2007), urban ecology is a useful approach because it integrates the natural and social sciences to study these altered environments and their regional and global effects (Grimm et al., 2008). In the 1970s, particularly, the realisation that cities lie at the core of many environmental and social problems led to a call to improve our understanding of the physical, biological and social components of cities and towns (McDonnell et al., 2009). Now, after twenty-five years of query, this discipline has elucidated many of the physical and chemical functions and processes of the urban domain (atmosphere, soils, hydrology, living and non-living elements) (McDonnell and Hahs, 2013), and where the flow systems of materials and energy link the biological and non-biological (Grimm et al., 2008). As these urban systems can be shown to be integrated, so too can human socio-economic structures, which play pivotal roles (Alberti et al., 2003, Marzluff et al., 2008). Coupled with the unknown effects of global change and the unprecedented expansion of human population and settlement, it's clear that an improved ecological understanding of cities and towns is crucial for mitigating human impacts at local, regional and global scales (McDonnell and Hahs, 2013, Felson et al., 2013, Elmqvist et al., 2013).

1.3.3.1 *Cultural or semi-natural ecosystems*

The concept of cultural (or semi-natural) ecosystems can be useful for understanding the place of vegetated roofs to both the urban environment and to the delivery of ecosystem services on regional and larger scales. A physical example of the human-inclusive world view in ecology, the concept of semi-natural ecosystems is based on the notion that all landscapes have some degree of human influence. To this end, the notion of "virgin" or "untouched" ecosystems is rejected. Just as most grasslands and savannahs are accepted to be products of millennia of traditional human use, the remote Arctic tundra is affected by atmospheric nutrient deposition and human-induced climate change. Acceptance of this concept varies across industrialised cultures, with greater appreciation in Europe. Given Europe's millennia of archaeologically documented human settlement, it is relatively easy to see how the landscape and its ecosystems evolved in tandem with humans. With a record of tool development from the Palaeolithic through to modern machinery, it is no stretch of the imagination to see how the effects of traditional versus modern management and tools will affect ecosystems and biodiversity (Davies and Davies, 1980). Similarly, knowing that human ecosystem management was much more diverse and localised prior to industrialisation it is relatively easy to understand why some native species depend upon traditional methods if they are to persist (Bakker, 2005).

1.3.3.2 *Novel ecosystems*

Altered ecosystems that have been significantly changed by human activity, often in relation to invasive species or climate change, have been variously described as "novel", "emerging", or "no-analog" ecosystems (Milton, 2003, Hobbs et al., 2006, Williams and Jackson, 2007). Combined with the breakdown of biogeographical barriers (through global transportation of species), our current era is set apart from previous ones because the rapid pace of change leads to the rapid appearance of novel environments, species combinations and altered ecosystem functions (Hobbs et al., 2006, Meyerson and Mooney, 2007). Indeed, the prevalence of novel ecosystems may be an inevitable consequence of the Anthropocene (Steffen et al., 2007, Hobbs et al., 2009), as many ecosystems have departed substantially from their historical trajectory (Hobbs et al., 2014).

A novel ecosystem is one in which the species composition and/ or function have been completely transformed from the historic reference. The decision on which version of history is most important will always be a debatable point; nevertheless many restoration projects are driven by commitment to historical qualities and re-establishing past relationships between people and ecosystems (Higgs, 2003). Hybrid systems might retain characteristics of the historic state but their composition and function now lie beyond the historic range of variability (Hobbs et al., 2009). The process by which ecosystem change occurs depends on abiotic forces and biotic responses, and the speed by which novel states emerge is determined by the timing of the alterations in question. If abiotic change occurs very intensively (e.g., changes in climate, land use, pollution, nutrient loading), and all or some of the biota are unable to survive or regenerate, then the transformed system will shift into a new system. Where only biotic changes are salient (e.g., significant declines in native species and/ or invasion by non-natives), then a hybrid system may emerge. Novel ecosystems are more likely to arise as the proportion of new species increases (Hobbs et al., 2009). New biotic assemblages affect key interactions and processes, and changes in animal-plant interactions, biogeochemistry or disturbance frequencies can lead to positive feedback loops where members of the novel system facilitate the maintenance (and sometimes spread) of that ecosystem and inhibit restoration of the previous (Hobbs et al., 2006).

Green roofs (and other urban ecosystems) can be defined as such due to their novel elements, but they differ from novel ecosystems of cultivated or degraded landscapes due to the management associated with the built environment (Hobbs et al., 2006, Lundholm and Richardson, 2010, Kowarik, 2011, Perring et al., 2013). Otherwise, green roofs line up nicely with the key characteristics outlined in the seminal paper on novel ecosystems (Hobbs et al., 2006). The first characteristic, novelty, refers to new species combinations with the potential for changes in ecosystem functioning. Indeed, the original intention for EGRs was to improve the urban environment through the ecological processes granted by the introduction of soils and living plants. The second characteristic, human agency, refers to ecosystems that are the result of deliberate or inadvertent human action but not dependent on continued human intervention for maintenance. Although EGRs do require maintenance at least once annually, undocumented observations suggest that the shallow substrate serves as an edaphic plagioclimax, which maintains stable vegetation and limits natural succession into woodland. This characteristic of human agency further imparts the perspective that green roofs can be considered a human response to urbanisation. Ecological research of extensive green roofs has recently begun treating them as novel ecosystems (Van Mechelen et al., 2015, Williams et al., 2014, Lundholm, 2015, Molineux et al., 2014). Given how nascent both fields of research are, there is every possibility that ecology-oriented green roof research could support our understanding of novel ecosystems overall.

1.3.4 Green roofs designed for biodiversity

Further to the commercial EGR systems that define the global market, ecologically designed alternatives can be found around the world, though these are limited to regional scales. The trend of "green roofs designed for biodiversity" emerged from research in Switzerland and the science-policy support mechanisms there (Gedge, 2003, Gedge and Kadas, 2004, Brenneisen, 2010a), though the principles and experiences served as important reference for practitioners in other parts of the world (Lundholm and Richardson, 2010, Macdonough et al., 2006). That research will be described later; this section intends simply to introduce these systems and how they relate to commercial EGRs. Specific details are not the emphasis here, but rather a brief history of these developments in biophilic expression in order to offer a sense of the possibilities for flat roofs with limited loading capacity.

The concept for green roofs designed for biodiversity arose from the sense that shallow vegetated roofs could support greater diversity than Sedum-dominated systems (Thommen, 1988, Mann, 1996). A key study in Basel experimented with variations in substrate (composition, depths and heterogeneity), vegetation (diversity, cover), and provisions for wildlife (e.g., structures providing opportunities to bask, perch, hide, nest); many birds were found to use these green roofs designed as habitat, including Crested Lark (*Galerida cristata*), Little ringed plover (*Charadrius dubius*), Lapwing (*Vanellus vanellus*), Skylark (*Alauda arvensis*), Common tern (*Sterna hirundo*), Meadow pipit (*Anthus pratensis*), Wheatear (*Oenanthe oenanthe*) and Greenfinch (*Carduelis chloris*) (Brenneisen, 2003). This concept was taken further by proponents in London, who developed green roof designs that could support the habitat needs of Black Redstart (*Phoenicurus ochruros*), a rare breeding bird in the brownfields of London's Thames corridor slated for redevelopment (Gedge and Kadas, 2004). These efforts concurrently led to the introduction of green roofs to the UK (Gedge and Frith, 2005), and to a policy plan for "living roofs" in London with explicit reference to supporting biodiversity (Greater London Authority, 2008). The London Biodiversity Partnership's Black Redstart Action Plan was instrumental in broadcasting the benefits of green roofs to the mainstream, while also proving that these birds would indeed breed on green roofs provided they were designed appropriately (Gedge, 2003).

By contrast with Sedum-based EGRs, biodiverse roofs feature greater emphasis on the substrate; in many cases recycled aggregate is left to colonise naturally or is seeded with annual wildflower mix or local seed source (Kadas, 2006). However, the absolute icon of the nature conservation potential of green roofs is the Lake Water Treatment facility for Zurich. This facility was one of the first to be constructed with reinforced concrete in this region in 1914; each of the five buildings was covered with earth in order to moderate the temperatures inside. Specifically, 50 mm sand and gravel were lain down for drainage, upon which 150 to 200 mm topsoil was placed, for a total of 30,000 m^2 (Brenneisen, 2010b). Apparently the roof was not planted. The soil obviously included the local seed bank, as an extraordinarily diverse meadow developed, featuring 175 plant species typical of wet meadow, including nine orchids and numerous other species that had become rare in the eastern Swiss plateau since the roofs construction (Brenneisen, 2004). Although it is not an EGR, this roof serves the example of what can happen when the conditions are created for ecological processes to happen, in the absence of human interference.

1.4 Ecological research on green roofs

Most of the published research on extensive green roofs has focused on horticulture, engineering, and design, with comparatively little work from ecology (Blank et al., 2013). Of the ecological research, most has examined opportunities of habitat for invertebrates and birds by green roofs; plant ecology research is hardly represented in the English language literature (Piana and Carlisle, 2014). To be clear, green roof horticultural research is abundant (Dvorak and Volder, 2010), but any plant ecological work has been limited to experimental microcosms in which horticultural metrics such as establishment and growth rate are recorded rather than ecological measurements like diversity or cover abundance. Of the few plant ecological studies conducted on actual EGRs, these have been limited to young roofs less than 10 years since installation (Rowe et al., 2012, Bates et al., 2013, Dunnett et al., 2008b). A small body of work has surveyed well-established green roofs in Germany, but most have been confined to unpublished dissertations or manuscripts (Thommen, 1988, Riedmüller, 1994, Buttschardt, 2001, Poll, 2008, Darius and Drepper, 1983) and those published in journals are in German (Bornkamm, 1961, Bossler and Suszka, 1988), with a few exceptions (Köhler, 2006, Köhler and Poll, 2010). Similarly, beyond surveys of soil-dwelling arthropods (Schrader and Boening, 2006, Madre et al., 2013) and microorganisms (McGuire et al., 2013, Rumble and Gange, 2013, Molineux et al., 2014) little is known about the soil ecological processes that occur on green roofs, yet much research has gone into developing and testing blends (Kolb et al., 1982, Rowe et al., 2006, Emilsson, 2008).

For these and other reasons, the study of engineered EGRs as dynamic ecosystems subject to the laws and processes of nature has hardly been touched upon (Francis and Lorimer, 2011, Cook-Patton and Bauerle, 2012). Further to the typical barriers to fully understanding natural ecosystems and processes (e.g., the requirements for LTER), the ecological investigation of EGRs is challenged by complications related to access. For one, the relative newness of this technology to most parts of the world means that old examples of these engineered systems are geographically limited to Germany where they were first developed in the 1970s. For another, roof access rests upon the cooperation of building authorities (e.g., building owner, landlord, estate management) who can easily evade contact if the research does not interest them. Reliable documentation on an old green roofs construction, component details and maintenance history can be impossible to access, especially if institutional practices discard unused records and files after ten years, as is the case in Germany. Lastly, the lack of studies may also be due to the limited interest by traditional ecologists for urban sites (McDonnell, 2011).

1.4.1 EGR plant screening trials

The first native plant screenings for green roof systems date from the early 1980s in Germany. Conducted mostly in Hannover and Weihenstephan, these trials screened species and cultivars of regional provenance, but also species with promising traits originating from dry grasslands, mountains cliffs and talus slopes (Kolb et al., 1982, Krupka, 1985), as well as steppe, heath and sandy habitats (Liesecke, 1979, Kolb et al., 1983). Equal emphasis was given to the screening of potential substrates (Penningsfeld, 1979, Kolb et al., 1982) and to approaches for successfully establishing vegetation on gravel roofs (Kolb et al., 1983). Techniques like sowing Sedum cuttings (Liesecke, 1985) eventually became standard industry practice. The titles of most of these works make clear their intent to determine the optimal green roof build-up (Liesecke, 1979), from the technical perspective of the vegetation (Liesecke, 1981), as well as cost (Kolb et al., 1982). By 1985, the first book of research proceedings was published which disseminated all the factors thought to be essential for the creation of extensive green roofs, including site specific factors, plants and vegetation forms (Krupka, 1985)(Krupka, 1985). The first English-language article was published the following year (Kolb and Schwarz, 1986).

North America serves as an example of demonstration for more recent plant screening trials for EGRs. Compared to Europe, there are exponentially more eco-regions on this continent and, accordingly, a tremendous selection of species originating in habitats with analogous conditions to extensive green roofs. Since 1998, screening trials of native vegetation for EGRs there have come to include sub-tropical, semi-desert, humid continental, and temperate coastal climate zones (Dvorak and Volder, 2010, Butler et al., 2012). Particularly well-represented are the Atlantic Maritime Coast and the South Central Great Lakes because of the green roof research centres in those regions. As in the German experience, plant screening trials have been integrated with the testing of different substrate types and/or depths (Rowe et al., 2006, Getter and Rowe, 2008, Thuring et al., 2010), soil amendments (Licht and Lundholm, 2006), irrigation treatments (Wolf and Lundholm, 2008, Monterusso et al., 2005, Schroll et al., 2011), stormwater performance (Simmons et al., 2008, Lundholm et al., 2010) and surface temperatures (MacIvor and Lundholm, 2011b).

Experiments have begun accruing which illustrate that green roofs in hot and dry climates are feasible but that their system design and appearance will differ from cooler and wetter climates (Simmons et al., 2008, Benvenuti and Bacci, 2010, Van Mechelen et al., 2014a, Williams et al., 2010). Drainage layers may not be appropriate in hot and dry climates, for example (Simmons et al., 2008), and a great variety of Mediterranean xerophytes from various life forms await application (Benvenuti and Bacci, 2010, Van Mechelen et al., 2014b). Since extensive green roofs in hot and dry climates will not always be green, certainly not without irrigation, an approach embracing seasonality, change and process may be required if they are to be distinguished from intensively managed roof gardens. The opportunity to apply ecological knowledge while discouraging uniformity can lead to local distinctiveness with the benefit of maximizing biodiversity and the provision of ecosystem services. There is much potential yet to be realised in hot and dry climates; the uncertainty of climate change makes this area of research pertinent for many climate zones.

1.4.2 Green roof phytosociology

By the middle of the 20th century great volumes of literature had accumulated to describe plant associations, their distribution and interrelations in Europe. It wasn't long until discerning eyes noticed the spontaneous vegetation growing on gravel rooftops, presumably seeing them as one more association to be catalogued into this growing atlas. Dr. Reinhard Bornkamm applied phytosociological methods to the vegetation TPGs in Göttingen. At the time of Bornkamm's initial investigations, post-war re-construction was slowing and the inclusion of green spaces on urban structures had progressed in many cities around the coming to a close (Osmundson, 1999). Bornkamm's paper is purely scientific in its descriptions of roof vegetation, however, without advocacy or speculation on this ecologically interesting construction type. To the ecologist, spontaneously vegetated roofs hint at ecological processes, both novel and classic. This pioneering work inspired a number of ensuing studies in Berlin (Darius and Drepper, 1983, Poll, 2008, Köhler and Poll, 2010), Osnabrück (Bossler and Suszka, 1988), on gravel roofs in Switzerland (Thommen, 1988), and a few others that could not be accessed. The two most consistent communities will be reviewed here.

1.4.2.1 Sedo-Scleranthetea (Dry meadow of sandy soils)

The Class *Sedo-Scleranthetea* (Br.-B. 55 em. Th. Müller 1961) was identified on all TPG and gravel roofs, if only at shallow roof edges where the gravel layer is very thin (mean 68 mm) (Bornkamm, 1961). EGRs never had enough associate species for a full community classification (Thommen, 1988, Buttschardt, 2001). By definition, the *Sedo-Scleranthetea* constitutes poor grassland of acid or siliceous and sandy soils upon which the vegetation forms open or loosely covered stands that are usually two-layered and consisting primarily of low-growing herbs, short-culmed and thin-leaved grasses, mosses and lichens (Ellenberg, 1986). The herbs are represented predominantly by succulents, in particular Sedum species, and winter annuals. The TPG roofs surveyed featured a mix of species native to sandy grassland and entisol with annual or short-lived species of field and ruderal communities.

This Class divides further into several sub-orders and associations, all of which are heavily dependent on annual precipitation and fluctuate, accordingly, between prevalence of annuals versus succulents and drought-tolerant mosses. Indicator species of the *Sedo-Scleranthetea* include *Arabidopsis thaliana, Arenaria serphyllifolia, Brachythecium albicans,* *Ceratodon purpureus, Poa bulbosa, Rumex acetosella, Sedum acre, S. rupestre, S. sexangulare, Veronica arvensis.* Sub-orders and associations which were defined on vegetated roofs – both spontaneous and EGRs – include the Order *Sedo-Scleranthetalia* (Br.-B 55) (with indicator species *Cerastium pumilum, Sedum album, Sempervivum tectorum*) and the Associations *Alysso alyssoiidis-Sedion albi* (Oberd. and Th. Müller 61) and *Saxifrago tridactylitis-Poetum compressae* (Kreh 45) (Gehu and Leriq 57).

1.4.2.2 Poetum anceptis-compressae (Typical Poa meadow)

The typical Poa meadow is the definitive community of spontaneously vegetated TPG roofs, covering the largest surface area of all roofs studied. In Göttingen and Berlin, it occurs on loamy gravel ballasts over 100 mm deep (Bornkamm, 1961, Köhler and Poll, 2010). Further south, Thommen (1988) and Buttschardt (2001) defined the *Saxifrago tridactylis-Poetum compressae* sub-community. This community is defined by relatively dense meadow dominated by the rhizomatous grass *Poa compressa* and scattered with ruderal species. Closed swards of *Poa compressa* will exclude all other plants in depths above 150 mm while depths less than 100 mm loosens up the grass to permit annual and ruderal species to establish (Bornkamm, 1961, Buttschardt, 2001, Bossler and Suszka, 1988). In Berlin, Darius and Drepper (1983) observed how Poa meadows converted to *Saxifrago-Poetum compressae* at roof locations susceptible to erosion.

1.4.3 Natural succession on spontaneously vegetated gravel roofs

A study of natural succession on spontaneously vegetated gravel roofs concluded that the various plant communities identified developed as a result of two factors, namely time since installation and substrate depth (Thommen, 1988, p. 39). Similar to the tables developed to predict species/ plant communities that would develop in different substrate depths, a two-dimensional illustration of plant community development on gravel roofs in Switzerland are shown as a combined effect of substrate depth and time (**Figure 1.9**). This illustration shows that the earliest plant community type to emerge on sun-exposed gravel roofs can establish gravel as shallow as 20 mm (the ruderal *Conyzo-canadensis-Lactucetum serriolae*), but that this is soon overtaken by the *Sisymbrietalia* (or *Dauco-Melilotion*). From five years on, plant community development on gravel roofs depends largely on the substrate depth, such that depths up to 50 mm will support the *Sedo-Sempervivetum ceratodontetosum* while depths from 30 to 90 mm will develop into the *Saxifraga tridactylitis-Poetum compressae* and (from

15 to 25 years) the *Centrantho-Parietarion*. After 40 years, gravel roofs with 40 to 150 mm depth will support the *Alysso-Sedetum* (or *Sileno-Cerastietum*) while depths greater than 90 mm will support the *Poetum anceptis-compressae* (or meadow with annual grasses) (Thommen, 1988).

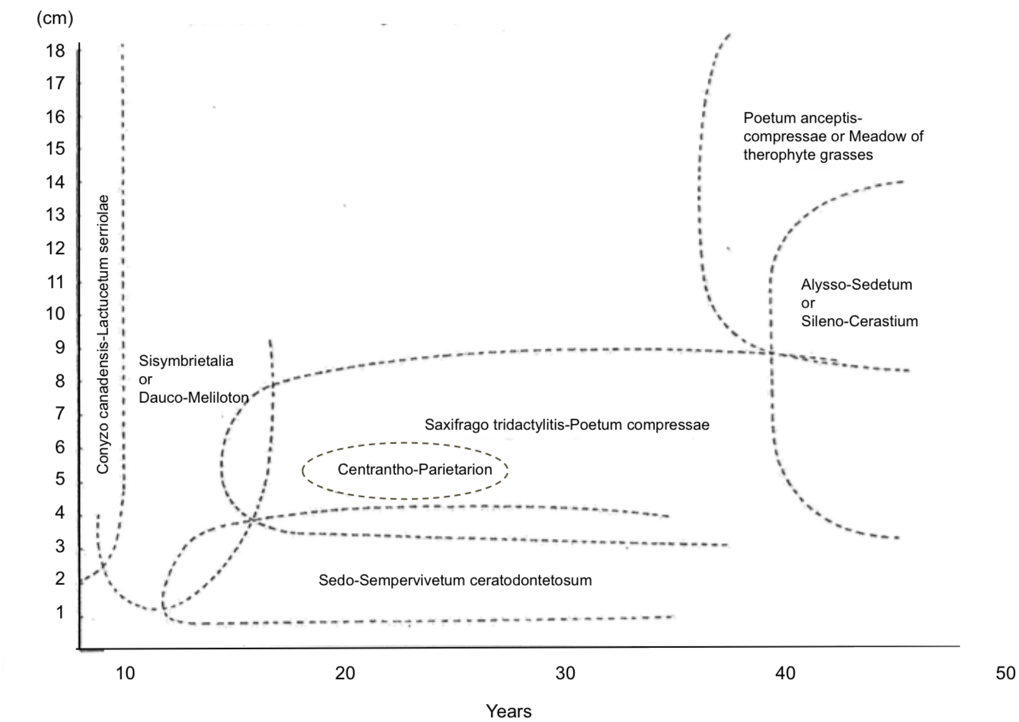


Figure 1.9. Natural succession of plant communities on sun-exposed gravel roofs in Basel over time (years) and in various depths (cm). Modified from Thommen (1988) (p. 41).

By contrast, the old spontaneous TPG roofs surveyed in Berlin (Darius and Drepper, 1983) and Osnabrück (Bossler and Suszka, 1988) did not exemplify any successional stages, and those authors reported that the vegetation appeared to have been stable for decades. The substrate of those TPG roofs been not been altered in any way since the 1950s (with certainty in Berlin), and both studies concluded that these systems had established a steady state of litter production, humus formation and mineralisation. The younger gravel roofs surveyed as a TPG contrast in Osnabrück, however, were still in the early stages of very slow humus formation, and the examined samples were very humus poor, likely because the vegetation was limited to pioneering mosses and lichens (Bossler and Suszka, 1988). These studies demonstrate the importance of substrate depth not only in determining species composition on green roofs, but concurrently in driving natural succession and long-term soil-based processes like humus formation.

1.4.4 EGR biodiversity research

Considerable ecological research on green roofs has studied invertebrates and habitat potential of these systems for biodiversity. Since this dissertation is focused on the ecology of EGR vegetation and substrates, this body of research will be reviewed because any fauna will inevitably have some sort of impact. This field of research has recently arrived at a point of scientific scrutiny, as well, through the examination of several of the hypotheses to the biodiversity conservation value of EGRs (Williams et al., 2014).

1.4.4.1 Soil-dwelling invertebrates and microbes

The soil-dwelling invertebrates that become established in green roof substrates are predominantly generalist cosmopolitan species of dry, exposed, disturbance-prone habitats (Buttschardt, 2001, Schrader and Boening, 2006, Rumble and Gange, 2013, McGuire et al., 2013, Madre et al., 2013, Jones, 2002), but these are apparently unstable and vulnerable to population crashes (Rumble and Gange, 2013). Similar to plants, then, the living conditions on green roofs also select invertebrate taxa that can tolerate high temperatures, low soil moisture, and impoverished food webs. The abundance of springtails (Collembola) on two EGR in London (UK) (between 6-7 years old) was also high, but were also shown to be unstable and vulnerable to population crashes believed to be caused by high temperatures, low soil moisture, and impoverished soil food webs (Rumble and Gange, 2013). These studies indicate that while green roof substrates may support organisms involved in soil food webs, the living conditions therein tend to select taxonomic compositions featuring hardy, stress-tolerant species.

In their snapshot study (which used pitfall traps on a roof over 4 weeks in August 1982) of two old TPGs in Berlin, Darius and Drepper (1983) found that the roofs had far higher counts of Oribatid mites than ground-level green spaces, ranging from 10,000 to more than 25, 000 individuals/ m^2 on the TPGs compared to only 3,000 individuals/ m^2 at ground-level. Snapshot samples of old extensive green roofs in Karlsruhe (six roofs between two and seven years old) (Buttschardt, 2001) and Hannover (ten roofs between 7-15 years)(Schrader and Boening, 2006) found an abundance of springtails, with higher densities on roofs than ground-level reference habitats.

1.4.4.2 Mycorrhizal fungi

Experiments have shown that mycorrhizal fungi will readily colonize green roofs (John et al., 2014, Heim and Lundholm, 2014, Molineux et al., 2014), and can be successfully inoculated (McGuire et al., 2013). In New York City, a survey of ten experimental green roofs (150 mm substrate and planted with a range of native species) found a diverse fungal community spanning all the major phyla, though most were associated with disturbed environments (McGuire et al., 2013). This study found high richness and abundance of arbuscular mycorrhizae (AM), which have symbiotic associations with a variety of herbaceous plants (e.g., facilitating greater access to nutrients and moisture) (Bardgett, 2005). Although AM colonization levels were not quantified in that study, two Sedum roofs in London reported increased root length (49% ±4) when colonized by mycorrhizal fungi with some individual plants with root growth increased by 76% (Rumble and Gange, 2013). In Halifax (Nova Scotia), a survey of an experimental green roof after four years observed mycorrhizal colonization of the roots of some plant species (e.g., *Danthonia spicata, Solidago bicolor*) although it was notably absent for others (*Sedum acre*) (John et al., 2014). A study which involved the inoculation of different microbial groups into an experimental green roof in London revealed that bacteria had greater biomass in shallower substrates while fungal biomass varied with depth and substrate type (Molineux et al., 2014). The balance between fungal-based and bacterial-based energy channels (Moore and Hunt, 1988) has major implications on nutrient cycling, mineralization and succession due to the corresponding regulation of trophic levels (Wardle, 2002). Soil organisms play fundamental roles to decomposition, nutrient cycling, and the physical alteration of the soil environment (Lavelle et al., 1995); more work on the microbial ecology of green roof substrates can offer a clearer understanding of green roof ecology.

1.4.4.3 Surface-dwelling and highly mobile invertebrates

Surveys of various green roofs in Böblingen (Germany) and Linz (Austria) showed that extensive green roofs were visited by flying insects (including bees and butterflies) and spiders, while roofs combining elements of both extensive and intensive systems and featuring depths from 100 to 400 mm supported much greater invertebrate diversity, including snails, beetles, spiders and cicadas (Mann, 1996). This positive correlation between heterogeneous substrate depths with invertebrate diversity has been corroborated by studies in Basel (Switzerland) (Brenneisen, 2009) and London (England)

(Jones, 2002, Kadas, 2006, Kadas, 2011). The latter studies identified a remarkable number of species found on green roofs with nature conservation designations. In the first three-years of the Basel study, for example, 78 of the spider species identified were listed in the Swiss red data book as being of conservation concern, with eight listed as potentially endangered (Brenneisen, 2009). In London, a preliminary survey of eight extensive green roofs (between 1 to 10 years old) recorded 136 species of invertebrates, of which some of the noteworthy species were uncommon nationally and others were 'nationally rare' or 'nationally scarce' as defined by the UK red data book (Jones, 2002). A further study in London found nationally rare and scarce spider species, as well as beetles of national importance on Sedum-dominated extensive green roofs and on 'brown' or 'biodiverse' roofs (Kadas, 2006). That study noted that species-richness continued to increase on the roofs designed for biodiversity, but declined on the Sedum roofs (Kadas, 2011). Such findings have not since been replicated by other published work, however.

With an interest in the processes that shape invertebrate assemblages on green roofs, a study of forty green roofs and forty parks in Zurich revealed that community composition of carabid beetles and spiders is influenced by local environmental conditions, whilst those groups with comparatively greater mobility (including bees and weevils) are determined by habitat connectivity (Braaker et al., 2014). The conclusion was that green roofs do offer valuable habitat for many invertebrates and have the potential to function as 'stepping stones', both for highly mobile and less mobile taxa. This study also suggests that enhancing green roofs by diversifying local environmental variables can increase their ecological value by enabling higher connectivity between green spaces (Braaker et al., 2014). By contrast, a French study of more than 100 extensive green roofs found that the surrounding environment exerted only a minor influence on composition, abundance and species richness of four invertebrate groups (spiders, beetles, true bugs and hymenopterans) (Madre et al., 2013). The latter group includes ants, which, although they don't receive much mention, have been observed in many studies. Ant species noted on green roofs include *Lasius niger* and *Formica cuniculari* (Madre et al., 2013, MacIvor and Lundholm, 2011a), as well as *Camponotus sp.* (MacIvor and Lundholm, 2011a).

Structurally heterogeneous vegetation has been shown to support greater species richness of invertebrates, especially bees (Madre et al., 2013, Tonietto et al., 2011). In Halifax (Canada), plant species richness did not have a significant influence on insect diversity

(MacIvor and Lundholm, 2011b), but this was attributed to the small sample size (five roofs). In Chicago, a survey comparing bee communities on six green roofs, six parks and six prairie sites found that the green roof with the highest recorded bee species and individuals was planted with prairie species and also had the highest plant diversity of all green roofs (Tonietto et al., 2011). Recent work on an experimental green roof in downtown Toronto suggests that native bees may be disadvantaged in cities with a prevalence of Sedum-dominated green roofs because exotic bee species were observed to collect significantly greater loads of Sedum pollen (MacIvor et al., 2014). Since bees are highly mobile and can forage for flowers vertically between green roofs and at ground level, they are presumed to benefit more from green roofs than other insect species (Braaker et al., 2014).

Varying the composition and depth of substrates seems to be key to improving the ecological value of extensive green roofs for most organisms. Deeper areas can serve as refuge from high temperature and low soil moisture (Buttschardt, 2001, Rumble and Gange, 2013), while the inclusion of features like stones, dead wood, ephemeral pools and nesting materials can provide habitat opportunities (Mann, 1996, Brenneisen, 2009). Greater depths also provide the resources for more structurally diverse vegetation, which benefits other organisms. Ideally, the construction and design of a green roof should take into account the wildlife and habitats of the surroundings as well as the specific conditions of the exposed space on top of buildings (Braaker et al., 2014).

1.4.4.4 Do EGRs support biodiversity conservation?

A recent review of EGR biodiversity research (Williams et al., 2014), which examined six unstated hypotheses in this literature, agreed with one hypothesis, namely that “EGRs have greater organism abundance and species diversity than conventional roofs”. However, insufficient empirical basis was found to support the hypotheses that “EGRs can support species diversity, composition and abundances of organisms comparable to ground-level habitats”, that “EGRs designed specifically to support native organisms support greater species diversity and abundances than standard EGRs” or that “EGRs can replicate ground-level ecological communities”. This study warned about the generalisation of the hypothesis that “EGRs can aid rare species conservation”; available evidence confirms that some, but not for all, rare taxa can benefit from EGRs. Lastly, while evidence has shown that flying organisms will use EGRs as habitat, this review warns that the hypothesis “EGRs can facilitate movement of organisms through urban landscapes” must take into account the broader landscape. The authors of this critique concluded that EGRs may help achieve the conservation goals for urban biodiversity, but that the goals need to be realistic, well-defined and measured to evaluate success, just like ecological projects at ground-level.

1.5 Research questions and aims

This research strives to describe and understand how EGR systems develop over time, using vegetation and substrate as ecological indicators. Understanding their ecology may reveal their true contributions to the built, social and natural environments over the long term. Although related, the disciplines of plant-, community-, soil-, and urban ecology have not given green roofs much consideration; this work may therefore also illustrate opportunities for integrating ecological green roof research with these and other disciplines. This work therefore addresses the gap in plant ecology research on EGRs through its methods and preliminary findings. With the ambition of contributing to the nascent foundations of ecological query on green roofs, this work strives to advance and align green roof research and practice with the various disciplines and proponents of urban ecology. The initiation of progressive approaches to green roof research, practice and policy can help to improve the quality of life in urban environments and beyond, for all organisms.

1.5.1 Research aims

- To characterise mature EGR vegetation in terms of life form cover abundance and species diversity.
- To characterise EGR substrate development > 20 years after installation.
- To identify plausible ecological theories or models which describe the processes that occur on EGRs over time
- To propose models illustrating and predicting vegetation development on EGRs over time.

1.5.2 Research questions

- If successional changes can be observed on EGRs, what are the main drivers and mechanisms?
- Do emergent community characteristics result with time, such that roofs with similar properties have similar species composition/ abundance/ diversity?
- Do EGR substrates retain their recommended properties over time, as specified by the FLL?

2 Vegetation development on extensive green roofs over time

This chapter opens the query of how EGR vegetation and substrates develop with time. The commercial ideal would have all the originally chosen species persist and multiply, with any gaps filled by these and other desirable species to create a species-rich tapestry that lasts for decades with minimal maintenance. Indeed, the species selected by the early green roof pioneers took ecological reference from plant communities of analogous environmental conditions whose species-richness is maintained by disturbance in plagioclimax (e.g., dry grasslands) with the aim of achieving this type of vegetation. Many species from these original lists remain popular for EGRs around the world, yet little is known of their long-term performance nor how species diversity and composition develop on EGRs over time or under varying conditions. If EGRs are intended as green infrastructure solutions for an increasingly urbanising planet, then understanding the long-term performance of their vegetation and substrates is imperative.

The industry partner on this project, one of the first EGR system manufacturers in Germany, ZinCo GmbH always wanted to know how the vegetation on its earliest systems had evolved. This PhD research was uniquely positioned to examine this question. The author's spoken and written fluency in German greatly facilitated the work, not to mention familiarity with the region through connections with the University of Hohenheim and with the green roof community. ZinCo was able to locate a number of old green roofs and to lift the usual barriers of physical access (through building contacts) and access to background information for some of them. In addition, an interview was arranged in June 2010 to meet the company's first green roof installer, Thomas Hövekamp, in order to gain more information on the roofs surveyed and details on any of the surviving documentation. Since 1990, Hövekamp has been running a small business that is specialised in green roof installation (GrünDach Technik Systems GmbH).

2.1 Literature review: plant ecological surveys of mature green roof vegetation

Surveying well-established green roof vegetation using ecological methods is scarcely represented in green roof research, though some examples do exist. A small body of work has examined vegetation development on spontaneously vegetated TPG roofs in different German cities, including Göttingen (Bornkamm, 1961), Berlin (Darius and Drepper, 1983, Poll, 2008, Köhler and Poll, 2010), Osnabrück (Bossler and Suszka, 1988), and on gravel roofs in Switzerland (Thommen, 1988). In the case of TPG roofs, they were apparently not intentionally seeded or planted (Buttschardt, 2001, Göbelsmann and Hippert, 2004, Grant, 2006, Adler, 2005) though some may have been laid with sod (Köhler, 2006, Poll, 2008).

On TPG roofs in Göttingen, Bornkamm (1961) found that recently installed roofs were first colonized by annuals (also known as ruderals or therophytes), but that this cover decreased after about ten years as the dominant grass, *Poa compressa,* expanded in cover. In Basel, Thommen (1988) was interested in the succession of a similar roof type, based by sand and varying depths of gravel ballast. Substrate depth was deemed a crucial factor, but climate was ultimately treated as the primary cause for differing directions of succession. **Figure 2.1** illustrates the various plant communities on those roofs in the dry-warm climate of Basel.

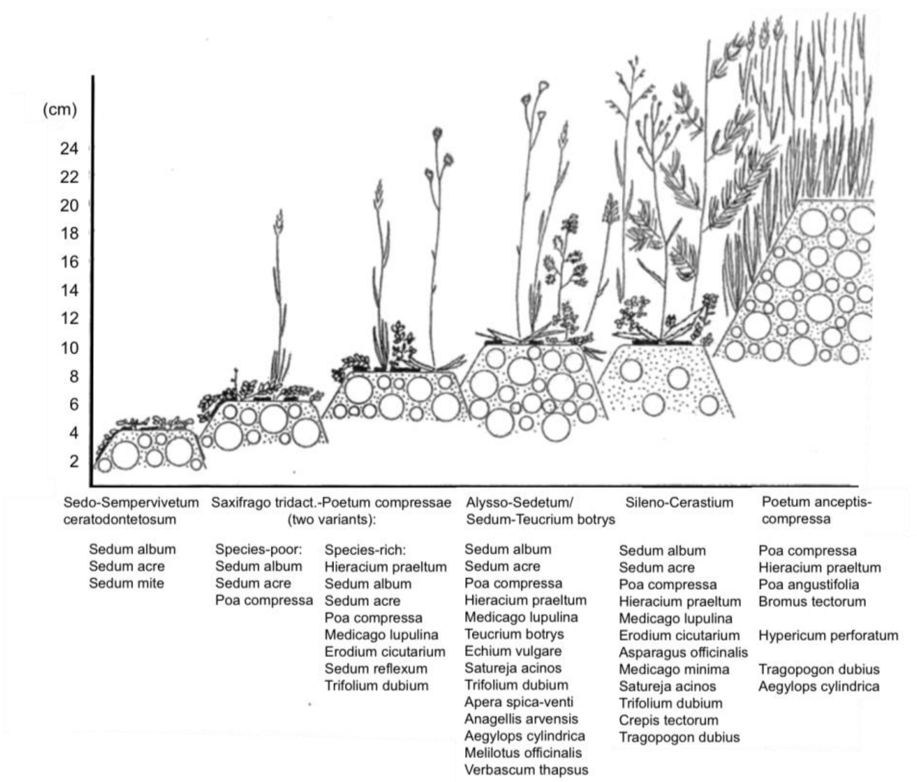


Figure 2.1. Species assemblages for different gravel depths in Basel after 20-30 years. Modified from Thommen (1988).

In the early 1900s, Berlin had around 2,000 TPG roofs of which 50 survived the wars and ten survived the renovation trend of the 1980s (Adler, 2005, Arhendt, 2007, Poll, 2008). By the start of the new millennium, the undisturbed surfaces of these remaining TPG roofs had become wild meadows, having been colonized by seed dispersal (Köhler, 2006). Since the sealing compound of these roofs consisted primarily of tar, which also functions as a long-term root repellent, these roofs remained leak-proof, and the aerated construction of the roof guaranteed long-term impermeability, too.

The longest-running study of EGR vegetation describes nineteen years of data from two roofs (sampled twice per annum) evaluating how plant species richness is affected by roof area, slope, age, water availability and other factors (Köhler, 2006). Installed in 1985, the Paul-Linke-Ufer (PLU) green roof was the first inner-city residential project in Berlin integrated with a monitoring program of the numerous environmental technologies, which included an EGR subdivided into ten sections (total 650 m^2). Prototypic pre-cultivated vegetation mats on the PLU were placed onto 100 mm substrate (expanded clay, sand and humus). The second site, Ufa-Fabrik, was installed with three EGRs (total 2,000 m^2) between 1986 and 1990, with 100 mm substrate (sandy garden soil, 10% expanded clay) and seeded with alpine wildflower meadows. This study found that species numbers fluctuated significantly depending on moisture availability, whether irrigated (provided during establishment and then stopped) or precipitation patterns. For example during a dry month (June 1998) eight species were found compared to twenty-five species during wet periods (June 1987 and May 2005). Species richness was also attributed to the proximity to green spaces that were sources of the propagules of colonizing species, as well as the provision of shade for a variety of exposures. That study found that five species persisted over time and were present every year (*Poa compressa, Festuca ovina, Sedum acre, Allium schoenoprasum, Bromus tectorum*), and that some of the initial annual pioneers and weeds (from 1986) had disappeared by 2005.

A study aiming to understand the development of roof vegetation and substrates over time united the findings from three studies of TPGs and four of EGRs (Köhler and Poll, 2010). The EGRs were all built in the 1980s in Berlin (Baier, 1988; Blödorn and Krause, 1992; Jänel, 1996) (these papers could not be accessed), and the TPGs were up to 100 years old. One of the three TPG datasets was from Berlin (Darius and Drepper, 1983), the others were from Göttingen (Bornkamm, 1961) and Osnabrück (Bossler and Suszka, 1988). With respect to species diversity, the meta-analysis found that old extensive green roofs (from the 1980s) supported around seventy species, whereas the older TGP roofs supported around forty-five species. The authors attributed this disparity in diversity to the initial plantings as well as the different growing substrates and systems. The north-facing aspects had the most plant cover and diversity compared to roofs with other exposures, such that roofs facing east and south were dominated by Sedum species, whereas the other most dominant species, *Allium schoenoprasum*, had its highest abundance on west-facing roofs where grasses were most poorly represented. With respect to these findings, this study recommended that south- or south-east facing roofs are better used for purposes other than roof vegetation, such as solar panels.

Long-term observations of EGR vegetation have been conducted in other parts of the world, too, though not for as long as the studies described above. In Sheffield (UK), the species composition of fifteen herbaceous perennial and grass species were observed over five growing seasons on eighteen (roof-level) test beds featuring varying treatments (depth, irrigation) and replications (Dunnett et al., 2008). This study found a major divergence in plant responses owing to the two depths (100mm and 200 mm), in that the majority of the taxa (11 of 15) maintained their numbers in the deeper substrate, while the shallower depth only supported four taxa over time. In addition to the greater density of plants per unit area at 200 mm, those plants also tended to be significantly taller, were wider spreading and flowered twice as long as individuals from the same taxa growing in the shallow substrate (100 mm). Total biomass was also greater in deeper substrate (200mm), but species richness and diversity were greater in the shallower depth, which the authors attribute to the reduced vigour of planted species in 100 mm of substrate and the greater proportion of bare surface for colonizing species to establish in. Indeed, the main differences between the two depths arose from the greater proportion of wind-blown herbs in the shallow substrate (100 mm).

In the USA, a study of twenty-four raised roof platforms in East Lansing (Michigan) found that only six of the original twenty-five species were still alive in all substrate depths (25, 50, and 75 mm) after seven years (Rowe et al., 2012), and that absolute cover amongst the surviving species only varied in the deeper substrate. At 50 mm and 75 mm, *Phedimus spurius* and *Sedum middendorffianum* were the dominant species, while the succulents *Sedum acre* and *S. album* covered the most area in 25 mm. A study of two 'brownfield' roofs in Birmingham (UK) showed that substrate moisture seemed to be the most limiting factor controlling plant growth (Bates et al., 2013). In spite of the lower water availability in 2010-2011, mosses and Sedum acre had the most sustained expansion of cover throughout the four-year study period. Indeed, mosses and Sedums are exceptionally resilient to limited moisture in green roof habitats (Emilsson and Rolf, 2005, Nagase and Dunnett, 2010). As in the other studies, these researchers also associated decline in cover with exposure, as this trend was less pronounced in areas that offered some shade and shelter from wind.

2.1.1 Research aims and questions

Vegetation and soils are the foundation of terrestrial ecosystems, as they determine the biotic composition and higher levels of organisation within that system (Cilliers and Siebert, 2011), like food webs and trophic structures (Barbour et al., 1999). Plant species diversity can therefore be treated as a key determinant of biodiversity in general and as an important influence on ecosystem function, even though the relationship between the latter is not linear (Cardinale et al., 2012). Indeed, since any species represents a "package" for all the genetic and trait variation that influences the metabolism and function of an organism (Cardinale et al., 2012), species richness is a layered and complex measure of biodiversity. This research uses measurements of vegetation and soil in order to determine the ecological function that extensive green roofs maintain twenty to thirty years after installation. This chapter therefore addresses one aim and one question of the research.

- **Aim:** To characterize mature EGR vegetation in terms of growth form cover and species diversity.
- **Question:** If successional change can be observed on EGRs, what are the main drivers & mechanisms?

Satisfactory explanations to these will be gained over this and ensuing chapters. In order to help direct their continuous resolution, this preliminary chapter will focus on some clearly defined objectives.

2.1.1.1 Objectives of the chapter

The objectives for this chapter involve the examination of several relationships:

- Relating the cover of growth forms and species diversity on old EGRs
- Relating EGR vegetation development with time (roof age)
- Relating EGR vegetation development with abiotic/ environmental conditions
- Relating EGR vegetation development with substrate characteristics

2.2 Methods

Since the green roof industry began in south-west Germany, the oldest roofs are located in this region, within 50 km from the city of Stuttgart (**Figure 2.2**). South-west Germany, the warmest part of the country, is typified by a continental climate in which summers often feature hot periods of > 30°C temperatures and winters may feature extended periods of cold and snow (Wikipedia contributors, 2014). The sample was restricted to old roofs in this region that could be easily accessed. In addition to six of ZinCo's oldest EGRs, three non-ZinCo green roofs were sampled, for a total of nine EGRs ranging from 20 to 33 years since installation. Knowledge of and contacts for the non-ZinCo roofs were gained through the network of green roof professionals. Most notably, the author had known John Döveling (Stuttgart Dept of Cemetaries, Gardens and Parks and based at Killesberg) for several years and had visited the roof at Killesberg with a green roof study tour in 2008 and 2012 (Green Roof Safari). In addition to that roof, Döveling connected the author with the manager of the roofs of Stuttgart Rathausgarage complex.

Figure 2.2. The EGRs surveyed are in south-west Germany, within 50 km from Stuttgart city centre.

2.2.1 Description of the roofs surveyed

Roof selection was determined by availability of accessible old roofs located within the same climatic region. The roofs surveyed included a range of construction types, including both pitched and flat, some with partial shade and others with none. This diverse selection presents opportunities for description although it also poses challenges to analysis. **Table 2.1** presents the roofs, in the order of age, with reference to their physical constructions (area, slope, depth) and environmental conditions (aspect). **Figure 2.3** provides visual impressions in the same order. In spite of their differences, the roofs are all based by typical EGR substrates (i.e., mineral: organic ratio; under 100 mm deep), use multiple-layered systems, and feature dominant Sedum coverage with varying cover by flowering herbs and grasses. While the species-poor roofs consisted mainly of Sedum, the more diverse roofs featured taller forbs and grasses over a base layer of Sedum, termed Sedum meadow. Some of the roofs featured prototypic systems and/ or materials, some of which became commonplace to the green roof industry while others were not taken up. In addition to the brief descriptions here, **Appendix 1** provides more detailed information on the roofs.

Table 2.1. Details of nine old EGRs sampled over two growing seasons (2010, 2011) in Stuttgart region. Data for substrate depth is displayed as the mean ± the standard error.

Roof name (in order of age)	Year Installed	Area (m2)	Slope (°)	Aspect	Depth (mm)
Killesberg	1991	450	30	N- and S-face	84.67±0.68
S-Rathausgarage, lower	1990	1000	0	none (flat)	69.71±0.71
S-Rathausgarage, PV	1990	1300	0	none (flat)	75.24±2.94
FH Nürtingen	1987	258	0	none (flat)	72.29±4.19
Römermuseum, Köngen	1987	350	17, 15	NW-SE-facing	78.13±5.61
Gärtnereihof Tübingen	1986	2160	15	N- and S-face	61.48±0.60
Esslingen VB Area 1	1986	1860	0	none (flat)	53.33±0.46
Esslingen VB Area 2	1986	2064	0	none (flat)	58.11±0.64
Pliensaufriedhof	1977	500	0	none (flat)	61.56±0.59

Figure 2.3. The nine EGRs sampled in southwest Germany were constructed between 1977-1991 and are arranged in order of increasing age from the top-left.

2.2.1.1 Pliensaufriedhof (1977)

The oldest roof surveyed, at Pliensau cemetery, is based by a 70 mm water retention drainage board, and is planted with Sedums, small shrubs and grasses. Although it is technically a simple intensive green roof (FLL, 2008), and a section of the roof was planted with *Teucrium chamaedrys* and *Festuca ovina,* its substrate depth and Sedum-dominated vegetation are equivalent to EGRs. Original documentation from ZinCo reports the use of a "Systemerde Dachgarten" (Technical roof garden soil) but the details of its composition are not specified. A contact from ZinCo suggested it was probably a blend involving topsoil, since technical aggregates were not available at the time of its construction, but that it likely adhered with the FLL recommendations to a degree (Appl, 2014). This roof is located on a ridge overlooking the Neckar valley, and receives partial shade from neighbouring pines in a sheltered, park-like environment. Skylights and a path intersperse the dense Sedum cover, and a few mounded anthills were perceptible beneath the smooth carpet of Sedum (**Figure 2.4**).

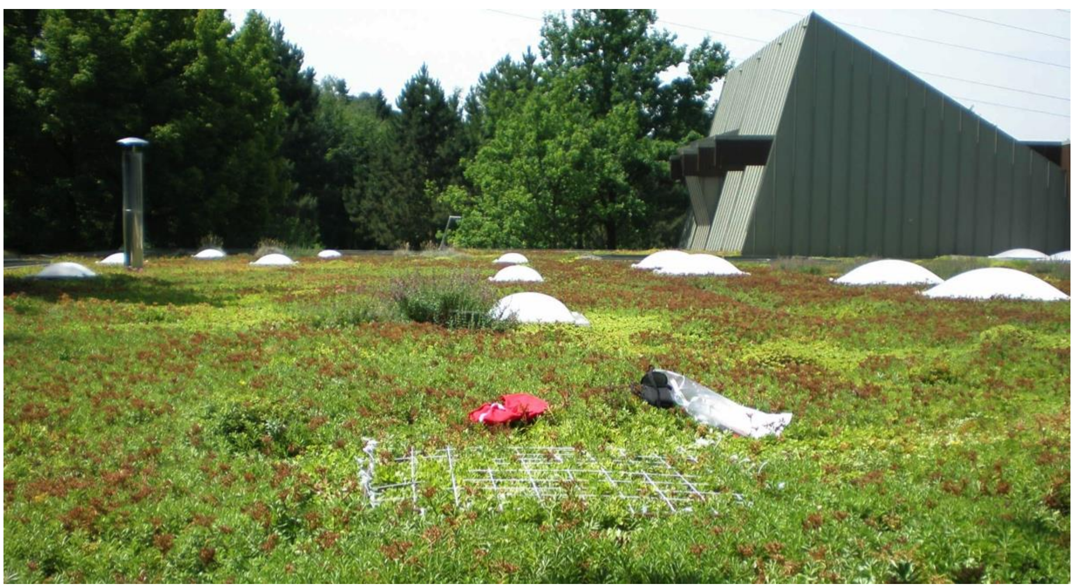


Figure 2.4. Facing north on the roof at Pliensaufriedhof.

2.2.1.2 Esslingen Verkehrsbetrieb (two roofs: Areas 1 and 2) (1986)

Next in age, two EGRs at Esslingen bus depot (Verkehrsbetrieb) are interspersed by roof shafts that are long and cover the length of the roof (**VB Area 1**) or smaller and more spaced

(**VB Area 2**). These roofs were Thomas Hövekamp's first green roof installation (May-June 1986) and were based by 100 mm expanded clay (which was pumped up) and 10-20 mm organic substrate. Interspersed in geometric design and buried to be flush with the substrate surface, 3,000 styrofoam "Floraterra" modules, pre-grown with Sedums and Thyme, were used to create instant green and visual interest by geometric placement; these did not succeed as a commercial product. Other than a conversation with the original installer (Hövekamp, 2010), no information was available for this roof complex. Beyond permitting access, site staff had no interest in it. These roofs have the largest surface area of all the roofs surveyed (1, 860 m^2, 2, 064 m^2, respectively). Being located in a dense industrial zone, they do not receive any shade from neighbouring features (**Figure 2.5**).

Figure 2.5. Aerial view of the two roofs at Esslingen Verkehrsbetrieb. Image courtesy Google Maps.

2.2.1.3 Gärtnereihof Tübingen (1986)

The EGR installed on the facilities for Tübingen's Department of Gardens and Landscape (**Gärtnereihof**) (1986) was the first pitched roof of its kind. As a result of negotiations with ZinCo, the original plan to have grass turf unrolled on both aspects was changed to limiting grass turf to the north-face and planting drought-tolerant taxa on the south-face.

Apparently, the grassy side steadily declined in cover. After the Department took over the roof maintenance (1988), the Head Gardener oversaw staff efforts to gradually fill in the gaps of failing grass with Sedum from the south-face (Braun, 1992). Additional background information for this roof includes correspondences (e.g., with FH Nürtingen), ZinCo brochures, and the results of a substrate analysis six years after installation (Sailer-Schmid, 1993). The original specifications of substrate composition and species lists are uncertain, however, because the only documentation found is a sample invoice that was never completed. The base of the north-facing roof is in contact with the canopy of an adjoining row of trees, while the south-face is totally exposed (**Figure 2.6**).

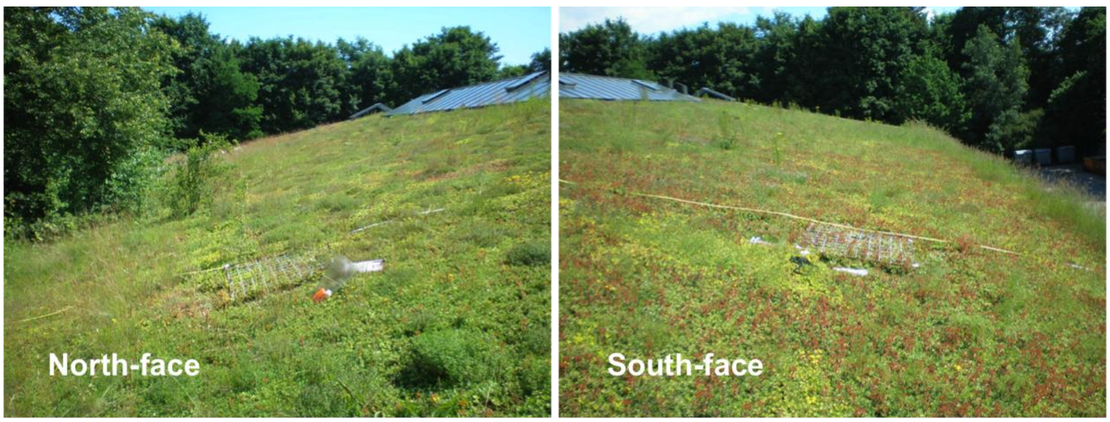


Figure 2.6. Facing north-east on the roof at Gärtnereihof Tübingen.

2.2.1.4 Römermuseum at Köngen (1987)

In Köngen, the **Roman Museum** (1987) was another first for pitched roofs, this one more steeply and irregularly sloped than Tübingen (**Figure 2.7**). The architects' vision for the building, which reflects the dimensions of a Roman fort, was for two asymmetrical, triangle-shaped green roofs to portray the ground under which visitors must pass in order to explore the site's history. The green roofs were fitted with wooden frames to prevent the substrate from slipping. Documentation from ZinCo reports that both roofs were uniformly planted with Sedum cuttings and an herb-grass mix, and installed with 50 mm substrate, but the original installer remembers 70-80 mm (Hövekamp, 2010). The smaller (70 m^2) north-facing roof (15°) is relatively low to the ground (3-5 m) and partially sheltered by the row of trees beside the building to the north-west and by the 3 m wall which supports the larger (230 m^2), south-facing roof (17°). The latter is more exposed due to its higher elevation (3-30m from ground-level), aspect, and lack of shade. A generic product sheet for “Dachgärtnerenerde” (roof garden soil) associated with this roof indicates 39% expanded shale, 15% volcanic clay (Vulkaton), 23% bark compost and 23% rice husks.

Figure 2.7. The Römermuseum in Köngen features a south-facing roof (left) and a smaller, lower roof facing north (right).

2.2.1.5 FH Nürtingen (1987)

The small EGR at the technical college in Nürtingen is easily observed through the windows of its adjoining wall that faces north (**Figure 2.8**). It is neatly enclosed by another wall facing east and by a parapet (1.5m). With landscape gardeners from the institute’s botanical gardens based in the neighbouring building, FH staff expected the green roof and its vegetation would be keenly observed for many years. Unfortunately, already after the first five years, maintenance had been reduced to annual mowing and removal of biomass, and no documented observations were made beyond the initial planning phase (Hüttenmoser, 2010). According to a sales receipt, the substrate comprised 80 L technical soil (“Erdsubstrat”), 60 L each of expanded shale and Floraperl (an expanded aggregate) and 2.2 tons of moraine sand. In addition to the predominant Sedum meadow character, the shaded zone from the adjoining wall supported a unique flora including woodland mosses and herbs as well as a colony of Common spotted orchids (*Dactylorhiza fuchsii*). Apparently a single orchid appeared in in 2000, and by 2010 a colony of 30 individuals had self-established (Hüttenmoser, 2010). Unfortunately, the perimeter of this roof was destroyed a few months after being surveyed, as it was held responsible for water damage in a lecture hall below.

Figure 2.8. Aerial view of the small roof sampled at FH Nürtingen. Image courtesy Google Maps.

2.2.1.6 Stuttgart Rathaus Parking Garage: PV and lower roof (1990)

In Stuttgart City Centre, the parking garage complex for the City Hall (Rathaus) consists of two roofs (**Figure 2.9**), one with a row of PV panels (Rathaus PV) and a lower roof (Rathaus lower) that receives some shelter from the PV roof and from neighbouring buildings. Although predominantly covered by Sedum meadow, these roofs also feature mounds that support higher statured plants (e.g., *Yucca* spp.). As shall be described in the methods, the mounds were not sampled. Installed between spring and autumn 1990 with seed, pre-grown plants and cuttings, these roofs were a pilot project with the intent to educate councillors and others in order to gain support for the city's green roof initiative. From 1992 until 2008, the roofs were maintained once per year, typically end-June to early July. Maintenance ceased in 2008, as the parking facility was scheduled for demolition, but the financial crisis of 2009 prevented this from happening. By summer 2011, the City was still trying to decide what to do with the building.

Figure 2.9. Aerial view of the two roofs at Stuttgart Rathausgarage. Image courtesy Google Maps.

2.2.1.7 Stuttgart Killesberg (1991)

At Stuttgart Killesberg, a pitched Sedum meadow sits atop the City of Stuttgart's Department of Gardens, Cemetaries and Forests, but initially served as the headquarters for the International Garden Exhibition (IGA) in 1990, during which time the green roof served for demonstration. The contact person for accessing this roof had initiated and managed Stuttgart's green roof incentive and support program for nearly twenty years (Döveling, 2009) and was keenly interested in this research. According to architectural plans, this roof was seeded with the same seed mix as the Rathausgarage roofs in July 1991. Herr Döveling recalled that the substrate blend involved some topsoil (verbal communication), but no records were available. A drip line ran the length of the roof peak and irrigation was provided for the first three months. Due to the steep slope (**Figure 2.10**), substrate samples were not collected from this roof although depth measurements were taken concurrent with floristic sampling.

Figure 2.10. The roof at Killesberg features a clear north-south gradient.

2.2.2 Background and original information

Background information with original specifications was only available for some roofs, in some cases from ZinCo GmbH (Köngen, Pliensau, Tübingen) or from buildings in which interested staff had retained documents (FH Nürtingen, Tübingen, Killesberg). Some roofs had technical drawings that included reference to species lists and substrate depths (Köngen, Rathausgarage complex). Written documentation for four roofs (Köngen, Tübingen, Verkehrsbetrieb roofs) were complemented by an interview with Thomas Hövekamp who established ZinCo's installation team in 1984. The two Verkehrsbetrieb roofs were his first-ever installation, followed by Köngen and Tübingen. Written documentation for these roofs, which he signed and/ or authored, was therefore extended by his memory which included actions that were not documented (e.g., depth specified versus depth installed). Other personal information gained on the roofs in question included conversations with Frau Beate Hüttenmoser had just started working FH Nürtingen when that roof was initially installed and who kept all the records. The former manager at Tübingens Garden Department, Herr Braun, left several years' worth of detailed work records and observations of that green roofs vegetation development. Finally, information on the Killesberg roof was forthcoming from John Döveling, who had observed it closely since its installation.

Records from the oldest roof (Pliensaufriedhof) indicate probable observance to the recommendations that eventually became akin to industry guidelines (FLL) and, since the other roofs were all built during the time of the FLL guidelines, it is assumed that they adhered to those specifications. This pertains mainly to the substrate properties, such as soil pH between 6.5 and 8.0, soil organic content below 65 g/L, and substrate depth less than 200 mm. Even if the materials and methods were not yet established in those early years of the industry, such as substrate components, it is possible that the materials used would have satisfied the guidelines which were nascent recommendations at the time (Appl, 2014). Maintenance contracts for all the roofs had not been renewed about 10 years before the surveys were conducted (Hövekamp, 2010, Starke, 2010, Hüttenmoser, 2010, Heller, 2011). However, given that some of these roofs are easily accessible (e.g., door-access to FH Nürtingen, permanent ladder at Pliensaufriedhof and Tübingen) and located on buildings associated with gardening departments (same roofs), independent maintenance in the form of weeding cannot be ruled out entirely. Typical EGR maintenance includes weeding, planting, fertilization, and irrigation (FLL, 2008).

2.2.3 Sampling methods

Primary survey methods with ecological objectives were used in order to describe the vegetation and substrate of these EGRs. Sampling plots were defined using a 1m2 quadrat, with between 12 and 18 quadrats per roof. The number and placement of quadrats was determined by site conditions, vegetation homogeneity, environmental gradients, and the statistical requirements of sampling (Kent and Coker, 1994). The random placement of quadrats gives any point within the sampling area an equal chance of being sampled (Kent and Coker, 1994). Since the aim of this work was to characterise EGR vegetation, quadrats were sampled from areas based by EGR system constructions (e.g., depth) and therefore featuring characteristic vegetation. Random placement was too simplistic for roofs with mounds or shallow gravel edges, where the vegetation differs from the greater roof expanse, so roof vegetation in those cases was stratified in advance of sampling. Stratifying, or dividing, vegetation into homogeneous (uniform) versus heterogeneous (non-uniform) patches prior to placing samples is beneficial for clustering major sources of variation (van der Maarel, 2005). This and related sampling approaches are described per roof in the section that follows.

2.2.3.1 Random sampling at systematic intervals (FH Nürtingen)

The vegetation of the small roof at at FH Nürtingen appeared to be completely uniform with no obvious gradients, except for gravel edges, a few ant mounds and two skylights, sothe roof was divided up length-wise by intervals of approximately 4.5 m and quadrats were located along these intervals, for a total of 8 transects running the width of the roof (**Figure 2.11**). Quadrats were placed roughly every 3 m, following the length of the transects but keeping clear of edges and structures.

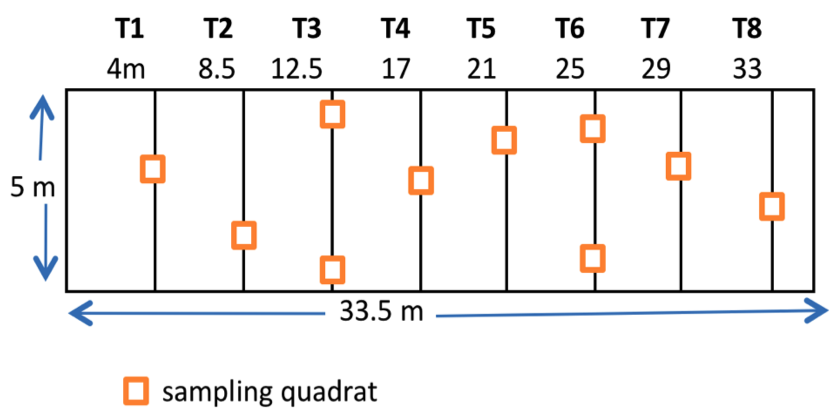


Figure 2.11. Layout of quadrats in systematic interval sampling at FH Nürtingen.

2.2.3.2 Random sampling along transects (Köngen)

For the triangular shaped, pitched Sedum roofs in Köngen, a grid of transects was prepared in advance of sampling along which quadrats were then randomly located (**Figure 2.12**). Transects permit the description of maximum variation across an environmental gradient and covering the shortest distance (Kent and Coker, 1994) In this case,the transects ensured that the whole of the roof would be sampled (with the exception of the gravel edges). The larger south-facing roof was surveyed with 13 quadrats and 5 quadrats sampled the north-facing roof.

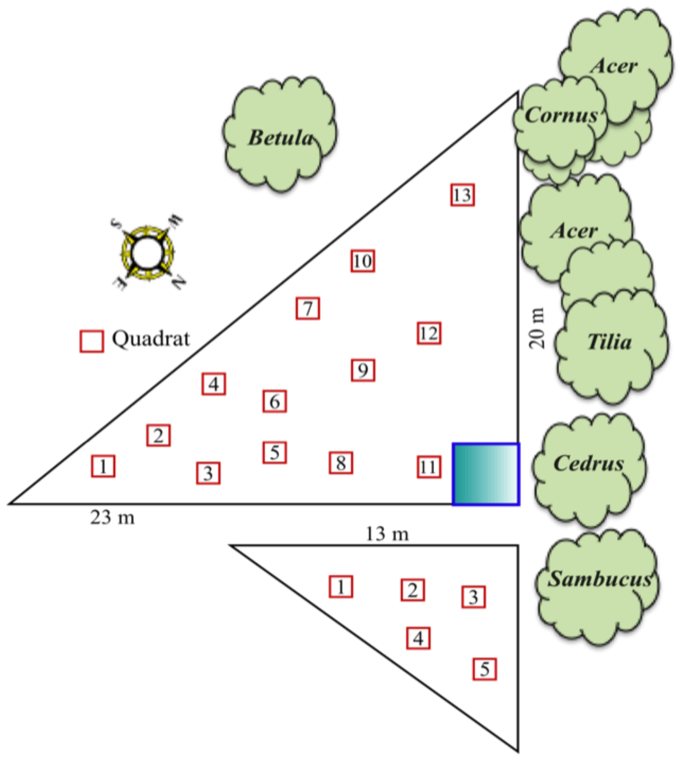


Figure 2.12. Quadrat placement at Köngen followed random sampling methods on a grid of transects for the two roofs.

2.2.3.3 Stratified random sampling (Pliensaufriedhof, Esslingen VB roofs, Stuttgart Rathausgarage roofs)

Given the uniformity of the dominant roof vegetation and the clear distinction of this from other planted forms, like mounds, stratified sampling methods helped to direct random quadrat placement within the uniform vegetation. . In those cases, the physiognomic groups present were defined first (e.g., succulent cover as distinct from shrubby mounds), and sampling then followed for the vegetation of interest (i.e., EGR vegetation) through the random placement of quadrats within the designated area. Thus, the Sedum dominated areas on Pliensaufriedhof, the Esslingen Verkehrsbetrieb roofs and the Rathausgarage roofs were randomly sampled with care taken to avoid gravel edges and non-uniform patches featuring shrubby mounds, skylights or PV panels. The example of this approach is shown for Rathaus PV in **Figure 2.13**.

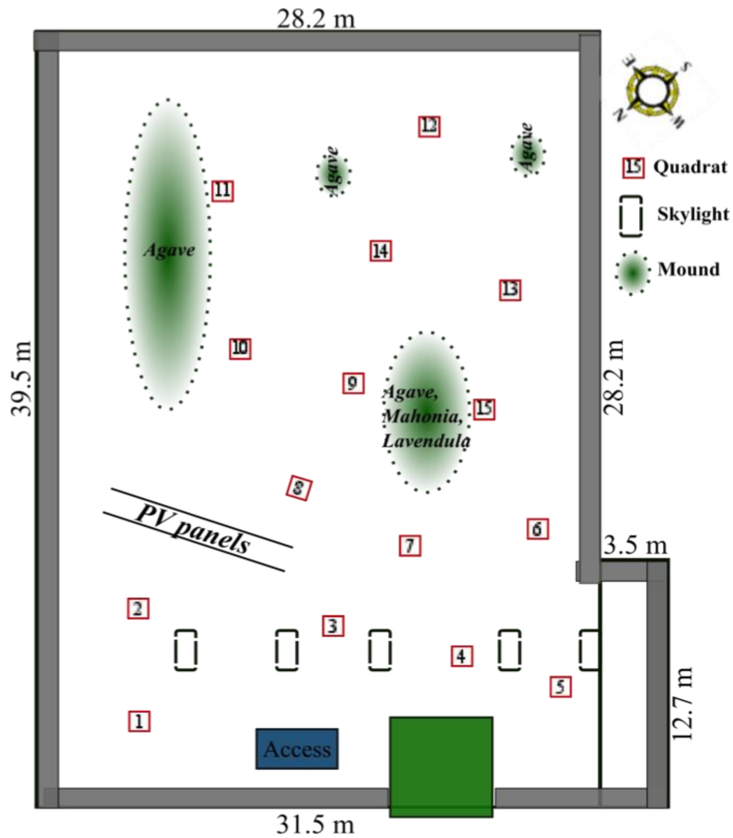


Figure 2.13. Quadrats were randomly placed at Rathaus-PV following stratification, which avoided the vegetation of mounds and edges.

2.2.3.4 Transect sampling on pitched roofs (Tübingen, Killesberg)

Slope and aspect create visually obvious environmental gradients on the pitched roofs at Tübingen and Killesberg, so these roofs were sampled using transects, avoiding roof edges and any non-uniform vegetation. In Tübingen, for example, four randomly designated transects were lain from the roof peak with two randomly located quadrats placed symmetrically per aspect (i.e., at the same distance from the roof peak) (**Figure 2.14**). In transect 1 (T1), quadrats 1 and 2 were randomly designated 6 m and 2.5 m from the roof peak on the south-facing slope, so quadrats 3 and 4 on the same transect were located at 6 m and 2.5 m from the peak on the north-facing slope. Similarly, five randomly selected transects were lain across the ridge of the Killesberg roof but, due to window gables which interrupt the roof surface, only three transects ran the full width of the roof. These systematic samples were as randomly placed as the quadrat they reflected on the opposite slope.

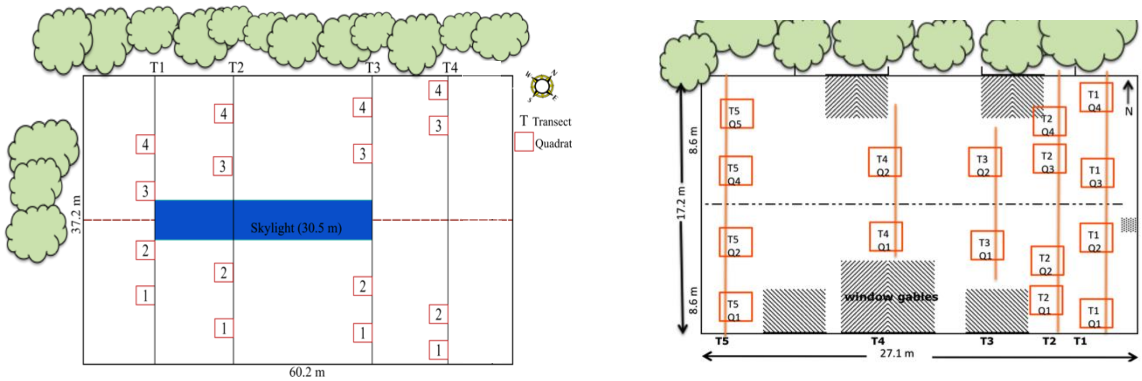


Figure 2.14. Transects and systematic random symmetric quadrats were used at Tübingen and Killesberg.

2.2.4 Data collection

The surveys took place over two growing seasons (2010, 2011), with each roof sampled once for vegetation and substrate, sometimes over the course of several days (**Table 2.2**). Given the singular frequency of surveys per roof, they will sometimes be described as "snapshot surveys" because the quality of the data is like that of a photograph: colourful and detailed but static to that particular moment in time. In order to provide the option for return sampling, the corners of all sample plots were marked with permanent labels and detailed maps were prepared which illustrate quadrat locations.

Table 2.2. Sampling details and dates for nine old EGRs in south-west Germany.

Roofs in order surveyed	Year Surveyed	Date of floristic sampling	Date of substrate sampling	Total # quadrats
Gärtnereihof Tübingen	2010	24 June, 7 July	14 October	16
FH Nürtingen	2010	2, 6 July	11 August, 11 October	12
Römermuseum, Köngen	2010	8, 12 July	13 October	18
Pliensaufriedhof	2010	9 July	13 August	15
Esslingen VB Area 1	2011	9, 10 June	6 September	14
Esslingen VB Area 2	2011	14, 15 June	5 September	14
S-Rathausgarage, PV	2011	8, 11, 12 July	8 September	15
S-Rathausgarage, lower	2011	12, 14, 15 July	9, 12 September	14
Killesberg	2011	7 June	N/A	18

2.2.4.1 Floristic sampling

Methods on sampling and describing vegetation referred to the National Vegetation Classification Users' handbook (2006). Floristic description was accomplished using the traditional tool of quantitative plant ecology, a 1 m^2 quadrat (Braun-Blanquet, 1932, Mueller-Dombois and Ellenberg, 1974). Floristic sampling occurred from mid-June to mid-July and substrate collection occurred in late-summer or early-autumn from the same quadrats, immediately following removal of above-ground biomass (this data was not used). Plants falling within sampling quadrats were identified to the level of species and also grouped into physiognomic growth form groups.

2.2.4.1.1 <u>Percent cover</u>

For every plant recorded in a sample, an estimate was made of its quantitative contribution to the vegetation. Cover is a measure of the vertical projection on to the ground of the extent of the living parts of a species (Rodwell, 2006), and describes how much of a species or growth form is present in a sample, irrespective of how frequently the species is encountered in other samples. Using the Domin cover thresholds (**Figure 2.15**), cover was visually estimated per quadrat for various levels of detail, notably individual species and growth form groups (%). The latter was estimated as the percent cover of the group as a whole, and not as the sum of cover values of individual species. Using terminology of vegetation description, abundance can be referred to as 'dominant', or 'prominent' and 'abundant' where there is high cover but no real dominance. For low cover, expressions such as 'sparse' are used (Rodwell, 2006). Even within vegetation that is not conspicuously layered, total cover values can exceed 100% because of structural overlap of the plants. This overlap was included in some of the analyses, however, because it gives a fuller description of the vegetation sampled.

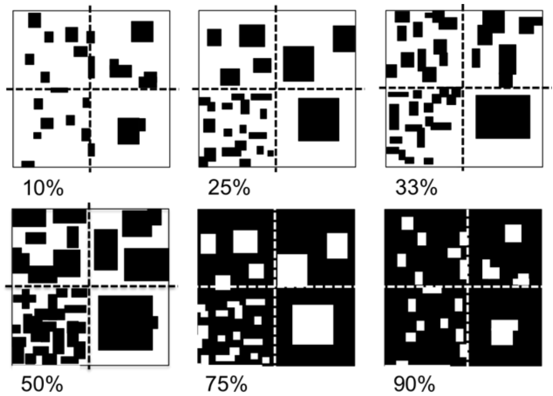


Figure 2.15. Visual interpretation of Domin cover/ abundance thresholds. In the diagrams, each sub-square has the same total area of black. The top left diagram, for example, has 10% black in each sub-square. Modified from Rodwell (2006).

2.2.4.1.2 Growth forms

With the objective of describing different landscapes through plant physiognomy, various classification systems for describing plant "life forms", "growth forms" or "basic forms" have been developed since von Humboldt (1806). Growth form is a purely morphological term, as influenced by the environment, as opposed to "life form", which is more encompassing and broad (Mägdefrau, 1982). Since growth form describes the overall character of a plant this shall be used here. Although it has been revised and modified by various authors, the main structure of Raunkiaer's (1934) ecologically oriented system of classification makes it the most widely applied scheme, whereby growth forms are defined by the position of the buds (or organs from which new shoots or foliage develop after an unfavourable season) (Mueller-Dombois and Ellenberg, 1974). In brief, Raunkiaer (1934) relied primarily on winter characteristics and based his system on bud position:

- **phanerophytes** (phanero = visible): buds at tips of branches (usually trees), associated with moist, warm environments;
- **chamaephytes** (*chamae* = dwarf): buds near soil (shrubs and herbs), associated with cool, dry climates;
- **hemicryptophytes** (*hemicrypto* = half hidden): buds die back to ground in winter; associated with cold, moist climates;
- **cryptophytes** (*crypto* = hidden): buds buried by soil; associated with cold, moist climates;
- **therophytes** (*thero* = summer): no buds but emphasis rather on seed production (i.e., annuals); associated with deserts and grassland

On the basis of their similarities in structure and function, species and individuals can be grouped into classes which display obvious relationships to important environmental factors. Since growth forms like grasses, shrubs and forbs represent different life history strategies, resource use patterns, and suites of environmental adaptations, growth form diversity can also be considered a coarse surrogate for the functional diversity of a plant community (Lavorel and Garnier, 2002, Lundholm et al., 2010). Grouping species has the drawback of masking the variation of ecological strategy within each group, but it can also reveal important environmental factors influencing the structure of the vegetation. Viewing plant communities as assemblages of functional types rather than species brings several advantages: community complexity can be reduced without compromising the loss of processes; processes are clarified, and modelling is greatly facilitated (Colasanti et al., 2001). Likewise, treating large numbers of species individually can hinder the analysis and interpretation of the broader functional aspects of the vegetation (van der Maarel, 2005).

Joenje and During (1977) showed that there is a strong correlation between growth form and life strategy. For the purpose of this work, EGR vegetation was divided into physiognomic groups with general consideration of plant strategies (**Table 2.3**). For instance, although they qualify as forbs, succulents were treated as a distinct growth form because of their unique structures and strategies. Succulents are popular on EGR plant lists around the world (Snodgrass and Snodgrass, 2006) and many species/ cultivars from the most prevalent genus, Sedum, can tolerate extreme conditions yet perform well in favourable conditions (Durhman et al., 2007, Thuring et al., 2010). Shallow substrate depths tend to limit the number of species that can survive on EGRs, but Sedums create reliable vegetation cover which absorbs moisture, prevents erosion, inhibits colonisation, and requires hardly any maintenance (Dvorak and Volder, 2010).

Table 2.3. Species were grouped into physiognomic growth form groups

Growth form	Vegetation type
woody	trees, shrubs, sub-shrubs
graminoid	grasses, sedges
succulent	succulent and crassulacean species
forb	herbaceous flowering plants
geophyte	bulbous flowering plants
cryptogam	mosses, liverworts, lichens

Herbaceous plants, or forbs, encompass a great range of forms, life histories, and inter-relationships. The forbs most commonly used on EGRs are species that can persist through difficult conditions, but also colonise and self-establish through various dispersal strategies (e.g., wind blown seeds). Forbs also represent the potential for ecological interest through the provision of nectar and pollen sources for pollinating insects and animals, and trophic impacts on food webs.

Geophytes, or bulbs like *Allium* spp, can maintain a dominant presence on some green roofs, such as those described in Berlin (Köhler, 2006, Köhler and Poll, 2010). Given their physical bulk and seed size (certainly compared with wind-dispersed seed), bulbs are less ecologically dynamic in that they cannot colonise EGRs without human directive.

Woody growth forms here include tree and shrubs. On extensive green roofs, these usually consist of spontaneously colonised seedlings that rarely persist because they are either weeded or killed off by drought, extreme temperatures, or shallow depths, although they may persist if the conditions permit. Although Thyme is woody, it was treated as a forb since most of the other woody species encountered were colonizing tree saplings and/ or had been planted in "non-uniform" (and therefore unsampled) parts of a roof.

Cryptogams, mainly mosses and lichens, colonise roofs easily but are generally unintentional components of green roof vegetation. Without bryological expertise, identification can be difficult, which makes the impact and dynamics of these organisms an elusive point for such field studies. Experiments in Halifax (Canada) have started exploring the influence of mosses and lichens on neighbouring species as well as temperatures of modular green roof boxes (Heim and Lundholm, 2013, Heim et al., 2014).

2.2.4.1.3 Species diversity

The number of different species (or cultivars) is an important metric of representation within the vegetation. Accurate identification of plants and cryptogams was verified by Prof. Dr. Reinhard Böcker, Professor of Landscape Ecology and Vegetation Science at the University of Hohenheim (and currently compiling a new Flora for Stuttgart). A record of those identified species was kept in a small herbarium of pressed plants, and cryptogams were kept in dry paper bags. For plants that could not be identified, simple identifier names were given (such as “opposite-leaved herb”) and they were treated as a species within that growth form. Any species recorded in the quadrats that were atypical of the uniform vegetation were treated as outliers. Two sedges and an orchid at FH Nürtingen, for example, extended beyond the drip zone and into one (*Dactylorhiza fuchsii, Carex humilis)* or more (*C. flava*) quadrats. Since these species were exceptions to the uniform vegetation of this roof, were not found on any of the other roofs, and were associated with the unique conditions of shading and moisture beside the adjacent wall, they were removed from the dataset for most analyses. If species from original lists were not encountered in the quadrat samples, whole-roof reconnaissances were conducted in order to confirm their presence or absence.

2.2.4.2 Substrate sampling

The same quadrats sampled for vegetation were sampled for substrate. Depth measurements included the substrate surface until the filter sheet separating the substrate from the drainage layer. Mean depth per quadrat was calculated from three depth measurements at different edges, and the values from all quadrats served to calculate mean depth per roof. Killesberg was not sampled for physical and chemical soil properties due to the difficulties and dangers associated with its steep slope, but sampling of the other eight roofs was accomplished using a (100 mm) soil corer (Firma Schwab, Waidhofen). Between ten and twenty-five litres are required for physico-chemical analysis (FLL, 2008), so twenty litres (20 L) were collected per roof, with between one and two cores per quadrat. Cored gaps were re-filled with a commercially available green roof substrate. Before being united into a single sample for each roof, each core was cleared of vegetation and its core profile was photographed for the record. Substrate data therefore include depth (n=134), and nitrogen, phosphorus, potassium and magnesium (as measured in mg/L), soil organic content (g/L) and soil pH (as measured by $CaCl_2$) (all n=8).

Soil analyses were conducted in adherence with the FLL recommendations, which provide detailed testing procedures. To begin with, any evaluation of EGR substrate properties is based on a standardized level of compaction (i.e., the Proctor hammer compaction test as per DIN 18127, or ASTM D698) in order to replicate the compression that occurs over time. To determine maximum water capacity (MWC), substrate samples were fitted into 150 mm cylindrical test samples, compacted, saturated and then left to drip freely for 2 hours (i.e., until field/ container capacity) (FLL, 2008). Maximum water capacity (vol. %) is the water content that remains after the substrate has reached field capacity. Air volume (% vol.) is the difference between total pore volume and water content at maximum water capacity. The amount of organic content (g/ L) in a green roof substrate is determined by ash content and loss due to burning, which is achieved by incinerating test samples at 550°C (in a muffle oven) until the weight readings have stabilized and no more loss is detected. The standard DIN 19684 method was used to measure soil pH whereby a 0.01 molar solution of $CaCl_2$ was added to the sample and then measured after three hours (using a pH-meter). More details on the methods, analyses and results for substrate are given in Chapter 6.

2.2.4.3 Abiotic/ environmental variables

To account for environmental gradients influencing the roofs, variables were measured which reflect quadrat-level and roof-wide influences that may vary across a roof and can influence the vegetation per quadrat. Roof-wide variables are those that extend in influence across the roof like roof age (time since installation) (n=136). Quadrat-level, or quadrat-specific, variables included slope, aspect, and shade. Since aspect is an ordinal variable lacking quantitative meaning, any results pertaining to this must be interpreted with reference to field observation. For analysis, these were ranked into ordinal variables (**Figure 2.16**).

Roof level: age	
1	20-21 years
2	22-23 years
3	24-25 years
4	> 26 years

Quadrat-level: slope	
0	0-4.5° (0 to 1/12)
1	5-9.5° (1 to 2/12)
2	10-14° (2 to 3/12**)**
3	15-18.5° (3 to 4/12)
4	>19° (>4/12)

Quadrat-level: aspect	
0	none
1	N-facing
2	S-facing
3	both

Quadrat-level: shade	
0	none
1	half-day
2	majority of day

Figure 2.16. Ordinal rankings for environmental variables.

2.2.5 Data analysis

In order to encompass the diversity of EGR roof constructions and the numerous biotic and environmental variables that influence EGR vegetation over time, this chapter introduces preliminary correlation analyses with the aim of identifying important relationships between vegetation, substrates, environmental variables, and time. Statistical tests were performed in SPSS versions 19-22 (IBM Inc.). A two-tailed Spearman's (*rho*) rank correlation test was selected to detect relationships between the dependent (vegetation and substrate) and independent variables (roof age, slope, aspect, shade). This non-parametric test was useful because some of the data was ordinal and most of it was not normally distributed. Interpretations of the strength of the different effect size statistics take reference from the guidelines proposed by Cohen (1988); large effects had correlation coefficients 0.5-1.0; medium strength effects were 0.3-0.49. Preliminary tests were performed to ensure no violation of the assumptions of normality, linearity and homoscedasticity.

It is important to note that established correlations between two variables do not necessarily imply that the relationships are causal, but simply that there may be causal interactions. Two variables might appear to be correlated but their relationship can be spurious if another "lurking" variable is producing that effect (rather than the two variables alone). Correlation analysis cannot indicate when a given correlation is spurious, nor can it identify any lurking variables that might cause a spurious correlation. The small sample size also poses limitations to any conclusive interpretations from these results. With regards to the matter of possible spurious correlations, these results may serve as points of consideration for the scenarios or dynamics that they suggest, and as preliminary insights into the direction of relationships.

Spearman's is a robust measurement for the strength and direction of a relationship, as indicated by the positive or negative sign in front of each correlation coefficient. Accordingly, it should be noted that the relationships implied by the test always have two possible interpretations, denoted in the discussion by *vice versa.* For example, if roof age and grass cover are negatively correlated, this could be interpreted as older roofs having less grass cover, but also as younger roofs having more. If the correlation test detected significant relationships, further analyses were conducted to examine these further, either here or in later chapters. The objectives of this analysis address the key questions summarized by the following hypotheses.

2.3 Results

Overall, 94 species were identified on the nine EGRs sampled, including 6 woody species, 12 graminoids, 42 forbs, 11 succulents, 3 bulbs and 20 cryptogams. The master species list for all roofs, organised by growth form grouping and with indication of how many quadrats each species occurred in per roof (frequency), is given in **Table 2.4**. Taxonomic authority on nomenclature followed Tutin et al. (1993) for vascular plants, Purvis et al. (1992) for macrolichens, Hill et al. (2008) for bryophytes and The Plant List (2013) for graminoids.

Table 2.4. Full species list, with frequency, for the vegetation of nine EGRs.

Species by growth form	Pliens q=15	VBA1 q=16	VB A2 q=14	Tüb q=14	FH Nü q=12	Köng q=18	R-PV q=15	R-low q=14	K'berg q=18
Forb	species frequency (# quadrat occurrences per roof)								
Achillea millefolium L.		1	5			1			
Campanula rotundifolia L.					*3*				
Cerastium arvense L., Sp. Pl. 438 (1753)									1
Convolvulus arvensis L.	1								
Coronilla varia L.						7			
Crepis tectorum L.		2	12				15	14	
Dianthus carthusianorum L.							6	12	
Dianthus deltoides L.				1	4		1		1
Erigeron annuus (L.) Pers.		2							

Fragaria vesca L.				2					
Geranium spp.	1								
Geum urbanum L.					1				
Hieracium pilosella L.	2			2	12		5	6	
Hypericum perfoliatum sensu Hayek pro parte, non L.						4			
Hypericum perforatum L.			7	1	7				
Linum perenne L.							13	12	2
Lotus corniculatus L.					9				
Medicago lupulina L.					2				
Nepeta mussinii Sprengel ex Henckel							2		
"Opposite leaved herb"									4
Petrorhagia prolifera (L.) Ball & Heywood								3	
Petrorhagia saxifraga (L.) Link.		1	9	8					
Picris hieracioides L.							1	5	
Potentilla argentea L.									2
Potentilla erecta (L.) Räuschel							6		

Potentilla tabernaemontani Ascherson					3		11	11	
Potentilla recta L.		1	8					4	
Solidago canadensis L.					2				
Taraxacum officinale Weber	6	4	1		7		9	7	2
Thymus praecox Opiz				10					
Thymus pulegioides L.									2
Thymus serpyllum L.		14	10		3		6	5	
Trifolium arvense L.		1			3				7
Trifolium campestre Schreber		2					5	2	
Trifolium dubium Sibth.					1				
Trifolium pratense L.				1	1				
"Unknown herb"	1								
Verbascum nigrum L.								1	
Verbascum thapsus L.						1			
Veronica spicata L.							5	8	3
Vicia hirsuta (L.) S.F. Gray				15					
Vicia sepium L.	4								

	Pliens q=15	VB A1 q=16	VB A2 q=14	Tüb q=14	FH Nü q=12	Köng q=18	R-PV q=15	R-low q=14	K'berg q=18
Succulent	species frequency (# quadrat occurrences per roof)								
Sedum acre L.								1	
Sedum album L.		2	1						
Sedum album "Coral Carpet"				4					9
S. album "Murale"									12
S.kamtschaticum "Weihenstephaner Gold"	10		1	14		5			
S. hybridum L.	10	11	14	16		10	9	3	
S. rupestre L.				8			15	13	17
S. sexangulare L.		12	11	14	9		13	10	13
S. spurium Bieb.	10	13	5	12					
S. telephium L.			1				2		
Sempervivum tectorum L.		1							

	Pliens q=15	VB A1 q=16	VB A2 q=14	Tüb q=14	FH Nü q=12	Köng q=18	R-PV q=15	R-low q=14	K'berg q=18
Graminoid	species frequency (# quadrat occurrences per roof)								
Agrostis stolonifera L.					9				
Agrostis tenuis Sibth.		4	4						
Arrhenatherum elatius (L.) P. Beav. ex. J. & C. Presl.				3	6				
Carex flava L.					4				
Carex humilis Leyss.					1				
Festuca ovina L.		1	1	5	6	18	7	7	8

Festuca rubra L.				3	3				
Poa angustifolia L.			1	1					
Poa compressa L.			2		11		2	5	
Poa pratensis L.				2		2			
Setaria viridis (L.) P.B							11	13	9
Vulpia myuros L. C.C. Gmel.								4	9
	Pliens q=15	VB A1 q=16	VB A2 q=14	Tüb q=14	FH Nü q=12	Köng q=18	R-PV q=15	R-low q=14	K'berg q=18
Geophyte	species frequency (# quadrat occurrences per roof)								
Allium flavum L.							10	3	
Allium schoenoprasum L.		7	14						
Dactylorhiza fuchsii L.					1				
	Pliens q=15	VB A1 q=16	VB A2 q=14	Tüb q=14	FH Nü q=12	Köng q=18	R-PV q=15	R-low q=14	K'berg q=18
Crytogam	species frequency (# quadrat occurrences per roof)								
Cladonia furcata (Huds.) Schrader		1	14		1				
Cladonia cf scabriscula (Huds.) Schrader					2		6	3	2
Peltigera spp.							3	3	3
Brachythecium rutabulum (Hedw.) Schimp.								4	
Brachythecium cf. albicans1 (Hedw.) Schimp			3						

Brachythecium cf. albicans2 (Hedw.) Schimp								4	
Brachythecium cf. albicans3 (Hedw.) Schimp		1							
Bryum1								5	
Bryum2							8	13	
Calliergonella cuspidata (Hedw.) Loeske						3			6
Ceratodon purpureus (Hedw.) Brid.									7
Dicranum scoparium Hedw.					3				
Eurhynchium praelongum (Hedw.) B., S. & F (stokesii)					6				
Hypnum1							9	8	
Hypnum2		6	11						
Philonotis fontana (Hedw.) Brid.					3				
Polytrichum juniperinum Hedw.					2				
Pseudoscleropodium purum (Hedw.) M. Fleisch		8							
Racomitrium elongatum Ehrh. ex Frisvoll					6				
Starry yellow moss							1		6

	Pliens q=15	VB A1 q=16	VB A2 q=14	Tüb q=14	FH Nü q=12	Köng q=18	R-PV q=15	R-low q=14	K'berg q=18
Woody	species frequency (# quadrat occurrences per roof)								
Acer campestre L.				2					
Acer pseudoplatanus L.				1	5			1	9
Carpinus betulus L.									2
Unidentified seedling					4				
Pinus sylvestris L.	2								
Teucrium chamaedrys L.	3								

The most diverse roof (FH Nürtingen) recorded 32 species that included 15 forbs, 1 bulb, 7 graminoids (including 2 sedges), 7 cryptogams and 2 woody species. The next most diverse roof (Rathaus lower) had 30 species that included 17 forbs, 4 grasses, 1 bulb, 7 cryptogams and 1 woody species. Compared to its neighbouring roof with PV panels (Rathaus PV) which apparently had the same original species list, the more sheltered conditions of the lower roof may explain the greater number of species recorded. Four of the roofs surveyed (Tübingen, VB A1, VB A2, Killesberg) had just over twenty species (20, 21, 21, 23, respectively), all with similar numbers of forbs (8, 9, 7, 9, resp.), succulents (6, 5, 6, 4, resp.), several grasses (5, 2, 4, 3, resp.) and most with cryptogams (0, 4, 3, 5, resp.). On the opposite extreme, the most species depauperate roofs (Köngen and Pliensau), recording 9 and 11 species respectively, were predominantly covered by Sedum with sparse representation by other growth forms.

2.3.1 Relating cover and species diversity of growth forms

Cover by the five growth forms correlated positively with species diversity of the same growth forms, and different growth forms had varying relationships to each other’s cover. Other than succulents, the other growth forms all had large and significant relationships between their own cover and species diversity (shown bolded in **Table 2.5**). Some growth forms had significant relationships with species diversity of other growth forms, too, most notably bulb cover with species diversity of cryptogams (*rho* = -.425, $p < .001$, $n = 136$) and cryptogam cover with bulb species diversity (*rho* = .361, $p < .001$, $n = 136$). Recalling that bulbs are unlikely to colonise green roofs without human aid, and that cryptogams are independent colonisers, these results may be linked with other relationships or dynamics that this analysis can not reveal. The lacking relationship between species diversity and cover by succulents may reflect the fact that Sedum-dominated roofs can be extensively covered by just two or three species.

Table 2.5. Results from Spearman's correlation (*rho*) relating growth form cover with species diversity

		Growth form cover (%)				
		bulb	cryptogam	succulent	forb	grass
Species diversity	# bulb species	.742***	.361***	-.190*	.137	-.077
	# cryptogam	.425***	.856***	-.485***	.248**	.281**
	# succulent	.152	-.070	.287**	.102	-.339***
	# forb	.083	.315***	-.374***	.732***	.124
	# grass	-.012	.225**	-.248**	.194*	.783***

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Cover by succulents correlated negatively with the diversity of other growth forms. The large effects between succulent cover with species diversity of cryptogams (*rho* = -.485, $p < .001$, $n = 136$) and forbs (*rho* = -.374, $p < .001$, $n = 136$) suggest that extensive succulent cover inhibits the diversity of these growth forms (or *vice versa*). This may be true in some cases, where Sedums with dense foliage and creeping stems inhibit such growth forms, though it is not uncommon to see these growth forms growing together, either. Succulent species diversity was negatively correlated with grass cover (*rho* = -.339, $p < .001$, $n = 136$), which suggests that roofs with greater diversity of succulent species had less grass cover (or *vice versa*). Only two growth forms were correlated in cover with each other. Cryptogam cover had a negative correlation with succulent cover (*rho* = -.424, $p < .01$, $n = 136$) and a positive relationship with bulb cover (*rho* = .357, $p < .001$, $n = 136$). This implies that cryptogam cover was greater when bulb cover was greater, but that it declined when succulent cover increased (or *vice versa*). Field observations challenge the generalization of the latter, since mosses and lichens can often be observed growing alongside and beneath Sedum species on green roofs.

2.3.2 Relating green roof vegetation with time (roof age)

Grasses had the strongest relationship with roof age, such that older roofs had significantly less grass cover (*rho* = -.716, $p < .001$, $n = 136$) and significantly fewer grass species (*rho* = -.595, $p < .01$, $n = 136$) (**Table 2.6**). Cryptogams also had a negative relationship with roof age, such that older roofs had significantly less cryptogam cover (*rho* = -.314, $p < .001$, $n = 136$) and fewer cryptogam species (*rho* = -.445, $p < .01$, $n = 136$), through the effects were only medium strength. This implies that the older roofs sampled often had fewer grass and cryptogam species (and/ or that younger roofs had more). Succulent cover and diversity had the smallest response to roof age.

Table 2.6. Results from Spearman's rank correlation (*rho*) relating roof age with cover (%) and species diversity of five growth form groups.

	Growth form	Roof age
cover (%)	bulb	$-.238^{**}$
	cryptogam	$-.314^{***}$
	succulent	.128
	forb	-.134
	grass	$-.716^{***}$
species diversity	# bulb spp	.030
	# cryptogam spp	$-.445^{***}$
	# succulent spp	.102
	# forb spp	$-.294^{**}$
	# grass spp	$-.595^{**}$
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$		

2.3.3 Relating EGR vegetation development with environmental/ abiotic conditions

Extensive green roofs are subject to harsh environmental conditions and green roof vegetation typically receives little protection from solar radiation, wind, or precipitation and the shallow, mineral substrates offer very little buffering capacity from extreme temperatures, frost, drought, or other.

2.3.3.1 Vegetation and substrate depth

From the roofs surveyed, grasses were the only growth form with positive relationships to substrate depth, and with the most significant relationships with depth (**Table 2.7**). Deeper substrates supported more grass cover (*rho* = .432, $p < .001$, $n = 134$) and more grass cover species diversity (*rho* = .351, $p < .001$, $n = 134$). Bulb species diversity also had a significant, but negative, association with depth (*rho* = -.395, $p < .001$, $n = 134$). This implies that EGRs with deeper substrates had less bulb species but more species of grass, as well as more cover by grasses (or, vice versa, that shallower depths support less diversity and cover by grasses and more bulb species). The other growth forms did not respond to depth, which is to be expected for cryptogams and succulents, which have shallow rooting requirements. Species-level responses to depth will be examined in Chapter 4**.**

Table 2.7. Results from Spearman's rank correlation (*rho*) relating substrate depth with vegetation (cover and species diversity of five growth form groups, both variables n=134).

		Substrate depth
cover (%)	bulb	-0.045
	cryptogam	-0.032
	succulent	-0.073
	forb	-0.101
	grass	.432***
species diversity	# bulb	-.395***
	# cryptogam	0.002
	# succulent	-.227**
	# forb	-0.030
	# grass	.351***

Substrate depth also had significant correlations with abiotic variables, in particular a negative relationship with roof age (*rho* = -.481, $p < .001$, $n = 134$) but also with slope, aspect and, to a lesser degree, shade (**Table 2.8**). This suggests that substrate depths were significantly shallower on older (versus younger) EGRs; on pitched (versus flat) roofs; on roofs with both- or south-facing aspects (versus north-); and on roofs without shade (versus shade for majority of day). The FLL guidelines were designed to rule out compaction because EGR substrates are shallow to begin with, and such a trend could pose serious issues to the long-term function of shallow EGRs. The effects associated with depth shall be investigated more closely in Chapter 4.

Table 2.8. Results from Spearman's rank correlation (*rho*) relating substrate depth with abiotic variables (n=134).

	Substrate depth
Roof age	$-.481^{***}$
Slope	$.430^{***}$
Aspect	$.369^{***}$
Shade	$-.296^{**}$
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$	

2.3.3.2 *Vegetation and slope, aspect and shade*

Shade had negligible effects on the vegetation surveyed, while slope and aspect had significant correlations, in particular with species diversity of bulbs (*rho* = -.451, $p < .001$, n = 136; *rho* = -.450, $p < .001$, $n = 136$, respectively), cryptogams (*rho* = -.324, $p < .001$, $n = 136$; *rho* = -.449, $p < .001$, $n = 136$, resp.) and forbs (*rho* = -.486, $p < .001$, $n = 136$; *rho* = -.513, $p <$ .001, $n = 136$, resp.) (**Table 2.9**). This suggests that sloped roofs often supported fewer species from these growth forms, while the flat roofs surveyed had more. Since shade has only three possibilities, the average correlation (the correlation coefficients squared, averaged, and square rooted) was tested in a post-hoc power analysis, revealing a power (1-β err prob) of 0.54 (G-power, version 3.1, University of Düsseldorf, calculated December 15, 2015). This is not particularly powerful, and may reflect the small number of quadrats sampled that bore any shade.

Table 2.9. Results from Spearman's rank correlation (*rho*) relating slope, aspect and shade with cover (n=134) and species diversity of five growth form groups (n=134).

		slope	aspect	shade
cover (%)	bulb	.017	-.123	-.106
	cryptogam	-.310***	-.411***	.098
	succulent	.185*	.254**	.095
	forb	-.309***	-.269**	-.035
	grass	.281**	.237**	-.225**
species diversity	# bulb	-.451***	-.450***	.059
	# cryptogam	-.324***	-.449***	-.036
	# succulent	.153	.107	.009
	# forb	-.486***	-.513***	-.223**
	# grass	.115	.135	-.278**
* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$				

Cover by grasses and succulents had negligible responses with slope and aspect. This means that quadrats located on pitched roofs did not have significantly different cover or diversity by these growth forms than flat roofs. It is interesting that the graminoid and succulent growth forms had positive relationships to these variables, while the other growth forms were negative.

Slope and aspect influence roof vegetation from the basis of incoming solar radiation, and field observations can substantiate this distinction of growth form compartmentalization. Three of the nine EGRs surveyed had slopes greater than 15°, of which Tübingen and Killesberg had north-/ south-facing aspects and Köngen had north-west and south-east facing aspects. The steeply pitched south-facing slopes at Killesberg supported mainly Sedums, cryptogams and annual grasses, while the north-facing slopes supported Sedum meadows, defined by tall herbs and grasses above a continuous succulent cover (recall **Figure 2.10**). Although forb cover and diversity had significant correlation effects with slope and aspect (while grass and succulents had none), the visual effect of these dynamics were not as evident *in situ*. This may indicate the strength of influence by these abiotic variables, and the different plant responses, but it may also imply the likelihood of lurking variables. For instance, the large negative correlation between aspect and forb diversity may be a result of competition by grasses rather than inadequacy by forbs in such conditions, and might also implicate the effects of slope and aspect on moisture and nutrient availability, pH, etc. Species-level responses to these variables, along with inter-relationships with depth, will be examined in Chapter 4.

2.3.4 Relating vegetation development to substrate characteristics

Of the substrate variables sampled, the only significant correlations with vegetation were between soil organic content (C_{org}) and bulbs, and a weak association between phosphorus and succulent cover (**Table 2.10**). These results suggest that roofs with more C_{org} had significantly less bulb cover (*rho* = -.934, $p < .001$, $n = 8$) and fewer bulb species (*rho* = -.976, $p < .001$, $n = 8$), and that roofs with substrates high in phosphorus also had more cover by succulents (*rho* = .708, $p < .05$, $n = 8$). Since bulbs only occurred on three roofs (FH Nürtingen, Esslingen Verkehrsbetrieb roofs), and given that data analysis for these variables limited the sample size so considerably, these effects are not exceptionally robust. The consideration of individual species' responses to different substrate variables may shed more light on the role of substrate to vegetation development (Chapters 5 and 6).

Table 2.10. Results from Spearman's rank correlation (*rho*) relating substrate variables (n=8) with cover and species diversity of five growth form groups.

		Soil properties					
	Growth form	Soil organic content	pH	N	P	K	Mg
cover (%)	bulb	-.934**	0.349	0.06	-0.528	-0.419	-0.434
	cryptogam	-0.407	-0.229	0.036	-0.38	-0.539	-0.193
	succulent	0.571	-0.06	0.048	.708*	-0.143	0.108
	forb	-0.262	0.299	-0.214	0.024	0.429	-0.252
	grass	-0.238	0.144	0.238	-0.024	0.095	0.072
species diversity	# bulb	-.976***	.344	.024	-.600	-.317	-.393
	# cryptogam	-0.647	0.639	0.299	-0.43	-0.06	-0.096
	# succulent	-0.31	-0.108	-0.571	0.244	0.024	-0.515
	# forb	-0.595	0.683	0.262	-0.268	0.31	-0.275
	# grass	-0.143	0.275	0.19	0	0.262	0.06
* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$							

The quadrat-level variables of slope and aspect both had large, negative associations with soil pH (*rho* = -.760, $p < .05$, $n = 8$; *rho* = -.768, $p < .05$, $n = 8$) which suggests that pitched roofs often had lower pH values or, vice versa, that flat EGRs with no particular aspect often had higher pH values (**Table 2.11**). In terms of soil nutrients, slope and aspect both had large, positive associations with soil phosphorus (P) (*rho* = .775, $p < .05$, $n = 8$; *rho* = .751, $p < .05$, $n = 8$), which means that pitched roofs often have higher P levels. Closer examination of site conditions are required if the results for aspect are to be interpreted. Species-level responses to substrate variables, including depth, will be examined in the chapters that follow.

Table 2.11. Results from Spearman's rank correlation (*rho*) relating substrate variables with slope (n=8), aspect (n=8) and shade (n=118).

	slope	aspect	shade
C_{org}	0.504	0.514	-.006
pH	-.760*	-.768*	-.108
N	-0.630	-0.592	-.260**
P	.775*	.751*	-.288**
K	-0.126	-0.218	-.235*
Mg	-0.253	-0.204	.377***
* $p < 0.05$ ** p < 0.01 *** p < 0.001			

2.4 Discussion

2.4.1 Distinguishing plant growth forms: different approaches

In retrospect, other approaches to distinguishing plant growth forms could have lent a greater degree of detail to some of the descriptions made by these surveys, in particular within the bryophytes and within the forbs. Glime (2015) suggests that the classification of bryophytes as acro- or pleurocarpous is "somewhat analogous to Raunkiaer's system" (4-5-3), these terms implying individual shoot architecture and colony form or structure of different bryophytes. **Acrocarpous** species are usually unbranched or sparsely branched and generally upright, with the sporophyte at the apex of a stem or main branch and with terminal sporangia. **Pleurocarpous** species, on the other hand, are typically prostrate and form freely branched mats producing sporangia on short, specialized lateral branches or buds (Glime, 2015). Regrettably, these distinctions were not familiar to the author at the time of sampling but should be included in future work.

Similarly, the growth form defined as "forb" could have been distinguished further into perennials and annuals. Within the Raukiaer system, annuals are described as "therophytes" and are associated with conditions of drought and open grassland. Although many of the spontaneous colonizers of the roofs surveyed were recognized to be annual, they were not distinguished from perennial forbs in the methodology. As with the bryophytes, future work should undoubtedly include this distinction. Indeed, the role of annual species to EGR vegetation became a point of interest within the literature during the time of this research (Nagase and Dunnett, 2013, Nagase et al., 2013, Van Mechelen et al., 2014a, Van Mechelen et al., 2014b).

2.4.2 Treatment of aspect, slope and shade

The variable of aspect can pose statistical issues to quantitative field studies, and a variety of mathematical and technical approaches have been developed for this and its influence on other variables. These issues were unfortunately not known to the author at the time of field surveys, nor were mathematical equations considered, but integrating such quantification into future work of this nature may prove useful.

Taken together, the quadrat-level variables of slope, aspect and shade can yield a proxy to solar radiation that, when combined with latitude, can yield estimates of incident radiation and heat load index. The aspect of a slope can be defined as the direction (or azimuth) that the slope faces and will strongly influence potential direct incident radiation and temperature (McCune and Keon, 2002). For example, an unshaded roof on a northeast-southwest axis will experience warmer temperatures on the southwest aspect because afternoon sun produces higher maximum temperatures than the equivalent slope with morning sun. McCune and Keon (2002) propose an equation for approximating heat load, with aspect rescaled to a scale of zero (coolest, northeast) to one (warmest, southwest):

Heat load index: $\frac{1-\cos(\theta-45)}{2}$

where Θ = aspect in degrees east of north.

However, a 1° south-facing slope will receive the same heat load as a 30° south-facing slope, yet the latter would be considerably warmer, so an equation is required which considers the steepness of the slope. McCune and Keon (2002) provide a useful starting point for such calculations. A methodological approach, the sky-view factor (ψ_s) can be used to characterise the shade of neighbouring buildings or vegetation on a site. Although originally developed for assessing the spatial variability of urban areas, like the geometry of urban canyons (Grimmond et al., 2001), methods for calculating the sky-view factor could easily be adapted for green roof ecological surveys.

2.5 Conclusions

The findings from these preliminary analyses serve as a first step towards answering the research question about successional change, and towards the aim of characterising mature EGR vegetation. The work from this chapter has therefore prepared the ground to address these along with other questions and aims in the chapters that follow. From the basis of the preliminary analyses here, it may be hypothesized that the main drivers behind vegetation change on EGRs include the abiotic growing conditions of the roof environment, such as slope and aspect, as well as substrate depth. There are probably also dynamics occurring between the growth forms.

2.5.1 Vegetation dynamics

Most growth forms related significantly in cover with their own species diversity, with the single exception of succulents, which lacked significant relationships with their own diversity and with cover by other growth forms. Visual observations substantiated these results; succulents dominated the vegetation of all the roofs surveyed and often created extensive cover with only a few species. Some Sedums, like *S. album*, exhibit Crassulacean Acid Metabolism (CAM), which allows them to avoid water stress by switching their carbon metabolism to the CAM pathway (Sayed, 2001). When induced by water stress, CAM plants can keep their stomata closed during hot days to reduce water loss, then open again in the cooler evening to take up nocturnal $CO_{2,}$ and decarboxylate it during the day for photosynthesis (Black and Osmond, 2003). When water is available *S. album* can assimilate carbon following the C_3 pathway, but then switch to CAM when drought occurs (Black and Osmond, 2003). Still, in spite of this faculty, this plant was lost from the Rathausgarage roofs. Other known CAM plants encountered on these old roofs include *S. acre*, *S. telephium* and *S. rupestre (alias S. reflexum*) (Sayed, 2001), some of which did not persist either. CAM plants have slow growth rates relative to C_3 and C_4 plants (Black and Osmond, 2003), and typically qualify as S-strategists under CSR theory (Grime, 1974).

On a similar note, the exception of succulents (from other growth forms) of declining cover abundance and species richness over time merits further reflection into the dynamics occurring on EGRs over time. In addition to their well-suited life strategies, as described already, these results suggest that succulents are immune to some of the pressures that influence the other growth forms. The possibility that substrate depth declines over time, for example, would impact roof vegetation in favour of taxa that are shallow-rooting and able to access the resources they need from minimal soil volumes. Exposure of the roof environment to atmospheric deposition and air pollution could, equally, favour this life form over other taxa. To elaborate on these possibilities, closer examination of substrate properties over time, including depth, will follow in later chapters.

2.5.2 Roof vegetation, time (roof age) and abiotic/ environmental conditions

Extensive green roofs are subject to harsh environmental conditions and green roof vegetation typically receives little protection from solar radiation, wind, or precipitation and the shallow, mineral substrates offer very little buffering capacity from extreme temperatures, frost, drought, or other. With consideration of the growing conditions on extensive green roofs (Köhler and Poll, 2010, Köhler, 2006, Köhler, 1990), and based on our understanding of urban vegetation change over time (Kowarik, 1990, Pysek, 1993, Trepl, 1995, Chocholouskova and Pysek, 2003, Pysek et al., 2004, Knapp et al., 2010), these results suggest that cover and diversity of growth forms on EGRs decline over time. In other words, older roofs support extensive cover by fewer growth forms and fewer individual species, while younger roofs would have more diverse cover, both for growth forms and species.

The only growth form that responded significantly to roof age was grass, as well as a subdued response by cryptogams. The latter dynamic would be problematic if true, since EGRs are shallow to begin with. Much green roof research substantiates this relationship between grass cover and diversity with substrate depth, which (Monterusso et al., 2005, Nagase and Dunnett, 2013, Dunnett et al., 2008, Schroll et al., 2011, Krupka, 1985).

However, grass cover and diversity also responded significantly to substrate depth, which was negatively correlated with roof age. Substrate depth also had significant effects with slope and aspect and with species diversity of all growth forms except succulents and grasses. A study in Michigan USA found that different exposures to sunlight influenced soil moisture content and chlorophyll fluorescence of some green roof plants, which would clearly influence plant performance (Getter et al., 2009). In their study of native species for EGRs in maritime Canada, MacIvor and Lundholm (2011) suggest that solar radiation should be included as an important covariate for studies examining plant and green roof performance. On two old EGRs in Berlin, Köhler (2006) found that floristic species diversity was significantly affected by weather-related factors, like temperature and precipitation, and that it could be increased through enhanced initial plantings and the provision of microclimates (e.g., shaded areas). The complexity of these responses will be deconstructed and these effects examined more closely in ensuing chapters.

3 Classifying mature EGR vegetation into types

The preliminary analyses of the previous chapter identified that the composition of mature EGR vegetation is affected by a variety of conditions, often in combination. Of the variables measured, the mechanisms driving EGR vegetation dynamics over time include abiotic variables like substrate depth, slope and aspect. Although climatic variables were not measured, factors such as temperature and precipitation patterns undoubtedly influence vegetation dynamics, too. The preliminary characterisation of mature EGR vegetation in terms of growth form cover and species diversity indicated that succulents and grasses behaved differently from the other growth forms. Succulents were the only growth form that did not relate significantly in cover abundance with its own species diversity; grass cover and diversity were the only significant relationships with substrate depth. Yet substrate depth had a significant negative relationship with roof age, and depth in turn had significant associations with slope and aspect. Given the exceptional and strong responses by succulents and grasses, closer examination of these growth forms may grant some insight into EGR vegetation dynamics.

3.1 Literature Review: plant community ecology of green roof vegetation

This chapter reviews the main factors directing plant community formation as identified for green roofs and other ecosystems. The results will consider species-level dynamics, including presence/ absence of species from original lists, as well as colonising species. It therefore builds upon the results from the previous chapter by considering the abundance of persistent species along with the abundance of colonising species. What role do unintentional species (ruderals, weeds) play to the long-term diversity of EGRs; how prevalent are they? Are certain colonising species impossible to exclude, inevitably forming an important component of green roof plant communities? Is there a roster of cosmopolitan volunteers (i.e, weeds) that inevitably colonise every green roof, regardless of where or when it was installed? This will further inform the question of the drivers and mechanisms of successional change on EGRs, and support the continued characterisation of mature EGR vegetation.

With respect to the two growth forms that responded so uniquely from the others, this chapter will characterise them ecologically and thereby expand the research aim of characterizing mature EGR vegetation. Based upon these species-level characterisations, the chapter will begin to consider the research question of whether emergent community characteristics result on EGRs with time. To this end, the characterised vegetation will be re-configured by roof and grouped according to similarities/ dissimilarities.

3.1.1 Factors in green roof plant community formation

As might be expected, no single factor was deemed key to plant community development, but rather a variety of factors in combination, including roof age, substrate depth, accessibility, maintenance/ intensity of use, moisture, shade, slope, aspect, and history of the roof. The loosely similar communities identified for spontaneous gravel roofs could be due, on the one hand, to the similar local substrate used on the roofs per region and the seed bank contained therein. On the other hand, if the exogenous factors on roofs are consistently inhospitable, it is plausible that the vegetation is held in a sort of ‘early successional sere’. Rather than the climax of traditional succession theory, the processes on roofs can perhaps be better described by the edaphic (soil) and biotic (often anthropogenic) plagioclimaxes, whereby community development is deflected or arrested by limited soil depth and/ or human intervention, as per Tansley (1958).

The “Typical Poa meadow” was classified as a climax community for spontaneously vegetated gravel roofs because it seems to be stable for decades at a time (Bornkamm, 1961, Darius and Drepper, 1983, Bossler and Suszka, 1988, Thommen, 1988, Buttschardt, 2001). In Göttingen, Bornkamm observed that this meadow community would attain cover dominance on undisturbed, unshaded roofs with at least 100 mm gravel, and that completely closed cover will occur in around 120 mm. This community exhibited exceptional cover by higher plants, most of which die back in summer. Species richness was augmented with weedy annuals through the provision of shade as well as shallower depths. In depths under 100 mm, the grass loosened into a weedier meadow comprising *Bromus tectorum, Setaria viridia* and *Eragrostis minor* which thrive in 50 to 120 mm (Darius and Drepper, 1983, Thommen, 1988). Buttschardt (2001) suggested that the communities of TPG roofs in Karlsruhe developed after 30 to 40 years, and that establishment of the characteristic species took between 10-30 years. He also pointed to variability and the short-term nature of these communities as a result of limited propagule inputs and inevitable fluctuations in environment and growing conditions. If the more demanding species of dry meadows are envisioned for green roofs, and propagule source habitats are not present in the surrounding areas, then seed should not be spared in the installation, and additional seed would bolster the seed bank (Riedmüller, 1994, Buttschardt, 2001).

3.1.1.1 Persistence and regeneration

Persistence and regeneration within any plant community can be at least partially attributed to seed bank and seed rain. Seed rain is basically the external input of propagules to a plant community, and seed banks are populations of seeds in the soil that can persist for periods ranging from a year to decades, depending on the species (Roberts and Feast, 1973, Silvertown, 1981, Templeton and Levin, 1979). Soil seed banks are dynamic systems of inputs and losses (**Figure 3.1**) that include inputs from local and distant sources as well as human introductions. Seed banks hinge on the expression of dormancy in the soil (Luken, 1990), and losses occur through seed predation, physical destruction, and decay (Harper, 1977). Common environmental treatments that break seed dormancy include access to light and oxygen, soil disturbances, and periods of cold or of mechanical damage (Burrows, 1990, Luken, 1990). A number of seed bank oriented successional studies have shown that species in seed banks are often not present in the vegetation (and vice versa, that species in the vegetation may not be represented in the seed bank), suggesting that fundamental differences exist in the abilities of species to regenerate from seed stored in the soil (Grubb, 1977, Rebele, 1992).

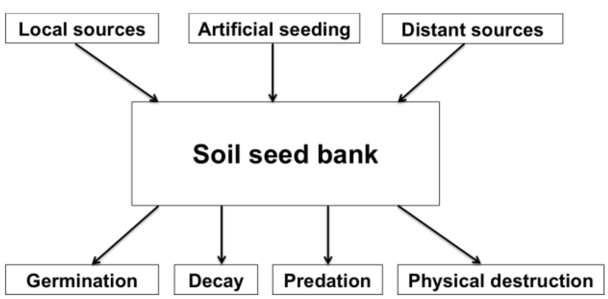


Figure 3.1. Feedbacks and dynamics of soil seed banks. Modified from Luken (1990: 41).

Early successional species (i.e., ruderals) produce large numbers of small seeds and form persistent seed banks, which are stimulated to germinate by high and fluctuating temperatures and light that is not filtered by a plant canopy (Fenner, 1987). By contrast, competitive species like late-successional, shade-tolerant trees express little delay between dispersal and germination, lack well-developed dormancy and do not develop persistent seed banks (Canham and Marks, 1985). Unlike R- and C-strategists, stress-tolerators rely less on seeds and more on vegetative expansion for their regeneration since attachment to the parent reduces mortality risk for offspring (Grime, 2001). Propagule availability and environmental conditions must be well matched in order to balance the complexity of seed response with environmental stimuli. Even if germination has been successful, ensuing plant growth requires resources and protection from destructive factors (Harper, 1977).

3.1.1.2 Colonisation and seed rain

Seed rain represents colonization through spatial dispersal, or the arrival of vegetative or sexual propagules from locations outside of a site (Brown, 1992). The seed rain reaching a site depends on the proximity and numbers of parents contributing seed as well as their fruiting period, not to mention the agents of dispersal (e.g., wind, insect, bird, mammal) (Burrows, 1990) (p. 361). Animals disperse seeds physically and intestinally, and human-dispersed species, also known as weeds, include agrarian and ornamental escapees. Wind-dispersed seed, which typify ruderal strategists, are smaller and lighter compared with other forms of dispersal and often bear attributes to assist floating, like achenes. Wind-dispersed species are more frequent in urban than agricultural habitats, which may be due to fragmentation and the dynamic nature of urban landscapes (Lososova et al., 2006).

Given their physical disconnect from other vegetated areas both in elevation and by urban infrastructure, seed dispersal on EGRs is largely limited to wind- and animal- dispersed species, though human-dispersal is also a prevalent source. A survey of ninety vegetated roofs in Karlsruhe found that a third of the vegetation (34%) was wind-dispersed and animal-dispersed (32%), and the other third was human-dispersed (14%), self-seeded (6.8%), and rain-dispersed (12.6%) (Buttschardt, 2001)(p. 83, 99). An experiment studying colonization patterns across two depths of planted green roof subplots in Sheffield (UK) found that wind-dispersed colonization yielded greater total biomass in 200 mm but that the shallower depth (100 mm) supported greater proportions of weeds, both wind- and animal-dispersed, as well as higher species-richness, diversity and biomass (Dunnett et al., 2008). Compared with the deeper depth, the shallower depths presumably offered fewer resources for planted species, making them less vigorous and thereby leaving open spaces for weedy species to colonize.

In northern France, Madre et al. (2014) identified 176 colonizing vascular plant species on 115 green roofs. The majority were common urban species, of which 86% were native and a few even had protected status in that region. Similar to the Sheffield study, and corroborated by work in Berlin (Köhler and Poll, 2010), substrate depth played the most important role in species diversity of spontaneously colonizing plant species. The functional composition of spontaneous vegetation on green roofs may also be shaped by maintenance intensity, building height, and green roof age (Madre et al., 2014). The same French study found that the diversity and community composition of spontaneous green roof species were not noticeably affected by habitats occurring nearby, probably due to the type of habitats and the conditions on the roof. A sterile landscape of mown lawns and ornamental planting beds will not deliver as many propagules as one supporting species-rich meadows and naturalistic, multi-structured habitats.

3.1.2 Classifying EGR vegetation into recurring types: emergence?

To date, the classification of EGRs into vegetation types has largely been based upon their construction, specifically the vegetation that can be expected for certain substrate depths. The FLL (2008) specifies several types, with EGRs as the most lightweight system of which the vegetation is defined by shallow growing substrate depths and low maintenance. Intensive green roofs are permitted on buildings with greater structural loading are often designed for aesthetic interest and physical access, such that greater depths support a great diversity of vegetation, including trees and shrubs. Semi-intensive green roofs classify between extensive and intensive systems in terms of weight, substrate depth, maintenance, and species selection. As an alternative to these classifications, practitioners in the US have developed the “comprehensive green roof”, which unites the attributes of intensive and extensive system in order to improve the resiliency and function of green roofs in the more extreme climate of the American Midwest (Meyer, 2014).Recent work has attempted to classify roof vegetation on the basis of ecological principles. For example, a green roof ecological typology was proposed on the basis of a survey of spontaneous vegetation on 115 green roofs in northern France (Madre et al., 2014). Similar to the results of this and other studies (Köhler and Poll, 2010) the French researchers found that species diversity of spontaneous vegetation was significantly influenced by roof age and substrate depth, with small effects from surface area, building height and maintenance intensity. They proposed using a stratum classification approach, which describes the changes in ecosystems over time (e.g., accumulation of soil organic matter) through the layers of vegetation (Bournerias, 1979). A vegetation type under this system is named according to the upper stratum that represents more than 20% of the total area of vegetated cover (and which includes the strata of the lower classes). The three ecological types proposed by these authors for extensive green roofs include:

- **Muscinal stratum**: composed of cryptograms, fungi and small herbaceous plants including creeping succulents (like Sedum);
- **Herbaceous stratum:** dominated by (non-woody) herbaceous flowering plants and grasses that can exceed 1 meter in height at maturity;
- **Arbustive stratum:** woody species (shrubs, young trees) from 1 to 7 meters high;

In this classification, the muscinal stratum is equivalent to extensive green roof, the herbaceous stratum to semi-intensive, and the arbustive stratum to simple-intensive green roof. While this approach is helpful to awakening the notion of treating green roofs as functional ecosystems, the classification framework proposed does not allow for the characterisation of different types of plant communities within each stratum. Also, the terminology does not facilitate understanding that these hierarchical strata may be nested within each other. Just as phytosociology is perhaps too specific for green roofs, this stratum method may be too vague.

With the aim of quantifying the functional diversity of different green roof systems, a study in Belgium allocated a total of twenty-nine trait values to the species lists of 57 commerical green roof systems (Van Mechelen et al., 2015). Resonant with most (if not all) ecological green roof studies, the latter found that green roofs with deeper substrates supported the greatest plant diversity; accordingly, deeper roofs also supported the highest functional diversity. Clustering the 57 roof systems resulted in three types, each characterized by a number of significant indicator species and attributes. The "*Sedum* type" (22 systems) has the shallowest depth (50 mm on average), features succulent species installed mainly by cuttings or mats, and has significantly lower species richness than the other two types. The "*Dianthus-Thyme* type" (27 systems) occurs on depths of around 90 mm and, installed by seeding, features diverse taxa including *Sedum*. Lastly, the "*Linaria-Galium* type" (8 systems) has similar depths and species richness to the latter but is installed mainly by plugs and features a near absence of succulent species. Being limited to lists of initial species composition, field research is needed to advance the results of that work from theory to practice.

Having been informed that the EGRs surveyed for this reseach had not been maintained for several years, one research question that arose inquired whether emergent community characteristics could be detected. The concept of emergence implies that the properties of a species assemblage cannot be entirely explained by its individual components (Mayr, 1982). Uncertain of what the fieldwork would reveal, the philosophical basis of this question placed observation and description first, such that the possibility of discerning underlying processes could potentially lead to theory. This approach is contrary to mainstream scientific practice, which has traditionally created theory first (Ponge, 2005). In terms of the roofs surveyed, emergent properties might be defined as convergence (or divergence) of species assemblages, which could result if the patterns, processes and interactions on all EGRs lead to similar (or different) outcomes. This could be measured at various levels, whether species diversity and species assemblage, proportionate cover by different growth forms, or other. If mature EGR vegetation expresses consistent characteristics on different roofs regardless of location, supplier, installer, etc., then a degree of complexity greater than the effect of individual species could be described as emergence. By contrast, emergence would not apply if all EGRs support completely unique vegetation.

3.1.3 Research aims and questions

This chapter continues to refine the research questions and aims of the previous chapter, and also undertakes the question of emergence, which can be condensed into three specific objectives.

- **Aim**: To characterize mature EGR vegetation in terms of LF cover abundance and species diversity
- **Question**: If successional change can be observed on EGRs, what are the main drivers & mechanisms?
- **Question:** Do emergent characteristics result with time?

3.1.3.1 Objectives of the chapter

The objective for this chapter is to classify the EGR vegetation surveyed according to similarities/ dissimilarities, and applies different analyses to extract any patterns.

- To determine species persistence and loss on EGRs after more than 20 years
- To characterise EGR vegetation: grasses and succulents
- To classify EGR vegetation into communities or vegetation types

3.2 Methods

The methods of data collection will not be repeated, but the methods and approaches taken for the analyses are outlined. All statistical tests used the software package SPSS versions 19-22 (IBM, Inc.)

3.2.1 Data analysis

3.2.1.1 Defining persistence and colonisation

Documentation and background information were available for a few of the roofs surveyed (Tübingen, Stuttgart roofs), and will be used to enhance the snapshot surveys in evaluating EGR vegetation development. Technical documentation for some of the roofs was available from ZinCo in the form of sale offers, technical drawings or roof summaries, and staff from some of the buildings had retained original documentation in the form of invoices, drawings, and correspondences. Species lists were limited to sales offers or footnotes from architectural plans. Granted, without final invoices there is no guarantee that the materials specified were used, particularly since species lists may be revised at the last minute with substitutions (personal experience). Still, since the EGRs are assumed to line up with industry standards, we can also assume that their species lists are relatively consistent.

Certain assumptions were therefore made to form a basis from which to understand how the vegetation may have attained its current composition. Given the original species lists that were available, and the knowledge of typical EGR plant lists, "intentionality" was defined as a confident, if rudimentary, metric for characterising EGR vegetation. **Intentional species** are defined as having been on the original plant lists, or are assumed to have been planted or sown. It is highly likely, for instance, that typical green roof plants (*e.g., Achillea millefolium, Campanula rotundifolia, Dianthus spp, Sedum spp.*) were intentional and have therefore persisted over time. Intentional grass species, according to original documentation, include *Agrostis tenuis, Festuca ovina, F. rubra, Poa compressa, P. angustifolia* and *Setaria viridis*.

Non-intentional species, by contrast, are those that are able to colonise and self-establish through dispersal mechanisms, like wind-blown seed. Cryptogams like mosses and lichens are highly mobile growth forms because of their spore-based reproduction (Doyle, 1970). In addition, it is unlikely that tree seedlings or wind-dispersed ruderals (e.g., *Convolvulus arvensis, Erigeron annuus, Medicago lupulina, Taraxacum agg.*) were intentionally planted or sown. Grass species absent from the species lists and likely colonisers include *Agrostis stolonifera, Arrhenatherum elatius, Poa angustifolia, Vulpia myuros*. The distinctions of intentional/ non-intentional are given in the master species list of **Appendix 2**.

3.2.1.2 Characterising grasses and succulents

Grasses are adaptable and variable growth forms that occupy a wide range of habitats, soil types and climatic zones, including nutrient-rich agrarian landscapes, salt marshes, semi-arid plains and harsh alpine crags (Hubbard, 1992, Burrows, 1990). By contrast, the succulents most frequently used on EGRs, from the Crassulaceae, are hardy perennials of well-drained sites and usually originate from habitats typified by limited moisture and direct exposure to solar radiation (Stephenson, 1994, Snodgrass and Snodgrass, 2006). On the basis of the ecological distinctions between these growth forms, different approaches are used to characterise them.

3.2.1.2.1 Method for characterising EGR grasses

Given the range of ecological niches that grasses can occupy, not to mention their plasticity (Hubbard, 1992), and considering that EGRs are especially susceptible to stress and disturbance, which are two of three selective forces directing a plant's adaptive strategy (i.e., CSD equilibrium), allocating CSR signatures to grasses can help to characterise their ecology, habitat, and their role to mature EGR vegetation. CSR theory was introduced in Chapter 1 as a coherent and predictive a model for natural succession, but it can also give insight into the properties of a habitat through the life history traits and phenologies of the species living there (Grime, 2001). From a reference list of ca. 1,000 European species allocated with CSR signatures, each grass species identified was ascribed with an adaptive life strategy (Hunt et al., 2004). In cases where an EGR species was not on the reference list, the signature of its nearest equivalent (from the basis of taxonomic and ecological similarity) was used. This occurred only in the case of *Agrostis tenuis*, for which the nearest equivalent chosen was *A. canina*.

3.2.1.2.2 Method for characterising succulents

Since the succulents typical of EGRs can create extensive cover with only a few species/ cultivars, usually reproducing vegetatively, cover abundance by proportion with the cover of other growth forms is a practical measurement for assessing their role to mature EGR vegetation. In order to evaluate the role of succulents to the EGR vegetation sampled, the mean cover values that were estimated per growth form per quadrat were re-calculated as proportionate to 100% total cover (**Table 3.1**). So, while the analyses of the previous chapter(s) represented the vegetation as over-lapping layers, this analysis has the advantage of removing the overlap above low-growing spreading succulents by taller statured forbs, grasses and any woody species.

Table 3.1. Comparing cover by succulents/ quadrat in (versus not) in proportion with other growth forms.

	Mean succulent cover/ quadrat		**Standard Deviation**	
Roof name	**Non-proportionate**	**Proportionate**	**Non-proportionate**	**Proportionate**
FH Nürtingen	6.50	19.73	6.03	39.80
Köngen	40.50	55.72	18.93	49.67
Pliensau	50.07	96.74	22.37	17.77
Tübingen	26.12	56.92	6.12	49.52
VB A1	27.34	33.41	7.88	47.17
VB A2	15.15	17.58	5.15	38.06
Rathaus-PV	33.52	42.80	9.14	49.48
Rathaus-lower	23.27	34.55	9.12	47.55
Killesberg	26.08	38.18	13.40	48.58

A comparison of the two datasets (not proportionately corrected versus proportionate) illustrates that around 20% of the original data is not explained (R^2=0.79202). Re-configuring succulent cover proportionate to 100% with the other growth forms can therefore elucidate some differences not yet addressed by the role of succulents to EGR vegetation. The upper right quadrant of **Figure 3.2** represents EGRs with both high succulent cover and a high proportion of other growth forms. The data point in that corner, for Pliensaufriedhof, illustrates that succulents had the most cover overall (mean: 50.7% ± 22.37) yet, when calculated in proportion with other growth forms, succulent cover was nearly 100% (mean: 96.74% ± 17.77). The absence of data points at the top left of the graph mean that bare soil was not observed on the roofs surveyed, while the bottom right implies that no roofs had high cover by succulents and low proportion of other growth forms. The lower left quadrant represents roofs that had low succulent cover and a low proportion of other growth forms. The lowest two points (FH Nürtingen and VB Area 2) had low succulent cover whether proportionately corrected with other growth forms (mean: 19.73% ± 39.80; 17.58% ± 38.06) or not (mean: 6.50% ± 6.03; 15.15% ± 5.15) (resp.).

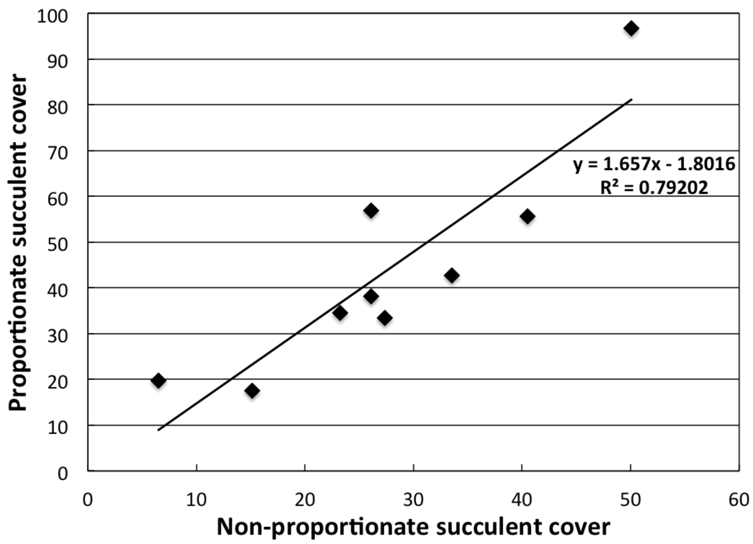


Figure 3.2. Re-configuring succulent cover proportionate to 100% with the other growth forms explains more about this growth form than the original, not proportionately corrected data (R^2=0.79).

In order to determine if there was a significant difference in proportionate cover by the six growth forms on the nine roofs surveyed, a Related-Samples Friedman's Two-Way Analysis of Variance by Ranks was conducted. This non-parametric test was used because the sampled populations are not normally distributed.

3.2.1.3 Method for classifying EGR vegetation types: cluster analysis

Using the data re-configured by the analyses above, the nine EGRs surveyed will be grouped according to (dis)similarities in their vegetation composition. Cluster analysis is a multi-variate statistical technique for grouping objects based on calculations of all the inter-object (dis)similarities (Willett, 1988, Krzanowski, 2000, Divjak and Fieller, 2014). Clustering methods are heuristic, or experience-based, techniques for problem solving and discovery but, though the groups created take reference to some concept of "what a group embedded in some space should be like" they cannot usually refer to the processes occurring in the field (Legendre and Legendre, 2003) (p. 306). The hierarchical formation of clusters is illustrated with a dendrogram model. If the EGRs sampled can be satisfactorily distinguished into groups, then this may support the classification of different EGR vegetation types and inform the research question of whether emergent properties arise on EGRs.

Specifically, the nine EGRs were clustered based on proportionate life form cover using hierarchical clustering and average linkage. Agglomerative ("bottom up") algorithms were used whereby each observation begins in its own cluster and the groups gradually emerge further up the hierarchy. The resulting polythetic classifications allow each roof in a cluster to have some, or many, terms in common with each of the other roofs in that cluster, but without any specific terms required for cluster membership (Divjak and Fieller, 2014). Ward's method was used because it is known to give a reliable result for uncertain analyses. Ward's allows two clusters to merge "if the increase in sum of squared distances of the members of the new cluster from their mean is smaller than for any other possible merger between two clusters" (Divjak and Fieller, 2014, p. 426). The use of squared distances "penalises spread out clusters and so results in compact clusters without being as restrictive as complete linkage" (*ibid*).

3.3 Results

3.3.1 EGR species composition after 20-30 years: persistence, loss and gain

As per the methods and materials described above, the abundance data from each roof was re-calculated at the level of quadrat (i.e., sampling plot) for the proportion of persistent (intentional) versus colonising (non-intentional) species coverage per roof. Most roofs had between 60 and 95% cover by intentional species (**Table 3.2**). Maximum coverage by intentional species for all roofs was upwards of 86%, of which three roofs had at least one quadrat with 100% coverage by intentional species and five others had quadrats with over 90%. Minimum coverage by persistent species was generally above 50%, although one roof (FH Nürtingen) had a minimum of 32% cover on one quadrat. Most of the roofs surveyed had more than 70% mean cover by intentional species with a moderate range across quadrats. The high mean values can be attributed to the Sedum basis of all roofs, and the range may indicate the conditions that permit a diversification of vegetation, whether slope, aspect, depth, or other.

Table 3.2. Proportion and cover (%) by intentional species for nine EGRs after 20-30 years.

Roof name (in order of age)	Total # species	Intentional species (%)	% cover abundance that was intentional		
			average plot	min.	max.
Killesberg	23	57	75.7	59.6	92.3
Rathaus-PV	26	62	77.5	64.9	94.0
Rathaus-low	30	47	69.8	52.8	86.4
FH Nürtingen	32	41	66.5	32.0	93.6
Köngen	9	56	89.7	55.0	100.0
Tübingen	21	67	89.3	74.7	99.5
VB A1	21	57	88.7	68.3	100.0
VB A2	21	62	78.1	63.6	94.7
Pliensau	11	36	96.5	81.6	100.0

FH Nürtingen (FH Nue) stands out from the other roofs with the largest range (32 to 93.6% cover) (**Figure 3.3**). This variation is most certainly due to the range of conditions across this roof and the opportunities presented to different species. In particular, one edge of this roof touched the wall and occurred under the drip zone of that adjoining roof, which created shaded, mesic conditions that supported (unintentional) species not found on any of the other EGRs, including mosses (*Polytrichum juniperum, Eurhynchium praelongum, Philonotis fontana*), forbs (*e.g., Geum urbanum*), and a colony of orchids (*Dactylorhiza fuchsii*). The opposite edge of the same roof had an unusually shallow substrate that supported hardy xerophytes including (unintentional) mosses and lichens (*e.g., Racomitrium elongatum, Cladonia spp*).

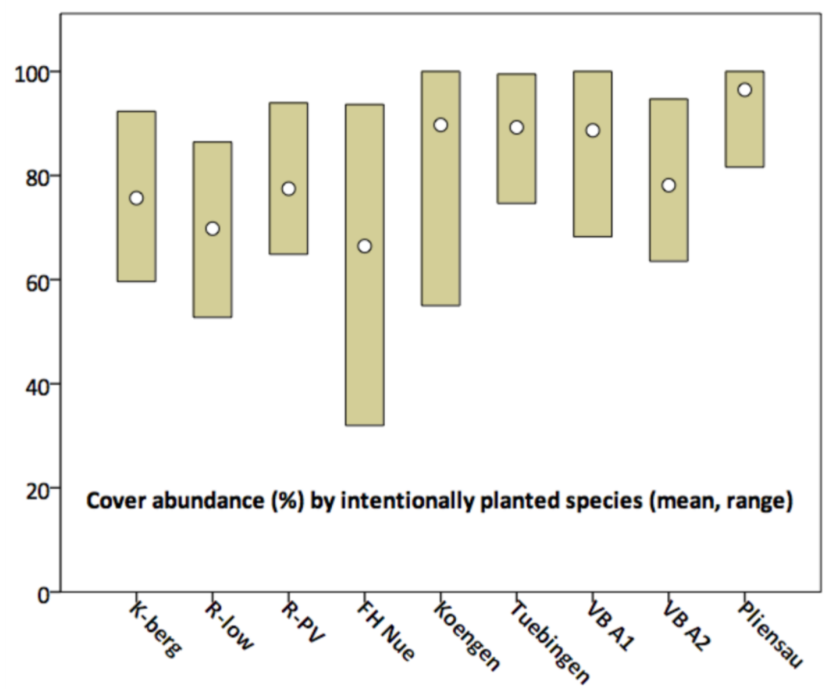


Figure 3.3. Mean cover abundance (%) by intentional species for nine EGRs, as well as range.

The two roofs with the highest cover abundance by intentional species, Köngen and Pliensau, also recorded the fewest species, which were dominated by Sedums. For Köngen, the large range of intentional versus non-intentional species cover may be attributed to the range of conditions provided by the two pitched roofs; while the north-face supported tall grasses and herbs, as well as a moss (*Calliergonella cuspidata*) typical of moist, base-rich habitats (British Bryological Society, 2015), the south-face was xeric and Sedum-dominated. Mean cover (%) by intentional species per quadrat on this roof was quite high – almost 90% –because the (intentional) Sedums maintained an extensive ground cover. Similar to

Köngen, Pliensaufriedhof in Esslingen had a very high mean cover (96.5%) by intentional species due to dominance by Sedum species. The tiny range here is attributed to the small species list on a homoegenous roof area; other than three species of Sedum and a patch of *Teucrium chamaedrys*, the survey recorded single individuals of *Convolvulus arvensis,* an unknown *Geranium* species, an unknown herb, a couple occurrences of *Hieracium pilosella, Taraxacum agg,* and *Vicia sepium*, and a few *Pinus* seedlings.

The other six roofs are somewhat more consistent in the mean and range of cover by intentional species. The Gärtnereihof Tübingen had extensive Sedum ground cover diversified slightly by the 15° slope and the north-south gradient. The two roofs at Esslingen Verkehrsbetrieb (VB A1 and VB A2) were apparently installed with identical materials and species within days of each other, as were the three Stuttgart roofs (the Rathausgarage complex within days; Killesberg a year later). Non-intentional species on these six roofs included between two and seven species of cryptogams (lichens, mosses), a few individuals of weedy herbs (*e.g., Crepis tectorum, Hypericum perforatum, Potentilla argentea, P. recta, Picris hieracioides, Taraxacum agg, Trifolium spp, Verbascum spp*), a fine-leaved annual grass (*Vulpia myuros*) and a few tree seedlings. In spite of their similarities, these roofs recorded varying numbers of species and of intentional and colonising species.

By contrast to the mean cover values discussed above, percent cover by intentional species is much less in relation to number of species (**Figure 3.4**). This graph shows a sort of polarisation of extremes, in which the roofs with either the most or the fewest species also had the lowest cover by intentional species. In spite of their domination by Sedum, cover by intentional species on the two species-poor roofs accounted for less than 40% (Pliensau) and just under 60% (Köngen). At the right of the graph, FH Nürtingen is apparent with its thirty-two species, of which around 40% were intentional. Stuttgart Rathausgarage lower roof had thirty species, of which just under 50% were intentional. These extremes contrast quite clearly with the five other roofs, which had between twenty-one and twenty-six species and higher cover by intentional species, between 55-70%.

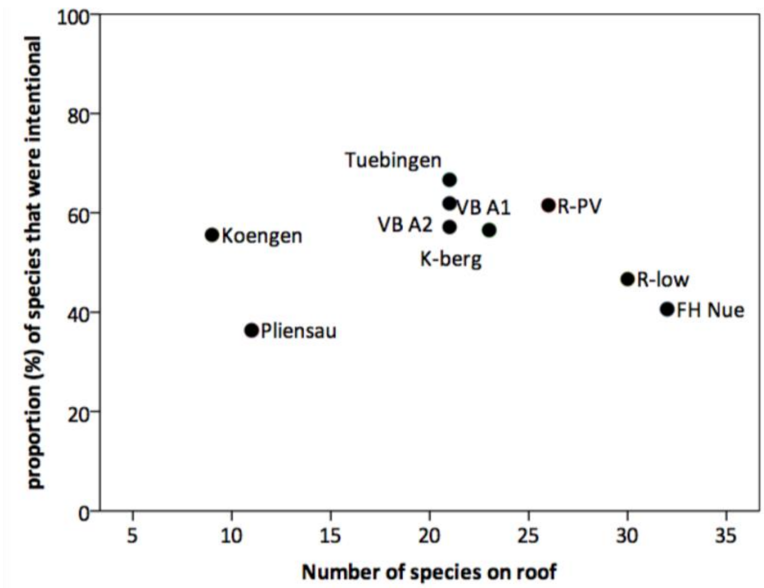


Figure 3.4. Number of species and the proportion (%) that was intentional and persisted on nine EGRs > 20 years.

In order to portray the composition of intentional/ non-intentional species, two roofs with original species lists shall be investigated more closely. As mentioned in the methods, if species from original lists did not appear in the quadrat sampling, whole-roof reconnaissances were conducted to confirm presence or absence.

3.3.1.1 Gärtnereihof Tübingen

The twenty-one species recorded at Gärtnereihof Tübingen included half (twelve) of the original list (total 24 species) while nine of the species observed were not on that list (**Table 3.3**). Of the fourteen species that persisted, six of the eight succulent species maintained extensive cover, in particular *Sedum floriferum, S. hybridum* and *S. sexangulare,* which were recorded in nearly all of the sixteen quadrats sampled. The other eight persistent species are relatively common on EGRs, especially *Dianthus deltoides, Festuca ovina, F. rubra* and *Hieracium pilosella, Petrorhagia saxifraga* and *Thymus praecox*, though most were found in fewer quadrats than the persistent succulents. The twelve species from the original list that were not found in the 2010 surveys included three succulent species (*S. acre, S. cauticolum,* and *Sempervivum spp*.) and two cultivars of *Festuca rubra.* Cultivated form or not, the *F. rubra* identified in 2010 did not form a visible component of the vegetation and was only found in three of the sixteen quadrats. The other lost species are otherwise commonly found on green roof plant lists (*Achillea millefolium, Sedum acre, Sempervivum spp.)* or occur in analogous habitats, like dry meadows (*Daucus carota, Origanum vulgare*) or in disturbed, anthropogenic habitats (*Lolium perenne, Matricaria chamomilla*). It's possible that these species were extirpated by an event, like intense drought, and lacked the seedbank to rejuvenate.

Table 3.3. Of the twenty-four species originally planted/ sown on Tübingen Gärtnereihof, only fourteen remained and seven new species were recorded in 2010.

Gärtnereihof Tübingen, species list	Total cover	# quadrats (of 16)
Achillea millefolium	0	
Agrostis tenuis TRACENTA	0	
Daucus carota	0	
Dianthus alpinus	0	
Dianthus deltoides	10	1
Festuca ovina duriusenta SCALDIS	61	5
Festuca rubra commutata ATLANTA	21	3
Festuca rubra rubra PERNILLE	0	
Festuca rubra trichophylla ARTIST	0	
Hieracium pilosella	6	2
Lolium perenne MAJESTIC	0	
Matricaria chamomilla	0	
Origanum vulgare	0	
Petrorhagia saxifraga	84	8
Poa pratensis BARON	18	2
Poa pratensis angustifolia	1	1
Sedum acre	0	
Sedum album Coral Carpet	17	4
Sedum cauticulum	0	
Sedum floriferum "Weihenstephaner Gold"	565	14
Sedum hybridum "Immergrünchen"	1286	16
Sedum reflexum	35	8
Sedum sexangulare	612	14
Sedum spurium "Coccineum"	410	12
Sempervivum spp.	0	
Thymus praecox cv	634	10
# species persistent:	14	
# species lost:	12	
New in 2010		
Acer campestre	1	2
Acer pseudoplatanus	1	1
Arrhenatherum elatius	1	3
Fragaria vesca	26	2
Hypericum perforatum	5	1
Trifolium pratense	5	1
Vicia hirsuta	390	15
# species gained:	7	

Total species recorded in 2010:	21	

Of the seven new species identified in 2010 in Tübingen, most were limited to a few quadrats although Hairy vetch (*Vicia hirsuta*) occurred in fifteen of the sixteen quadrats with considerable cover. The other colonising species included two tree seedlings, a few specimens of Wild strawberry (*Fragaria vesca*), and unique instances of Tall oat-grass (*Arrhenatherum elatius*), Red clover (*Trifolium pratense*) and Perforate St. John's Wort (*Hypericum perforatum*). The success of the *Vicia* is likely due to its annual life cycle and its capacity to fix nitrogen, while the limited extent of the other species may be due to the same drivers and mechanisms that prevented some of the original species from persisting, whether extinction from a drought event, lacking seedbank, or the limited resources associated with EGR growing conditions.

3.3.1.2 Rathausgarage PV roof

The twenty-seven species recorded at Rathaus PV included sixteen from the original list and eleven new species (**Table 3.4**). The most abundant of the intentional species included *Allium flavum, Linum perenne, Sedum reflexum, S. sexangulare,* and *Setaria viridis*, all occurring in ten or more of the fifteen quadrats sampled. The Small yellow onion (*Allium flavum*) was visually prominent here during its flowering period, and the relatively low cover values (compared to the *Sedum* species) reflect the vertical structure of this thin-leaved growth form. The blue flowers of Perennial flax (*Linum perenne*) also make a strong visual impression on this roof; its frequency (13/ 15 quadrats) and total abundance (307%) was similar to *S. sexangulare* (347%). Although it was abundant and frequent, the Green bristle grass (*Setaria viridis*) was only evident upon close inspection due to its small stature; it can grow 100-600 mm high (Hubbard, 1992), but never exceeded 100 mm (*data not shown*).

Table 3.4. Of the 39 species originally planted/ sown on Rathaus-PV, only 16 remained and 11 new species were recorded in 2011.

Rathaus-PV, species list	Total cover	# quadrats (of 15)
Agrostis tenuis	0	
Allium flavum	90	10
Dianthus carthusianorum	48	6
Dianthus deltoides	18	1
Digitaria sanguinalis	0	
Festuca mairei	0	
Festuca ovina	129	7
Hieracium pilosella	87	5
Inula hirta	0	

Linum perenne	307	13
Nepeta musinii	0	
Nepeta racemosa	49	2
Onobrychis sativa	0	
Plantago major	0	
Poa compressa	9	2
Poa nemoralis	0	
Polygonum aviculare	0	
Potentilla argentea	0	
Rumex acetosella	0	
Saponaria ocymoides	0	
Saxifraga aizoon	0	
Sedum acre	0	
Sedum album	0	
Sedum album Coral Carpet	0	
Sedum album Murale	0	
Sedum cauticolum	0	
Sedum floriferum	0	
Sedum hybridum	474	9
Sedum reflexum	1191	15
Sedum sexangulare	342	13
Sedum spurium	0	
Sedum telephium	4	2
Sempervivum spp	0	
Setaria viridis	851	11
Silene uniflora	0	
Thymus pulegioides	0	
Thymus serpyllum	50	6
Trifolium arvense	0	
Veronica spicata	39	5
# species persistent:	16	
# species lost:	23	

New in 2011

Crepis tectorum	520	15
Lichen Cladonia cf. scabriscula	107	6
Lichen Peltigera spp.	10	3
Moss Hypnum1	163	9
Moss Bryum2	148	8
Moss starry yellow	40	1
Picris hieracioides	3	1
Potentilla erecta	39	6
Potentilla neumanniana	122	11
Taraxacum agg.	21	9
Trifolium campestre	51	5
# species gained:	11	

Total species recorded in 2011: 27

The twenty-three species from the original list that were not found in 2011 (59%) represented all growth forms, including grasses, succulents, and herbaceous perennials. While it was not surprising that species normally found in mesic meadows did not persist (e.g., *Inula hirta, Nepeta musinii, Rumex acetosella*), several species of disturbed wastelands and rocky habitats did not persist either, including some with ruderal characteristics (*Polygonum aviculare, Plantago major*, *Poa nemoralis, Saponaria ocymoides, Saxifraga aizoon, Trifolium arvense*) and several stress-tolerant succulents (*Sedum acre, S. album, S. cauticolum, S. floriferum, S. spurium, Sempervivum spp.*), suggesting that effects beyond adaptive strategy can influence extirpation from an EGR.

Among the eleven spontaneous colonisers, Narrowleaf hawksbeard (*Crepis tectorum*) was exceptionally prevalent and occurred in every quadrat; its high total abundance can be explained by basal rosette leaves. The name of this species implies its affinity for the roof habitat, which includes the cracks of roofing tiles (Archibold and Wagner, 2007) and exemplifies its ruderal qualities (Grime, 2001). Five of the eleven new species were cryptogams, some of which occurred in over half the quadrats (*Hypnum 1, Bryum 2*).

3.3.1.3 Rathausgarage lower roof

The thirty species recorded on the lower roof of the Rathausgarage complex included thirteen from the original list and seventeen new species (**Table 3.5**). Compared to the neighbouring PV roof, the lower roof had three fewer persistent species and seven more colonisers. The most abundant of the intentional species included *Dianthus carthusianorum, Linum perenne, Sedum reflexum, S. sexangulare,* and *Setaria viridis*, all occurring in ten or more of the fifteen quadrats sampled. Of the 39 species on the original list, twenty-six were no longer present in 2011. Some of these absent species could have been overlooked in the sampling work, being fine and inconspicuous (*Agrostis tenuis*) or possibly confused with other species/ cultivars in the sampling (*Festuca marei, Potentilla spp, Thymus spp*). However, most of the absent species are easily recognizable and should have been apparent in the reconnaissance surveys had they been present on this roof (*e.g., Digitaria sanguinalis, Inula hirta, Nepeta spp, Onobrychis sativa, Plantago major, Polygonum aviculare, Saponaria ocymoides, Saxifraga aizoon, Silene uniflora*).

Table 3.5. Of the 39 species originally planted/ sown on Rathaus-lower roof, 13 persisted and 17 new species were recorded in 2011.

Rathausgarage-lower, species list	Total cover	# quadrats (of 14)
Agrostis tenuis	0	
Allium flavum	74	3
Dianthus carthusianorum	283	12
Dianthus deltoides	0	
Digitaria sanguinalis	0	
Festuca mairei	0	
Festuca ovina	116	7
Hieracium pilosella	210	6
Inula hirta	0	
Linum perenne	168	12
Nepeta musinii	0	
Nepeta racemosa	0	
Onobrychis sativa	0	
Plantago major	0	
Poa compressa	42	5
Poa nemoralis	0	
Polygonum aviculare	0	
Potentilla argentea	0	
Rumex acetosella	0	
Saponaria ocymoides	0	
Saxifraga aizoon	0	
Sedum acre	1	1
Sedum album	0	
Sedum album Coral Carpet	0	
Sedum album Murale	0	
Sedum cauticolum	0	
Sedum floriferum	0	
Sedum hybridum	280	3
Sedum reflexum	879	13
Sedum sexangulare	143	10
Sedum spurium	0	
Sedum telephinium	0	
Sempervivum spp	0	
Setaria viridis	595	13
Silene uniflora	0	
Thymus pulegioides	0	
Thymus serpyllum	196	5
Trifolium arvense	0	

Veronica spicata	105	8
# species persistent:	13	
# species lost:	26	
New in 2011		
Acer pseudoplatanus	1	1
Crepis tectorum	509	14
Cladonia cf scabriscula	15	3
Peltigera spp.	4	3
Moss Hypnum1	183	8
Moss Bryum1	100	5
Moss Brachythecium cf. albicans1	96	4
Moss Brachythecium cf. albicans3	67	4
Moss Bryum2	235	13
Petrorhagia prolifera	30	3
Picris hieracioides	17	5
Potentilla neumanniana	167	11
Potentilla recta	36	4
Taraxacum agg.	18	7
Trifolium campestre	5	2
Verbascum nigrum	2	1
Vulpia myuros	53	4
# species gained:	17	
Total species recorded in 2011:	30	

Among the seventeen spontaneous colonisers, the most abundant species were *Crepis tectorum, Potentilla neumanniana* and the Moss labelled *Bryum2*. The latter occurred in thirteen (of fourteen) quadrats, but most of the other six colonising cryptogams occurred in three to five quadrats, with one (*Hypnum 1*) found in eight. *Potentilla neumanniana*, a stress-tolerator (Grime, 2001) commonly found on green roof species lists (ZinCo GmbH, 2014) was relatively frequent, occurring in eleven quadrats on this roof but only as a few individuals. In addition to two additional cryptogams, some other colonising species occurred on the lower but not the PV roof, like an *Acer* seedling, a few specimens of *Petrorhagia prolifera,* the biennial *Verbascum nigrum* and the annual grass, *Vulpia myuros.*

3.3.1.4 Discussion

Comparisons between original species lists and the vegetation surveys of 2010 and 2011 suggest that up to half of the originally planted/ sown species did not persist after > 20 years. The conceptual framework relating biodiversity dynamics with environmental change is useful for discussing this, particularly as EGR systems are known to be susceptible to catastrophic climatic episodes that can lead to the extinction of entire taxonomic groups [e.g., soil arthropods, as per Rumble and Gange (2013)]. A “forcing event” like this creates complex causal chains and contingencies that cause the extinction or immigration of one or more populations or species, whether immediate or delayed (Jackson and Sax, 2010). Such stochastic factors can ultimately drive species over their extinction threshold, especially if they are rare (and therefore vulnerable to extinction) (Hanski and Ovaskainen, 2002). Central to this framework is the notion of “biodiversity balance”, however, which is defined as the net difference between immigration (immediate or eventual) and extinction (Jackson and Sax, 2010). So, while a climate extreme may induce mortality among remaining populations, it can also lead to pulses of recruitment that facilitate persistence (Jackson et al., 2009). growth form

With regards to the species that were observed by these surveys, the “new” or colonising species were both more numerous (Rathaus lower) and less so (Rathaus PV, Tübingen) than the species that persisted. Successful colonisation is only possible given a number of requirements, including suitable sites, sequential successes in the dispersal of propagules, establishment of individuals, survival to reproductive maturity, and growth and persistence of populations via continued reproduction (Jackson and Sax, 2010). As described already, a couple studies have examined colonisation on EGRs, with the longest observation being six years (Dunnett et al., 2008). Several German studies that surveyed old green roofs refer to the importance of seedbank for the maintenance of species diversity on green roofs over time (Buttschardt, 2001, Köhler, 2006, Köhler and Poll, 2010). A similar commentary was made by a comparative study of three mesocosms in the UK (two EGR build-ups with 100 and 150 mm substrate, and one control of 150 mm EGR substrate over topsoil), whereby fewer species were able to flower and seed over one growing season due to the limitations to seed bank recharge (Olly et al., 2011). It is also important to recall that “intentional” in the case of EGR species lists may include species that are sometimes considered to be ‘weedy’, such as *H. pilosella*. This species has been on EGR species lists since the early days (Krupka, 1992) and was present on the existing species lists (i.e., FH Nürtingen, Tübingen, all 3 Stuttgart roofs). While gardeners or horticulturalists might perceive it as a weed, *Hieracium* maintains excellent cover with its basal rosette and its enduring yellow flowers are a great resource for pollinators. With regards to grasses, colonising species were minimal both in cover abundance and in stature. The annual grasses are so small they are easy to overlook, while larger unintentional grasses like *Arrhenatherum elatius* and *Poa angustifolia* only occurred in special conditions like deeper soils (*e.g.* on anthills or small mounds), shade or sheltered edges.

3.3.2 Characterising EGR grasses and succulents

Since analyses from the previous chapter indicated that grasses and succulents responded uniquely to many of the variables to which other growth forms had strong associations, they shall be examined more closely using the methods described above, in order to further the research aim of characterising mature EGR vegetation.

3.3.2.1 Grasses: relative cover with other growth forms

In order to determine the effect of grass cover on the vegetation composition of the EGRs surveyed, mean cover values were calculated per roof and re-calculated as proportionate to 100% total cover (**Table 3.6**). The aim was to remove any physical overlap by the growth forms and demonstrate their proportionate cover. Relative to total cover by all growth forms per roof, grass cover appears to decline over time (column 3: Relative total abund. (%) grass). The four oldest roofs had less than 5% relative cover abundance by grasses, whereas the five youngest EGRs had around or over 20%. Of all the species identified on these roofs, grasses rarely made up more than 20% of the species composition (column 4: % species that were grasses). Other than Pliensaufriedhof, which did not feature any grasses in the sampling area, most roofs had around or less than 20% cover by grasses. The final two columns of **Table 3.6** list the maximum and minimum grass cover recorded for each roof, and demonstrate the variation in grass cover per quadrat. Several roofs feature at least one quadrat without any grasses (0%) and others had considerable grass cover (e.g., Killesberg over 65%, Rathaus-PV over 35%, VB A2 over 25%). The roof with the greatest maximum, Köngen, had two quadrats with between 95- 98% grass cover (*Festuca ovina,* Q13, N-Q1) and one quadrat with the minimum of 3% *(Poa angustifolia*, Q11).

Table 3.6. Proportional cover abundance on 9 EGRs with interest in grass cover and diversity.

Roof name (in order of age)	Total # species	Relative total abund. (%) that was grass	% species grasses	Grass cover (%) per plot	
				maximum	minimum
Killesberg	23	34.50	13.00	65.79	0.00
Rathaus-low	30	17.40	13.30	37.89	0.92
Rathaus-PV	24	20.10	11.50	35.13	0.00
FH Nürtingen	32	40.20	21.90	57.91	28.99
Köngen	9	28.70	22.20	100.00	3.45
Tübingen	21	2.80	23.80	12.88	0.00
VB A1	21	0.80	9.50	5.45	0.00
VB A2	21	4.30	19.00	25.52	0.00
Pliensau	11	0.00	0.00	0.00	0.00

The relationship between total cover abundance (%) by grasses per roof (i.e., recorded in all quadrats) and the proportion (%) of those grasses that were intentional and persisted over time is illustrated in **Figure 3.5** (values given in **Table 3.7**). This makes it clear, for example, that a large proportion of FH Nürtingen (at the right extreme of the chart) was grassy. Indeed, 138% of the total cover abundance on that roof comprised grass species and, of those species, almost 70% were intentional. Next in grassy abundance, of the 80% cover that grasses comprised of the total plant cover on Killesberg, almost 70% were intentional species that had persisted over 20 years. At the opposite extreme, Tübingen and the two Verkehrsbetrieb roofs supported very few grasses (as indicated by their location along the x-axis), but over 80% of the grasses sampled were intentional species that had persisted over time (*Agrostis tenuis, Festuca ovina, F. rubra, Poa angustifolia, P. compressa*). The other roofs (Köngen and the Rathausgarage complex) had equally high proportions of intentional grass species, from total cover abundance by grasses of between 40% and 70%. It appears that the majority of grasses on the EGRs surveyed were intentional, suggesting that colonisation pressure by grasses is low.

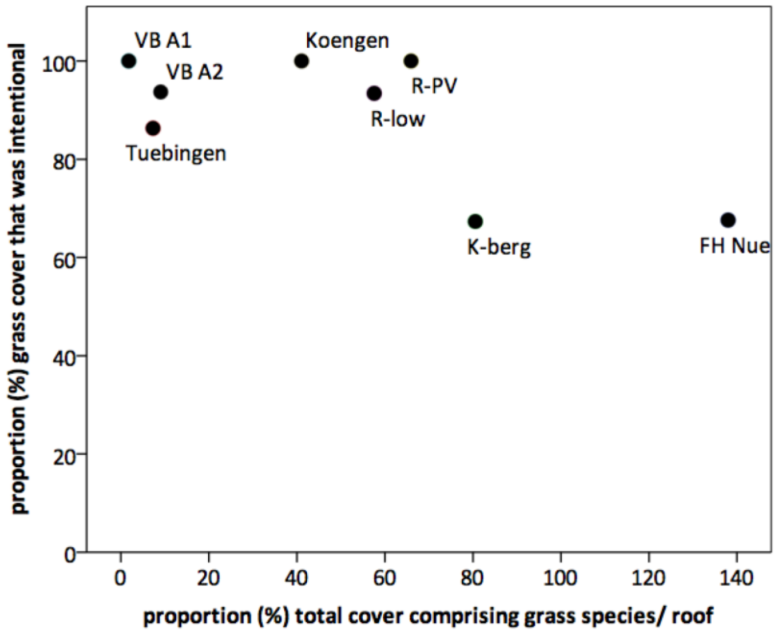


Figure 3.5. Total abundance (%) comprising intentional grass species for nine EGRs.

Table 3.7. Total grass cover abundance and the proportion (%) that comprised intentional species on nine EGRs.

Roof name (in order of age)	Total grass abundance	Intentional cover (%) that was grass
Killesberg	233.4	75.9
Rathaus-PV	330.7	70.4
Rathaus-low	327.5	77.6
FH Nürtingen	343.0	65.3
Köngen	142.8	85.8
Tübingen	262.8	89.4
VB A1	213.3	88.1
VB A2	209.1	78.5
Pliensau	156.9	96.7

3.3.2.2 Adaptive life strategies of typical EGR grass species

All grass species were ascribed with an adaptive life strategy from a reference list of ca. 1,000 European species allocated with CSR signatures (Hunt et al., 2004) (**Table 3.8**).

Table 3.8. Life strategies of the grasses identified on the EGRs surveyed, using CSR signatures

Grasses identified	CSR signature	Original list?	Occurrence
Agrostis stolonifera L.	CR		FH Nürtingen
Agrostis tenuis L.	SR/CSR	Yes	Esslingen VB roofs (both)
Arrhenatherum elatius L.	C/CSR		FH Nürtingen, Tübingen
Festuca ovina L.	S	Yes	all roofs except Pliensau
Festuca rubra L.	CSR	Yes	FH Nürtingen, Tübingen
Poa angustifolia L. Gaud.	S/CSR	Yes	Tübingen, VB A2
Poa compressa L.	S/CSR	Yes	FH Nürtingen, VB A2, both Rathaus
Poa angustifolia L.	CSR		Köngen, Tübingen
Setaria viridis L. P.B	R	Yes	three Stuttgart roofs
Vulpia myuros L. C.C. Gmel.	R		Rathaus PV, Killesberg

One of the most popular grasses for EGRs, *Festuca ovina*, is a classic stress-tolerator (S-strategist) (Grime, 2001). S-strategists can persist through frequently stressful conditions that other species cannot tolerate, like shallow, well-drained mineral soils in high light environments. Commonly known as Sheep's fescue, this densely tufted perennial is productive in open situations, like heath, moor or mountain grassland, on rather poor, well-drained shallow soils (both basic and acidic) (Grime and Curtis, 1976, Hubbard, 1992). This species does not have rhizomes but reproduces through profuse seed rain, such that the gaps in the vegetation may be full of its seedlings (Grime and Curtis, 1976). *F. ovina* was indeed the most prominent grass observed, occurring on every roof. It was on all the available species lists, so may have been sown on the roofs for which no lists were available, too. The fact that it remains so consistently abundant may be owing to its strategy as a stress-tolerator.

The next most prominent grass, *Poa compressa* is both stress-tolerator and a generalist (S/CSR) that occurred on four of the roofs surveyed (FH Nürtingen, VB A1, and both Rathausgarage roofs). Commonly known as Flattened meadowgrass, this is the characteristic species of the "Typical Poa meadow" identified by green roof phytosociologists for spontaneously vegetated gravel roofs. That community covered the greatest surface area of all the TPGs surveyed in Göttingen (Bornkamm, 1961), Berlin

(Darius and Drepper, 1983) and Osnabrück (Bossler and Suszka, 1988), but was less represented in Karlsruhe (Buttschardt, 2001) and Switzerland (Thommen, 1988), possibly due to climate or variations in substrate depth. Bornkamm found that recently installed TPG roofs in Göttingen were first colonized by weedy annuals, and that this shifted after about 10 years to dominant cover by *Poa compressa*. A stiff perennial which spreads by wiry rhizomes, *P. compressa* colonises sites with shallow, well-drained soils such as poor grassland, dry banks and wasteground, as well as the tops of old walls and ruins (Hubbard, 1992). Its spreading root system sometimes develops into clonal colonies, which may explain the cover it maintains over time. This grass was on some of the original species lists.

Given their stoloniferous habits and partly ruderal life strategies, the two tufted perennial *Agrostis* species were not as prevalent as one might have expected. The competitive-ruderal (CR) *Agrostis stolonifera* only occurred on one roof (FH Nürtingen), where its leafy stolons formed a dense sward along with *Poa compressa*. The frequency of this grass (9/ 15 quadrats) contributed to the meadow character of this roof. Competitive ruderals are adapted to circumstances of minimal stress where competition is restricted to moderate intensity of disturbance (e.g., fertile pastures and meadows) (Grime, 1977). The stress-tolerant generalist (S/ CSR), *Agrostis tenuis*, is associated with habitats of intermediate fertility (Hubbard, 1992), and it spreads by shorts rhizomes and sometimes by stolons to form loose or dense turfs. This grass was found with low cover abundance (between 2-12% cover) in four quadrats on each of the Verkehrsbetrieb roofs. Though this roof complex was not accompanied by an original species list, *A. tenuis* was specified on a few other roofs (e.g., Tübingen, Rathausgarage) and could well have been sown on these roofs as well. If so, then the individuals observed could be remnants from an earlier population.

Some grasses (*Arrhenatherum elatius, Festuca rubra, Poa angustifolia*) were found in only a few circumstances, like the base of a sloped roof or slightly protected edges. These species are associated with cultivated meadows, pastures, and slightly moist meadows and pastures in central Europe (Ellenberg, 1986), and their pure CSR signatures (C/CSR for *A. elatius*) indicate their capacity for perennial growth, which can be dominant in productive habitats like meadows (Grime, 2001). This flexibility is exemplified by the loosely tufted coarse perennial *A. elatius*, which is a frequent dominant of productive soils (Grime and Curtis, 1976). This competitive generalist colonised two patches at the base of Tübingen's slope

(T3Q4, T4Q1) as well as one quadrat mid-slope (T3Q3), and maintained considerable cover at FH Nürtingen, with cover abundance from 5 to 30% in six of the twelve quadrats sampled.

The two grasses designated as CSR strategists (*Festuca rubra, Poa angustifolia*) represent plant forms that are restricted to habitats in which competition is limited to moderate intensities by the combined effects of stress and disturbance (e.g., unfertilized pastures and meadows) (Grime, 1977). The EGR locations on which they were found likely embody this complex of conditions. The slender rhizomatous *F. rubra* was found sparsely on the EGRs at Tübingen and FH Nürtingen. In Tübingen, it occurred in three quadrats at the base of the slope (T2Q1, T2Q4, T3Q1), on both north- and south-faces, with low cover abundance (3%, 15%, 3%, respectively), while in Nürtingen it occurred in three quadrats ranging in cover from 2% to 47% to 99%. Similarly, the creeping rhizomatous Smooth meadow grass, *Poa angustifolia*, occurred sparsely in Tübingen (T2Q4, T3Q4, both north-facing) and in Köngen, where it was represented by one quadrat each on the north- and south-faces.

Two small annual grasses (*Setaria viridis, Vulpia myuros*) were found only on the three Stuttgart roofs (with the exception of *Vulpia* on Rathaus PV). *Setaria* was apparently in the Stuttgart seed mix, which means that it has persisted over time, but *Vulpia* likely colonized through dispersal. These ruderals often maintained extensive coverage, though their small stature made little visual impression to the vegetation overall. These species were associated with other drought-tolerant taxa in particularly xeric conditions. For example, two south-facing quadrats at Killesberg (T1) in which *Setaria* and *Vulpia* were well-represented (between 40 and 80% cover abundance) also featured between 40 and 85% cover by *Sedum album, S. reflexum* and a few instances of *F. ovina* and the moss *Ceratodon purpureus*. The south-facing quadrats on this roof featured cracked substrate which were probably exacerbated by the steep slope. These two small grasses only occurred on the south-facing quadrats of that roof, generally in the same cover abundance. While *Setaria* was abundant in most of the quadrats of the Rathaus roofs, *Vulpia* was not observed on Rathaus PV; on the lower roof it was abundant in one quadrat (Q1, 42%) and sparse in three others (with 3-5% cover abundance).

3.3.2.3 Discussion

The disparity in grass cover may be associated with the fact that the younger roofs had bigger species lists, as well as some unique environmental gradients (slope and aspect on Killesberg; mesic versus xeric edges on FH Nürtingen; sheltering from adjacent buildings on

Rathaus lower). The older roofs, from Tübingen onwards, had varying degrees of cover and representation by grass species. Grass cover on the two roofs at Esslingen Verkehrsbetrieb (VB) was visibly associated with the microclimatic effects created by the differently arranged light shafts, like shading or the effects of wind vortices. VB Area 1 has a compact arrangement of long, rectangular shafts occupying most of that roofs surface area, while Area 2 features square shafts scattered more widely apart. The former roof supported only two grass species while the latter had four.

The reason some species occurred only on some roofs may be attributed to the variables measured, like roof age, substrate depth, and environmental conditions per roof, but there are likely other ecological variables in effect, such as colonisation through seed rain, supply by seed bank, and conditions for germination, establishment and reproduction. In Berlin, Köhler (2006) found that proximity to green spaces and exposure to seed rain influenced species diversity on two old EGRs, and that grass establishment and persistence were most influenced by exposure to irradiation and fluctuating ambient temperatures.

3.3.3 Succulents: in proportion to other growth forms

Correlation effects associated with the vegetation of the EGRs surveyed suggest that succulents function differently from the other growth form groups. Whereas the other growth forms interacted with each other, succulents hardly had any associations, neither with other groups nor themselves. Whereas certain variables correlated with the same direction relationship for all growth forms, succulents expressed the opposite direction. Without the certainty of original species lists and proportions, it is difficult to know whether these results are associated with vegetation dynamics or if such relationships have been in place since the point of installation. It is possible, however, to consider the relative cover abundance of these growth forms alongside the other growth form groups, and to test the strength of the relationships identified. The relative cover of the six growth forms comprising the vegetation are given as mean cover values re-calculated as proportionate to 100% total cover (**Table 3.9**).

The north-facing roof at Köngen was treated as an outlier for this analysis because the vegetation and conditions on that small roof (5 quadrats) were so dramatically different from the larger south-facing roof (13 quadrats) and from the other roofs. Three of Köngen's nine species were restricted to the north-facing roof (*Achillea millefolium, Sedum floriferum* and *Calliergonella cuspidata*) and, although removing those five quadrats led to less proportionate cover by cryptogams and forbs, grass cover was hardly affected and succulents gained only marginally greater proportion of total cover. This is given for reference (shaded row); only the results from the larger, south-facing roof are used for this analysis.

Table 3.9. Relative proportionate cover abundance of growth forms on nine old EGRs, in order of roof age, showing mean with standard deviation.

Roof	# spp	Succulent	Forb	Grass	Bulb	Cryptogam	Woody
Killes-berg	23	38.18±30.60	2.78±6.85	37.11±30.27	12.44±12.19	5.17±7.28	4.31±12.81
Rathaus-lower	30	34.55±18.91	25.52±28.49	21.37±17.06	7.85±27.46	10.61±7.53	0.11±0.55
Rathaus-PV	24	42.80±22.50	13.51±16.04	28.06±28.62	7.66±18.82	7.97±14.02	0.00
FH Nürt.	32	19.73±23.65	30.08±29.56	23.00±9.73	2.02±9.06	24.32±26.16	0.84±1.84
Köngen (both)	9	55.72±30.79	4.18±9.24	28.24±24.25	0.00	11.85±35.71	0.00
Köngen South	6	68.61±21.93	2.44±2.73	28.95±12.30	0.00	0.00	0.00
Tübing.	21	56.92±26.16	37.14±26.07	3.19±24.57	0.00	0.00	2.75±23.20
VB A2	21	17.58±8.40	18.01±20.81	2.63±7.94	49.46±53.30	12.32±9.56	0.00
VB A1	21	33.41±17.51	52.80±41.55	1.09±3.57	5.67±23.42	7.03±13.94	0.00
Pliens.	11	96.74±87.31	1.59±5.59	0.00	0.00	0.00	1.67±7.09

Succulents on all the roofs had relatively consistent cover abundance, while the other growth forms varied. Grasses had consistent cover (between 20-40%) on the younger roofs (Killesberg, the Rathausgarage roofs, FH Nürtingen and Köngen), and considerably less on the older roofs (between 0-3%), for example. These values suggest the visual composition for a typical quadrat, and succulents clearly maintained the most consistent cover on all roofs (**Figure 3.6**). Pliensaufriedhof, which had one of the smallest species lists (11 species) had the most extensive cover by succulents (96.74%) (± 87.31%), while grasses, bulbs and cryptogams were not at all represented. The south-face at Köngen, which was the second most species depauperate roof, had 68.61% (± 21.93%) cover by succulents, with no cover whatsoever by bulbs, cryptogams or woody species. Otherwise, the other roofs (with > 20 species) had more varying cover by succulents and other growth forms.

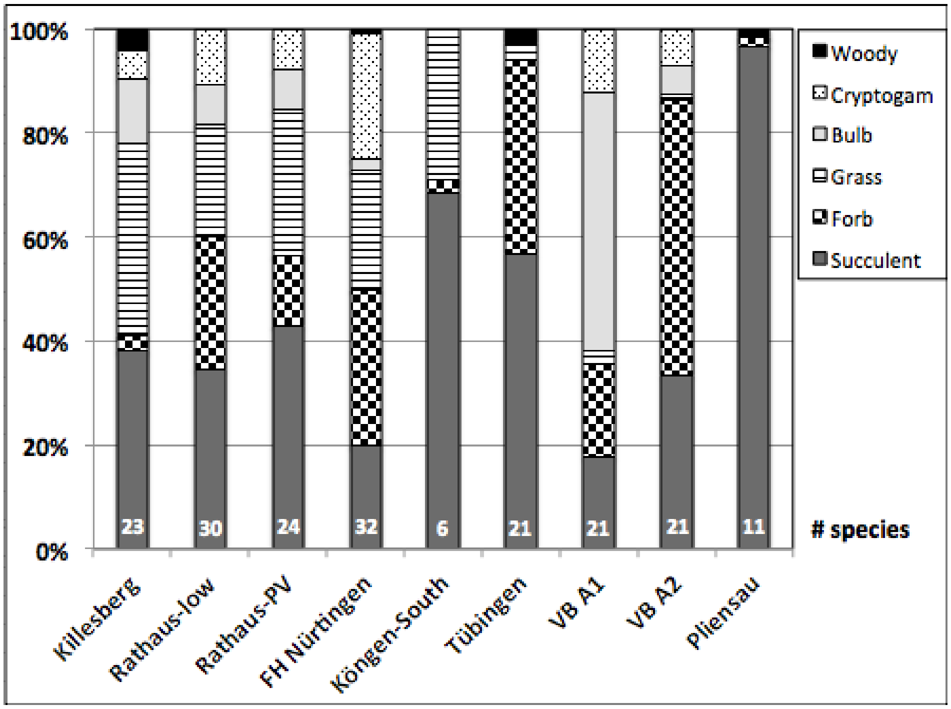


Figure 3.6. Relative cover abundance of growth forms on nine old EGRs [NB: Köngen South is used (n=13), exempting the 5 north-facing quadrats from that roof].

A Related-Samples Friedman's Two-Way Analysis of Variance by Ranks was conducted to determine if there was a significant difference in proportionate cover by the six growth forms on the nine roofs. The roofs surveyed did indeed have significantly different proportionate cover by the different growth forms, X^2 (5, n = 9) = 20.62, p < .001). Inspection of the means ranking showed succulents with the highest rank (5.33), followed by forbs (4.44), grasses (3.67), bulbs (2.72), cryptogams (2.94) and woody species (1.89). Friedman's Pairwise Comparisons reveal that succulents had significantly different cover abundance from woody species (T = 3.44, p < .001) and bulbs (T = 2.61, p < .001). Since woody species were generally limited to self-established tree seedlings, this is an obvious effect. Bulbs, on the other hand, are not as mobile for self-colonisation and therefore only occur on roofs when they have been intentionally sown or planted. Bulbs only had substantial cover on three of the roofs surveyed (VB A1, VB A2, Rathaus PV) (occurring in 7, 14, and 10 quadrats, respectively) and had sparse cover on Rathaus lower (3 quadrats).

3.3.4 EGR vegetation types

In order to determine which roofs had the strongest effects that led to the statistics described above, a hierarchical cluster analysis using Ward method and average linkage was conducted. Dissimilarity data provides information on the degree of 'closeness' or proximity of each unit to every other unit. The dendrogram model allows clusters to form hierarchically, such that the most broadly similar objects are loosely clustered to the right and, as the similarity criterion becomes increasingly less relaxed (moving left on the dendrogram), groups become formed by aggregating with one another. Roof name (and roof number) are given on the y-axis, and the scale of clustering coefficients on the upper x-axis indicates the gradation of similarity/ dissimilarity between the roof clusters (**Figure 3.7**).

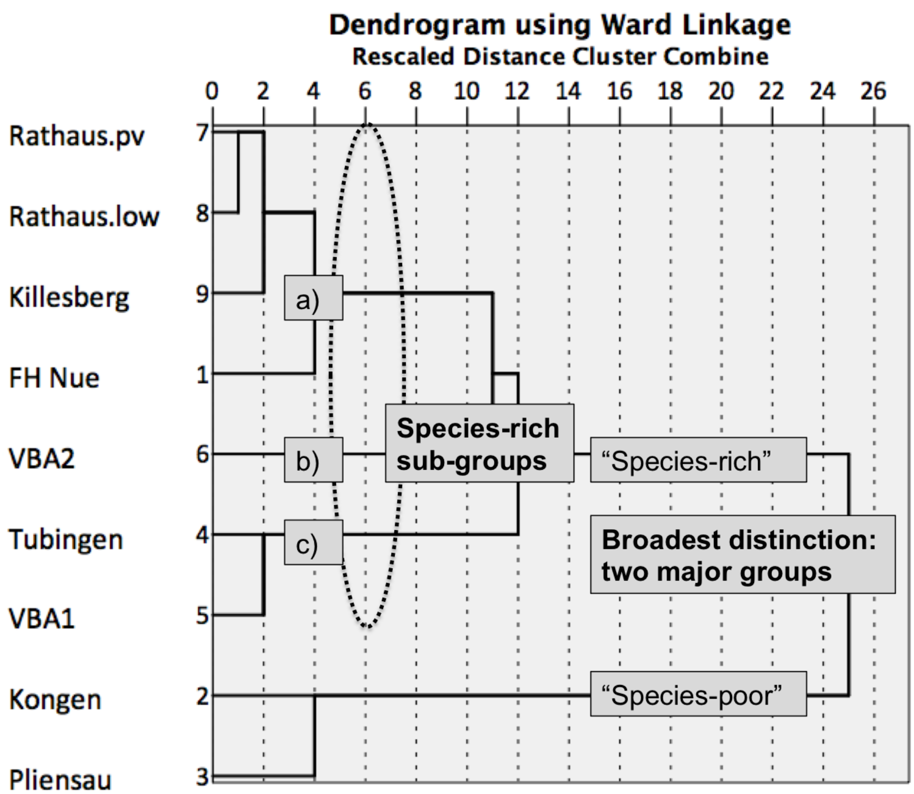


Figure 3.7. A cluster analysis for nine old EGRs reveals two major groupings, or vegetation types, with reference to proportionate cover abundance and three sub-groups.

With respect to proportionate growth form cover of the roofs surveyed, the dendrogram shows two major hierarchical groupings of roofs, with the broadest differentiation occurring at a linkage distance of twenty-five (Broadest distinction: two major groups). The two major groups are distinguished as "Species-rich" and "Species-poor". These groupings shall be examined more closely to determine whether they serve to define recurring EGR vegetation types and emergent properties.

3.3.4.1 *"Species-poor Sedum roof" (2 roofs)*

This group consists of two closely related roofs (linkage distance: 4) - Köngen (south) and Pliensau - which are distinct from the other roofs by their low species counts (6, 11, respectively), of which succulents had the highest cover while forbs had exceptionally low numbers and cover. Plant cover on these roofs was predominantly succulent (68.61% ± 21.93 and 96.74% ± 87.31, resp.) with sparse cover by forbs (2.44% ± 2.73 and 1.59% ± 5.59, resp.). As mentioned, the removal of the north-facing quadrats at Köngen reduced cryptogam and forb cover, but hardly affected proportionate grass cover and only marginally enhanced succulent cover. Both roofs lack any cover by cryptogams, bulbs or woody species, and do not match up with any of the vegetation forms described by Krupka (1992). This grouping can therefore be described as "Species-poor Sedum roof".

3.3.4.2 *"Species-rich Sedum meadow" (7 roofs)*

The "Species-rich Sedum meadow" group contains the other seven roofs (linkage distance: 12), which are sub-divided into three sub-groups (a, b, c). Compared to the roofs described above, these EGRs support more species and more cover by forbs, grasses and bulbs, but still have consistent cover by succulents. Visually, these roofs give the impression of a flowering meadow with sparse and often tufted wildflowers and grasses above a steady ground cover of succulents and cryptogams. These roofs may be treated as expressing floristic variations between Sedum-Moss-Herbaceous and Sedum-Grass-Herbaceous forms (Krupka, 1992). Varying cover abundance by different growth forms led to three sub-groupings, which will be described individually and given descriptive headings.

3.3.4.2.1 a) "Floristically-diverse Sedum meadow"

The roofs in Nürtingen and Stuttgart had the most recorded species of all the roofs surveyed, and similar proportionate cover by succulents, grasses and forbs. Sedum cover on FH Nürtingen was 19.73% (±23.65), while forbs covered around 30% (± 29.56), grasses covered 23% (± 9.73) and cryptogams covered around 24% (± 26.16). This latter growth form is likely the distinguishing point between that roof and the Stuttgart roofs (linkage distance: four), as none of those had more than 10% cover by cryptogams. Killesberg was similar to the Rathausgarage roofs in its proportionate cover by Sedums (38.18% ±30.60) and grasses (37.11% ±30.27), but the sparse cover by forbs, bulbs and woody species on this roof marks a point of distinction (linkage distance: two). The Rathausgarage roofs (PV and lower) were floristically very similar (linkage distance: one), with succulent cover of 42.80%

(±22.50) and 34.55% (±18.91) (resp.); forb cover of 13.51% (±16.04) and 25.52% (±28.49) (resp.); grass cover of 28.06% (±28.62) and 21.37% (±17.06) (resp.); bulb cover of 7.66% (±18.82) and 7.85% (±27.46) (resp.); and cryptogam cover of 7.97% (±14.02) and 10.61% (±7.53) (resp.). Woody species had negligible cover on these two roofs.

The three Stuttgart roofs featured several forb species not detected on any other roofs, such as *Linum perenne, Nepeta racemosa, Petrorhagia prolifera, Picris hieracioides, Potentilla argentea, P. erecta, Sedum acre, Setaria viridis, Verbascum nigrum, Veronica spicata* and *Vulpia myuros*. The Rathausgarage complex and FH Nürtingen also featured bulbs not found anywhere else, Allium flavum and Dactylorhiza fuchsii. Overall, however, these roofs all had consistent and continuous ground cover of succulents beneath the taller meadow species, hence this vegetation type can be described as “Floristically-diverse Sedum meadow”.

3.3.4.2.2 b) “Sedum with Chives”

The Area 2 roof at Esslingen Verkehrsbetrieb was unique amongst all the roofs surveyed for its extensive coverage by Chives, *Allium schoenoprasum*, which had proportionate cover of 49.46% (±53.30), considerably more bulb cover than any other roof. Succulents and forbs had similar cover proportions on this roof (17.58% ± 8.40, 18.01% ± 20.81, resp.), followed by cryptogams (12.32% ± 9.56). Grass cover was sparse (2.63% ± 7.94) and no woody species were recorded. The forbs identified are typical EGR species (*Achillea millefolium, Petrorhagia saxifraga* and *Thymus serpyllum*) as well as some common weedy ruderals (*Crepis tectorum, Hypericum perforatum, Potentilla recta, Taraxacum officinale*). Sedums and Chives had the most consistent cover, occurring in most (if not all) quadrats. This combination of co-dominance by Sedum and Chives is not uncommon for EGRs (Köhler, 2006) and seems to define a distinct vegetation type: “Sedum with Chives”.

3.3.4.2.3 c) “Sparse Sedum meadow”

The roofs at Tübingen and Verkehrsbetrieb Area 1 are as closely related as the three Stuttgart roofs (linkage distance: 2). The most notable difference distinguishing these roofs from the seven others is the low proportionate cover by grasses (3.19% ± 24.57 and 1.09% ± 3.57, resp.). Cover by succulents and forbs are not dis-similar from the other roofs, although these roofs have the highest number of species comprising these growth forms. Whereas the two roofs that were defined by Sedums (Köngen, Pliensau) only supported two and three species (resp.), Tübingen and VB A1 supported six and five species of succulents (resp.). Similar to the “Sedum with Chives” roof, the forb species on these two roofs are either typical green roof plants or weedy ruderals, but they supported a few more forb species than VB A2. Floristically, the vegetation on these roofs may be considered intermediate between the Floristically-diverse Sedum meadow and the Species-poor Sedum roof, and is therefore defined as “Sparse Sedum meadow.”

3.3.4.3 Discussion

These results resonate with other works (Krupka, 1992, Madre et al., 2014, Van Mechelen et al., 2015), but also express that vegetation development on green roof after more than two decades may lead to site-specific compositions. The forms described by Krupka (1992) are useful for the purpose of prescribing general vegetation for different depths; indeed, this table is used in the FLL guidance (2008). The field surveys of this research disagree with the results of Van Mechelen et al. (2015), likely because their theoretical analyses could not incorporate time-based effects of ecological dynamism. While their “*Sedum* type” lines up with the “Species-poor Sedum roof”, the other two types they describe ("*Dianthus-Thyme*” and “*Linaria-Galium*”) feature species that were not even found on the roofs surveyed. This could be owing to extinction of certain species over time; indeed, they refer to commercial species lists and therefore presence/ absence of initial species composition without reference to relative abundance or post-installation dynamics. In addition, the effect of regional or local influences (e.g., climate, propagule sources) is not considered in their model, which would likely have region-specific influences on the species composition of EGRs over time.

As novel ecosystems, EGR vegetation can be classified according to technical properties and diversity values (Madre et al., 2014, Van Mechelen et al., 2015). The role of green roofs for providing ecosystem services is becoming increasingly acknowledged (Carter and Jackson, 2007, Cook-Patton and Bauerle, 2012, Gaston et al., 2013, Lundholm et al., 2010, Perring et al., 2013, Norton et al., 2015, Lundholm, 2015). Methods for enhancing green roofs’ capacity to deliver services over the long-term can therefore have significant implications to the health and well-being of current and future organisms, both human and other. First, however, our understanding of the relationship between biodiversity and ecosystem functioning on EGRs must be clarified. While the functional diversity of “Sedum type” roofs was significantly lower than the other two roof types described by Van Mechelen et al. (2015), species-poor EGRs have been observed to outperform more diverse systems on some ecosystem services, like roof cooling (Lundholm et al., 2010). Thus, although scientific evidence is accruing to show that biodiversity, species functional traits and phylogenetic relationships are linked with ecosystem function (Cardinale et al., 2012, Hooper et al., 2005, Isbell et al., 2011, Quijas et al., 2012), the application of this query to EGRs and other novel ecosystems is still very limited.

The question of emergence on EGRs can be treated as a conceptual expression of the phytosociological work of spontaneously vegetated roofs, by which ecologists tried to classify the spontaneous vegetation of old gravel roofs according to plant community science. Other than the very broad class, *Sedo-Scleranthetea*, no recurring associations could be satisfactorily confirmed. The precise methods of phytosociology were developed from many years' work studying natural and semi-natural ecosystems (Braun-Blanquet, 1972) and may not be not appropriate for urban ecosystems (Hill et al., 2002). Still, considering the adaptive strategies represented by the species on the EGRs surveyed, the assemblages identified by the cluster analysis are not random. The broadness of the vegetation types defined, both by this and the phytosociological work, supports the notion that green roofs are novel ecosystems, which typically contain (historically) unprecedented species combinations co-existing under new abiotic conditions (Hobbs et al., 2009). With relation to the classification of anthropogenic plant communities, phytosociologists have proposed deductive methods for synthesizing the vegetation units from the varied man-made landscape within the framework of the Braun-Blanquet approach (Kopecky and Hejny, 1978). This approach may relate to green roofs because its "top-down" perspective (i.e., from Class to Order, Alliance to Association) allows for more generalized vegetation types.

These results suggest that the original designs and intents of the early EGR industry have been partly successful. Extensive, low-maintenance plant cover is created by some of the intentional species, and pressure by unintentional species is minimal. In this case, Sedums are the champions having not only fared well but having also reduced opportunities for colonisation by forming dense and closed cover. If the original intention was to create species-rich meadows, with Sedum cover for seasonal resilience, however, then only some of these roofs would qualify as successful. This ethos of seasonal planting design was explained to the author during a 3-month internship with a green roof company near Freiburg im Breisgau (2002): wet periods allow forbs and grasses to flourish, while extended periods of drought have the reverse effect and promote succulents. Although not formally recognised as a "best practice", this may nevertheless convey the ecological intuition of green roof contractors in southwest Germany, since their work includes maintenance contracts for several years after installation.

3.4 Conclusions

3.4.1 EGR vegetation over time: persistence, gain and loss

These results suggest that a significant proportion of the intentional species planted/ sown on the EGRs surveyed did not persist after twenty or more years, and that some new species were able to colonise. The variations in coverage by persistent versus colonising species may be attributed to the established vegetation, to the propagule inputs, and to environmental site conditions. The species that persisted and those that were lost included typical and non-typical green roof plants. Few of the colonising species were dominant enough to define the vegetation character of the EGRs sampled. These dynamics of persistence, gain and loss may be explained by the different forms of regeneration (e.g., seed bank, seed rain), by the conditions required for regeneration to occur, and probably by disturbance. Moreover, evidence of such dynamics implies consideration of EGRs as novel urban ecosystems whereby abiotic factors can modify trophic interactions (Hobbs et al., 2009), and different species mixes exhibit different suites of functional traits (Van Mechelen et al., 2015) that can in turn affect ecosystem function (Diaz et al., 2004).

3.4.1.1 Persistence

If intentional species are to persist on EGRs over time, then they must be suited to EGR growing conditions and they must have regenerative strategies that allow them to persist over generations. Most of the species that persisted embody life histories or adaptive strategies that allow them either to tolerate or avoid stress (e.g., succulence or annual life cycles). For many ecosystems, seed (whether as seed bank or seed rain) determine the persistence of individual species to that community (Janssens et al., 1998, Plue et al., 2010, Kalamees and Zobel, 2002, Kalamees and Zobel, 1998, Partel et al., 1998). Furthermore, the persistence and viability of seed in the soil is a crucial consideration (Thompson et al., 1997, Bekker et al., 1998), not to mention the conditions required for the seedlings to survive and develop there. The restoration of species-rich grassland, for example, requires sown seed but also the conditions for germination (light, temperature, humidity) and growth (e.g., soil chemical characteristics) to permit establishment, survival and persistence of the desired community (Janssens et al., 1998).

A study of EGR seed banks on TPG and EGRs in Karlsruhe found that EGR substrates had remarkably low volumes of seed, of which the majority originated from the roof vegetation (*Arabidopsis thaliana, Bromus tectorum, Dianthus carthusianorum, Lepidium virginicum*) (Lang, 2000). In that study, most of the colonising species (*Betula pendula, Sambucus nigra, Poa angustifolia, Solidago canadensis, Oxalis dillenii, Veronica hederifolia*) would not germinate on the roofs, but could be induced to germinate on experimental plots and in laboratory conditions. Numerous other species were abundant and frequent on the roofs but did not germinate at all (*Acer spp., Portulaca oleracea*). While the summer annual, wind-dispersed species (*Conyza canadensis, Erigeron annuus*) could be verified in the experimental plots, many of the winter annuals could not (*Saxifraga tridactylites, Cardamine hirsuta*). This unpublished study could not be accessed, but was described by Buttschardt (2001) (p. 118).

Other studies report that species colonisation of vegetated roofs over time leads to an inevitable shift in the plant community with a strong trend towards species impoverishment (Riedmüller, 1994, Buttschardt, 2001, Bornkamm, 1961), though this depends on substrate depth, existing plant cover and provision of moisture (Dunnett et al., 2008, Schroll et al., 2011, Madre et al., 2014). From his surveys of eight EGRs in Karlsruhe, Buttschardt (2001) found that 38-48% from the original species lists had disappeared three to eight years after installation. While the *Sedo-Scleranthetea* assemblages became enriched with fluctuating incidences of short-lived ruderal species, that study estimated that between ten and thirty years were required until these annual components became sufficiently established within the seed bank.

While some of the persistent species from the roofs with original lists from this research are known to reproduce by seeds (e.g., *Dianthus spp., Festuca spp., Hieracium pilosella, Linum perenne, Petrorhagia saxifraga*), others, including those with the most abundant coverage (*Sedums*) regenerate through vegetative expansion, like rhizomes or ramets, which confers a low risk of mortality to the offspring through attachment to the parent (Grime, 2001). Thus it may be that the species that did not persist on these roofs do not have the appropriate regeneration strategies for EGRs.

3.4.1.2 Gain

The colonising species arrived on their own, via mechanisms like wind-dispersal, which implies that seed rain is an important aspect of EGR vegetation composition. A study of two old EGR in different parts of Berlin noted that proximity to green spaces and exposure to seed rain influenced species diversity (Köhler, 2006). Wind-dispersal was most prevalent (34%) strategy comprising the vegetation of sixteen green roofs (12 TPG, 4 EGRs) in Karlsruhe (Buttschardt, 2001) (p. 86). Plant invasion on green roofs seems to occur predominantly on patches of bare substrate (Dunnett et al., 2008). In grassland ecosystems, invasion by non-resident species often intensifies after drought disturbances, when mortality leads to gaps in previously closed vegetation (Davis et al., 2000). This occurrence on EGRs can be observed where annual grasses and xeric mosses colonise the cracked substrate of particularly harsh roof locations. The invasion process depends upon environmental conditions (e.g., resource enrichment or release) that have a variety of causes but which occur only intermittently, and which coincide with the availability of invading propagules (Davis et al., 2000).

3.4.1.3 Loss

Although the species lists comprised species originating from analogue habitats, many of those original species were not found in the roof surveys. This loss of species could be due to several reasons. For one, regionally native, non-xeric species may simply not be fit for EGRs since the environmental conditions there may be better matched with analogue habitats occurring further south. Given the episodic incidents of severe stress that occur on EGRs, not to mention the other challenges of the EGR growing environment, xeric species likely outcompete other functional types. If regeneration is not possible, then those species become extinct. The shallow depths of well-drained EGR substrates and the growing conditions imposed by exposure to wind, sun and extreme temperatures are known to limit plant diversity (Boivin et al., 2001, Olly et al., 2011, Bates et al., 2013), and the diversity of other organisms (Schrader and Boening, 2006, Rumble and Gange, 2013). The establishment and persistence of grass on two old EGRs in Berlin were found to be most strongly influenced by exposure to irradiation and to fluctuating ambient temperatures (Köhler, 2006). Considering that roof membranes can exceed 70°C, even in mild climates (Connelly et al., 2006), any exposed substrate will become prohibitively hot, particularly if it is darkly coloured (Buttschardt, 2001). Long-term monitoring could reveal whether species impoverishment on EGRs occurs as the result of a single catastrophic event or as a gradual process.

The popular notion that EGRs could support diverse plant communities over the long-term was negated by early ecological studies of green roofs (Riedmüller, 1994, Buttschardt, 2001). From his surveys of TPG and EGRs, Buttschardt (2001) disagreed with the statement by Kolb and Schwarz (1986) that EGRs can support red-listed species. Another study concluded that the re-creation of species-rich dry meadow on green roofs could only be accomplished if intensive maintenance comparable with that of a botanical garden were provided (Riedmüller, 1994) (p. 35). From his experiments, that author stated that even if species-rich dry meadows from that climate zone were to be successfully established, the homogeneous EGR substrate, with its tendency to desiccate, would prevent long-term persistence by that community and eventually shift to dominance by drought-tolerant vegetation. As mentioned already, a subtle but crucial shortcoming to the approach of using species from analogue habitats for EGRs is that the most appropriate analogues are probably actually several latitudinal degrees to the south, and possibly also associated with special geological and ecological features. To date, this biogeographic detail has not been acknowledged.

3.4.2 EGR vegetation composition after > 20 years

Based on these results, the species identified as comprising mature EGR vegetation can be classified according to the duration of their persistence. Consideration of life history and adaptive strategies, with reference to CSR theory, was helpful to this end. The species that classify as stress tolerators (e.g., most Sedum species/ cultivars, *Festuca ovina*) have apparently persisted since being planted/ sown on these green roofs; such long-term persistence in the form of compact, slow growth and vegetative reproduction are hallmarks of the stress tolerator strategy (Grime, 1977). By contrast, persistence in the form of a life cycle that is either rapid annual or short-lived perennial, with investment into seed rather than vegetative development, is characteristic of the ruderal strategy (Harper, 1977). The persistence by stress tolerators can therefore be classified as long-term, while persistence by ruderals is can be defined as short-term but also incoming colonisers. Due to the snapshot quality of the surveys, it is not possible to know how long the “lost” species persisted, whether their persistence can be described as medium-term or short-term. Plant adaptive strategies will be considered in more detail in the chapters that follow.

3.4.3 Characterising EGR vegetation: succulents and grasses

The most abundant grass species identified, *Festuca ovina*, persisted in great abundance compared to other species. Since this species is a stress tolerator (or S-strategist), it may be that the stressful EGR conditions impose filters that limit the persistence and establishment of other life strategies over time. The two ruderals on the Stuttgart roofs imply that the lethal combination of stress and disturbance is not uncommon on those roofs. Being annuals, these grasses probably vary in cover per year and per season, along with the weather. Recalling that these surveys are like a snapshot in time, it's possible that the other life strategies are not long-term components of EGR vegetation, either, but rather opportunists that will claim and hold environmental niches offering suitable conditions while they last. Succulents dominated the vegetation of all the roofs surveyed, often creating extensive cover with only a few species. As mentioned already, some Sedums exhibit Crassulacean Acid Metabolism (CAM), which allows them to avoid water stress by switching their carbon metabolism to the CAM pathway (Sayed, 2001).

3.4.4 EGR vegetation communities or types

This chapter concludes that green roof vegetation does not remain static, and that it may converge over time with subtle divergences into different vegetation types. Beyond the small group of two "**Species-poor Sedum roofs**", the "**Species-rich Sedum meadow**" type was separated into three sub-types defined by a Sedum groundcover beneath tall grasses and herbs (both intentional and colonising). Before confirming these EGR vegetation groups as recurring emergent community types, the role of environmental conditions must be integrated into the model. Chapter 5 will therefore investigate rooftop conditions more explicitly and re-classify the EGR vegetation types accordingly.

4 Substrate depth over time

Preliminary analyses suggested that substrate depth decreases with time, and that roof slope and aspect were significantly correlated to substrate depth. Such dynamics could pose issues to the long-term function of these systems, especially a decline in substrate depth since EGRs are the shallowest of all green roof types (FLL, 2008). The decline in depth on shallow EGRs over time is an entirely undocumented phenomenon, so this chapter will examine the results associated with depth more closely. The EGRs in this study are early examples of systems that became widespread after the industry and market had established. They may have adhered to the early recommendations, such as substrate composition and particle size, even though standardised materials and methods were not yet available (Appl, 2014). With regards to practical implications of this work, then, these roofs can be considered comparable to the early installations of other markets, which might also be susceptible to unanticipated changes.

4.1 Literature review

4.1.1 Depth and the FLL guideline

Substrate depth fundamentally affects EGR vegetation, whether in terms of establishment and growth (Durhman et al., 2007, Getter and Rowe, 2009, Thuring et al., 2010, Rowe et al., 2012), species dominance and cover diversity (Emilsson and Rolf, 2005, Dunnett et al., 2008b, Nagase and Dunnett, 2010) or survival across challenging seasons (Boivin et al., 2001, Getter and Rowe, 2007). Shallow depths limit the long-term resilience of green roof floral assemblages (Olly et al., 2011, Madre et al., 2014), and inhibit the growth of taller vegetation (Dunnett et al., 2008a, Durhman et al., 2007). However, when planted with a diversity of life forms, like grasses and tall forbs (which require deeper depths than succulents), EGRs can provide a greater range of ecosystem services, including stormwater capture, roof temperature and albedo (Lundholm et al., 2010, 2014). Some suggest that EGR substrate depths should not be less than 120 mm (Köhler and Poll, 2010, Nardini et al., 2012) or 200 mm (Dunnett et al., 2008b) if they are to function for engineered performance as well as visual and ecological diversity.

Species-depth tables have been used for EGR design guidelines since the early days of the industry (Krupka, 1992), with the purpose of outlining the different types of vegetation that can be supported by different depths. Accompanying the table in the guideline indicating which life forms will grow best in different depths, the FLL attaches a note that “the regional climatic conditions and the specific site conditions, which can vary considerably from each other, necessitate a thinner or thicker construction layer within the given range” (p. 43). In addition to this life form table, the guideline refers to the predicted effects that different depths will have on runoff retention, and also recommends various approaches for preventing substrate compaction or loss during planning, manufacture and installation.

In Germany, the FLL guidelines and industry practice together were designed to rule out losses in depth from the point of installation. The DIN 18127 laboratory standard (Proctor Test) for substrate manufacture ensures that a substrate has already factored compression into its ordered volume; depending on the substrate many companies who provide EGR substrates often calculate the volume for an installation using settlement factors of between 1.1 and 1.25 [e.g., (ZinCo, 2013), p. 15]. These two practices should rule out any significant compression. Another point of compaction occurs when green roof substrates are installed using hydraulic blower trucks, which can compromise particle size distribution due to shattering (Roth-Kleyer, 2006). Since 70% of EGR installations in Germany used blower trucks in 2002 (Roth-Kleyer, 2002), the FLL (2008) recommends prescribing granulometric distributions with greater proportions of large particles. From his survey of relatively young EGRs Buttschardt (2001) observed that particle size distribution had shifted beyond the FLL recommendations within four years, which he attributed to this form of delivery.

For all the detailed specifications and methods in the FLL guidance, surprisingly little reference is made explicitly to substrate depth over the long-term. No mention of depth whatsoever is made in the chapter of inspection methods for post-installation tests on drainage and substrate layers. Although each new edition is refined to include the most current advances in materials, methods and approaches (Lösken, 2004), there is no evidence of feedback from performance monitoring. Given how crucial substrate depth is to green roof performance, this lack of time-oriented perspective seems a questionable blind spot to such an important document. Without any contradicting information, it would seem that the guidance is only intended for installation and the early years of establishment. The physical and chemical properties of the EGRs surveyed will be contrasted with the FLL recommendations in Chapter 6.

Beyond Germany, the FLL guidelines are an important reference for nascent green roof markets; the best practice code for UK green roofs, for example, was adapted and "significantly based on the German FLL guidelines" (GRO, 2014) (p. 2). In North America, when loosely-regulated green roof technology was being implemented at the turn of the 21st century, the FLL guidelines were used in order to identify minimal performance expectations and prevent error and failure (Philippi, 2005). As mentioned earlier, the FLL guideline is not a standard but a measure of technical application for professionals, suppliers, installers, and municipal or state regulators. The first page of the document clarifies that users must employ common sense and that the guidance cannot guarantee fault-free results (FLL, 2008). Since regions without any recent history or experience using living architecture usually lack a culture of ecological or regenerative design and intervention, emerging green roof markets that refer to these guidelines may lack the common sense that it implies.

Green roofs can be twice as expensive in emerging compared to mature markets and substrate is the biggest cost factor in green roof construction when materials, methods of delivery, expertise, and standards have not yet been established (Philippi, 2011). So, if pioneering practitioners in these situations refer to these guidelines for the minimum requirements in order to keep costs down, it is likely that very shallow depths are specified. If depth does in fact decline over time, various aspects of green roof performance by these systems will be compromised. Without long-term research on EGR systems, such is the case with stormwater performance (Li and Babcock, 2014), the effectiveness of the guidelines cannot be substantiated beyond the period of establishment.

4.1.2 Depth and green roof ecology

All green roof phytosociological studies determined the various plant community classifications according with substrate depth (Bornkamm, 1961; Darius and Drepper, 1983; Bossler and Suszka, 1988; Thommen, 1988, Buttschardt, 2001). While depth is of unequivocal importance to the vegetation that can grow and persist, it also influences soil-based processes and the directions that natural succession may take; this is especially true for hard surfaces with little soil (Yuan et al., 2006). The first systematic survey of spontaneously vegetated TPGs (in Göttingen, Germany) classified plant communities according to depth (Bornkamm, 1961). Based on the results from over thirty TPGs, the shallowest depths (mean: 30 mm) were designated for Moss community, and increasing depths supported a Weed community (mean: 84-96 mm), a Tread community (mean: 96 mm), and the Typical Poa meadow (mean: 134 mm, minimum 110 mm). Of the two forms of Poa meadow identified, the "Typical Poa meadow" (*Poetum anceptis-compressae*) occurred on unshaded gravel roofs (mean: 114 mm) which had 94% cover but were relatively species-poor (six species) compared with shaded variants which had more species (twelve) but less cover (68%). The "Poa meadow rich in weeds" (*Poetum anceptis-compressae chenopodietosum albi*) occurred on gravel roofs (mean: 134 mm) and supported eleven species that had 84% cover. A study of five (90 year-old) TPGs and three (20 year-old) gravel roofs in Osnabrück found that younger gravel roofs were still in the early stages of very slow humus formation, the lack of humus was attributed to the vegetation that was limited to pioneering mosses and lichens (Bossler and Suszka, 1988). This and other TPG studies demonstrate the importance of substrate depth not only in determining species composition on green roofs, but concurrently in driving natural succession and long-term soil processes, like humus formation.

Similarly, in Karlsruhe, Buttschardt (2001) outlined four types of roof vegetation according to substrate depth on TPG and EGR roofs. Cryptogams dominated depths from 10-60 mm, while 20-200 mm supported a carpet- or patchwork cover by Sedums interspersed by low-growing spring annuals (*e.g., Cerastium pumilum, Veronica praecox, Arabidopsis thaliana, Erophila verna*)*,* creepers (*e.g., Stellaria media*) and grasses (*e.g., Poa annua, Poa bulbosa, Eragrostis minor*). Depths of 100-400 mm supported low-growing herbaceous species, including chamaephytes (e.g., *Dianthus deltoides, D. carthusianorum Lamium hybridum, Achillea millefolium, Anthemis tinctoria, Capsella bursa-pastoris*), low-growing grasses (e.g., *Koehleria glauca, Festuca spp, Setaria viridis*), and geophytes (e.g., *Allium schoenoprasum*). The deepest substrates surveyed, 300-1500 mm, were defined by tall, freestanding grasses (*Aspera spica-venti*) and herbaceous perennials (*Dianthus carthusianorum*), and less frequent ruderal species (*Conyza canadensis*, *Erigeron canadensis*).

Depth is widely accepted as the main point of distinction between green roofs and ground-level ecosystems. This is usually attributed to the lack of resources available to green roof plants, owing to the disconnection from a greater soil profile (Krupka, 1985). The influence of stress caused by shallow, predominantly mineral substrates has not been thoroughly quantified for EGRs, but it is an intuitively comfortable notion that plant growth and diversity should be inhibited in a sun-baked and desiccated substrate. A London study of soil microarthropods on EGRs described dramatic population crashes associated with periods of extended drought and high temperatures (Rumble and Gange, 2013), but the environmental conditions were not reported. In Birmingham, a replicated experiment of three EGR microcosms (100 or 150 mm aggregate over typical EGR systems; 150 mm aggregate over a topsoil control) found that shallower depths in the EGR plots correlated with the number and severity of drought events, unlike the control plots (Olly et al., 2011). Those authors attributed the poor performance of the EGRs plots to the substrate and the limited rhizosphere (e.g, inadequate soil moisture and other resources), but made no mention to the drainage layer beneath the EGR system, which augments water loss from the substrate and out of the system. An additional treatment exempting drainage layers might indicate the role that substrate depth alone plays to drought.

4.1.3 Research aims and questions

Since a significant loss of substrate depth over time would pose consequences to long-term EGR performance, both in terms of vegetation but also engineered benefits, the objective of this chapter is to examine these results more closely. The outcomes may further inform the **research question** of identifying the main drivers and mechanism behind vegetation change on EGRs, and address the **aim** of proposing models to illustrate EGR vegetation development over time.

- **Aim:** To continue characterising mature EGR vegetation
- **Question**: If successional change can be observed on EGRs, what are the main drivers & mechanisms?

4.1.3.1 Objectives for the chapter

The objectives for this chapter involve the examination of the depth results more closely, and refer to other datasets where applicable.

- Quadrat-level detail: aspect, slope and depth
- Roof-level detail: mean depth and expanded dataset

4.2 Methods

First, in order to assess the power of the result from this small sample size, the correlation coefficient from depth and roof age (*rho* = -.481, $p < .01$, $n = 136$) was used for a post-hoc power analysis. According to the power analysis, a sample of at least 37 roofs is required if loss of substrate depth over time were to be sufficiently proven (G-power, version 3.1, University of Düsseldorf, calculated May 1, 2013) (Faul et al., 2009). Considerable coordination, time, and effort would be required to assemble a sample of such magnitude. Since substrate depth was measured per quadrat, this variable can be examined at the level of quadrat, as well as mean values per roof. Different approaches will be used to examine these different levels of detail. Since depth was measured for every quadrat on the nine roofs surveyed, this data will be examined with greater resolution as quadrat-level analyses. Mean depth data from the nine EGRs will also be examined, together with an amalgamation of data from eight EGRs of similar construction and geography (ca. 100 km from Stuttgart region) surveyed by Buttschardt (2001).

4.2.1 Data analysis

4.2.1.1 Quadrat-level query

The variations in depth will be examined at the level of quadrat with reference to mean, minimum and maximum records, and with speculation of how these might have changed from initial depths. Background information on the original depth installed for each roof will be introduced ("assumed initial depth") and then compared to the depths measured (ranging from the filter cloth to the top of the substrate profile, but not including the litter layer). To address the preliminary results that substrate depth was positively correlated with slope (*rho* = .430, $p < .001$, $n = 134$) and aspect (*rho* =.369, $p < .001$, $n = 134$), depth measurements taken per quadrat will be examined with regards to location along the roof slope (ridge, central, base) and aspect. Lastly, in order to determine the relationship between substrate depth and species composition, the abundance records of the 95 species identified will be subjected to Spearman Rank Order Correlation analysis. Preliminary analyses were performed to ensure no violation of the assumptions of normality, linearity, and homoscedasticity. This non-parametric test was chosen because the data do not have a normal distribution.

4.2.1.2 Roof-level query: mean depths

Using the records of mean depth per roof, the surveyed EGRs will be arranged into ordinal age groupings in order to determine any significant differences in depth and roof age. A Kruskal-Wallis test will be used as the non-parametric alternative to one-way between-groups analysis of variance. The measurements from this small sample will then be expanded with the inclusion of mean depth data from eight EGRs surveyed by Buttschardt (2001) in Karlsruhe. Those roofs were installed around the same time as the youngest ones in this study (i.e., early to mid-1990s) and adhered with the FLL guidelines of the time (FLL 1995). They were, therefore, all younger than the roofs surveyed for this study and surveyed ten years earlier. Amalgamating these two datasets nearly doubles the sample size from nine to seventeen and extends the timeframe to include roofs ranging from two to thirty-three years after installation. After a brief description of those roofs, the records of mean depth from this expanded sample size will be tested with a one-sample t-test.

4.3 Results

4.3.1 Quadrat-level query

4.3.1.1 Descriptive: depth measurements per quadrat/ roof

The mean, minimum and maximum depths per roof, along with median and standard deviation, are given in **Table 4.1**. In addition to the mean values for Köngen, the measurements for the north- and south-facing roofs are given separately, as two rows. The final two columns refer to any assumed initial depths with reference to the sources of those assumptions. Since this information was not available for all roofs surveyed, some cells are blank. Of all the roofs surveyed, FH Nürtingen and Killesberg had the greatest variability in substrate depth and VB Area 1 had the least. The latter roof had the smallest depth measurements overall, including smallest mean depth (52. 8 mm), smallest median (51 mm), and smallest standard deviation (6.66 mm). Neighbouring VB Area 2 had the next lowest values for depth (mean: 58.13 mm; median: 58.8 mm; SD 8.9 mm). By contrast, the pitched roof at Killesberg had the deepest depth measurements of all roofs, with the deepest mean (84.7 mm) and median (79.6 mm).

Table 4.1. Summary of substrate depth per roof (mm), presented in order of roof age.

Roof name (in order of age)	N	Mean	Min	Max	Range	Med-ian	Assumed initial depth	Source of assumption
Killesberg	18	84.7	68.0	115.0	47.0	79.6	80	detail sections (1:10)
Rathaus, lower	14	69.8	53.0	81.0	28.0	69.5	100	detail sections (1:10)
Rathaus, PV	14	64.4	46.0	81.0	35.0	65.0	100	detail sections (1:10)
Köngen (both)	16	70.6	54.0	111.5	57.5	70.0	70-80	T. Hövekamp (verbal)
Köngen-S	11	71.2	54.0	89.3	35.3	70.3		
Köngen-N	5	69.1	56.0	111.5	55.5	69.7		
FH Nürtingen	11	72.3	45.0	92.0	47.0	70.3	20-90	hand-written record
Tübingen	16	61.5	47.0	84.3	37.3	58.8		
VB A1	14	52.8	46.0	65.0	19.0	51.0	120	T. Hövekamp (verbal)
VB A2	14	58.1	47.0	73.0	26.0	58.8	120	T. Hövekamp (verbal)
Pliensau	15	61.6	50.0	76.7	26.7	63.3		

Three roofs had outlier records for depth (Tübingen; VB Area 1; Köngen), but Köngen was the only roof with a significant outlier (N-Q4) (**Figure 4.1**). The two outliers at Köngen were recorded on the north-facing roof (111.70, 138.70 mm). One of the highest values within the upper quartile for that roof was also from the north-face (N-Q2: 80.30). The south-facing roof at Köngen had thirteen quadrats (depth measurements were taken for ten), which is similar to the number of sampling plots on the other roofs (e.g., Rathaus-PV: 15; Rathaus-lower: 14; FH Nürtingen: 12; Verkehrsbetrieb roofs: 14; Tübingen: 16), so any analyses excluding the north-facing quadrats at Köngen do not compromise the dataset of that roof.

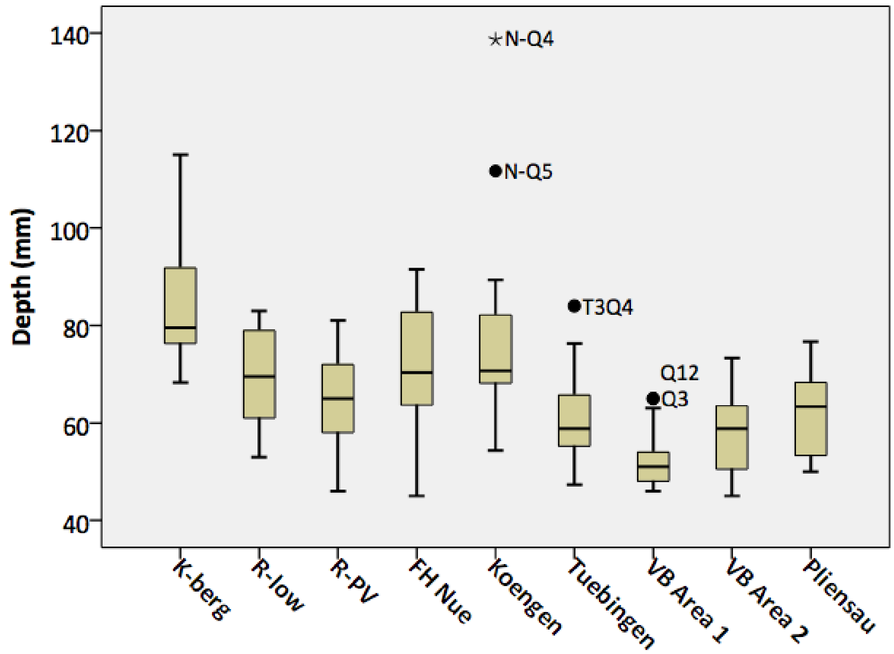


Figure 4.1. Depth measurements for the roofs surveyed show a few outliers, of which one was significant.

No original depth values were available for the roofs of Pliensaufriedhof or the Gärtnereihof in Tübingen. A letter from the architect of the Killesberg shows a detail from an architectural drawing that specifies 80 mm substrate for the green roof. Detail sections (1:10) from architectural drawings for the Rathausgarage complex (PV and lower roof) report a specification of 100 mm substrate. Beyond these drawings, no further information was available on original depth specifications. In Nürtingen, hand-written records from the time of installation (1987) suggest 90 mm depth at roof centre and 20 mm substrate along the edges. This discrepancy was intentional, owing to the interest in vegetation technologies by the FH (Hüttenmoser, 2010). This documentation was received after the vegetation surveys had been completed, but the stratified sampling method avoided non-homogeneous vegetation so this variation in depth should not have skewed the data collected. Documentation from a 1989 maintenance contract bid for the Römermuseum in Köngen by ZinCo (then Metall Dachtechnik GmbH) reports that 50 mm substrate was originally installed in 1987. However, in an interview in 2010, the lead contractor of the roofs construction (who also signed this bid) said that 70 or 80 mm substrate were more likely installed (Hövekamp, 2010). Hövekamp also explained that the substrate profile at the

Verkehrsbetrieb roofs comprised a 100 mm layer of LECA (Lightweight Expanded Clay) topped by 10 or 20 mm organic matter, interspersed with the styrofoam modules.

The minimum and maximum values around the mean (**Figure 4.1**) illustrate that some roofs had very large variations in substrate depth while others were quite small. The two roofs with the greatest mean depths also had the largest range of depths measured; the north-face of the Römermuseum roof in Köngen and Killesberg stand out with the greatest mean depths. The youngest and steepest roof, Killesberg, had a mean depth of 85 mm with a maximum of 115 mm and a minimum of 68 mm. On the two roofs of the Römermuseum in Köngen, the small north-facing roof (n=5 quadrats) measured a wide range of depths, from 56 to 111.5 mm, while the larger south-facing roof (n=13 quadrats) had a similar minimum depth (54 mm) but a shallower maximum (89 mm). FH Nürtingen also had a considerable range in substrate depth measurements (47 mm), of which the maximum values (92 mm) match up with the depths quoted for the central section of that roof (90 mm), but the shallowest (45 mm) exceed the minimum depth quoted (20 mm).

Next in depth and range, Tübingen, had mean depth of 61 mm, with a smaller range of measurements (37.3 mm) than the previous roofs. The Rathausgarage complex roofs were similar, with mean substrate depths of 64 mm (PV) and 70 mm (lower roof), and ranges of 35 mm and 28 mm (respectively), of which 81 mm was the maximum depth measured for both. The roof at Pliensaufriedhof ranged in depth from 50 to 77 mm, and had the smallest range measured. The two roofs at Esslingen Verkehrsbetrieb (VB Areas 1 and 2) recorded the shallowest mean depths (53 and 58 mm, respectively) as well as the lowest range of depths (19 and 26 mm, respectively). Site visits confirmed the single comment offered by the contact for this roof that it had not been maintained in at least 10 years; wind scour had exposed the membrane in many areas and flooding (by evidently blocked drains) has led to lightweight LECA particles everywhere (**Figure 4.2**). This extreme mobility by the LECA aggregate can perhaps explain the decline in depth on this roof; indeed the styrofoam modules featured on this roof in geometric patterns had originally been buried flush with the substrate but were completely exposed in some locations. Personal experience has witnessed a LECA-based green roof in the UK scoured and blown off by wind, so it’s possible that the extremely shallow depths on these roofs is attributed to physical loss of this sort.

Figure 4.2. Blocked drains on VB A2 led to the re-positioning of the lightweight (LECA) substrate component; several areas have been scoured to expose the waterproofing.

4.3.1.2 Substrate depth over time: assumed initial depth 100 mm

Building upon the variations in depth per quadrat presented above, the analysis that follows is based upon the assumption that the EGRs surveyed were installed with 100 mm substrate. According to conversations with Thomas Hövekamp (2010) and colleagues at ZinCo, 100 mm was a common depth on these early roofs and any deviations could be related to uneven levelling in spots. Depth was therefore re-calculated as "substrate loss" (with 100 mm as the assumed initial depth), and roof age and substrate loss were tested as co-variates against depth. The oldest and youngest roofs, Pliensaufriedhof and Killesberg, were treated as outliers because their substrates were not representative of EGR substrates (both with visibly less/ no lightweight aggregate and apparently blended with some topsoil). Although not significant, **Figure 4.3** suggests a slight trend of substrate loss over roof age for the EGRs ranging from 21 to 25 years old ($R^2 = .275$). The y-axis is loss of substrate depth, so values lower down the axis mean that less depth was lost, or that a measurement was close to 100 mm. The two oldest roofs shown here (25 years, VB Areas 1 and 2) are likely responsible for the positive trend in substrate loss since no quadrats in these roofs were deeper than 65 or 73 mm.

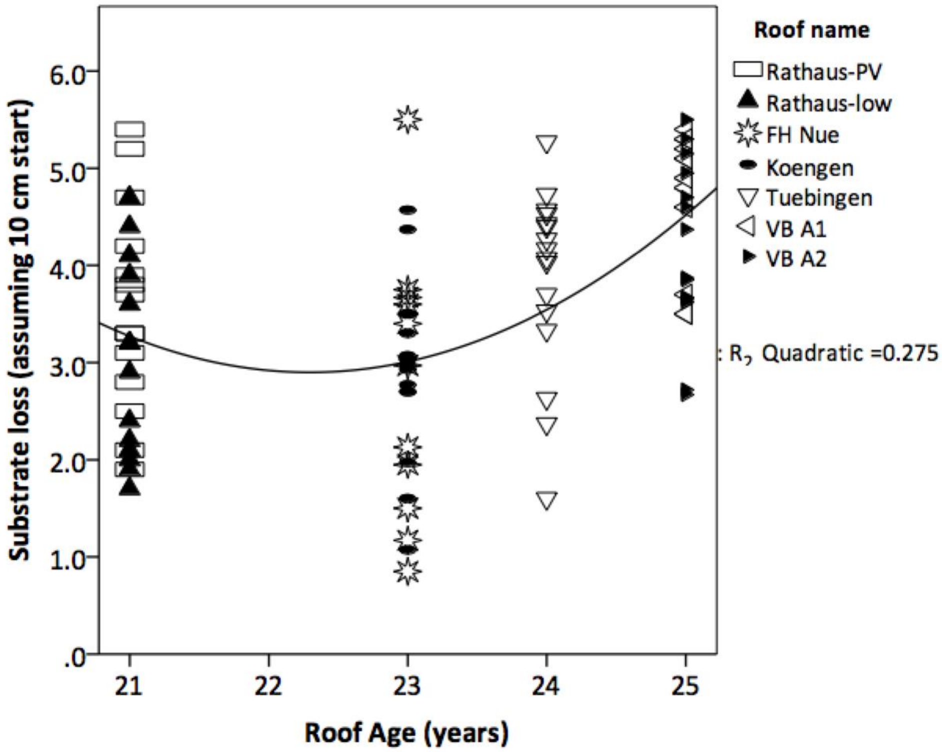


Figure 4.3. Substrate loss (assuming initial depth of 100 mm) for seven EGRs of various ages.

By contrast, the other roofs had at least some quadrats with under 20 mm loss, or depths between 80 and 100 mm. FH Nürtingen and Köngen (both 23 years at time surveyed) showed the greatest range of substrate lost, with several records of less than 20 mm and a few between 40 and 55 mm (**Table 4.2**). These variations might simply represent the variable depths described already (e.g., deeper substrate in centre of roof at FH Nürtingen and on north-facing roof in Köngen). The quadrat-level measurements therefore illustrate the considerable variability in depth on the roofs surveyed. Given that 100 mm initial depth is a strong assumption, and considering the enormous variation recorded for substrate depth, these results offer no conclusive evidence of decreasing depth over time as a general trend. The next section will investigate whether sloped roofs exemplify any recurring patterns in depth at the level of quadrat.

Table 4.2. Substrate loss per quadrat for seven EGRs (assuming 100 mm initial depth)

		Depth (mm)	
Rathaus-PV		Measured	Loss
	Q1	58.0	42.0
	Q2	72.0	28.0
	Q3	53.0	47.0
	Q4	48.0	52.0
	Q5	81.0	19.0
	Q6	67.0	33.0
	Q7	63.0	37.0
	Q8	46.0	54.0
	Q9	N/A	0.0
	Q10	75.0	25.0
	Q11	69.0	31.0
	Q12	67.0	33.0
	Q13	61.0	39.0
	Q14	79.0	21.0
	Q15	62.0	38.0

		Depth (mm)	
Rathaus-lower		Measured	Loss
	Q1	61.0	39.0
	Q2	56.0	44.0
	Q3	59.0	41.0
	Q4	53.0	47.0
	Q5	71.0	29.0
	Q6	64.0	36.0
	Q7	83.0	17.0
	Q8	79.0	21.0
	Q9	68.0	32.0
	Q10	68.0	32.0
	Q11	81.0	19.0
	Q12	76.0	24.0
	Q13	80.0	20.0
	Q14	78.0	22.0

VB A1		Measured	Loss
	Q1	46.0	54.0
	Q2	63.0	37.0
	Q3	65.0	35.0
	Q4	49.0	51.0
	Q5	48.0	52.0
	Q6	51.0	49.0
	Q7	52.0	48.0
	Q8	49.0	51.0
	Q9	47.0	53.0
	Q10	52.0	48.0
	Q11	47.0	53.0
	Q12	65.0	35.0
	Q13	54.0	46.0
	Q14	51.0	49.0

		Depth (mm)	
VB A2		Measured	Loss
	Q1	72.8	27.2
	Q2	73.3	26.7
	Q3	61.3	38.7
	Q4	63.5	36.5
	Q5	63.8	36.2
	Q6	53.0	47.0
	Q7	54.0	46.0
	Q8	47.0	53.0
	Q9	61.5	38.5
	Q10	63.3	36.7
	Q11	48.5	51.5
	Q12	50.5	49.5
	Q13	45.0	55.0
	Q14	56.3	43.7

		Depth (mm)	
Köngen		Measured	Loss
	S-Q1	56.3	43.7
	S-Q2	80.3	19.7
	S-Q3	70.3	29.7
	S-Q4	N/A	
	S-Q5	N/A	
	S-Q6	84.0	16.0
	S-Q7	69.3	30.7
	S-Q8	70.7	29.3
	S-Q9	72.3	27.7
	S-Q10	67.0	33.0
	S-Q11	89.3	10.7
	S-Q12	54.3	45.7
	S-Q13	69.7	30.3
	N-Q1	69.7	30.3
	N-Q2	65.0	35.0
	N-Q3	65.0	35.0
	N-Q4	73.0	27.0
	N-Q5	73.0	27.0

		Depth (mm)	
Tübingen		Measured	Loss
	T1Q1	55.7	44.3
	T1Q2	66.7	33.3
	T1Q3	63.0	37.0
	T1Q4	47.3	52.7
	T2Q1	52.7	47.3
	T2Q2	59.3	40.7
	T2Q3	76.3	23.7
	T2Q4	73.7	26.3
	T3Q1	58.3	41.7
	T3Q2	54.7	45.3
	T3Q3	59.7	40.3
	T3Q4	84.0	16.0
	T4Q1	64.7	35.3
	T4Q2	57.3	42.7
	T4Q3	54.3	45.7
	T4Q4	56.0	44.0

		Depth (mm)	
FH Nürtingen		Measured	Loss
	Q1	78.7	21.3
	Q2	45.0	55.0
	Q3	85.0	15.0
	Q4	70.3	29.7
	Q5	88.3	11.7
	Q6	64.0	36.0
	Q7	62.5	37.5
	Q8	80.5	19.5
	Q9	66.0	34.0
	Q10	91.5	8.5
	Q11	63.3	36.7
	Q12	N/A	

4.3.1.3 Depth, slope and aspect

The final quadrat-level analysis of depth addresses the preliminary result that substrate depth was correlated with slope and aspect. These results imply that greater depths usually occurred on pitched roofs with south-facing aspects, or that shallower depths occurred on flat roofs without a particular aspect. One might hypothesize that these results reflect the location of sampling plots along a roof slope, such that deeper depths occur at the base of the slope and shallower depths at the top. In order to examine this more closely, the depth measurements recorded per quadrat for the pitched roofs were tested according to their location along a slope (ridge, central, base) and whether they occurred on a north- or south-facing slope (**Table 4.3**).

Table 4.3. Depth measurements per quadrat for three pitched EGRs (slope location, aspect)

Roof	Quadrat	Location	Aspect	Depth (mm)
Köngen	N-Q1	ridge	North	56.33
	N-Q2	ridge	North	80.33
	N-Q3	ridge	North	70.33
	N-Q4	central	North	138.67
	N-Q5	base	North	111.67
	S-Q1	ridge	South	84.00
	S-Q2	ridge	South	69.33
	S-Q3	ridge	South	70.67
	S-Q4	central	South	72.33
	S-Q5	ridge	South	67.00
	S-Q6	central	South	89.33
	S-Q7	base	South	54.33
	S-Q8	ridge	South	69.67
	S-Q9	central	South	0.00
	S-Q10	base	South	65.00
	S-Q11	ridge	South	0.00
	S-Q12	central	South	73.00
	S-Q13	base	South	0.00
	Quadrat	**Location**	**Aspect**	**Depth (mm)**
Tübingen	T1Q4	base	North	47.33
	T2Q1	base	South	52.67
	T4Q3	ridge	North	54.33
	T3Q2	ridge	South	54.67
	T1Q1	base	South	55.67
	T4Q4	base	North	56.00
	T4Q2	ridge	South	57.33
	T3Q1	base	South	58.33
	T2Q2	ridge	South	59.33
	T3Q3	ridge	North	59.67
	T1Q3	ridge	North	63.00
	T4Q1	base	South	64.67
	T1Q2	ridge	South	66.67
	T2Q4	base	North	73.67

	T2Q3	ridge	North	76.33
	T3Q4	base	North	84.00
	Quadrat	**Location**	**Aspect**	**Depth (mm)**
Killesberg	T5Q1	base	South	68.25
	T2Q2	ridge	South	73.75
	T2Q1	base	South	74.00
	T3Q2	ridge	South	74.75
	T1Q4	base	North	76.25
	T3Q3	ridge	North	76.50
	T1Q4	base	North	77.50
	T3Q1	base	South	78.00
	T5Q3	ridge	North	78.75
	T1Q2	ridge	South	80.25
	T5Q2	ridge	South	82.75
	T5Q4	base	North	88.00
	T3Q4	base	North	91.00
	T1Q3	ridge	North	91.75
	T1Q3	ridge	North	97.00
	T4Q1	ridge	South	99.75
	T4Q2	ridge	North	100.75
	T1Q1	base	South	115.00

A Kruskal-Wallis test revealed that substrate depths recorded at different locations along the slope were not significantly different (ridge, n = 26, central, n = 4, base, n = 19), X^2 (2, n = 49) = 2.011, p = .366. In Köngen, for example, although the two deepest depths were recorded in the quadrats located centrally and at the base of the north-facing roofs slope (N-Q4: 13.87 mm; N-Q5: 11.17 mm), the shallowest depth recorded on this roof complex was a base measurement from the south-facing roof (S-Q7: 5.43 mm). In Tübingen, the two shallowest depths were measured in quadrats located at the base of the slope, one facing north (T1Q4: 47.3 mm) and the other facing south (T2Q1: 52.7 mm). The two quadrats at the lowest possible sampling location of the roof slope (T4Q1; T4Q4) did not have exceptionally deep nor shallow depths (64.7 mm; 56 mm), either. At Killesberg, the deepest depth was a base location (T1Q1: 115 mm) but the next four deepest depths were near the ridge (T4Q2: 100.8 mm, T4Q1: 99.8 mm, T2Q3: 97 mm, T1Q3: 91.8 mm). So, although the preliminary analyses picked up on the trace of a trend from the overall data set, closer inspection of the pitched roofs shows that the differences in depth were not significant along the location of the slope.

Similarly, a Mann-Whitney U Test revealed no statistically significant differences in depth measurements between north- (Md = 77, n = 22) and south-facing aspects (Md = 69.67, n = 27), U = 215.50, z = -1.638, p = .101, r = -0.234. Many of the deepest depths did occur on north-facing slopes, as in Tübingen, but the four deepest depths in Köngen and Killesberg occurred on two north and two south-facing slopes, comprising samples located at different points of the roof slope (i.e., base, central, and ridge locations). These quadrats (N-Q4 at Köngen: 138.67 mm; and at Killesberg T1Q1: 115 mm and T4Q1: 99.8 mm, both south-facing) were outliers by comparison with the other measurements, although they were not significant outliers (**Figure 4.4**).

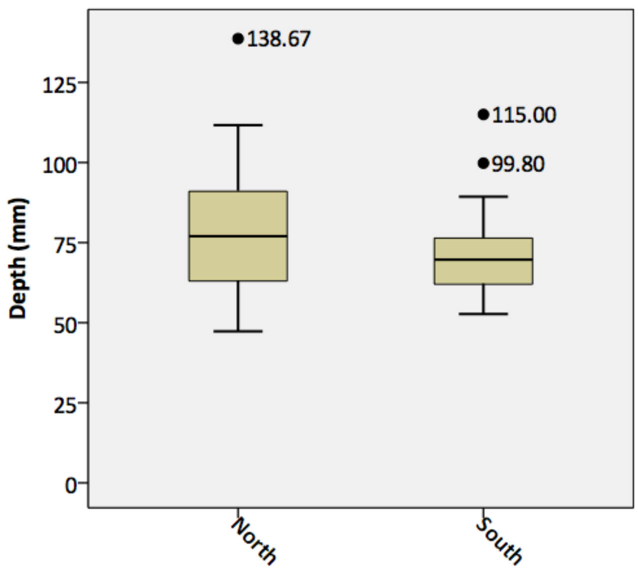


Figure 4.4. Quadrats located on north-facing aspects had a greater range of depths measured but did not differ significantly from south-facing quadrats.

Contrary to what one might expect, these results suggest that substrate depth was not significantly influenced by location along a slope, nor the aspect it faces. In spite of their prototypic constructions, the custom-built erosion control barriers at Köngen may therefore be considered a tribute to these early systems. Still, Killesberg is even steeper and doesn't feature such retention features, yet substrate depth was not deeper at base locations along the slope. Of course, the survey methods only sampled uniform vegetation, which means that extreme edges were avoided, such as the very base or top of a slope, but in some cases such vegetation extended very near to the edges (e.g., Killesberg T5Q1 and Q4; Tübingen T4Q1 and Q4).

4.3.1.4 Species-level responses to depth

The relationship between substrate depth and species composition is well researched from the horticultural perspective, but the ecological dynamic between EGR vegetation and substrate depth over time is unknown. The data from these surveys represent snapshot observations of mature EGR vegetation. Abundance records of the ninety-five species surveyed were subjected to a correlation analysis with depth. The relationship between species cover abundance and substrate depth was investigated using Spearman's rank correlation coefficient. There were significant relationships between eleven species and substrate depth (**Table 4.4**). The three species exhibiting the largest effects (*Sedum hybridum*, *S. spurium* and *Thymus serpyllum*) all had negative relationships with depth [(*rho* = -.403; *rho* = -.430; *rho* = -.436 (respectively), all *n* = 131, *p* < .001], which implies that these species were less abundant in deeper depths and, vice versa, more abundant in shallower depths. These species are popular green roof plants and occurred on the majority of the roofs surveyed. According to these results, they were most abundant in shallow depths, which concurs with field observations.

Table 4.4. Substrate depth had significant correlations with the cover abundance of eleven species.

Species abundance correlated with substrate depth (*rho*)	Correlation Coefficient	N	Coefficient of determination
Allium schoenoprasum	-.347**	131	12.04
Festuca ovina	.377**	131	14.21
Moss_Hypnum2	-.333**	131	11.09
Moss_Calliergonella cuspidata	.248**	131	6.15
Petrorhagia saxifraga	-.257**	131	6.60
Sedum album Murale	.351**	131	12.32
Sedum hybridum	-.403**	131	16.24
Sedum spurium	-.430**	131	18.49
Thymus serpyllum	-.436**	131	19.01
Trifolium arvense	.304**	131	9.24
Vulpia myuros	.258**	131	6.66

The other species with significant responses to depth had weaker effect strengths [as per Cohen (1988)], and the direction of relationships varied. Like the Sedums and Thyme mentioned already, *Allium schoenoprasum*, the moss *Hypnum2* and *Petrorhagia saxifraga* all had negative relationships with depth. Little is known about the moss, which could only be identified to genus, but the vascular species are popular green roof plants because of the cover they maintain through self-seeding as well as their tolerance to drought (Kolb et al., 1983, Krupka, 1992). By contrast, *Festuca ovina,* the moss *Calliergonella cuspidata, Sedum album Murale, Trifolium arvense* and *Vulpia myuros* all had positive relationships meaning that they had greater cover abundance in deeper depths. The strength of the relationship and the amount of shared variance are important elements of this analysis (Pallant, 2010), because of the small sample size. The coefficient of determination indicates that these variables share very little of their variance; the three species with the largest effects and the highest percentage of variance did not share more than 19% of their variance with substrate depth. This is an important reminder of the influence of small sample size on significance levels.

4.3.1.5 Discussion on quadrat-level analyses

Other studies that have examined the influence of slope and/ or aspect on EGRs have been interested in the vegetation or substrate composition but have not reported on depth. For example, Köhler and Poll (2010) found that north-facing aspects supported the greatest plant coverage on vegetated roofs in Berlin, and that aspect played a significant role in species composition due to light tolerance by different species, but they do not address how these might influence substrate depth. Studies of spontaneous vegetation on TPG and flat gravel roofs noted that shaded roofs had substantially more humus than sun-exposed roofs, as a result of the accumulation of undecomposed vegetation and organic matter (Bornkamm, 1961, Thommen, 1988), but they didn't refer to the impact of this accumulation on depth. Research into the substrate composition of EGR systems over time, whether on actual roofs (Liesecke, 2006), on testing platforms (Rowe et al., 2012), or in test plots (Jauch and Fischer, 2000) observed that soil organic content increases over time, but again none reported on the depth over time.

Aspect and slope influence the climatic effects of light and temperature, among others, which will certainly influence the vegetation, so the differing depths could be related to the associated plant biomass and perhaps also the processes of decomposition under certain climatic conditions. The north-facing roofs were located close to trees whose shade and litter would affect soil moisture, pH and soil carbon, not to mention microclimate factors like humidity, temperature. Such growing conditions affect not only decomposition rates but also the proliferation of mosses and subsequent influences from this on the vegetation and soil-based processes. Perhaps the influence of slope and aspect on substrate depth cannot present clear and apparent trends because of the lurking variables and complex ecological processes they are involved in.

In terms of substrate loss, the only physical disruptions observed that might have led to losses in substrate depth were observed on the Esslingen Verkehrsbetrieb roofs, which had the shallowest depths measured. If Hövekamp's recollections were correct (100 mm LECA with 10-20 mm organic layer over top), then these roofs lost over 60 mm in substrate depth. The use of LECA has become less popular in Germany, with preference instead for recycled materials like crushed brick (Appl and Ansel, 2004), but it is still listed as a green roof substrate in other places (Molineux et al., 2009). Similarly, none of the depth measurements on the Rathaus roofs exceeded 81 mm, so if they really were installed with 100 mm substrate then up to 54 mm depth was lost in some places. No wind scour or other physical removal was evident on these roofs, however. Location along the slope of pitched roofs was not found to have a significant association with substrate depth, which may be a tribute to the design of these roofs. The variability in depth measurements recorded can perhaps be attributed more to the uneven distribution of the substrate upon installation than to processes.

Of all the species identified, those that responded significantly to depth were typical green roof plants (*Allium schoenoprasum, Festuca ovina, Petrorhagia saxifraga, Sedum spp, Thymus serpyllum*) and ruderal colonisers (*Trifolium arvense, Vulpia myuros*) and two mosses (*Hypnum spp, Calliergonella cuspidata*). The relationships revealed by this quadrat-level analysis indicate that depth is an important factor to EGR species composition over time. Recalling earlier analyses on persistence, gain and loss of species, substrate depth might act as a selective filter for the species that persist over time, in conjunction with other factors.

4.3.2 Roof-level query: mean depth

The results from the quadrat-level analyses were not conclusive that substrate depth decreases with time, so this section will describe the observations at a broader scale, that of mean values and including an expanded dataset. Working first with mean depth per roof, the surveyed EGRs were arranged into ordinal age groupings (**Table 4.5**). A Kruskal-Wallis Test revealed a statistically significant difference in substrate depth across the four age groupings (Age 1, n = 46: 20-21 years; Age 2, n = 26: 22-23 years; Age 3, n = 44: 24-25 years; Age 4, n = 15: > 26 years), χ^2 (3, n = 131) = 41.77, p < .001). The removal of the north-facing quadrats at Köngen did not influence these results (p < .001), so data from both roofs were included in the analysis. The two oldest roof age categories (24-25 yrs and >26 yrs) recorded much smaller mean ranks (39. 43; 52.6, respectively) than the other two age groups, both of which had mean ranks of 85. The youngest age group (20-21 years) recorded the highest median score (*Md* = 34) of the other age groups, of which the second youngest group (22-23 years) had a median value of 19 while the two oldest groups had median values of 6. These results suggest that substrate depth of the youngest EGRs surveyed was significantly deeper than the older roofs.

Table 4.5. Mean substrate depth on nine EGRs of different age groups.

Roof name	Roof age grouping	Mean depth (mm)
Rathaus-lower	20-21	69.79
Rathaus-PV		64.36
Killesberg		84.69
FH Nürtingen	22-23	72.28
Köngen		78.13
Tübingen	24-25	61.48
VB A1		52.79
VB A2		58.13
Pliensau	> 26 yrs	61.56

Nine EGRs is considerably less than the minimum requirement of thirty-seven roofs (for statistical rigour), but considering how little work has examined old EGRs in the first place, this sample can be considered a starting point. In order to expand these limited results further, a dataset from Karlsruhe may complement this work.

4.3.2.1 Amalgamated dataset: mean depth

The eight EGRs surveyed by Buttschardt are numbered in order of age, such that B1 is the youngest roof (2 years since installation) and B8 was the oldest (7 years). The code name given to each roof by Buttschardt is included in parentheses beside the roof name; the prefix "sy-" implies that they are system roofs. Similar to the roofs in this study, the Karlsruhe sample included a couple pitched examples (B2, B6), and large as well as small surface areas (**Table 4.6**). Other than two single-layered systems (B4, B8), in which the substrate concurrently serves for drainage, the Karlsruhe roofs were 3-layer constructions (i.e., substrate and drainage layers are separated by a filter sheet). Only two of the Karlsruhe roofs were located inside the old city centre (B3, B8), and the others were in less dense, newer parts of the city. Two of the Karlsruhe EGRs were pitched, of which the 15° roof on **B2** (Waldorfschule) had a western aspect, while the 12° apex slope on **B6** (Turnhalle) had equal aspects facing east and west, each 525 m^2.

Table 4.6. Amalgamated dataset of 17 EGRs in south-west Germany installed between 1977-1997 in order of age at time surveyed

Roof code	Roof name (in order of age)	Year Installed	Age	Area (m^2)	Slope (°)	System (# layers)	Mean depth (mm)
B1	Forschungszentrum Umwelt (syFZU)	1997	2	230		3 + veg mat	50.0
B2	Pavillon Waldorfschule (syWDF)	1996	3	89	15	3	60.0
B3	Sparkasse Sophienstr. (sySk)	1995	4	110		3	140.0
B4	Jugendtreff Oststadt (syJTO)	1994	5	300		1	80.0
B5	Klinikum OP (syK)	1992	7	380		3	120.0
B6	Turnhalle RB (syRB)	1992	7	1050	12	3	60.0
B7	Haid & Neustr. (syH+N)	1992	7	410		3	60.0
B8	Garagen Rudolfstr. 6 (syR6)	1992	7	37		1	140.0
K-berg	Killesberg	1991	20	450	30	3	85.0
R-low	Stuttgart Rathausgarage, lower	1990	21	1000		3	70.0
R-PV	Stuttgart Rathausgarage, PV	1990	21	1300		3	64.0
Köngen	Römermuseum, Köngen	1987	23	230	17	3	71.0
FH-Nue	FH Nürtingen	1987	23	258		3	72.0
VB A2	Verkehrsbetrieb Area 2	1986	25	2064		3 +modules	58.0
VB A1	Verkehrsbetrieb Area 1	1986	25	1860		3 +modules	53.0
Tueb	Gärtnereihof Tübingen	1986	24	2160	15	3 + veg mat	61.0
Pliensau	Pliensaufriedhof, Esslingen	1977	33	500		3	62.0

The 230 m^2 EGR of **B1** (Rotunde Forschungszentrum Umwelt) at the University of Karlsruhe was installed with 20 mm deep, pre-cultivated coir vegetation mats on top of a multi-layered system, and is framed by a border of concrete paving slabs. The north side of that roof is directly neighboured by the Hardt forest. The 110 m^2 EGR at **B3** (Sparkasse) was on an extension that served partly as terraces for flats on the first floor; it receives some shade from the north-west wing of the building and the paving elements have led to some wet patches. The single-layered system roof on the Jugendtreff (**B4**) featured a drainage element consisting of coarse slag and recycled cinder waste. The 380 m^2 EGR on **B5** (Klinkum neuer OP-Trakt) was divided into three sections divided by concrete borders; due to a higher building to the west this roof received partial shade by afternoon. (Buttschardt, 2001) (p. 41). Of the eight EGRs surveyed, only four (RB, WDF, H+N, JTO) were granted access for vegetation surveys, which involved permanent plots that were visited annually from 1997-1999. Substrate depths on the Karlsruhe roofs ranged between 50 and 140 mm, but only three (B3, B5, B8) had more than 100 mm.

Amalgamating this dataset with that from Buttschardt (2001) expands the sample to seventeen roofs starting at two years after installation. The north-facing roof at Köngen was excluded here because it was shown to be a significant outlier for mean depth. Extending the assumption that the Karlsruhe roofs were also initially installed with 100 mm substrate, a one-sample t-test found a statistically significant difference in mean substrate depth between roofs ($p < .05$) with a mean difference in depth of 63.8 mm and a 95% confidence interval ranging from 5.82 to 6.95. It seems unlikely that initial depth was under 70 mm, which would suggest some loss over time. Three of the Karlsruhe roofs (B3, B5, B8) recorded very deep mean depths of 120 mm or more, but the majority were under 60 mm. The depths of the roofs measured in this study were less variable, with none over 85 mm. A best fit line (R^2 = 0.145) suggests a weak negative relationship between substrate depth and roof age for this extended sample (**Figure 4.5**). This analysis affirms the variability in EGR conditions and constructions in the early days of the German market. Clearly a larger dataset is needed, as well as more monitoring of depth over time.

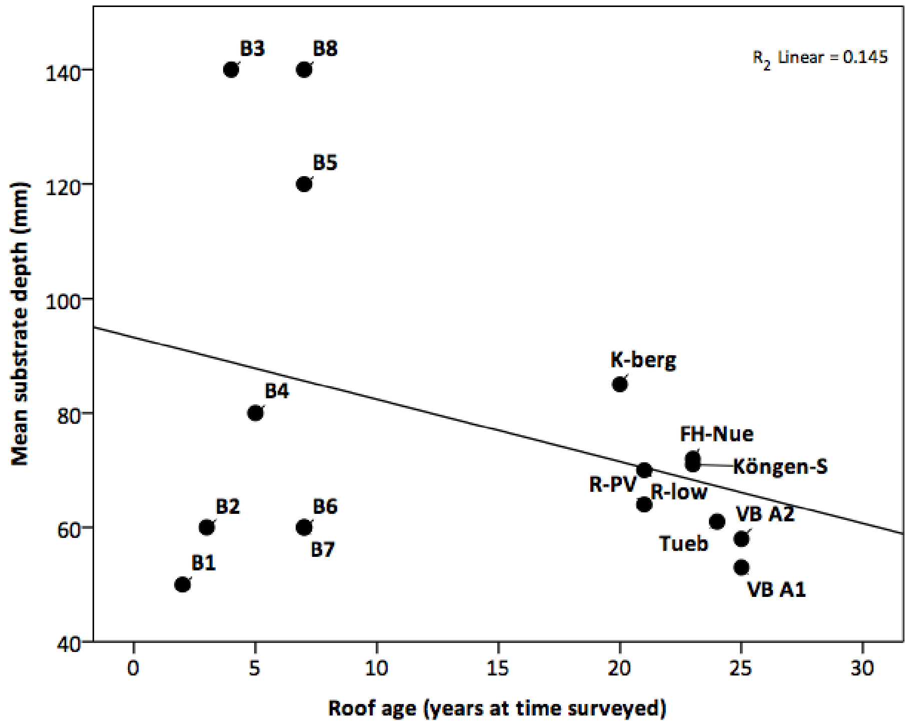


Figure 4.5. Mean substrate depth of EGRs over a timeframe from 3 to 33 years after installation (using data from Buttschardt, 2001).

4.4 Conclusions

Closer inspection of the associations between substrate depth with time, slope and aspect revealed subtle trends but no strong or consistent relationships. Indeed, the results from the quadrat-level analyses echo the results of the power analysis, that at least thirty-seven roofs are required to substantiate the relationship between depth and time. The provision of convincing background information would facilitate such work considerably. In spite of the amalgamated dataset featuring roofs of similar construction and regional location, variability amongst the roofs makes conclusions difficult.

No documentation for the roofs surveyed here mention how the substrate was installed. In any case, if the recommendations and guidelines for maintaining EGR substrate depths are insufficient for the long-term, and depths shrink beyond the minimal threshold, this will unequivocally have adverse repercussions for vegetation and ecosystem function, such as stormwater retention and other green roof benefits.

Of the nine EGRs surveyed, the older EGRs surveyed had significantly less depth than the younger ones. The amalgamated dataset of younger roofs from Karlsruhe suggested a negative relationship of depth over time. The tests assuming 100 mm original depth also suggested negative relationships between roof age and substrate depth, whether quadrat-level for the nine EGRs or mean depths for the expanded dataset of seventeen roofs. Due to the strength of that assumption, and given the variation recorded for depth, this chapter cannot conclude that EGR depth decreases over time. Location of a quadrat along a roof slope did not significantly influence substrate depth, nor did aspect (whether north- or south-facing, or flat without any aspect).

4.4.1 How is depth over time addressed by the FLL guideline?

Since no observations of EGR substrate depth over time on have been published, the opinions of German professionals with over 20 years' experience in the green roof industry and market were sought. Three colleagues (Dr. Gunter Mann, Optigrün International; Prof. Dr. Stephan Roth-Kleyer, FH Geisenheim; Jörg Breuning, Green Roof Service, LLC) agreed that substrate depth would likely have declined on older EGR systems, but that this would not happen nowadays because of the improvements to the FLL guidelines, specifically the specifications of less organic content and the refined parameters for substrate manufacture and methods of installation (Mann et al., 2013). Still, none could confirm this by personal observation. They declined to speak of the potential for declining substrate depth on EGRs in new markets. These conversations demonstrate confidence in the FLL guidelines, and the associated assumption that EGR substrate depth over time is stable and not a point of consideration or concern.

A similar correspondence with North American practitioners suggested that substrate depth on EGRs older than ten years is not commonly measured (Bass et al., 2013). One professional in Vancouver (Randy Sharp, Principal, Sharp & Diamond Landscape Architecture) did report "shrinkage" of 10 -20 mm on two roofs in that region: the Sechelt RCMP Justice Facility (installed 2002 with 80 mm) and Campbell River City Hall (installed 2005 with 50 mm). Given that those green roofs were installed relatively early in the development of Vancouver's green roof industry, and juxtaposing this with the German opinions, perhaps any occurrences of declining substrate depth over time is simply a phenomenon that is restricted to the early days of an emerging industry, and which will stabilise once standardised products, materials and methods are enforced.

The FLL guidelines are used as a reference for the development of green roof standards in regions with emerging green roof movements (Dvorak, 2011). In North America, for example, the American Society of Testing and Materials International (ASTM) Green Roof Sub-Group has published five documents, including a standard guide for the selection, installation and maintenance of green roof vegetation (ASTM E 2400 2006), standards for determining structural loads under dry and saturated conditions of green roof systems (ASTM E 2397 2005) and of dry and saturated substrates (ASTM E 2399 2005), and two methods for testing water permeability rates through drainage materials (ASTM E 2396 2005; ASTM E 2398 2005). As with the German guidelines, there is no reference to monitoring substrate depth over time.

5 Ecological conditions and processes on EGRs

The results presented in the previous chapters suggest that species diversity has declined since the roofs surveyed were installed, and that dominant cover abundance is often accomplished by succulent species (sometimes only a few). Succulents and grasses behaved oppositely to other life forms with respect to many of the variables tested, including slope, aspect, and cover abundance and species diversity of life forms. Two main EGR vegetation types identified by a cluster analysis ("Species-poor Sedum roof" and "Sedum meadow"), according to proportionate life form cover, were distinguished mainly by species diversity and species composition. This chapter seeks out the role of environmental and growing conditions on EGR vegetation, and the over-riding processes, causes and mechanisms that led to those results. Since the sample size available for this research was limited, this chapter elaborates into theoretical query as a broader means of perceiving and predicting patterns on the roofs surveyed and, potentially, on other roofs in other parts of the world.

5.1 Literature Review: the ecology of urban environments

After a thorough introduction to the environmental conditions of cities and urban habitats, the classical ecological theories briefly introduced in Chapter 1 will be explored in greater detail. In spite of the anthropogenic nature of EGRs, and the myriad interlinked factors that affect each site uniquely from the next, do certain environmental conditions determine species diversity or life form composition more than others over time? What are the environmental conditions on EGRs and how do they influence vegetation dynamics? Having characterised the vegetation with habitat indicators, this chapter builds upon the vegetation types clustered in Chapter 3 by typifying EGR vegetation further. With the EGRs accordingly distinguished into vegetation types, the most philosophical question posed by this research can be examined, namely whether emergent community properties develop on EGRs over time. In other words, do emergent community characteristics develop, such that similar growing conditions lead to similar EGR vegetation types and a convergence along common ecological trajectories (e.g., homogenisation versus diversification)?

Do EGRs fit any ecological models, at least conceptually? For instance, does EGR vegetation reach a steady state after a certain period of time (climax state of natural succession) or do stochastic disturbances keep things in perpetual dynamism (disturbance theory)? Can the proportion of persistent versus colonizing species on the EGRs surveyed be related to the dimensions and location of the roof (island biogeography theory, metapopulation dynamics)? Can the adaptive life strategies (CSR theory) of the predominant flora serve to demonstrate the environmental conditions that filter EGR species composition? Can the concepts of patch dynamics and fragmentation aid the speculation of short-term dynamics that led to the results observed?

5.1.1 The nature of urban ecosystems and urban vegetation

Zoomed out, the urban and urbanizing landscape is a complex mosaic of human modifications and built structures, with natural spaces slotted wherever and however urban designs and landscapes permit. Bearing very different conditions from rural surroundings, the urban environment creates novel combinations of stress and disturbance that can lead to altered ecosystem processes (Parlow, 2011) and a suite of environmental modifications (Gilbert, 1989). Changes to the soil environment along the rural-urban gradient, for example, lead to urban forests exhibiting highly altered litter decomposition and nitrification rates, soil carbon pools, and fungal and faunal densities (Pouyat et al., 1997), and such effects on nutrient and carbon cycling affect vegetation and species composition in the long term (Zipperer et al., 2000). By contrast with non-urban habitats, urban ecosystems are affected by a distinctly different kind, intensity and frequency of anthropogenic influence (Breuste et al., 2008). It's interesting to consider that urban environments may have more in common, ecologically, with other cities than with adjacent natural ecosystems (Savard et al., 2000, McKinney, 2002). Extensive green roofs differ from other urban ecosystems in their occurrence at higher elevations, exclusive use of engineered growing substrates, and their disconnect from ground-level resources (e.g., greater soil profiles) and physical disturbances (e.g., trampling). Still, many of the conditions typical of the urban environment likely affect roof- and ground-level vegetation similarly.

Urban vegetation can be described in as many ways as it can be perceived and the complexity and heterogeneity of urban ecosystems poses a challenge to even the most diligent ecologist. One major challenge to consistent descriptions is the implicit cultural subjectivity of the observer; one ecologist might define an urban area as a singular, homogeneous entity while another categorise it into distinct subunits. Similarly, some might combine anthropogenic factors into a single environmental variable whereas others correlate them with multivariate techniques. The classification and description of urban vegetation is further challenged by the blurred objectivity of what is natural (or native) and what is artificial (or non-native), not to mention the relevance of these distinctions in the first place. Some ecologists suggest that the prevalence of many urban species can be explained, very simply, by their propagule availability (Kowarik, 1990, Lundholm, 2011, Cilliers et al., 2008, Williams et al., 2009). Successful urban species are also known to demonstrate tendencies for exploitation, adaptation and ruderality (Grime, 2001, McKinney, 2002, Hill et al., 2002, Thompson and McCarthy, 2008), hence plants which exploit urban ecosystems are termed synanthropes (from the Greek *syn-*: "together with" and *anthro*: "man") (McKinney, 2002). Education and conditioning may also render one-sided opinions regarding urban biodiversity, such that one ecologist may grieve that a derelict site over-run with weedy vegetation is a lost opportunity for nature conservation while another celebrates that same site for its contributions to urban ecosystem services. Considering urban flora as part of cultural or novel ecosystems may facilitate understanding of and engagement with the dynamic reality of urban ecosystems (Hobbs et al., 2006, Fischer et al., 2013).

5.1.1.1 Urban soils and biogeochemical cycles

The soils of urban areas are extremely variable and can encompass almost any extreme of physical or chemical properties: soil pH can range from acid to alkaline; nutrient contents may be excessive to non-existent; there may be little to no buffering capacity; organic matter may be abundant to almost nil, and many sites may carry pollutant loads (Kendle and Forbes, 1997). Urban soil research is still a very young scientific discipline and, without any internationally accepted survey concepts, urban soils have been characterized in numerous different ways (Sauerwein, 2011). Given the variability between cities, the impotence of generalization within multivariate, anthropogenic and heterogeneous systems, and the numerous approaches for regarding urban soils, it is perhaps no surprise that so few conclusions have been made on their ecology, however noble the attempts (Byrne, 2007, Lorenz and Lal, 2009, Pavao-Zuckerman and Byrne, 2009).

While the processes and qualities occurring in urban soils do not relate to EGRs, whose substrate blends usually adhere to the FLL guidelines, EGRs are unequivocally influenced by biogeochemical cycles. Urban ecosystems have a fundamentally different biogeochemistry than non-urban systems because of the anthropogenic influences which control all points, inputs, and outputs (Pavao-Zuckerman, 2008). Given their central positioning for transportation and industry, for example, urban areas are point sources of CO_2 and other greenhouse gases (which influence the Earth's climate), as well as trace gases like NO, NO_2, O_3, SO_2, HNO_3, and various organic acids (Grimm et al., 2008). They also experience high rates of acid and N deposition and elevated atmospheric concentrations of CO_2, CH_4, and O_3, which can produce both growth-enhancing and growth-inhibiting effects on organisms (Grimm et al., 2008). These net effects fundamentally alter the physical, chemical and biological properties of urban soils, thereby shifting ecosystem functions and processes related to biogeochemical cycling. Green roofs are not exempt from these ubiquitous effects, but the effects on EGR vegetation have not been explicitly studied.

5.1.1.2 Urban climate: temperature, air quality

Urbanisation is accompanied by local changes in climate, including higher minimum temperatures and sometimes reduced maxima, as well as changes to precipitation patterns and weekly cycles (Grimm et al., 2008). Due to the physical properties of construction material, cities have completely different radiation and heat budgets (e.g., heat capacity, thermal conductivity) than non-urban landscapes (Parlow, 2011). The urban heat island (UHI) effect is a well-documented example of anthropogenic climate modification (**Figure 5.1**) that influences local and regional climates. Green roofs are used to dampen the impacts of UHI on water resources, energy consumption, air quality, human health, and biodiversity and ecosystem functioning (Crutzen, 2004, Hunter-Block et al., 2012, Jim, 2014a, Jim, 2014b, Zhao et al., 2014). In hot climates, UHI exerts additional stress on organisms, including humans, and may influence water resources by changing the surface-energy balance, altering not only heat fluxes but also moisture fluxes near the surface (Grimm et al., 2008). Continental climates experience the UHI more intensely than maritime situations, which have complex and windy weather systems (Kendle and Forbes, 1997). Still, green roofs' positive abatement of UHI in Japan (Takayama et al., 2008) has led to policy mechanisms supporting the implementation of green roofs in that maritime island state (Tokyo Metropolitan Government, 2007).

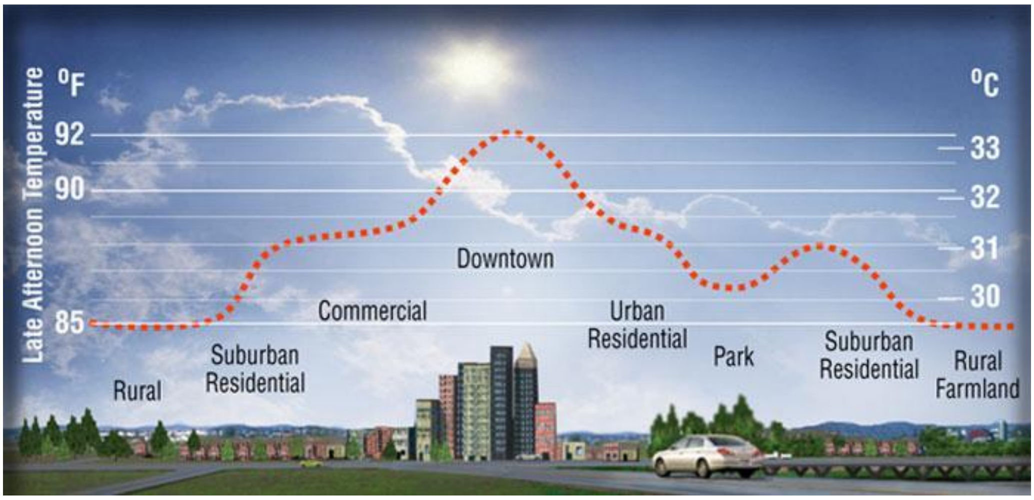


Figure 5.1. On a sunny afternoon, urban air can be 1-3°C warmer than nearby rural air. Source: Berkeley Lab, Heat Island Group.

Urban warming induces the formation of smog, and atmospheric ozone and carbon dioxide levels are frequently elevated in urban environments (Grimm et al., 2008). These changes in atmospheric chemistry have been shown to affect plant physiology and potentially also affect soil quality through alterations of plant-soil interactions and litter quality (Pavao-Zuckerman, 2008). Pollution from dust is also an urban issue, particularly if vegetation is inadequately provided; large trees can reduce over 50% of urban dust, and moderate spacing of urban trees encourages air to filter through, rather than being diverted, while also reducing wind speed (Kendle and Forbes, 1997). Several studies have found that EGRs can help to reduce air pollution (Yang et al., 2008, Currie and Bass, 2008, Rowe, 2011, Speak et al., 2012), although little documentation has studied the reverse, namely the effect of the urban climate on green roof vegetation. Lastly, wind patterns through aerodynamics, vertical turbulence and wind field are all influenced by the three-dimensional complexity and surface roughness of the urban boundary layer (Parlow, 2011), all of which can have major impacts on urban vegetation. Indeed, wind loading on green roofs can result in positive and negative pressures, friction, shearing, erosion and uplift (FLL, 2008b) (p. 35), hence standards to minimise wind damage are required for European (DIN 1-55-4) and North American green roofs (ANSI and SPRI, 2010).

5.1.1.3 Hydrology of urban environments

The hydrologic cycle is dramatically impacted by urbanisation, and reducing the associated negative impacts has led to increasing use of green infrastructure in cities around the world (U.S. Environmental Protection Agency, 2011, Hunter-Block et al., 2012, Kimmel et al., 2013). The natural hydrologic cycle includes precipitation, infiltration, groundwater flow and recharge, evaporation and condensation. Hard, sealed surfaces (i.e., roads, roofs, pavements) disrupt percolation, soil infiltration and aquifer replenishment, and stormwater infrastructure inhibits plant-water uptake and evapo-transpiration because it channels precipitation directly to rivers and, eventually, the sea. Urbanisation leads to significant changes in watershed behaviour, with local and global effects (Illgen, 2011). The magnitude of these impacts relate directly to the extent of surface sealing (Natural Resources Defense Council, 2013). In fact, some researchers have proposed that global warming and climate change are more the result of disrupted hydrologic cycles than atmospheric greenhouse gases (Kravčík et al., 2007, Schmidt, 2010); this 'water paradigm' states that reduced surface water and precipitation create a warmer and drier terrestrial environment which is maintained as a negative feedback (Schmidt, 2010). As introduced in Chapter 1, much research has quantified green roofs' ability to retain and detain stormwater runoff and to improve the urban climate through evapotranspiration.

5.1.1.4 Anthropogenic forces in urban ecology

Since urban environments are governed by human actions, anthropogenic forces are necessary elements of any study of urban ecology. From an ecological perspective, cities present unique mosaics of residential, commercial, industrial, and infrastructural sites interspersed with green spaces. These green spaces may be formal (e.g., parks, gardens) and informal (e.g., remnants of less modified vegetation), as well as "wild" functioning habitats such as natural watercourses, derelict industrial sites and overgrown gardens (Breuste et al., 2008, Williams et al., 2009). Many agree that conserving and enhancing urban biodiversity has unique implications for human well-being and public health (Gilbert, 1989, McKinney, 2002, Miller, 2005, Diaz et al., 2006, Goddard et al., 2010, Kowarik, 2011, Kellert et al., 2008). For extensive green roofs, the direct anthropogenic forces influencing EGR vegetation are typically intentional, such as species selection and maintenance, but anthropogenic forces can be unintentional and indirect, too, like species introductions via the substrate.

Cities and towns are hubs of transport and the networks to which they are connected facilitate the spread of species across various spatial scales (Kowarik, 1990, Pysek, 1993, McKinney, 2006, Ricotta et al., 2009). Particularly when they serve as ports for world trade, cities can qualify as propagule sources which can launch species to distributions of global scale. The concept of "biotic homogenization" implies that cities around the world will eventually all feature the same cosmopolitan assemblage of generalist species. Even though these species may enrich local biodiversity, this concerns conservationists because global species and genetic diversity are compromised when biologically unique ecosystems and species pools are lost (McKinney, 2006, Ricotta et al., 2008). The typical conditions of cities (warmer, drier, etc.), not to mention a continually warming climate, explain why many of the most prevalent urban weeds originate from dry, warm, high-light, pioneer habitats (Diaz et al., 2004, Ricotta et al., 2009). In addition, weedy organisms tend to have affinities to human activity (Thompson, 2014), and species like Norway rat, House mouse, Starling and House sparrow are found in all cities of Europe and North America (Jokimaki and Suhonen, 1998).

Little scientific research evidence backs the claims of biotic homogenization (Hitchmough, 1994, Dunnett, 2004). Research coordinated by the Convention on Biological Diversity (2012) found that the number of native species in cities is relatively high in spite of the pressures that would suggest otherwise (e.g., habitat loss and fragmentation), and that "concerns about biotic homogenization may be somewhat unfounded" (p. 9). Particularly in the northern Hemisphere (which is better studied than the south), 50% or more of the regional or even national species assemblage for many taxonomic groups occurs in cities. Indeed, several studies report that urban areas support important pools of biodiversity [e.g., Kühn et al. (2004), Kinzig et al. (2005), Pickett et al. (2008)], with some reports of greater native diversity in urban than neighbouring rural areas [e.g., Wania et al. (2006)]. A series of collaborative studies have recently begun to assess the nature and extent of ecological homogenization in urban USA (Groffman et al., 2014). Current understanding is conflicted; although towns and cities clearly offer prospects for biodiversity and must not be overlooked as opportunities for reversing the trends of extinction (Hooper et al., 2005), they also carry a potentially large extinction debts (Hahs et al., 2009, Duncan et al., 2011). Furthermore, the increase of impervious surfaces and compact urban development patterns offer limited opportunities for native vegetation to persist or colonise (Hahs et al., 2009).

5.1.1.4.1 Filters of natural selection: urban ecology and evolution

Anthropogenic forces also impact upon the behaviour, phenology, phylogenetics and morphology of city-dwelling organisms. Over the short-term, species phenotypes may change in response to anthropogenic forces, both direct (buildings, modified habitats, wildlife feeding) and indirect (noise and air pollution, altered temperatures, productivity and light). In the longer term, these selective forces can act as evolutionary filters that influence population genetics and life-history traits of urban species (Shochat et al., 2006, Grimm et al., 2008). From the perspective that the selective anthropogenic forces of urban environments may create a new type of natural selection, Shochat et al. (2006) suggest that the key to understanding urban patterns is to balance the study of processes at the individual scale with an integrated examination of environmental forces at the ecosystem scale. Mechanistic studies have demonstrated that urbanization can lead to changes in animal behaviour (Slabbekoorn and Peet, 2003, Shochat et al., 2004), including physical morphology (Yeh, 2004) and community structure (Shochat et al., 2004).

In anthropogenic (urban) environments, plant species are sourced from three sources: i) native species originally present in the area; ii) regionally native species originally absent from the area but which have colonized novel habitats created by urbanization; iii) alien species introduced by humans that escape to establish wild populations in urban environments (Williams et al., 2009). A meta-analysis using data from twenty-one urban floras in Europe and eight in the USA found that urban conditions constrain the functional diversity of urban floras, as evidenced by the lower phylogenetic diversity of urban alien species that are well adapted to these habitats (Ricotta et al., 2009). This would imply that urban alien floras are composed of phylogenetically related species, as a result of urban environmental conditions. Similarly, a time-series analysis covering three centuries for Halle (Saale), Germany, identified that some of the drivers behind urban floristic change included the higher urban temperatures, gardeners' preferences, and dispersal agents such as animals, vehicles, and greater wind turbulence (Knapp et al., 2010).

The notion of environmental filters and assembly rules offers a useful conceptual framework for modelling the forces that govern the assembly of biotic communities (Lake et al., 2007, Rahel, 2002, Williams et al., 2009, Diamond, 1975), and for comparing and contrasting restoration practices for different ecosystems (Nuttle, 2007). Within this framework, the assemblage structure and membership of a local species assemblage are determined by constraints, or filters, to dispersal, as well as biotic and abiotic features. For instance, if a species from the regional species pool is able to arrive at a site by dispersal, and if the environmental and biological conditions of the site are amenable to its establishment and survival, then this species will become part of the local assemblage (**Figure 5.2**). However, in heavily impacted systems the regional species pool may be diminished and the same constraints can lead to different assemblages (Lake et al., 2007).

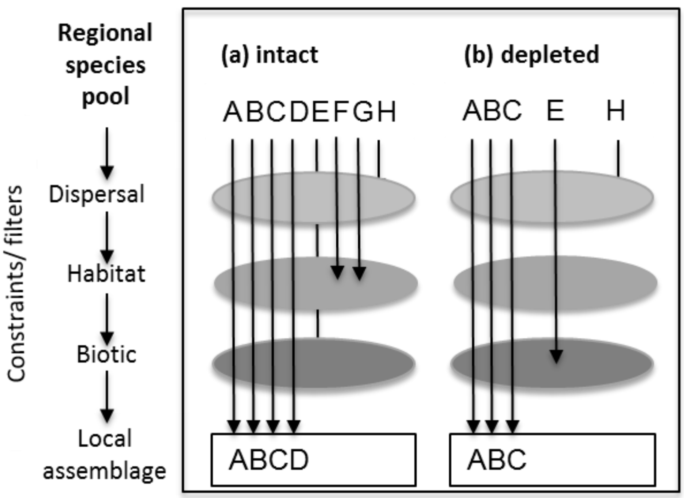


Figure 5.2. Varying responses to the constraints of a site can lead to different species assemblages in the same habitat, especially if the regional species pool is (a) intact or (b) depleted. Adapted from Rahel (2002) and Lake et al. (2007).

This conceptual framework can also help to advance a clearer understanding of the effects of urbanisation on urban floras, provided the inclusion of both remnant and novel habitats, and species of all designations (native, cosmopolitan, garden escapees, etc.). A framework proposed by Williams et al. (2009) is based on the assumption that the species pool of an urban flora will include any species that have managed to pass through four filters (**Figure 5.3**). The first two – habitat transformation and fragmentation –are anthropogenic filters present in most ecosystems, while the latter two – urban environmental conditions and human preference – are unique to cities. Each of these filters creates selection pressures that leave a "signature" on urban floras, owing to the non-random gain and loss of species, changes in species abundances, altered distributions of functional traits, and so on.

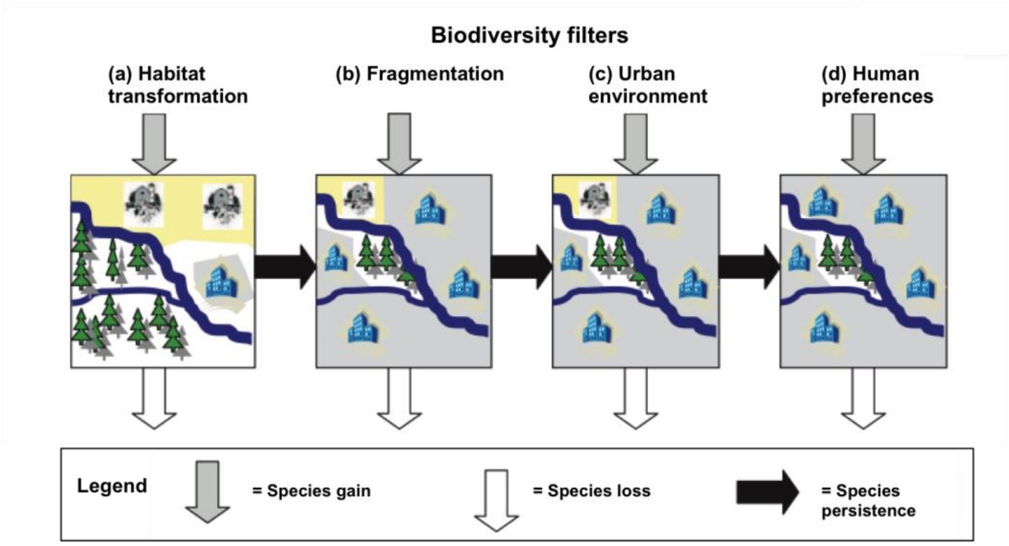


Figure 5.3. A schematic model of major urban filters that add (grey arrows) and remove (white arrows) plant species resulting in altered species persistence (black arrows). The four panels represent filters of plant diversity that may select on floristic composition, plant functional traits or the phylogenetic structure of communities. Although displayed in temporal sequence, different parts of an urban environment will likely experience each filter at different times, resulting in filters acting simultaneously within the entire urban environment. (a) Habitat transformation adds species by creating novel urban environments, and removes species due to the loss of native vegetation. (b) Fragmentation removes species that are unable to persist in small isolated areas, which can then be colonized by additional species. (c) Urban environments are unlike non-urban environments due to a suite of environmental changes (e.g. pollution, urban heat island) that can select for or against species. (d) Human preferences add and remove species. Each filter contributes to a suite of taxa that can persist in urban environments. Modified from Williams et al (2009).

5.1.1.4.2 <u>Social impacts: ecological ignorance leads to collective indifference</u>

An increasingly urbanised human population also influences urban vegetation and biodiversity when ecological awareness and appreciation for non-human life is lost (Savard et al., 2000, Millard, 2004, McKinney, 2006). If the relationship between humanity and nature is ultimately determined by culture (Lapka et al., 2012), it is unsettling that most Americans can identify hundreds of corporate logos but fewer than ten plant species (Hawken, 1994). Without ready access to non-urban locations, most city dwellers' natural experiences are limited to ornamentals and cosmopolitan species. As the gap widens between people and the natural world, collective ignorance may ultimately lead to collective indifference (Papworth et al., 2009). Without ecological awareness, public policies such as Endangered Species legislation lose public support (Kendle and Forbes, 1997, Mehmood and Zhang, 2001). The social-psychological condition of "shifting baseline syndrome" (SBS) defines the process whereby "the environment encountered during childhood becomes the baseline against which environmental degradation is measured later in life" (Papworth et al., 2009)(p. 93). The decline of expectations by younger generations of the quality and function of natural areas [as generational and personal amnesia, or the "extinction of experience" as per Miller (2005)] leads to a gradual shift in perceptions. So if 'normal' conditions become increasingly human-dominated, while sensitivity towards nature and non-human life becomes weaker, many species and habitats will lose increasingly more value and relevance in the public mind. Although little empirical evidence exists to test SBS, the certain trend of urbanisation suggests that this is a concept worthy of consideration.

Some of the benefits popularly cited for EGRs include aesthetic improvement, general health benefits and horticultural therapy, recreation and amenity space, and space for community building (Oberndorfer et al., 2007, Peck et al., 1999). More specifically, ecologically oriented green roof plantings, like "untidy" naturalistic vegetation, may offer veritable opportunities to shift public preferences away from the scenic aesthetics that are rooted in antiquated Victorian and modernist ideals (Loder, 2014). The latter study, which examined office workers' responses to views of prairie-style versus Sedum green roofs in Chicago and Toronto, found that green roofs instilled fundamental fascination and supported the biophilia hypothesis [as per Kellert et al. (2008)], but also that growing appreciation levels could be linked with eco-literacy and stimulating more contemporary world views. Intriguingly, that study noted exceptional sensitivity by almost all the participants to the perceived intention behind the green roof; since Sedum roofs represent the minimal planning requirement in those cities, they were less favoured because they implied less effort on behalf of building owner or municipality towards the quality of urban public life, public health, and larger environmental issues (*ibid*). Similar to how naturalistic planting designs at landscape-level are more acceptable when accompanied by signs of human care (Nassauer, 1995), green roofs featuring naturalistic vegetation may help to usher in a new urban ecological aesthetic

(Loder, 2014). Given that human access to green roofs is usually limited to views (sometimes from considerable distance), “cue to care” in this context might involve the provision of interpretative materials in order to educate people about the multi-functional benefits of certain design approaches .

5.1.2 Ecological principles for green roofs

All assemblages of plants, whether natural or designed, develop in accordance with ecological principles (Hitchmough, 1994). One aim of this research was to identify plausible ecological theories or models that describe the processes that occur on EGRs over time. Can EGRs be treated as functioning ecosystems in the first place? Or are they too contrived and highly engineered, too urbane, to be considered through the lens of ecological theory? Over the course of the 20th century, numerous ecological theories, hypotheses and models were developed with the central aim of conserving biodiversity and habitat. Specifically, these theories emerged from the quest to better understand how species diversity is influenced by broad habitat patterns of various shapes, sizes and internal structures, as well as their spatial relationships together and with the habitats of the surrounding landscape (Kendle and Forbes, 1997). An understanding of ecological principles can facilitate effective management, planning and design (Hitchmough, 1994), and ecological methods can offer insight into the dynamics and processes of urban landscapes and vegetation (Breuste et al., 2008). However, it’s also important to recall the limitations of conservation-oriented principles for urban ecosystems, for which considerably smaller datasets and timeframes exist. It may be tempting for researchers of urban ecology to borrow and apply models intended for unmanaged ecosystems, but implicit in such a transfer is the assumption that urban ecosystems are qualitatively similar to other ecosystem types (Kaye et al., 2006), which the previous section illustrated is not true.

Green roofs are relatively new objects to the scope of ecological query (Piana and Carlisle, 2014). Reference to a variety of ecological models may help to foster an understanding of the mechanisms directing the functions and developments of green roof vegetation as dynamic systems. Considering green roofs as plant communities physically isolated from other vegetated areas by a contiguous urban matrix, for example, recalls models of population dynamics resulting from biogeographic isolation (MacArthur and Wilson, 1967, Diamond, 1975) and fragmentation (Hanski, 1994, Harrison and Bruna, 1999). The effects of site-level pressures on EGR vegetation may be interpreted with reference to disturbance theory (Connell, 1978, Grime, 2001). Hierarchical patch dynamics (Wu and Loucks, 1995, Eriksson, 1996, White and Pickett,

1985) may prove useful for describing delineated vegetation types, and change in vegetation over time can draw from the theory of natural succession. Given its central role to the discipline of ecology, and its over-arching presence to the other theories, natural succession will be reviewed first.

5.1.2.1 Natural succession

The theory of natural succession strives to describe the drivers and mechanisms behind floristic change over time. The foundation set by the conceptual pioneers of the early 20th century has supported the development of a comprehensive framework that can now relate to other ecological theories, as well as research on plant community change and ecosystem management practices, like restoration ecology (Pickett et al., 2009). The early viewpoint of successional change, which implied a progressive change in the structure and species composition of the vegetation to a final “climax” community, was eventually replaced in favour by cyclical change implying that similar vegetation types will recur in the same place at various intervals of time (Grime, 2001). Using different language, changes in “autogenic succession” are brought about by the species and organisms already present (autogenesis means self-forming, from Greek: *aut-* = self; *gen* = produce), while “allogenic succession” (Greek: *allo-* = different, diverging) is brought about by external factors (Tansley, 1935).

Regardless of those contrary views, two main types of natural succession are recognised. Primary succession involves the colonisation of a new, skeletal habitat (i.e., initially lacking in soil and vegetation), such as a fresh lava field following a volcanic eruption. Spontaneous colonization of EGRs that were installed with sterilised substrate but not planted would theoretically qualify as primary succession, though this is not common practice (Nagase et al., 2013). Secondary succession, the more common circumstance, occurs in environments where higher plants are already present, if only as propagules in the soil. Old-fields were the classic focus of secondary succession, whereby abandoned cropland reverts back to forest in sequential stages (or “seres”). Mosaics of both types of succession are possible, too. Since green roofs are initially planted with select species, EGR vegetation is theoretically subject to secondary succession, although a catastrophic event exterminating all life could theoretically return it to primary forces.

5.1.2.1.1 Early successional models: facilitation onwards

The models of facilitation and initial floristic composition are of particular use to landscape practitioners (Hitchmough, 1994). The facilitation model is the classic version of plant succession and describes how, after a disturbance, a gradual succession of life forms facilitates colonisation for other life forms. Climax-oriented “old field succession” is illustrated by relay floristics (**Figure 5.4a**), where different life form groups colonize the site at certain stages of development (seral stages), eventually making conditions unsuitable for themselves but facilitating invasion by the next group (Clements, 1916). This model was termed "relay floristics" because the colonization by different life forms was seen to occur as in a relay, such that out-going species/ life forms create conditions for incoming species (Egler, 1954). Many early ecologists disagreed with the directional view of the facilitation model, but at the same time it was "so satisfying to most ecologists that it … dominated the field" (Connell and Slatyer, 1977).

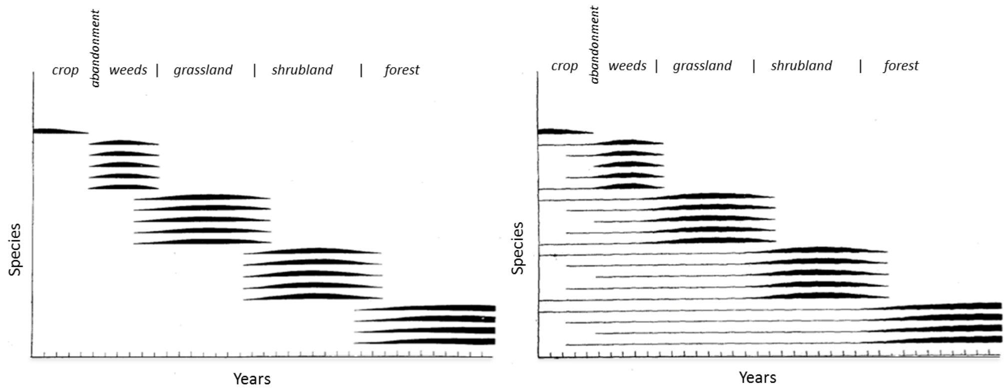


Figure 5.4. (a) Facilitation model and relay floristics: after cropland is abandoned, annuals and perennial herbs are the first to colonize, followed by shade intolerant woody species and finally the shade-tolerant trees and shrubs, which represent the climax state. **(b)** Initial floristic composition model: secondary succession is strongly directed by the propagules of a site's initial flora, which rise and fall from predominance in accordance with resources and stress. Adapted from Egler (1954).

The influence of seed rain, soil seed bank and propagule pressure on successional change led Egler (1954) to propose the initial floristic composition model (**Figure 5.4b**), which suggests that change across time in a plant community essentially comes from within, rather than from outside. Contrary to waves of invasion, as in relay floristics, this model illustrates that successional change is based upon pre-existing vegetation, seed bank and physical impacts (e.g., grazing and ploughing versus abandonment). In other words, most of the regenerating species after a disturbance event are already present before the event, and the nature of the disturbance event and the condition of the vegetation prior will determine which species arise. Although originally developed through old-field studies, this model has proven useful in the urban context (Rebele, 1992, Bornkamm, 2007, Rebele, 2008). One study, which examined colonization and early successional processes on three urban soils (representing a gradient of nutrient status: topsoil, ruderal soil, sand), found that successional stages could be distinguished by fertility level, organic matter content and seed pool. Specifically, the initial floristic composition factor was most important on topsoil, less important but still contributed to successional patterns on ruderal soil, and had no effect on sand (Rebele, 1992).

Developments on autogenic succession led to models based on stochastic processes, including attributes of distribution, dispersal, and plant life strategies (Burrows, 1990). Species competition with respect to changing resource and environmental gradients gained importance (Tilman, 1982, Pickett, 1976, Diamond, 1975), but it was Connell and Slatyer's (1977) three-fold model of facilitation, tolerance and inhibition that strengthened succession research and theory because it enhanced earlier models with the growing understanding of disturbance and plant life strategies. In addition to the original facilitation model, the "tolerance" model was based on the prediction that later species can tolerate lower levels of resources than earlier ones (owing to differently evolved life strategies for resource exploitation), and the "inhibition" model referred to the mounting evidence on the importance of competition whereby all species resist, or inhibit, invasion by competitors until they die or are damaged, thus releasing resources and allowing those colonisers to reach maturity and a steady state, or climax community.

5.1.2.1.2 Later successional models: environmental filters, functional traits

As empirical evidence amassed, succession theory moved towards more individualistic, kinetic schemes, which rejected the notion of stable end-points on the basis that disturbance is continually changing the vegetation; change and cycles are evident but no particular phase can be regarded as stable [e.g., (White, 1979)]. As originally proposed by Gleason (1939), species' individual strategies were seen to direct natural succession and, moreover, no two vegetation samples are alike either in quantitative or qualitative composition. As such, both species and ecosystem attributes play a role in succession. Whittaker's (1967) method of sampling vegetation along an elevation gradient was originally developed to test the 'community-unit theory' related to natural succession, but contributed more to the principle of community continuity. Gradient analysis also became a tool for urban ecological studies, most notably to quantify disturbance along urban-rural gradients.

Recalling CSR theory, one of its exceptional strengths for modeling succession is its capacity to interpret the subtle dynamics of plant community composition via plant adaptive strategies with direct relation to the conditions and resources of the site. For long-term studies, the conversion of vegetation data to CSR signatures have been used to over-ride interannual fluctuation in species' abundance, and to indicate changes "even within what may be thought of as relatively stable vegetation" (Hunt et al., 2004)

(p. 622). For example, by including CSR functional groupings to the species monitored in a long-term study (38-years) of a grass verge in Bibury, UK, Dunnett et al. (1998) showed how species adapted to environmental stress or disturbance (C-R, R, S) gained competetive advantage after warm dry springs and summers, whereas species adapted to more productive conditions (C, C-S) were disadvantaged.

5.1.2.2 Disturbance theory and patch dynamics

Disturbance is implicit in the theory of natural succession, and a body of theoretical and practical work has accrued which focuses entirely on disturbance and the associated dynamics. Indeed, the processes of growth, death and replacement, which define the dynamism of biological systems, are all attributed to disturbance. According to White and Pickett (1985), a disturbance is "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability or the physical environment" (p. 7). Resources are often made available by disturbances (Canham and Marks, 1985), though this is not always the case (Vitousek, 1985). Disturbance introduces stochastic influences on community composition that challenge the predictability of response. Fluctuating environments lead to multiple resetting of the local successional trajectory (Botkin, 1981), making "normalcy" difficult to define for any ecosystem (White and Pickett, 1985). Disturbances often create patchiness in an ecosystem, but when the effects are diffuse the patches can be difficult to define (Watt, 1947). As a fundamental and relatively discrete spatial unit, a "patch" is the basic building block for models which integrate population, community and ecosystem levels of organization (Forman and Godron, 1986). Definitions of patches are always relative to the system at hand, since community structure and behaviour vary locally, but the term does not establish any constraint on size, internal homogeneity, or discreteness (White and Pickett, 1985).

From the ecological and landscape perspective, urbanization leads to an increasingly fragmented landscape comprising numerous small patches with many edges and more biodiversity (Grimm et al., 2008). As such, urban landscapes can be described as mosaics of biological and physical patches within a greater matrix of infrastructure, social institutions, cycles, order, and so on. Sources of spatial heterogeneity within cities are both natural (e.g., disturbance regime, stresses) and human (e.g., introduction of exotic species, control or modification of natural disturbance agents) (Zipperer et al., 2000). The concept of *shifting mosaic* connotes a uniformity of patch distribution in time and space (Bormann and Likens, 1979). The concept of patch dynamics can be useful to describe situations in which local equilibria occur as feedbacks between community characteristics and disturbance events (Pickett and White, 1985a). Under this framework, an EGR could be defined as an *elevated urban vegetation patch*, whereby a single roof can be treated as a patch, though a large roof with a variety of distinct formations could be seen as comprising a variety of patches, too. Hierarchical patch dynamics incorporates certain "emergent properties" of ecological systems, such as metastability or persistence at the metascale, as opposed to the transient dynamics that usually characterize local phenomena (Wu and Loucks, 1995) (p. 439). Patch dynamics may be a useful conceptual approach for understanding (and managing) urban ecosystems, as it focuses on the creation of spatial and temporal dynamics between disturbance with consideration of how such heterogeneity influences the flow of energy, matter, species, and information across a landscape (Zipperer *et al.* (2000). The value of this approach is that disturbance is not treated as a key ecological principle but rather as one of the many components which lead to structural and resource changes within a landscape.

“Disaster” and “catastrophe” are two types of disturbance, whereby disaster occurs frequently enough that successive generations will experience it while catastrophes are rare occurrences unlikely to be experienced as a repeated, selective force (Harper, 1977). In evolutionary terms, disaster would likely increase fitness through selection, while catastrophe would have the opposite effect (White and Pickett, 1985). Due to the nature of their exposure and constructed form, EGRs are notably prone to disturbance, although this has not been explicitly quantified as such (perhaps for the same reasons that long-term green roof research is rare). Still, research has demonstrated that shallow EGR substrates are subject to extreme temperature fluctuations (MacIvor and Lundholm, 2011, Tabares-Velasco et al., 2012, Zhao et al., 2014) and that insufficient plant cover will permit heat flux through the substrate and into a building (Connelly et al., 2006, Simmons et al., 2008, MacIvor and Lundholm, 2011). Indeed, the harsh living conditions of these substrates are exemplified by work characterising the soil-dwelling invertebrates of typical EGRs as transient species of disturbance-prone habitats (Darius and Drepper, 1983a, Buttschardt, 2001, Jones, 2002, Schrader and Boening, 2006, Kadas, 2011, Madre et al., 2013, McGuire et al., 2013), which are unstable and susceptible to catastrophic population crashes (Rumble and Gange, 2013). The heat gain of the shallow mineral substrates explain why hot events will kill tree seedlings (Buttschardt, 2001).

The intermediate disturbance hypothesis, which is attributed to Connell’s (1978) work in tropical rainforests and coral reefs, states that species richness will be greatest in communities experiencing some intermediate level of disturbance. Presented in different terms, the "humped-back model of species richness" (**Figure 5.5**) was developed through laboratory experiments and field surveys of herbaceous vegetation in England (Grime, 1973b). A central tenet of the humped-back model is that in extreme environments organisms must exhibit a high degree of adaptive specialisation to survive. Many observations support these generalizations, although they can fall short in their vagueness by leaving too much unspecified (e.g., will intermediate disturbance enhance nutrient retention or productivity as well as richness?), but also by the challenges of quantification (i.e., how should the impact of disturbance be measured?) and because they do not explicitly state the maximum level of disturbance. Another disturbance hypothesis suggests that species richness should be maintained when disturbance recurs more frequently than the time required for competitive exclusion (Huston, 1979). Unfortunately, this hypothesis suffers from the same shortcomings as the previous.

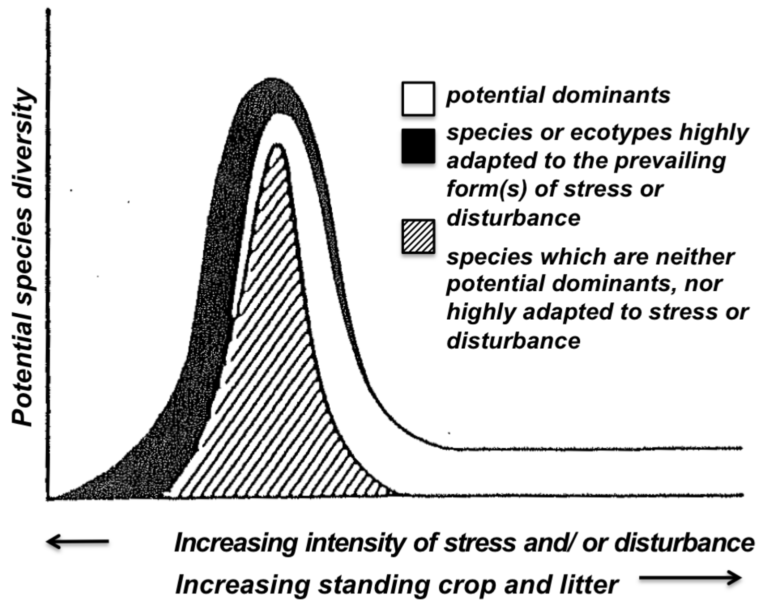


Figure 5.5. The "humped back model for species richness" describes the impact of a gradient of increasing stress and/ or disturbance upon the potential species density in herbaceous vegetation. Modified from Grime (1973a).

With the possibility of manipulating disturbance regimes, the urban context offers opportunities to study the effects of urbanization and different disturbance types, intensities, and frequencies on biotic communities and ecosystems (McDonnell and Pickett, 1990). Gradient analysis has been used to examine the spatially variable effects of urbanization by treating vegetation in terms of continuity and gradient relationships along urban-rural gradients (McDonnell and Pickett, 1990). Such studies have reported discernible peaks in species richness and diversity at moderate levels of disturbance along urban-rural gradients, including butterflies (Blair and Launer, 1997) and birds (Jokimaki and Suhonen, 1998). Urban areas are not uniform, however, and this pattern was not always consistent, as in the case of Carabid beetles in Brussels (Godefroid and Koedam, 2007). Whether the transect runs up a mountain or through a city, the gradient method supports the view that “environmental variation is ordered in space, and that spatial environmental patterns govern the corresponding structure and function of ecological systems, be they populations, communities, or ecosystems” (McDonnell and Pickett, 1990) (p. 1232). Interactions within the ecological systems, and between the environmental gradient and the ecological systems, will affect the distribution and behaviour of systems along the gradient.

5.1.2.3 Fragmentation, island biogeography, metapopulation theory

Dispersal is an important element of all theories intent on describing the mechanisms of plant community assemblage; the effects of fragmentation, disturbance and patchiness on species assemblage and community structure have interested ecologists for centuries (Pickett and White, 1985b, Forman and Godron, 1986). Fragmented habitats are typically biologically impoverished compared to intact habitats, and many studies have found that remnant fragments support fewer specialists but more widespread generalist species (Barbour et al., 1999). The loss of diversity and ecological function within habitat fragments can be partly explained by the relative importance of different mechanisms, like edge effects. In forests, for example, physical edges affect much of the biotic community through direct and indirect effects like increased wind and light penetration, and decreased humidity (Forman and Godron, 1986). Biological edge effects include invasion by aggressive competitors, which may attain exceptionally high abundances near edges thanks to subsidised resources from the greater matrix (Harrison and Bruna, 1999). Fragmentation may also lead to sequences or chain reactions of altered ecological interactions, like when important predators or seed dispersers are lost. Changes to the abundance of component species at lower trophic levels will also have implications for food webs and ecosystem function.

<u>Island biogeography</u> was developed to explain the gain and loss of species as a function of area and habitat fragmentation, with the basis of oceanic islands as truly isolated examples. The model relates an island’s species diversity with competition and rates of colonisation and extinction. More species are predicted on large, rather than small, islands because the extinction rate is lower. The theory also proposes that islands closer to the mainland or other islands would have more diversity than isolated islands because the rate of arriving species and colonists would be higher (Forman and Godron,

1986). Unfortunately, confirmation of the island biogeographic model has proven elusive (Forman and Godron, 1986). Some studies have supported aspects and certain predictions from it, while others demonstrate quite different patterns. Terrestrial urban habitats obviously differ from oceanic islands. Remnant habitats in urban environments in particular are immersed in anthropogenic influence, not to mention intense exposure to disturbance and pressure from introduced species (Godefroid and Koedam, 2003). Moreover, it can be difficult to decide whether observed patterns of species numbers are the result of environmental heterogeneity or the area as it is (Pysek, 1993). For green roofs in Berlin, this has been exemplified as proximity to green spaces, like parks or other sources of propagules (Köhler, 2006).

Broadening out from individual populations, <u>metapopulation theory</u> envisions that "a suite of populations … make up the distribution of species within a region" (Barbour et al., 1999) (p. 82). A metapopulation is therefore a system of spatially isolated species populations that are connected by dispersing individuals. Species will be patchily distributed over various scales (e.g., large, variously aged forest stands, or ant mounds in chalk grasslands), and populations are often semi-isolated as a result of habitat heterogeneity. So, a population on an island is considered a metapopulation because it's a subset of a greater population. Regionally, when habitats have become so fragmented that isolated populations cannot be expected to last for long, persistence can occur only via metapopulation dynamics (Hanski, 1998). While metapopulation theory has been applied for urban ecological designs, such as planting roofs with food sources plants for specific butterfly species (Snep et al., 2009), such projects rarely include follow-up monitoring so the outcome is unknown (Kephart, July 11, 2013, Williams et al., 2014).

Metapopulation theory differs from island biogeography in its assumption of networks of small patches with no persistent mainland habitat, and by focusing on the dynamics of only one species. Also contrary to island biogeography but in line with fragmentation, metapopulation theory makes an even stronger prediction about the importance of dispersal among habitat fragments: since there is no mainland, inadequate dispersal will lead not only to local but to regional species extinctions (Harrison and Bruna, 1999, Williams et al., 2006). Empirical studies have covered all types of biotic communities, but full validation of the metacommunity model has been forestalled for a variety of reasons. Simplified assumptions around dispersal (e.g. all species have the same dispersal ability) and competition (obeying a lottery with infinite number of sites and single-site occupancy) pose limitations to real-world models, and the absence of parameters that can be measured in the field challenge the empirical validation of mechanistic effects (Mouquet and Loreau, 2003). The patchiness of urban green areas can make dispersal difficult and risky, certainly for taxa with poor dispersal ability, and less mobile species, such as non-flying and ground-dwelling arthropods (Gilbert, 1989).

Connectivity is an important aspect of metapopulation theory, and that model predicts that providing a small amount of additional habitat and corridors should prevent extinction by increasing rates of dispersal (Harrison and Bruna, 1999). Theoretically, corridors and greenways can link and connect habitats to facilitate physical movement through fragmented landscapes as well as genetic transfer among populations, but they may also increase the vulnerability of the animals and plants using them, whether by increased predation and competitive invasion or if the quality of the corridor (e.g., roadside verges) threatens survival (Kendle and Forbes, 1997). The concept of source-sink dynamics purports that the long-term survival of a species may be better guaranteed by the combined effect of many populations, rather than a single one (Pulliam, 1988). By definition, source-sink populations are special cases of metapopulations because they include both persistent refuge populations and ephemeral populations that are maintained through dispersal (Eriksson, 1996)(p. 248). This concept has been observed on EGRs in their benefit to ground-nesting birds, like Lapwing (*Vanellus vanellus*). On Swiss EGRs without provision of water and nourishment, hatched chicks will perish of starvation (Baumann, 2006) which effectively renders those roofs as population sinks for this priority species. Overall, consistent and sufficient evidence has yet to substantiate the demographic significance of 'sink' habitats or the efficacy of corridors in promoting regional persistence (Harrison and Bruna, 1999). Several studies have found that green corridors made "little difference to the diversity of plants and beetles found in towns and cities by virtue of their function as corridors" (Angold et al., 2006)(p. 203). Given the pressures inherent to urban environments (including predation, exposure, erratic resources, and general stochasticity) and the complex needs of organisms, corridors are insufficient provisions in themselves. Indisputably, greenways and corridors should never substitute the protection of large, intact nature reserves in urban or suburban landscapes (Breuste et al., 2008).

5.1.2.4 Reconciliation ecology: opportunities for change

Over a century of ecological study has invested tremendous energy and effort into the central goal of halting the rate of biodiversity decline and preventing the forthcoming (or current) extinction cascade (Chapin et al., 2000, Sala et al., 2000, Diaz et al., 2006, Zalasiewicz et al., 2010), but the unabated loss of biodiversity and increase of fragmented habitats (Millennium Ecosystem Assessment, 2005) suggests that these efforts have not been relevant enough to match humanity's economic and population metabolisms. Combined with the anticipated yet unknown effects of global warming and climate change, it is apparent that many of the assumptions underlying the theories designed for conservation planning are too simplistic to guide management accurately or to adequately explain the relationships observed (Kendle and Forbes, 1997). More pragmatically, one might argue that it is not the gaps in knowledge, but rather the lacking integration of conservation mandates with land use planning and policy.

Recognition of the complexities associated with unproven theories and, in some cases, stagnated hypotheses herald a new generation of ecological query. Based upon the knowledge of the importance of species-area relationships to conservation, reconciliation ecology was proposed as a more realistic and practical solution to conserve biodiversity because it recognizes that the greater proportion of the Earth's surface is human-dominated (Rosenzweig, 2003). This reality suggests that conservation of species must occur here rather than in the limited and, by comparison, miniscule areas set aside for reserves and restoration. This science-based approach alleviates the ambition to develop and prove theories and accepts that the natural world and human dominance are integrated forces unified by manifold processes and conditions.

Through reconciliation ecology, habitats that have been altered for human use can be designed, spatially arranged, and managed to maximize biodiversity while providing economic benefits (Marzluff, 2005) and ecosystem services (McKinney, 2006). To date, this is perhaps the best articulated approach which calls upon the involvement of ecologists in helping to design and manage new cities and reconstruct older ones (Grimm et al., 2008). Within the urban realm, green roofs can contribute to reconciliation ecology, as can living walls, road and railway buffers, private gardens, allotments, and public parks (Francis and Lorimer, 2011). However, unless these technologies and systems are widely implemented for their stated ecological benefits, their true potential will never be fully realized (Henry and Frascaria-Lacoste, 2012). The latter suggest that reconciliation ecology using green roofs will only be possible though "adaptive collaborative management" involving citizens, ecologists, industry, urban designers and architects. From the perspective of habitat creation, Lundholm & Richardson (2010) suggest that seeking habitat analogues that can support biodiversity should be taken as an important guiding principle for reconciliation ecology in urban and post-industrial lands. This is especially true for regions where green roof technology is just beginning to be introduced.

5.1.3 Research aims and questions

The research questions addressed in this chapter are directed by one of the aims of the research, which is to identify plausible ecological theories or models that describe the processes that occur on EGRs over time. The habitat conditions, which the EGR vegetation surveyed either endured or benefited from, will be described using indicators (Ellenberg Indicator Values) derived from the species data. The EGR vegetation types defined previously will therefore be classified further with reference to roof environmental conditions.

- **Aim:** To continue characterising mature EGR vegetation
- **Aim:** To identify ecological theories or models to describe the processes occurring on EGRs
- **Question:** Do emergent characteristics result with time?

5.1.3.1 Objectives of the chapter

This chapter opened with a description of urban environmental conditions and an introduction to the ecological theories that pertain to green roofs in order to prepare the conceptual treatment of EGRs as urban ecosystems. The objectives for this chapter therefore include:

- Characterising EGR growing conditions (and mature EGR vegetation)
- Deciding whether emergent properties can describe mature EGR species composition
- Conceptual development of ecological theories for EGRs

5.2 Methods

The results of the previous chapters suggested that the environmental variables of slope, aspect and depth had significant effects on EGR vegetation, and that EGR vegetation types could be clustered into distinct groups as determined by species diversity and life form composition. This chapter will more closely examine the role of environmental conditions on the vegetation surveyed and will attempt to further characterise different green roof vegetation types with the aim of understanding their formation over time. Data from the nine extensive green roofs surveyed over two growing seasons in 2010 and 2011 will be analysed with the aim of characterising the environmental conditions and elucidating any ecological theories that might explain the EGR vegetation surveyed.

5.2.1 Data and Analysis

5.2.1.1 Ellenberg Indicator Values (EIVs)

The ecological conditions of a site can be quantified directly by field measurements or estimated from the ecology of plant species. Since species' requirements reflect the ecological factors of a site, plant species have a long and continuing tradition of serving as bio-indicators (e.g., for agriculture, forestry, nature conservation) (Persson, 1981, Ewald, 2003, Otypkova, 2009). Based on extensive research dating to the 1950s, Ellenberg and colleagues (1991) were the first to list the ecological 'indicator values' for most European species (Persson, 1981). Since conducting measurements in the field is time-consuming and technically demanding (i.e., through the time and financing required), and because single measurements cannot express the values of variables that fluctuate strongly, ecological indicator values are beneficial for making visible what is not immediately perceptible (Diekmann, 2003, Kollmann and Fischer, 2003). Habitat qualities indicated by plant species and distributions include microclimate of light and temperature, soil moisture, pH, fertility, salinity and presence of heavy metals. This universally applicable numerical indicator value system has been widely used as well as refined, extended and adopted for other regions (Ewald, 2003, van der Maarel, 2005).

In order to characterise the environmental conditions of the nine EGRs surveyed, the species list was amended with available EIVs (Appendix 2). The environmental factors and habitat indicators defined by the EIVs are divided into three climatic factors (light, temperature, continentality) and three soil factors (humidity, soil reaction and nitrogen availability). Numerically, EIVs can express the average "realized niches" of species along these gradients on a nine point ordinal scale (1=low; 9=high), while a record of zero (0) implies an indifferent response to that factor and a blank record represents "uncertain classification" (Ellenberg et al., 1991). Mean EIVs are used for each species recorded per quadrat, with reference to its abundance. Any trees recorded were seedlings. Quotations within the results and discussion, which describe habitat conditions or geographic scope, are directly from Ellenberg et al. (1991). No statistical significance is attached to these descriptive observations.

It is important to note the appropriate use of EIVs and their limitations (Zeleny and Schaffers, 2012, Hill et al., 2000). Since EIVs are ordinal, they are generalised, typified observational knowledge that were never intended to replace measurements, but instead reveal decisive factors to be investigated further (Ellenberg et al., 1991). Similarly, calculated results are nothing more (or less) than evidence of trends with reference to “normal” behaviour of central European species. Interpretation should therefore be given breadth and critical attention. Ellenberg et al. (1991) stress that EIVs are meant to identify the ecological characteristics of the plant taxon, and never their requirements, since ecological requirements can only be credibly established through physiological inquiry of competition-free cultures. For example, some species may tolerate hostile and extreme conditions as a result of competitive pressure (e.g., acidic, or very dry habitats), but would perform better in less harsh conditions. Lastly, the potential range (physiological behaviour) of all plant taxa is typically greater than their range of existence (ecological behaviour) within the greater landscape (*ibid*, p. 12).

5.2.1.2 Cluster analyses

As in Chapter 3, a descriptive clustering approach was taken to group the roofs surveyed according to their (dis)similarities using the average linkage method. To determine the best fit for these data, roofs were grouped according to similarities in the range of EIVs, but with additional consideration of species richness (i.e., total number of species recorded per roof) and of cover dominance by non-dominant species. The variable of non-dominant species was included because most roofs featured one or two exceptionally dominant species. Discounting that cover and calculating the cover achieved by the other species was intended to reveal the floristic diversity of the roof vegetation above and beyond any monoculture effects by the single most dominant species.

5.3 Results and Discussion

5.3.1 Characterising EGR environmental conditions: EIVs

Not all of the species surveyed had EIV values assigned to them: of all the recorded species, 67 had EIVs, although these were not always complete. Only 61 species had allocated nitrogen EIVs. The habitat indicators used for the analyses that follow (climatic and soil factors) used the mean EIV of the species surveyed, as well as the range, for each roof. Salinity and heavy metal tolerance were not included. The results and discussion include examples from the associated species that indicate certain conditions and their definition. While trees and mosses were part of the analysis, they are not included in the discussions. The mean results for the six EIV conditions examined are given in **Table 5.1**.

Table 5.1. EIVs for the nine EGRs surveyed, showing minimum, mean (bold) and maximum values.

Light	Temperature	Continentality	Moisture	Reaction	Nitrogen
4 - **8.0** - 9	2 - **5.7** - 7	2 - **4.1** - 7	2 - **2.7** - 9	2 - **5.6** - 9	1 - **2.0** - 8

5.3.1.1 EIV climatic factors on EGRs

5.3.1.1.1 *Light*

The light EIV describes species' "occurrence in relation to the relative light intensity", with shade-loving plants at the lowest value (L1) and full-light species at L9. According to the vegetation surveyed, it appears that EGRs can support a range of light conditions, except for deep shade (L1-3). As **Figure 5.6a** shows, most roofs had a mean of L8, and the majority of species occurred in L7 (27 species) and L8 (23 species) (**Figure 5.6b**). The indicator L7 refers to "plants generally in well lit places but also occurring in partial shade" and includes species like *Agrostis tenuis, Allium schoenoprasum, Campanula rotundifolia, Hieracium pilosella, Hypericum perforatum*. Light-loving species (L8), like *Achillea millefolium, Agrostis stolonifera, Arrhenatherum elatius, Crepis tectorum* and *Dianthus carthusianorum*, are "rarely found where there is less than 40% relative light". The only half-shade herbaceous species surveyed, *Geum urbanum* (L4), occurred on one roof in shaded and moist conditions (FH Nürtingen, drip zone). The other L4 results were tree seedlings or mosses. The herbaceous "plants of full light, found only in full sun; rarely in less than 50% relative light" (L9) included *Petrorhagia saxifraga, Poa compressa, Potentilla recta* and *Sedum album*.

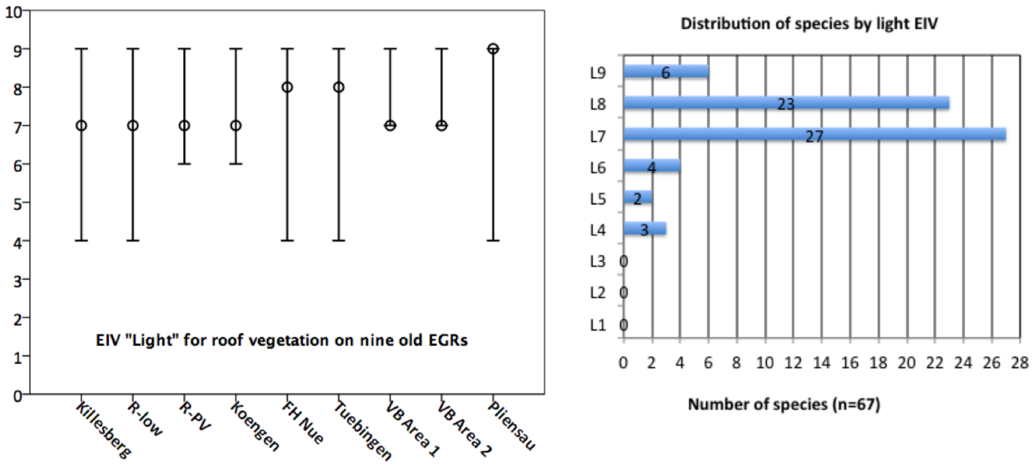


Figure 5.6. a) Range and mean for light EIV on nine roofs; **b)** Distribution of species for 9 categories of light EIV.

Other surveys of EGRs and/ or spontaneous tar-paper-gravel (TPG) roofs have described similar results and defined green roofs as full light environments with EIVs of 7-8 in

Osnabrück (Bossler and Suszka, 1988) and mean values of 7.1 in Karlsruhe (Buttschardt, 2001) and 7.2 in Berlin (Poll, 2008). The latter showed a majority of L7 and L8 for system roofs. Green roofs can therefore be defined as well-lit to high light environments.

5.3.1.1.2 Temperature

Temperature is defined by species' occurrence in the European temperature gradients from the Mediterranean to the Arctic and from lowland to alpine elevations (Ellenberg et al., 1991). The majority of species (22) were identified with T6 (**Figure 5.7b**), which was also the mean for most roofs (**Figure 5.7a**). T6 refers to a range of habitats (T5-T7), including "temperate warm indicators" (T5) and "warm indicators (in north-central Europe only, in relatively warm low-lying areas)" (T7). The **T6** species identified include *Convolvulus varia, Crepis tectorum, Erigeron annuus, Hypericum perforatum, Poa pratensis angustifolium, Potentilla argentea, Sedum acre, S. spurium, S. telephium, Setaria viridis, Solidago canadensis, Thymus praecox, T. serpyllum, Trifolium arvense, T. campestre, T. dubium,* and *Vicia hirsuta*. The warm indicators (**T7**) included species like *Petrorhagia saxifraga, P. prolifera, Potentilla recta, Veronica spicata,* and *Vulpia myuros*.

The only cool indicators (**below T5**) were three species of moss [*Eurhynchium praelongum* (T4), *Polytrichum juniperum* (T2), *Racomitrium elongatum* (T3)]. These mosses only occurred on FH Nürtingen, in the drip zone, and clearly stretch the range to appear cooler than is typical for EGRs. The lacking range on Köngen is due to the small species number (9) on that roof to begin with, of which many either lacked EIVs for temperature (*Hypericum perfoliatum, Sedum floriferum, S. hybridum*) or behaved indifferently (**T0**) (*Achillea millefolium, Festuca ovina, Poa pratensis, Verbascum thapsus*). *Coronilla varia* had the only EIV value on that roof: **T6.**

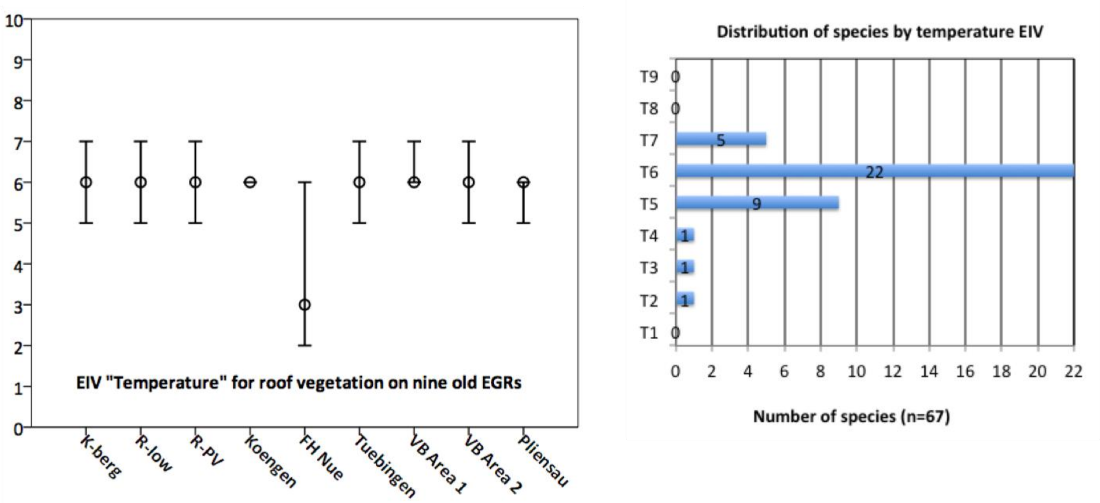


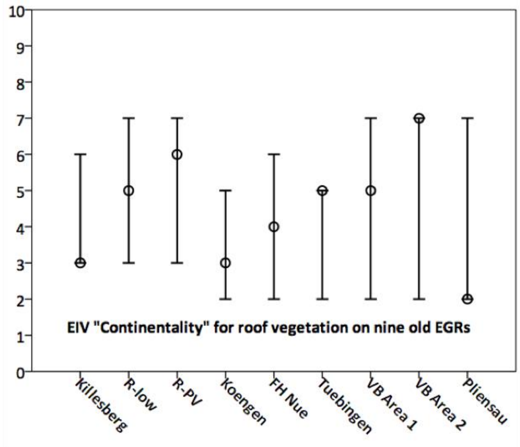
Figure 5.7. a) Range and mean for temperature EIV on nine roofs; **b)** Distribution of species for 9 categories of temperature EIV.

In their surveys of EGRs and TPG roofs, Buttschardt (2001) and Poll (2008) found similar results, with the majority of species at **T6**, though Bossler and Suska (1998) reported a mean of 5.3 in Osnabrück. Observations from northern France considered that species with high affinities for temperature may be more prevalent on older green roofs because they would have endured more hot periods than recently installed systems (Madre et al., 2014). Temperature measurements of vegetation layers on EGRs in Heidelberg (Germany) recorded over 60°C in summer and well below 0°C in winter (Riedmüller, 1994). Temperature conditions on EGRs are also influenced by the microclimate created by evapotranspiration, and this latter point is described by the next habitat indicator, continentality, which links temperature with moisture.

5.3.1.1.3 *<u>Continentality</u>*

Continentality refers to species' occurrence in the gradient from the Atlantic coast to the inner parts of Eurasia. In the urban context, continentality reflects the thermally enhanced situations, like urban heat island (UHI), which will influence urban vegetation, including plants growing on green roofs. In particular, the UHI reduces the number of annual frost days which, in relation to the continentality EIV, is associated with proximity to maritime, or oceanic, climates. On a scale of 1 to 10, C1 species would occur in oceanic climates with very few freezing days while species occurring in C8 through to C10 are found as far from the ocean as possible and, therefore, more prone to freezing temperatures.

In fact, the majority of the species surveyed (39) behaved indifferently to continentality (**C0**) and the most prevalent response (18 species) was **C5,** meaning "intermediate, weakly sub-oceanic to weakly sub-continental" (e.g., *Agrostis stolonifera, Cerastium arvense, Coronilla varia, Fragaria vesca, Geum urbanum*). After C5, the next most common record for continentality was **C3** (15 species), which reflects conditions that occur in "most parts of Europe" and support species like *Agrostis tenuis, Arrhenatherum elatius, Festuca ovina, Lotus corniculatus, Petrorhagia prolifera, Sedum acre, Potentilla argentea, P. erecta,* all *Trifolium spp.,* and *Vulpia myuros*. Next in abundance (11 species), and the mean value for most roofs (**Figure 5.8a**), **C4** reflects "suboceanic" species occurring "mainly in central Europe but spreading towards the East" (*Dianthus spp., Poa compressa, Sedum sexangulare, S. spurium, Thymus pulegoides*).



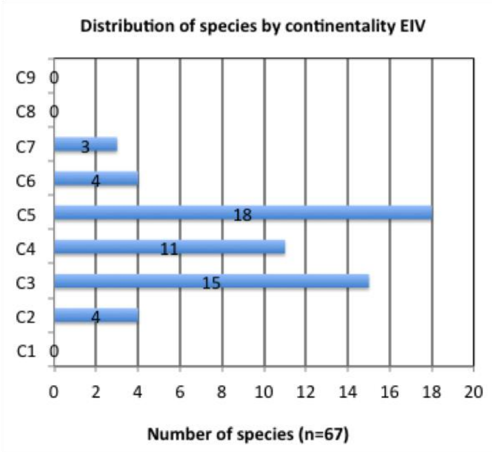


Figure 5.8. a) Range and mean for continentality EIV on nine roofs; **b)** Distribution of species for 9 categories of continentality EIV.

Sub-continental species (**C6**) "occurring mainly in the east of central Europe and the adjoining parts of Eastern Europe" included *Linum perenne, Veronica spicata,* and some mosses. The three species in **C7** (*Allium schoenoprasum, Crepis tectorum, Pinus sylvestris*) prefer the range between C6 and C8, and their sub-continental to continental ranges "spread into Central Europe from the east only into particular sites." The lowest continentality value (**C2**), held by *Sedum album, Sedum Coral carpet,* and *Sempervivum tectorum* (as well as *Carex flava*, in the drip zone at FH Nürtingen), define "oceanic, mainly in the west including western Central Europe". The lesser-represented extremes of the continentality spectrum indicate absence of continental to extremely continental (C8, C9) and extreme oceanic (C1) species. The majority of species from the surveys in Osnabrück, Karlsruhe and Berlin were C3 to C4 (Bossler and Suszka, 1988, Buttschardt, 2001, Poll, 2008). While the main areas of distribution for the species list is likely far more heterogeneous, a continental Eurasian core is nevertheless clear.

5.3.1.1.4 <u>Climatic influences: discussion</u>

Green roofs were defined as well lit to high light environments; other studies concur with the results here of light EIVs predominant between 7 and 8 (Bossler and Suszka, 1988, Buttschardt, 2001, Poll, 2008). EGRs also classify as warm habitats supporting species with continental preferences, but the lack of extreme EIVs for temperature and continentality suggest that these factors are tolerated in moderation. While EGRs were defined as warm environments, the absence of extreme warm indicators (T9) (i.e., from the Mediterranean to the warmest places in the Upper-Rhine region) or of species with very warm preferences (T8, or mostly sub-Mediterranean) may reflect the exposed nature of these habitats and the effect this has on temperatures. Parallel indicator habitats, like mountaintops, may feature warm temperatures but their exposure (to wind, frost, etc.) inhibits truly warm-loving (i.e., Mediterranean) species from establishing. In addition, a large proportion of the species surveyed were indifferent to continentality (**C0**), which implies that this is just one of several factors influencing species composition on EGRs.

The central European plant community that most closely resembles EGR vegetation is the Sedo-Scleranthetea (Thommen, 1988, Buttschardt, 2001), which occurs in full light on soils under 100 mm deep and comprises evergreen vegetation that flowers without pause from May through September (Ellenberg, 1986). Taken together, a few of the investigations of spontaneous vegetation on TPG and gravel roofs (Bornkamm, 1961, Thommen, 1988, Buttschardt, 2001) revealed a climatic gradient influencing species composition. With reference to Raunkiær plant life forms (i.e., based on the location of the plant's bud during seasons with adverse conditions, such as cold or dry seasons) (van der Maarel, 2005), Bornkamm (1961) observed that recently installed TPG roofs in Göttingen were first colonized by weedy annuals (therophytes) but after about ten years dominant cover had shifted to *Poa compressa,* a hemicryptophyte (i.e., perennating buds are above or just below ground). Noting that the grass roofs of Sweden were also dominated by hemicryptophytes, while gravel roofs in Heidelberg and Stuttgart (300 and 400 km south of Göttingen, respectively) are colonized mainly by therophytes, Bornkamm wondered whether the stable communities he observed in Göttingen were related to the sub-Atlantic, summer-cool climate. In other words, if the Göttingen roofs are at the southern limit of hemicryptophyte-roofs, this might explain why the Typical *Poa* meadow there can develop after 30 years in shade but only after 50-70 years in unshaded areas.

The effect of rooftop climatic conditions on plant community development can be inferred from a replicated experiment which strove to re-create species-rich dry meadows on a roof in Heidelberg (Riedmüller, 1994). When grown in depths under ten cm and exposed to full sun, this study found that only forty-eight of 108 species/ cultivars survived multiple growing seasons. Four plant families comprised those species, all typified by their capacities to avoid drought, whether through leaf physiology and metabolism (Crassulaceae, Saxifragaceae) or through bulbs which have water storage organs and limit their photosynthetic above-ground biomass to the cooler spring season (Iridaceae, Liliaceae). As an example, according to its EIVs *Allium schoenoprasum* is indifferent to temperature and moisture (Ellenberg et al., 1991).

5.3.1.2 EIV soil factors on EGRs

5.3.1.2.1 <u>Moisture</u>

The moisture EIV describes species' occurrences and habitats along a gradient from dry shallow soils and rocky slopes to wet marshy ground. Water on green roofs is often a limiting factor, so one would expect this EIV to characterise species of dry habitats and with tolerance for dry conditions. As expected, none of the species are typical of environments with fluctuating water tables, prone to inundation, or aquatic (L10-L12), nor do any qualify as indicators of strongly changeable moisture conditions (~). Many species (40) have not been classified with moisture EIVs (**M0**), but the sixty-seven allocated species create something like a normal distribution, with most species (18) occupying M4 and nine species in M3 and M5 (each) (**Figure 5.9b**). M4 is defined by species with a preference between M3-M5, indicating that the EGRs surveyed encompass the range between "dry site indicators" and "moist site indicators". The "moist site indicators" (**M5**), which "mainly occur on soils of average dampness, but are absent from both wet ground and places which may dry out" included *Arrhenatherum elatius, Fragaria vesca, Geum urbanum, Poa pratensis, Taraxacum officinale, Trifolium dubium,Verbascum nigrum* and *Vicia sepium*, several of which occurred once or a few times only. Some **M4** species include *Achillea millefolium, Cerastium arvense, Crepis tectorum, Hieracium pilosella, Hypericum perforatum, Lotus corniculatus, Medicago lupulina, Sedum telephium* and *Setaria viridis*.

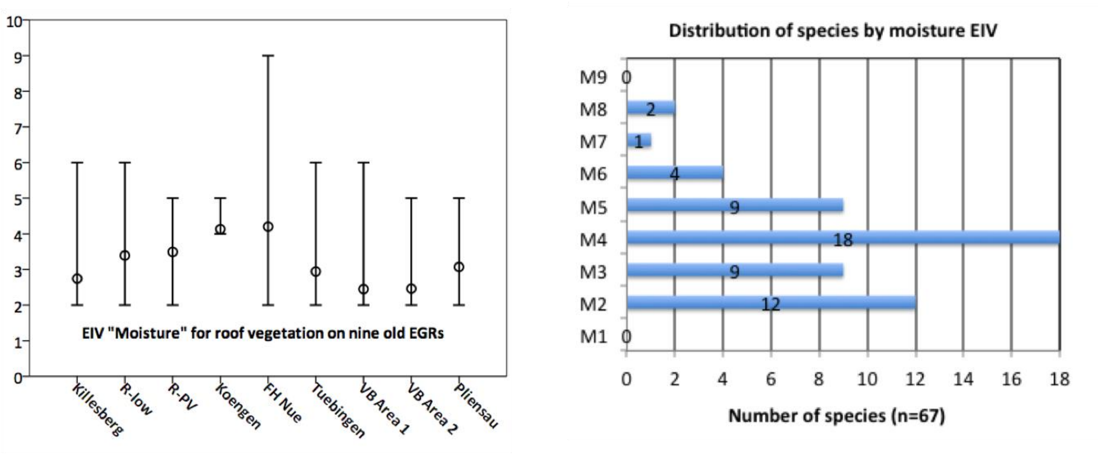
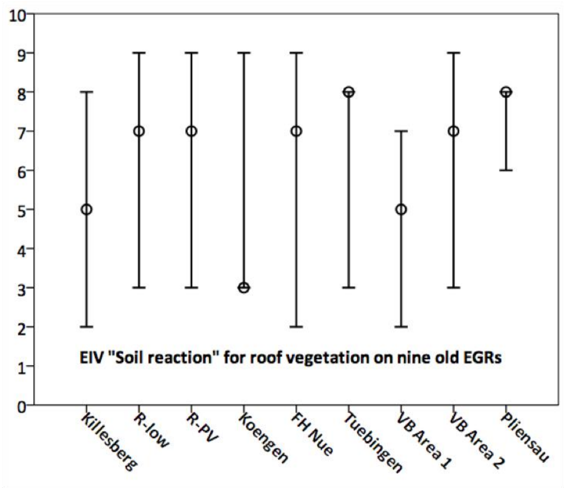


Figure 5.9. a) Range and mean for moisture EIV on nine roofs; **b)** Distribution of species for 9 categories of moisture EIV.

The mean EIV for most roofs was **M2**, which encompasses preferences between M1 and M3, or "indicators of extreme dryness" and "dry site indicators". The "dry site indicators" (**M3**) are "more often found on dry ground than moist places" and included many species common to dry, species-rich grassland, such as *Dianthus carthusianorum*, *D. deltoides, Petrorhagia prolifera, Potentilla recta, Thymus praecox, Veronica spicata,* as well as *Sedum spurium*. Twelve species were “indicators of extreme dryness” and “dry site indicators” (**M2**), including *Petrorhagia saxifraga, Poa compressa, Potentilla argentea, Sedum album, S. acre, S. sexangulare, Sempervivum tectorum, Thymus serpyllum* and *Vulpia myuros*. At the other extreme, the three “damp-site” or “moisture-loving” indicators (**M7, M8**) were found in the drip zone of FH Nürtingen and included two mosses and a sedge. The Sedum species designated with EIVs ranged between M2-M3. Another prevalent species, *Festuca ovina*, did not have an EIV for moisture and was classified instead with “indifferent behaviour”, meaning great amplitude or irregular behaviour in various regions.

5.3.1.2.2 Reaction (soil pH)

Reaction defines the gradient of soil pH in which species can be found. The EIV scale covers the full range of extremes: R9 infers basic reaction and indicates lime-loving species, while R1 infers extreme acidity. The results (**Figure 5.10**) suggest that most EGR species prefer weakly acid to weakly basic (i.e., neutral) substrates, with most occurring between R5 and R8. R5 indicates “fairly acid soils”, typified by species that are “only occasionally found in more acid, or in neutral to slightly alkaline situations”, while R8 encompasses the range of preferences between R7-R9 and features species that are “mostly seen on limestone or chalk”. R6 encompasses the range of preferences between R5-R7.



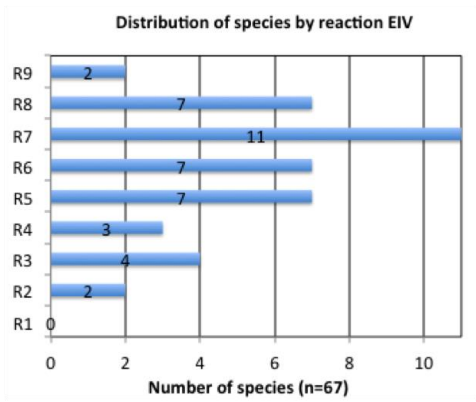


Figure 5.10. a) Range and mean for reaction EIV on nine roofs; **b)** Distribution of species for 9 categories of reaction EIV.

Most of the species (eleven) fell under **R7,** which is defined by “indicators of weakly acid to weakly basic conditions, including species that are never found on very acid soils” (e.g., *Allium schoenoprasum, Arrhenatherum elatius, Convolvulus arvensis, Dianthus* *carthusianorum, Lotus corniculatus, Petrorhagia saxifraga, Sedum telephium, Verbascum thapsus, Veronica spicata*). The species under **R8**, like *Linum perenne, Medicago lupulina, Picris hieracioides,* and *Thymus praecox*, indicate a range of preferences for weakly acid to weakly basic soils but also include lime-loving species that can always be found on calcareous soils. The two species described by the highest EIV (**R9**) were *Coronilla varia* and *Poa compressa* but these were not very prevalent to the vegetation. *C. varia* occurred in a single count on one roof and, other than good representation on FH Nürtingen (11 quadrats) *P. compressa* only occurred in a few quadrats on three roofs.

The lowest values recorded (**R3**) were "acid indicators" found "mainly on acid soils but…also…where there is a neutral reaction" (e.g., *Dianthus deltoides, Festuca ovina, Potentilla argentea*). The **R2** record (*Trifolium arvense*) indicates preferences between R1 and R2 (i.e. between extreme acidity and acid indicators); the other R2 record was the moss, *Philonotis fontana*. The German studies reported similar distributions of soil reaction for TPG and EGR roofs, with the majority of cases between R6 and R7 (Bossler and Suszka, 1998, Buttschardt, 2001, Poll, 2008).

5.3.1.2.3 Nitrogen

The EGRs surveyed indicate nutrient-poor conditions with respect to available nitrogen, of which the majority of species occurred between **N1-N3** (**Figure 5.11**). **N2** encompasses the range between N1-N3 and included many species that were typical of the meadow-like green roofs, like *Allium schoenoprasum, Campanula rotundifolia, Dianthus carthusianorum, D deltoides, Hieracium pilosella, Linum perenne, Petrorhagia prolifera, Poa compressa, Potentilla erecta, P. recta,* and *Veronica spicata.* **N1 s**pecies indicate "sites poor in available nitrogen" (*Festuca ovina, Petrorhagia saxifraga, Potentilla argentea, Sedum acre, S. album, S. sexangulare,* all *Thymus spp., Trifolium arvense, Vulpia myuros*), while **N3** *s*pecies are "more often found in N-deficient soils than on richer ones" and included a few nitrogen-fixers (*Coronilla varia, Lotus corniculatus, Trifolium campestre*). Next most abundant, **N7** species are "more often found in places rich in available nitrogen than in poor or average situations" and the species allocated as such were all non-intentional species (*Arrhenatherum elatius, Geum urbanum, Taraxacum officinale, Verbascum spp.*). Similarly, the single **N8** species (*Erigeron annuus*) was non-intentional, and was only recorded in two locations of one roof. N8 species can occur in N7 conditions but also in "extremely rich situations" (N9) (e.g., "cattle resting places")**.**

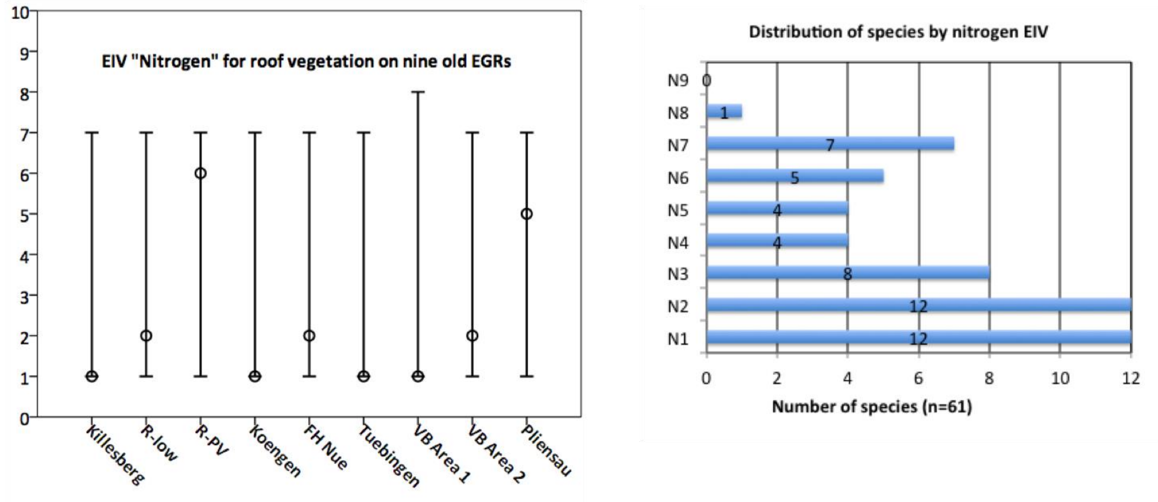


Figure 5.11. a) Range and mean for nitrogen EIV on nine roofs; **b)** Distribution of species for 9 categories of nitrogen EIV.

Finally, there were a number of species in **N4, N5** and **N6**, indicating a range in preferences for nutrient-poor habitats and average N-availability. **N4** species prefer the range between N3-N5 and included species like *Agrostis tenuis, Cerastium arvense, Picris hieracioides,* and *Vicia hirsuta.* **N5** indicates "sites with average N-availability" and included species like *Achillea millefolium, Agrostis stolonifera, Trifolium dubium* and *Vicia sepium*. Lastly, **N6** species prefer the range between N5-N7, meaning sites with average to rich N-availability and included species like *Crepis tectorum, Fragaria vesca, Poa pratensis,* and *Solidago canadensis.*

5.3.1.2.4 Soil-based influence: discussion

The species identified exhibited a range of tolerance for soil moisture and pH, but most of the plant cover was by those with preference for drier, nutrient-poor and acidic conditions. In terms of available nitrogen, typical EGR vegetation can be defined by species that perform well in conditions of very low nitrogen availability. Some German studies report similar results for moisture and soil reaction for TPG and EGR roofs (Bossler and Suszka, 1998, Buttschardt, 2001, Poll, 2008). Although one might have expected the old, sand-gravel substrate of TPGs to have different water-holding capacity compared to engineered EGR substrates, these studies did not detect any difference in moisture between EGR and TPG roofs (*ibid*). While the preponderance of moist site indicators (M4) may seem a bit surprising, when considering the range of conditions that occur on EGRs over the course of a single year one will recall that green roofs in continental climates typically experience excess water and drought interchangeably and by season. Accordingly, species that can tolerate both conditions will have a chance at long-term survival.

The nitrogen EIV implies species' occurrence in a gradient of fertility during the growing period. Other than the highest value (N9), the species/ roofs surveyed covered the full range of conditions. Buttschardt (2001) and Poll (2008) made identical observations on their surveys of EGRs in Karlsruhe and Berlin, while Bossler and Suszka (1998) reported nitrogen-poor conditions (mean: 2.9) for TPG roofs in Osnabrück. The distribution of species across all nutrient classes suggests that nitrogen (and perhaps other soil nutrients) is not a decisive factor to EGR species composition. Instead, since the species composition includes the range of nitrogen tolerances (N-poor to N-rich), species competition or functional traits could be a more informative point of consideration (e.g., nitrogen-fixers, stress-tolerators).

The habitat conditions ascertained here may be broadly representative of rooftop growing conditions, as other studies found no difference in EIVs between EGRs and TPG roofs (Bossler and Suszka, 1988, Buttschardt, 2001, Poll, 2008). Vegetation surveys in Berlin (Köhler, 2006) and in Basel (Thommen, 1988) concluded that the most important factors affecting plant diversity were climate-related, specifically temperature and rainfall distribution. Species richness on the Berlin roofs was significantly influenced by water availability, but comparatively unaffected by slope, roof age, or roof area (Köhler, 2006). Later surveys of the same roof in Berlin observed that increasing exposure to sunlight led to less plant cover, and that different aspects supported different species compositions (Köhler and Poll, 2010). While several experimental studies have tested the effects of plant life forms on green roof performance (e.g., water capture, heat flux), the reverse (i.e., the effect of these conditions on plant performance) has not been widely examined.

5.3.2 Characterising EGR vegetation types using cluster analysis with EIVs

Depending on the environment, the world that ecologists try to understand is most often a continuum and quite unlike the approach of other biological sciences; few ecological theories predict the existence of discontinuities in nature. Still, methods that distinguish similarities and differences are essential to numerical ecology (Legendre and Legendre, 2003). To determine which of the six EIVs, or ecological indicators, carried the most weight for EGR vegetation, cluster analysis was used to group roofs according to their similarities. The result of clustering ecological objects sampled from a continuum is often called a *typology* (i.e., a system of types), which may help to identify various *object types* that can be used to describe the structure of the continuum (Legendre and Legendre, 2003). By analysing environmental conditions (as EIVs) together with species number and with consideration for cover dominance by non-dominant species, this chapter refines the clustering from Chapter 3 to illuminate some of the key environmental factors that drive vegetation composition and species diversity on old EGRs (**Table 5.2**).

Table 5.2. Various proportions of cover by dominant species for nine EGRs

	Proportions of cover by dominant species for nine EGRs				
Roof name (in order of age)	Maximum abundance	Percent dominance	Average (by dominant spp)	Negative dominance	Negative average dominance
Killesberg	676.00	17.04	37.56	82.96	62.44
Rathaus-lower	879.00	18.98	62.79	81.02	37.21
Rathaus-PV	1191.00	24.25	79.40	75.75	20.60
FH Nürtingen	771.00	18.73	64.25	81.27	35.75
Köngen	1000.00	38.90	55.56	61.10	44.44
Tübingen	1286.00	30.58	80.38	69.42	19.63
VB A1	994.00	33.29	71.00	66.71	29.00
VB A2	1050.00	35.87	75.00	64.13	25.00
Pliensau	843.00	35.83	56.20	64.17	43.80

The dendrogram resulting from the analysis balancing EIV range, species number, and cover dominance by non-dominant species grouped the EGRs into three main clusters, termed “Sedum meadows”, “Species-poor Sedum roofs” and “Pitched Sedum meadow” (**Figure 5.12**). The broadest distinction, at linkage distance 25, is identical to the cluster analysis of Chapter 3, but in this analysis the roofs group into three groups (instead of the two major groups, recall “Species-rich” and “Species-poor”). The main difference from that analysis is that Killesberg does not associate with any roofs whatsoever but clusters alone (in Chapter 3 it clustered with both Rathaus roofs at linkage of 2, and with FH Nürtingen at linkage 4). Those results were purely on the basis of proportionate cover abundance, however. Since Killesberg exemplifies unique conditions (i.e., extreme slope, definite aspects), and since this chapter is interested in the environmental conditions that shape EGR vegetation over time, the separation of this roof into a single object cluster seems representative of the green roofs surveyed and their varying conditions.

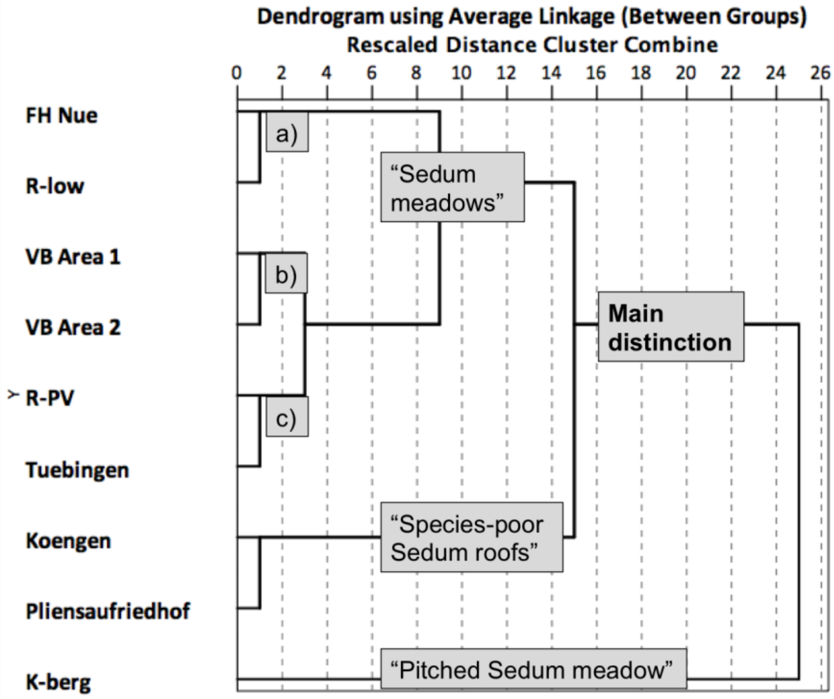


Figure 5.12. A cluster analysis for nine old EGRs reveals three major groupings with reference to environmental growing conditions (EIV range), species number, and dominance by non-dominant species.

Beyond the single object of Killesberg, the other roofs fall under a main distinction (linkage distance: fifteen) and separate into four groups, all clustered in close membership. Similar to Chapter 3, the group named "Species-poor Sedum roofs" is separated from the other roofs at the main point of distinction, and an aggregation of six roofs is divided into three clusters under the heading "Sedum meadows". These roof clusters will be described in the following section.

5.3.2.1 "Pitched Sedum meadow" (Killesberg)

Killesberg stands isolated as a single object cluster (linkage distance: 25), which implies that the vegetation on this steeply pitched roof is unlike all the other roofs with regards to EIV range, species number and cover abundance by non-dominant species. The 30° slope at Killesberg was unmatched by any of the roofs sampled. Indeed, the slope and north-south aspects create a tremendous range of growing conditions. The south face was visibly xeric, as the substrate was cracked in horizontal rills that only supported Sedum species, drought-tolerant mosses and small annual grasses. In stark contrast, the north face supported meadow-like vegetation with similar floristic composition to the Rathausgarage roofs, namely tall flowering herbaceous species above a consistent Sedum ground cover (attributed to the original species list). The inclusion of EIV range and species composition in this analysis classified the vegetation as “Pitched Sedum meadow”. The description nearly matches with the Sedum-Grass-Herbaceous vegetation form described by Krupka (1992), with the exception that xeric mosses were prevalent and that the substrate was shallower than his prescriptive 100-150 mm depth.

5.3.2.2 “Species-poor Sedum roofs” (Köngen and Pliensaufriedhof)

Köngen and Pliensaufriedhof clustered together in the cluster analysis of Chapter 3, too, but were separated from the other roofs at the broadest distinction (linkage distance: 25) versus a distance of fifteen here. In that chapter, these roofs related to each other in proportionate growth form cover at a linkage distance of four, whereas here the inclusion of EIV range, species number and cover abundance by non-dominant species tightens their membership to two. Since these roofs are Sedum-dominated with the fewest species, the title “Species-poor Sedum roof” is descriptive as an EGR vegetation type. With reference to Krupka (1992), this vegetation might be an example of the transitory Sedum-Moss-Herbaceous form.

5.3.2.3 “Sedum meadows” (six roofs in three clusters)

The roofs aggregated into three clusters are distinguished from the “Species-poor Sedum roofs” by their linkage distance (fifteen) and by their vegetation, which can be described as “Sedum meadows”. Excluding the isolation of Killesberg, the roofs clustered under this main distinction match the results from the cluster analysis of the previous chapter but the affiliations between roofs have shifted somewhat. Since these roofs all had similar numbers of species and species compositions, the distinctions between the three clusters here must be attributed mainly to the varying environmental conditions per site. The relationships, both within and between the designated clusters, agree with field observations. The top cluster in the dendrogram (a: FH Nürtingen and Rathaus-lower) is distinguished from the other clusters (b: Verkehrsbetrieb Areas 1 and 2; c: Rathaus-PV and Tübingen) at a linkage distance of 9. The latter two clusters related to each other at a linkage distance of three. The roofs within each of the three clusters related very closely at linkage distances of one. While these clusters all qualify as “Sedum meadows”, their distinctions are described as follows.

5.3.2.3.1 <u>a) “Floristically-diverse Sedum meadow”</u>

The analysis in Chapter 3 (with reference to proportionate cover) clustered these two roofs along with three other roofs (at varying distances of membership) and was descriptively named “Floristically-diverse Sedum meadow”. Of all the EGRs surveyed, FH Nürtingen and Rathausgarage-lower roof had the greatest number of species identified

(32 and 30, respectively), and also bore some subtle environmental gradients from neighbouring buildings (shade, moisture). This is most certainly the cause for their clustering in this analysis since their species lists support much greater EIV ranges than the other roofs. These roofs also had similar values of cover by dominant species (recall **Table 5.2**) that were quite different from the values of other roofs. If the high species diversity on these roofs can be attributed to the EIV ranges (i.e., the environmental conditions sustained by the vegetation), then this vegetation type can retain the name given previously: Floristically-diverse Sedum meadow.

5.3.2.3.2 b) "Sparse Sedum meadow with Chives"

The analysis in Chapter 3 grouped VB Area 2 alone as "Sedum with Chives", while VB Area 1 was clustered with Tübingen. Compared to VB A2, *Allium schoenoprasum* was not nearly as prevalent on VB A1, but Tübingen didn't support a single bulb, so the aggregation of those roofs in this analysis reflects the fact that they supported the same number of species (21) and, being identical neighbours, have similar environmental conditions and EIVs. These roofs also had the shallowest mean substrate depth, and little variation in those measurements. The sampling quadrats were restricted to uniform vegetation, but the variations in depth at other parts of the roof (e.g., scoured areas) obviously impacted species abundance and dominance on these roofs overall; this could have affected the areas surveyed, too. Considering their similar species composition and EIV ranges, the close membership between these roofs can be attributed to removing the weight of dominance by *Allium*. Recalling that the vegetation types for these roofs were formerly described as "Sedum with Chives" and "Sparse Sedum meadow", the results from this analysis can summarise the vegetation of the Verkehrsbetrieb roofs as "Sparse Sedum meadow with Chives".

5.3.2.3.3 c) "Sparse Sedum meadow"

The Chapter 3 cluster analysis grouped Tübingen together with VB Area 1 (named "Sparse Sedum meadow") while Rathaus-PV was clustered with the other Stuttgart roofs and FH Nürtingen (and named "Floristically-diverse Sedum meadow"). Here, Tübingen and Rathaus-PV are grouped together, most likely because both roofs lacked shade and were therefore more exposed (certainly by comparison with FH Nürtingen and Rathaus-lower), which led to a sparser meadow flora above a dominant Sedum cover. In addition to EIV range and species number, inclusion of the weighting factor of cover abundance by dominant species sets these roofs apart from the others. These roofs shared the highest values of maximum abundance (1286 and 1191, respectively), and of mean cover by dominant species (80.38, 79.40) compared to the other EGRs surveyed, which can be explained by the structural layering of the different life forms and species identified, of which dominant species maintained most of the cover. In other words, the combination of taller statured with creeping, ground cover species are responsible for the high values of maximum abundance, but the dominant species (in this case, Sedums) had over-riding dominance to the vegetation on these EGRs. Accordingly, these roofs can be described as "Sparse Sedum meadow."

5.3.2.4 EGR vegetation types: discussion

The results from this cluster analysis represent the vegetation on these roofs well. All the roofs surveyed are Sedum-dominated, so the roof clusters represent subtle differences in vegetation responses to the range of conditions that may occur. The extreme gradients on Killesberg result in its dissimilarity from the other roofs, and the clustered roofs bear resemblance to each other in floristic character and with regards to environmental conditions. Considering the range of growing conditions (implied by the EIVs), EGR vegetation dynamics like persistence, colonisation, competition and diversity may be explained by species' tolerance and opportunism to these conditions. Rather than grassy monoculture that may emerge in unmaintained grasslands, community simplification on EGRs may be described as dominant cover by few succulent species. It is important to recall that these differences are drawn from a small sample size, which limits the strength of conclusions. Nevertheless, the consistency of EIVs for EGRs surveyed in different cities, not to mention their similarity with TPGs (Bossler and Suszka, 1988, Buttschardt, 2001, Poll, 2008) and the consistent vegetation types described by these old roofs suggest that these results may qualify for other EGRs. Still, if more roofs in this region were to be sampled and analysed as such, it is likely that a number of new vegetation types would be defined.

5.4 Conclusions

5.4.1 Characterising EGR environmental conditions

These results indicate that the species that will persist on EGRs over the long-term must be able to tolerate a range of conditions, though opportunities sometimes exist for species that are less tolerant to extremes. With reference to EIVs, the species occurring on 20-30 year old EGRs are tolerant of warm temperatures, but also exposure to harsh conditions (irradiation, wind, frost, etc.). For European EGRs, this explains why most of the species identified had continental to Eurasian distributions, rather than originating from mild and humid oceanic climates. Indeed, moisture preferences ranged from extreme dry to moist sites of average dampness, but the dominant species prefer dry over moist sites. Preferences for soil reaction were neutral, but ranged from fairly acid to weakly basic conditions. Nitrogen preferences covered the full spectrum from nutrient poor to nutrient rich, but typical EGR species prefer nitrogen-poor conditions.

Knowledge of these growing conditions permits inference into the forces and mechanisms directing species assemblage over time for EGRs, at least for southwest Germany. The two broad EGR vegetation types ("Species-poor Sedum roof" and "Sedum-meadow roof") may represent assemblages that emerge as a result of roof-level environmental conditions, in combination with other factors like substrate depth, propagule availability, etc. Recalling the gaps in understanding of how EGR and other urban vegetation as influenced by urban environmental conditions, it is possible that these conditions (e.g., biogeochemical deposition, UHI, air quality) have influenced these results. More samples are obviously required if these vegetation types are to be empirically confirmed as recurring community types.

A series of experiments in Halifax (Canada) found that plant selection, survival and growth can improve ecosystem function (Lundholm et al., 2010), but that environmental conditions have an over-arching influence on this performance (MacIvor and Lundholm, 2011). With regards to roof surface cooling, different life forms reduced surface temperatures quite variably, but the treatments containing tall forbs performed the best for temperature and albedo (Lundholm et al., 2010). Considering the extended influence of vegetation types on substrate temperature, this would imply that taller plants with broad basal leaves or horizontal, large foliage are more effective than Sedum ground cover (Del Barrio, 1998, Lundholm et al., 2010, MacIvor and Lundholm, 2011, Blanusa et al., 2013). These observations convey the role of feedbacks by the microclimate created by different vegetation types, in which substrate properties (including the variables described here as well as depth) and the according vegetation affect each other and ensuing processes (e.g., decomposition, mineralisation, natural succession).

Closer examination of the EGR substrates sampled will build upon these results (Chapter 6), with consideration of the role that substrate composition on the EGR vegetation surveyed (e.g., factors of fertility, pH, or soil organic content). In addition to environmental conditions described as EIVs, other forms of pressure will be considered for their influence on species composition of mature EGRs (Chapter 7).

5.4.2 EGR species composition over time: emergent properties?

One of the original research questions asked whether emergent community characteristics develop over time, such that roofs with similar constructions (substrate, depth, species list) and properties (age, location, growing conditions, etc.) eventually assume the same species composition over time. Chapter 3 concluded that green roof vegetation is not static, and suggested that the roofs surveyed converged over time into two broad distinctions. While this chapter integrated more detail into the cluster analyses, the broadest distinction remained (“Species-poor” and “Species-rich”) but with the addition at the same linkage distance of a third “Pitched Sedum meadow”, and a few roofs shifted their cluster memberships.

Given the urban context, the question of emergence on EGRs may benefit from appropriate framing. For this purpose, EGRs can be considered novel ecosystems (Lundholm et al., 2010, Madre et al., 2014, Van Mechelen et al., 2015b, Lundholm, 2015), which support anthropogenic plant communities whose classification is most realistically achieved through deductive methods (c.f. Kopecky and Hejny, 1978). Indeed, every known phytosociological study that attempted to classify green roof vegetation identified unique flora for every roof surveyed, regardless of similarities in age, system build-up, location, environmental conditions, or otherwise (Thommen, 1988, Darius and Drepper, 1983b, Buttschardt, 2001, Köhler, 2006, Köhler and Poll, 2010). The consistent vegetation type identified by those works was the Class *Sedo-Scleranthetea*; more detailed classifications (i.e., Order, Alliance, Association) led to the equivalent of roofs clustering as solitary, individual groups.

The consideration of earlier works through this frame reveals that some proposals are too simplistic (Krupka, 1992, FLL, 2008a, Madre et al., 2014), whereas the results of others have been too specific (the phytosociology references above, but see Van Mechelen et al., 2015). On the conjoined basis of the literature and these results, we therefore hypothesise that green roofs with identical starting points (construction, properties) will probably converge at general points of similarity; however, the emergence of identical and recurring species compositions is highly unlikely. It might be argued that the notion of emergence is interesting as a theoretical construct, but without methods for empirical validation or for generating and testing hypotheses it is practically useless. By contrast, calls have been issued for the detailed examination of novel ecosystems, and in particular the development of methods for recognising, quantifying and managing them (Hobbs et al., 2009) such that we can “deal effectively with the new ecological world order” (*ibid*, p. 604). Such efforts can apply to green roofs as novel ecosystems; this gap in contemporary ecological understanding seems an obvious bridge where ecological research on green roofs could directly support urban ecology. The consideration of green roofs as novel ecosystems is still very new, so concepts other than emergence may be more suitable for explaining and predicting vegetation change over time.

5.4.3 Relevant ecological theories and models for EGRs

Conceptually, elements from certain ecological models resonate with the interests of this work, particularly natural succession and disturbance theory, but also fragmentation, island biogeography and metapopulation theories. The latter three may be applicable at the meta-scale, but this work is oriented to site-level processes and focused on vegetation change, so the theory of natural succession is the most relevant theory for this research. Even so, with validation of all these theories and models consistently forestalled, their application to this applied research may be more pedantic and academically interesting than genuinely useful. Certainly, its limitations of sample size, variables measured and time scale (i.e., static, "snapshot" surveys) prevent this work from directly engaging with theoretical development for urban ecological understanding. However, as it ultimately leads to Chapter 7, which will propose some models on vegetation development for EGRs, the questions raised and the gaps in knowledge and empirical evidence identified all contribute to that framework, thereby engaging theoretical discourse with pragmatic outcomes. To that end, the relevant aspects of succession and disturbance theory shall be outlined.

5.4.3.1 Natural succession and disturbance theory

Sedum-dominated EGRs are the industry standard, and if the EGR vegetation types surveyed are considered stable, then the concept of the edaphic plagioclimax (sensu Tansley, 1965) may help to describe the processes that create and maintain these vegetation types. In these terms, species assemblages that establish and persist (as stable, sub-climaxes) are the product of edaphic (but also drought-) stress issued by the shallow EGR substrate. In this context, the harsh conditions confronting plants at various life cycle points are sufficient to re-set the successional clock, such that the plant communities that result are determined by whatever is able to persist and by whatever is able to colonise rooftop habitats. Initial floristic composition can be useful to illuminate the importance of originally planted/ sown species to long-term EGR vegetation.

The European analogue identified for EGR vegetation, the *Sedo-Scleranthetea*, is highly dependent on annual precipitation and though species diversity will vary according to prevalent climatic conditions, overall the community remains intact and stable (Ellenberg, 1986). Through the lens of plant ecology, EGRs may be seen as unproductive, relatively undisturbed communities of which the most conspicuous feature is "*the absence or low abundance of species capable of attaining biomass peaks in the summer and the presence of a variety of S-strategists, many of which [have] long-lived leaves forming ever-green canopies showing little change in structure throughout the year*" (Grime and Pierce, 2012) (p. 111). This statement describes EGR vegetation very well, but actually refers to a limestone outcrop on ancient sheep pasture in which the short turf is composed exclusively of stress-tolerators (including cryptogams, herbaceous perennials and grasses). Models of vegetation dynamics for EGRs will be considered further in Chapter 7.

Countless studies have observed that drought stress (and/ or lacking moisture) is a major factor directing EGR species composition over time, but little research has directly quantified this or its impacts on biotic life on green roofs. If more sample sites were attainable, then there is every reason for green roofs to add to the development of disturbance or CSR theory and to urban ecological understanding (Felson and Pickett, 2005). Even for ground-level habitats, the basic concepts of stress and disturbance require clarification and new ways of translating different spatial scales and organisational levels must be developed (Rykiel, 1985). Indeed, until the hypothesis is translated into operational terms, and the interactions of stress and disturbance with other system-organizing disequilibrating factors examined, little progress can be made (Pickett et al., 1994). EGRs could be positioned to examine some fundamental questions since they are relatively discrete, protected ecosystems.

If stress and disturbance-related hypotheses are to be tested on EGRs, rigour must be employed. Major errors to ecological understanding occur when field measurements taken during stress- or disturbance-free years are incorrectly used for extrapolation in order to predict future system states (Pickett et al., 1994). When misleading extrapolations are made from insufficient information, the variance generated is also misunderstood. Considering that most ecological green roof research has been conducted as 'snapshots' this is clearly an important methodological aspect requiring amendment, namely the insistence of frequent and regular monitoring.

5.4.3.2 Reconciliation ecology

If urban ecological research has arrived to a point where ecologists must reach for the 'higher-hanging fruit' (McDonnell and Hahs, 2013), then green roof research must also begin asking more refined questions that are robust and ecologically relevant such that the resulting scientific outputs can provide explicit advice to practitioners. If EGRs are to match the contemporary issues of urbanisation, ecosystem services and biodiversity decline, then it is time for a renewal of their original intentions. This sentiment is expressed by the critique by Henry and Frascaria-Lacoste (2012) who challenge that EGRs are irrelevant means of reconciliation ecology if their installation is limited to products of the commercial green roof market.

6 EGR substrate development after > twenty years

6.1 Literature review

Soil serves as the central interface between the atmosphere and biotic life, being crucial to plant growth and the development of food webs, biotic communities and ecosystems. The belowground ecological processes of litter and stock reduction are related with mobilisation of nutrients and soil biota, all of which relate back to soil conditions like pH, organic content and soil moisture holding capacity. Despite the fundamental importance of soil to vegetation (and, by extension, to life on Earth), the soil environment and the plant rhizosphere are among the least understood habitats and communities on Earth (Bardgett, 2005). Indeed, soils may actually contain the majority of the Earth's species but most have yet to be identified by science (Wardle, 2002). This is largely owing to the scales of complexity around sampling natural soils without issuing human impact (Bardgett, 2005). Before introducing the essential properties, composition and behaviour of good EGR substrates, this chapter opens with a background on the commonalities of all soils, whether natural field soils, horticultural potting media or green roof substrates. This introduction will lead to the discussion and the aim of understanding for describing soil-based ecological processes on EGRs. For ease of discussion, the term 'soil' will be used in this introductory section to generalise all types of soil.

6.1.1 Soil basics

Depending on their origins and locations, soils can vary tremendously in their proportions, qualities and properties but there are some fundamental basics for classifying and defining them. Soils can be subdivided into five major components: i) mineral particles (the inorganic fraction); ii) organic matter (the remains of living organisms); iii) water (the 'soil solution' in which nutrients for plants are dissolved); iv) air (which fills the space between solid particles not filled with water); and v) living organisms (small animals and microbes, mycorrhizal fungi, plant propagules), all of which can be classified into three characteristics: physical, chemical and biological (Handreck and Black, 2010). Physical properties are those we can see and feel and include colour, structure, texture and behaviour towards water and air (Handreck and Black, 2010). At its most basic, the physical structure of mineral soil (i.e., sand grains and silt particles) is known as the soil skeleton (Ricklefs, 2001). As opposed with a purely organic soil (like peat), a skeletal soil is a weakly developed soil with minimal to no profile development (WRB, 2014), and is also defined as regosol by the FAO (WRB, 2014) or entisol by the USDA (1999). The chemical characteristics of soil are involved in soil-based chemical reactions and the supply of plant nutrients, and include pH, buffering capacity, cation exchange capacity (CEC) and nutrient charge. Lastly, the biological properties of soils are related to the activities of living organisms (Handreck and Black, 2010). In order to support biological processes, soils must provide root anchorage and serve as a reservoir for plant available nutrients and water while also maintaining sufficient air voids for root respiration (Nelson, 2011).

6.1.1.1 Soil structure

By definition, soil structure is "the arrangement, or organization, of the particles in the soil (i.e., the internal configuration of the soil matrix)" (Hillel, 1998: p. 101). Soil structure is strongly influenced by changes in climate and biological activity, and is vulnerable to destructive forces, both mechanical and physico-chemical. Altogether, soil particles form a mass of irregularly shaped and sized particles and is generally inconstant over time and non-uniform in space. In a sense, then, soil structure is impossible to measure quantitatively; the methods developed for characterising it don't measure structure itself, but rather the attributes that determine the structure (Hillel, 1998).

Soil can also be described as a system of phases, namely the solid phase (*soil matrix*), the liquid phase (*soil solution*), and the gaseous phase (*soil atmosphere*) (Hillel, 1998). Hypothetically, a soil that provides optimal growing conditions for plants comprises 50% solid matter (mineral and organic) and 50% pore space (water and air) by volume (*ibid*). In these proportions, more than half of the solid phase is occupied by mineral matter (meaning less organic matter), while the pore space is equally shared by water and air (since an increase in one is associated with a decrease in the other) (Hillel, 1998). Good soil structure is therefore based upon a balance of components, generally with moderate organic matter content (perhaps 3% or more), some clay, and calcium as the main exchangeable cation (Handreck and Black, 2010) (**Figure 6.1**).

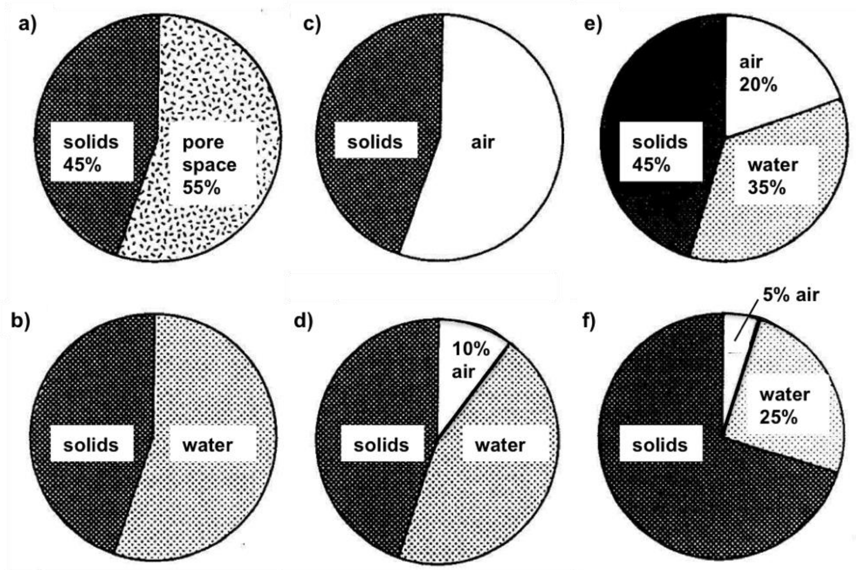


Figure 6.1. The proportions of solids, air and water in soils of various growing conditions: a) Good topsoil (approximate proportions of solids and pore space); b) Waterlogged; c) Completely dried; d) Minimum air-filled porosity for good growth of many plants; e) "Ideal" proportions of air and water for excellent growth; f) Severe compaction. Modified from Handreck and Black (2010) (p. 59).

A number of parameters have been defined for characterizing soils physically, elaborating upon volume-mass relationships amongst the soil phases and constituent parts. Since a comprehensive background in soil physics is beyond the scope of this thesis, only a selection of volume-mass relationships relevant to EGRs will be introduced. The sections that follow therefore describe the main constituents which determine soil structure, and how soil physical function is influenced by different situations and proportions of these.

6.1.1.1.1 Soil crumbs

The solid component of soil structure is defined by the bound aggregates of mineral and organic matter (Hillel, 1998). Soil crumbs, which come in all sizes and shapes, determine what kind of plants a soil can support, and how well. Natural soil crumbs, or soil aggregates, are also termed *peds*: when moist, a highly *pedal* soil contains many natural crumbs, whereas an *apedal* soil doesn't demonstrate peds. Crumb formation can be enhanced by increasing organic matter, iron and aluminum, clay and exchangeable cations, and is compromised by increasing the levels of exchangeable sodium and (to a lesser extent) magnesium (Handreck and Black, 2010). Organic matter helps to form crumbs mainly because the organisms it supports – slugs, worms, fungi, etc. – produce sticky slimes, casts and hyphae which bind mineral particles together. In addition to organic matter and microbes, soil crumbs are made stable by clay particles, which can form 'skins' around crumbs, and by positively charged cations, including especially calcium but also iron, aluminum and hydrogen. If levels of exchangeable magnesium exceed those of calcium, soil structure becomes 'tough' and difficult to cultivate, and high levels of sodium will render crumbs unstable when wet (Handreck and Black, 2010). As mentioned, soils low in organic content and which lack the organisms described above may be described as skeletal because their mineral particles do not bind together (Coleman and Crossley, 1996).

6.1.1.1.2 Pore space

Good soil structure requires spaces between crumbs, namely the pores that exist both between and within the crumbs and particles. Like crumbs, pores come in all shapes and sizes, from animal burrows to fissures created by plant roots. Total pore space is the percentage of soil volume that is not filled with solids. Compaction reduces total pores and it can vary "from as little as 30% in a heavily trafficked field and turf soil to about 95% in some peats" (Handreck and Black, 2010: p. 57). Ultimately, the shape and size of soil pores are the most important aspect of pore space on soil structure and on how well the soil can support plants. The size of a soil's pore space will influence the way in which the soil manages its air-water balance and how amenable the soil is to plant root exploration (Handreck and Black, 2010). The amount of water that a soil can hold implies its ability to support plants (Handreck and Black, 2010), and pore sizes influence water flow in mineral growing media, which may occur as film creep along the walls of wide pores, or as tube flow through narrow pores (Hillel, 1998). Large pores lead excess water away, while tighter, smaller pores hold water for plant use (USDA, 1999). As media become progressively drier, increasing matric suction causes hydraulic conductivity to drop; the physical affinity between water and the medium matrix is strengthened by negative pressure potential (Hillel, 1998).

Saturation, the wettest possible condition of a soil, occurs when all pores are filled with water. This rarely occurs in nature, however because air bubbles may remain encapsulated within the soil matrix, even when flooded, and a rise in temperature may cause these to effervesce within the soil (Hillel, 1998). Otherwise, pore size will determine different hydraulic behaviour by soils. *Micropores* are narrow, often discontinuous pores typically less than a micrometer wide which are tightly held within clayey soils. Water held in micropores "do not participate in ordinary liquid flow phenomena" (Hillel, 1998) (p. 119) and may deviate from hydrologic laws (e.g., capillarity, Darcian flow). Such water may be referred to as 'adsorbed', 'bound' or 'residual'. Adsorption occurs when water creates a film over particle surfaces with strong matric suction, or negative metric potential (**Figure 6.2**). The phenomenon of capillarity is illustrated by the meniscus that forms when a capillary tube is dipped in a body of free water (i.e., water at atmospheric pressure), and by the height of the water column that rises up inside the tube. The narrower the tube, the higher the water column. The water inside the tube is driven up by the pressure difference between the water outside and inside the tube, and will stabilize once this pressure is countered by gravity (Hillel, 1998; Handreck and Black, 2010). Capillary pressure potential (or matric potential) is an important mechanism for soil-water affinity (Hillel, 1998).

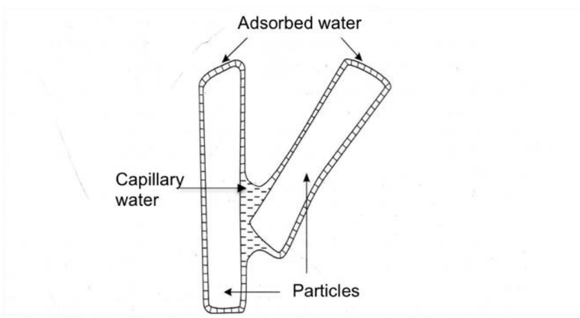


Figure 6.2. Water in unsaturated soil is subject to capillarity and adsorption, which combine to produce a "negative" matric potential, or a matric suction. Source: Hillel (1998) (p. 149).

Next in size, *capillary pores* range from several micrometers to a few millimeters. The water within these pores is retained by surface tension and moves as a result of capillary forces (Bunt, 1988). In coarse-textured soils, water may be confined almost entirely to the capillary wedges at the contact points between particles (**Figure 6.3**). This adhesion forms separate and discontinuous pockets of water, and does not promote vertical capillary rise (Hillel, 1998). EGR substrates contain relatively few fine particles, especially compared to field soils, which results in different conditions influencing capillary rise (and perched water tables) (Beattie and Berghage, 2004). Lastly, *macropores* can be visible to the naked eye and may occur as cracks or fissures in dried clayey soils or as a result of biological activity (e.g., burrows, root decay), and are therefore planar or tubular in shape. When empty of water, macropores form barriers to capillary flow and permit only very slow film-creep along their walls. When filled with water, however, they permit very rapid flow (Hillel, 1998).

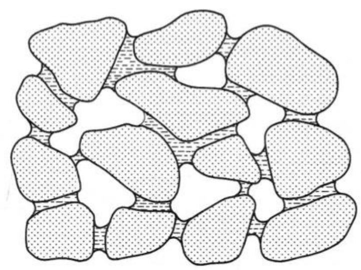


Figure 6.3. Water in an unsaturated course-textured soil. Source: Hillel (1998) (p. 205).

6.1.1.1.3 <u>Bulk density</u>

The volumetric distribution of solids, water, and air within a soil must ensure that critical pore spaces are available for root respiration and water storage. The density of solids in relation to pore spaces is a central element defining the volume and mass relationships of soil constituents, and includes density of solids (mean particle density), dry bulk density, total (wet) bulk density, dry specific volume, porosity, and void ratio. The various expressions of soil water content (mass wetness, volume wetness, water volume ratio, and degree of saturation) and of air-filled porosity (or fractional air content) are of equal importance to soil function (Hillel, 1998). The latter measurements are beyond the scope of this thesis and shall therefore not be elaborated upon, but a general introduction to bulk density will be presented in a way that respects the other volume and mass relationships occurring within soils.

Bulk density can be considered “a kind of opposite to the total pore space of a soil” (Handreck and Black, 2010: p. 59). Bulk density expresses the ratio of solid mass to total soil volume (including solids and pores together), often as grams of a dried cubic centimetre (cm^3) or millilitre (mL) of soil (Hillel, 1998, Handreck and Black, 2010). Bulk density is rarely constant, being affected by the structure of the soil (i.e., degree of compaction) and by its characteristics of swelling and shrinkage that are related to clay and water contents (Hillell, 1998). In general, more pore spaces mean a lower bulk density, which implies a lighter-weight soil. Organic materials have lower bulk densities than mineral soils because they have and create more pore spaces. Thus when considering volumetric quantities of different soil types, 1 m^3 of (dry) mineral soil typically weighs between 1000-1900 kg, while the same volume of (dry) organic material (e.g., peat moss) has a mass of 50-200 kg, which is between 3% and 20% the mass of the same volume sand or soil. In practice, soil weights are expressed as saturated weights so it is prudent to specify soils by mass rather than volume, and perhaps even to state the water content (Handreck and Black, 2010).

Bulk density represents the balance of air void spaces in the soil matrix volumetrically (e.g., mg/ m^3), and includes particle density (dry and wet), apparent density, and loose bulk density. If weight loading is the main limiting factor for a green roof, then bulk density is the most important physical characteristic of the substrate to be installed (Beattie and Berghage, 2004). The bulk density for green roof substrates is specified through particle size distribution (FLL, 2008, p. 58). Recalling that organic materials have lower bulk densities than mineral soils, this is an important point for EGR systems that are predominantly mineral and which must be lightweight. When mixed, the bulk density of the green roof substrate should be about 5 lbs/ ft^2 per inch of substrate depth (or approximately 960 kg/ m^3) (Beattie and Berghage, 2004).

6.1.1.1.4 *Compression, compaction, and consolidation*

When subjected to pressure, soil tends to compress, or increase in bulk density (Hillel, 1998). Similarly, compaction of pore spaces and settling while in transport may reduce the volume of soil ultimately delivered (Handreck and Black, 2010). When soils are compacted, crumbs and particles are pressed together which reduces the size of the spaces between them (Handreck and Black, 2010). When larger pores are collapsed by compaction, water movement into and within the soil is hindered which leads to reduced infiltration rates. When average pore size is reduced, i) water is held more tightly in small pores, which leads to reduced water availability (i.e., plants must use more force to access water), and ii) more water is retained in the soil after drainage has stopped (leading to a reduced air supply to roots). Compacted soils also have higher soil strength, which means that roots must navigate a matrix with few large pores and/ or pores with walls that cannot easily be pushed aside. Due to the energy required for navigating ‘strong’ soils, and to the physical barriers preventing the extensive development of a main root network for accessing nutrients and water, plants in compacted soils are usually stunted. Lastly, in systems where the water table is perched on top of a mineral layer, compaction of the materials comprising the root zone forces the water of the capillary fringe closer to the soil surface which can damage roots through lack of oxygen (Handreck and Black, 2010).

The nature of soil compression will vary depending on the degree of moisture, because water is 50 to 100 times more viscous than air; expulsion of air from a soil is nearly instantaneous whereas water escapes at a much slower rate (Hillel, 1998). Compression of a completely dry soil, whether under static pressure or vibration, “causes the particles to reorient and to assume a closer packing arrangement, thereby reducing the fractional volume of air” (*ibid*, p. 357). In saturated soils, by contrast, “any such reduction of porosity must necessarily take place at the expense of the fractional volume of water” (*ibid*, p. 357). The latter (compression of a saturated soil) is more precisely known as consolidation, and the term compaction “applies to the densification of an unsaturated soil by the reduction of the fractional air volume” (*ibid*, p. 358). Intense traffic on a wet soil can render the surface soil into a slurry which, upon drying, may set into a hard crust that is inhospitable for plant growth (Handreck and Black, 2010). Although soil compaction on roofs is nowhere near as problematic to field operations like agriculture and athletic turf, the physical repercussions do nevertheless merit attention for EGR substrates (Beattie and Berghage, 2004). Since EGRs have minimal depth from the start, and lack resources that natural soils can access for replenishment (e.g., fissured bedrock for exploration, large plants for organic inputs), the risk of compression is thoroughly addressed by the FLL guidelines (introduced later).

6.1.1.2 Organic content

Organic matter has numerous important benefits for soils and for vegetation. For one, organic matter binds together the soils mineral particles to form aggregates, thereby improving soil structure, water retention, and the supply of oxygen and water to plant roots (Havlin et al., 2005, Handreck and Black, 2010). Organic matter serves both as a source and regulator of nutrient supply because it increases cation exchange capacity, thereby reducing nutrient leaching (e.g., P, K, Ca, Mg) and concurrently makes those nutrients more available to plants (Havlin et al., 2005). Organic material can act as a reservoir for soil nitrogen, and its mineralization provides a continuous (if limited) supply of essential macronutrients like nitrogen, phosphorus, and sulphur to plants (Havlin et al., 2005). Organic matter helps to buffer soils against rapid changes in pH, thereby helping to control root disease. This is partly because the microorganisms that decompose organic matter concurrently reduce the level of disease-causing organisms in the soil (Handreck and Black, 2010). Soil organic content can also increase plants' ability to resist pathogens and other organisms causing diseases to roots and shoots (Handreck and Black, 2010).

Plants are the primary source of all organic matter through their biomass, both above- (shoots, twigs, branches, flowers, fruits) and below-ground (roots). The process of decomposition reduces plant parts to tiny and unrecognizable bits, which may occur as quickly as a few months in the case of softer plant parts (e.g., small roots, leaves, flowers) in moist environments (Wardle, 2002). Decomposition is caused by millions of microorganisms (mainly fungi, bacteria, actinomycetes) which feed upon plant tissues and upon each other, recycling the nutrient elements from the plant material for renewed use (Bardgett, 2005, Wardle, 2005). The dark-coloured humus that results is basically microorganism excreta, whereby microorganisms have rearranged the atoms through their decompositional activities to form large conglomerates (Handreck and Black, 2010). Humus therefore consists of large organic molecules containing mainly carbon, hydrogen and oxygen but also nitrogen and sulphur, plus smaller amounts of other elements. Humus is the most stable component of soil organic matter and has major effects on soil structure and a soils ability to hold and supply plant nutrients (Handreck and Black, 2010). The organic matter content of a soil will change with relation to its environment (Handreck and Black, 2010). Organic matter will accumulate when plant growth exceeds decomposition rates, as when plant growth is enhanced through fertilization on soils that can only support slow rates of decomposition (e.g., acidic) or it will decrease when plant material and litter is removed, or when the soil and vegetation are disrupted by water-logging, fire or cultivation.

6.1.1.3 Biological component: soil fauna

The recycling of nutrients from vegetation and substrate and the formation of soil crumbs and soil structure are essential functions for any ecosystem. Soil-based herbivores and carnivores, as well as soil microorganisms, are required for ecological processes like decomposition and nutrient recycling; as such, soil fauna can serve as indicators of ecosystem function and vitality (Bardgett, 2005). Macrofauna, like ants and earthworms, are known as ecosystem engineers because their feeding and burrowing activities amend soil structure and hydrology (Eldridge, 1993, Eldridge and Pickard, 1994, Debruyn and Conacher, 1994, Bardgett et al., 2001). Earthworms, for example, which are both voracious litter transformers and important soil engineers, can have dramatic effects on soil porosity and infiltration (Knight et al., 1992, Lavelle et al., 1995), significantly enhance rates of decomposition and C mineralization, stimulate total soil nutrient availability (N, P), and enhance plant nutrient uptake (Hobbie, 1992, Knight et al., 1992, Lavelle et al., 1995). Though mutualism is widespread, these organisms can also have adverse effects on ecosystems [e.g., see Yeates (1981), Martin (1991), Hyvonen et al. (1994)]. Consideration of the role that these biotic populations play for soil ecological processes may shine light upon the results already described in this and previous chapters, and on the nature of soil-based ecological processes on EGRs.

6.1.2 EGR substrates

The FLL (2008) specifies that organic content should not exceed 65 g/ L for any multi-layered green roof type, and no more than 40 g/ L for single layer constructions (both intensive and extensive). The guidelines agree that greater proportions of organic matter may be required, depending on the vegetation used (p. 61). The ideal EGR substrate comprises a balance of light-weight, well-drained mineral aggregate with sufficient organic matter to provide adequate water- and nutrient-holding capacity (Rowe et al., 2006). Good EGR substrates will maintain their structure and proportions over time, will not break down or lose too much depth by compaction or erosion, and will not leach nutrients in the runoff (Kolb and Schwarz, 1999). As a result, EGR substrates are 70-90% mineral (by volume) (Kolb and Schwarz, 1999), and may have 10-25% organic content (Beattie and Berghage, 2004) but usually less. Most research has explored the influence of different proportions of organic matter in EGR substrates on Sedum species, which have low demands (Rowe et al., 2006, Getter et al., 2007, Emilsson, 2008, Molineux et al., 2009), certainly by contrast with herbaceous perennials (Nagase and Dunnett, 2011). So, although it has numerous advantages to soil structure, water retention and plant performance, EGR substrates are specified with low proportions of organic matter (Miller, 2003, Beattie and Berghage, 2004, Dunnett and Kingsbury, 2004, Friedrich, 2005). The mineral and organic components are considered individually.

6.1.2.1 EGR mineral component

Early EGR research in Germany found that organic material does not hold up over time due to oxidation and compression (Kolb et al., 1983), so engineered “soil-less media” became commonly used. When designed with appropriate particle sizes, predominantly mineral substrates have been lauded for providing comparable moisture holding properties to high-organic mixes (Miller, 2003, Friedrich, 2005). The porosity of mineral substrates promotes excellent drainage and oxygenation for the root environment, but also holds sufficient water to support plant growth between rain events (Handreck and Black, 2010). Mineral aggregates also resist compression and shrinkage, thereby maintaining soil structure and further promoting drainage and aeration (Dunnett and Kingsbury, 2004) and longevity (Kolb and Schwarz, 1999). Other reasons for high mineral proportions are related to the EGR requirements of loading, water retention, resilience to compaction, and so on. The addition of aggregate fines or sand can help with water retention and possibly also with capillary action (Friedrich, 2005). The FLL (2008) provides specifications for several physical properties of the mineral component of EGR substrates. By mass, the proportion of slurry-forming components (particle size diameter less than .063) should be less than or equal to 15%, and the proportion of gravel (d > 4 mm) should be less than or equal to 50%. The limited nutrient and organic content of these substrates gives EGR vegetation (*i.e.*, hardy perennials like Sedums) advantage over competitive species that require more fertile soils (Kolb and Schwarz, 1999). Fewer weeds imply less maintenance, of course, which satisfies one of the economic arguments for EGR installations.

Ideal mineral aggregates for EGRs are lightweight, durable and inert. These may be derived from natural sources (e.g., volcanic materials like lava, scoria or pumice), recycled products (e.g., crushed brick or tile), or manufactured materials (e.g., LECA, expanded shale, clay or shale). Due to the energy required for their sourcing and manufacture, the latter materials have very high embodied energy and their use can impact the sustainability goals of a building due to life cycle costs (Oberndorfer et al., 2007, Kosareo and Ries, 2007). The expanded aggregates that are popular in North America are manufactured by passing raw minerals through rotary kilns which form, dry and fire the particles at temperatures over 1,200 °C (Spomer, 1998), liberating gases as bubbles within the minerals and causing them to bloat, or "expand", to 1.5 to 2 times their original size. Concurrent with this process, each particle is calcined, or covered by a ceramic-like coating, rendering the product chemically inert with high compressive strength (Northeast Solite Corporation, 2007, Expanded Slate Clay and Shale Institute, 2010). Since the 1990s, crushed brick and tile have become popular for EGR substrates in Germany, as they fulfil the mineral component requirements and are widely available as recycled materials (Roth-Kleyer, 2002, Appl and Ansel, 2004). Roofing tile is fired differently than brick and cannot be interchanged with the same results (Friedrich, 2005). In England, Molineux et al. (2009) found that three alternative aggregates (pellets of clay and sewage sludge; paper ash; and carbonated limestone) performed as well, if not better, as the standard brick-based EGR substrate that was imported from Germany. Other by-products like blast furnace slag, bottom ash, and diatomite filter waste are not recommended for EGR substrates (Friedrich, 2005).

6.1.2.2 EGR organic component

Although most plants prefer to grow in higher organic content, organic matter in EGR substrates is quite low. Early EGR research found that organic materials like humus decomposed and disappeared within the first few years (Kolb et al., 1983, Krupka, 1992). Too much organic content was also perceived as having negative consequences on soil aeration, plant performance and higher potential risks of nutrient leaching (Beattie and Berghage, 2004, Bilderback et al., 2005, Rowe et al., 2006). For all the research, discrepancies in the specification of organic materials and in the metric (volume versus mass) have led to confusion of how much organic content is best for regions with emerging green roof industries (Buist and Friedrich, 2008). Low organic content certainly offers advantages for EGR vegetation because moderately stressed plants are hardier and ultimately stand a better chance of survival when resources become suddenly limited, as in the case of drought (Rowe et al., 2006; Handreck and Black, 2010; Nagase and Dunnett, 2011). By investing more energy into root rather than leaf growth, as required to access deeper water and nutrients, moderately stressed plants will use those resources more efficiently (Handreck and Black, 2010).

Still, more organic content in EGR substrates can stimulate seed germination and root development, and improve general plant growth (Nagase and Dunnett, 2011). Of four different percentages organic matter (0%, 10%, 25%, 50% by volume) in a crushed brick substrate, 10% proved best for maintaining diversity and stable growth by four different growth forms regardless of watering regime (Nagase and Dunnett, 2011). Of equal importance, less organic matter on EGRs produces smaller plants and also invites fewer weeds to colonise, which means less maintenance is required (Nagase and Dunnett, 2011). Using low organic content in EGR substrates can reduce the leaching of nutrients, like N and P, which pollute surface waters (Moran et al., 2004, Emilsson et al., 2007, Villarreal and Bengtsson, 2005). Assuming healthy plant growth and normal biomass turnover, Beattie and Berghage (2004) estimated that organic matter on a well-established EGR would "probably stabilise at around 2-5% of the total roof medium volume" (p. 2).

6.1.3 Hydrologic-horticultural concepts for green roof substrates

The confined volume of EGR substrates may result in intense plant requirements for not only water, but also air and nutrients. Similar to field soils, EGR substrates must balance solid matter (mineral and organic) and pore space (water and air) by volume. Beattie and Berghage (2004) specify the allocation of water and air within pore space and state that the ideal EGR substrate consists of about 40% solids, 40% water storage and 20% aerated pore space, which is close to the "ideal proportions" illustrated in **Figure 6.1e**, which allocates 45% to solids, 35% to water and 20% to air. Maintaining both good drainage and water retention is vital, if somewhat contradictory, for plant survival on EGR systems designed for drought-tolerant vegetation. On the one hand, enough water must be retained to support plants through periods of drought, yet waterlogging from poor drainage can cause root damage from inadequate aeration. Waterlogging causes more mortality to green roof plants than intermittent drought (Dunnett and Kingsbury, 2004). The hydrologic parameters that are central to soil-water relations on EGRs are outlined below.

6.1.3.1 Maximum water holding capacity

The hydrologic properties of the substrate will ultimately influence the design load of a green roof. So, in order to prudently determine the “dead load” of a green roof for the purpose of structural engineering, maximum water capacity and field capacity of the substrate must be included into the calculations. On extensive green roofs, maximum water capacity (MWC) is a measure of the capacity for water retention by both substrate and granular drainage layers. For EGRs designed for drought-adapted vegetation, the MWC of substrate in an installed/ compacted state should be greater than or equal to (≥) 35% by volume. For single-layer constructions, intensive greenings should have MWC ≥ 30% by volume, and extensive greenings ≥ 20% by volume (FLL, 2008: p. 62). For systems using aggregate drainage layers, “the engineering and materials used must ensure that the artificial water table can rise” and, in addition to providing for this perched water table, “sufficient dry space must be left above the maximum water table level” (FLL, 2008: p. 51) to prevent waterlogging and to ensure that excess water can freely drain away. The FLL states that MWC should never exceed 65% for any green roof system, whether intensive or extensive. In horticultural terms, MWC is known as available water (Handreck and Black, 2010), namely the amount of water a substrate can hold when between field capacity and the permanent wilting point.

6.1.3.2 Water permeability

Water permeability (Kf mod.) calculates how quickly water will infiltrate and drain through a material, whether substrate or drainage layer, as a function of the gradient and depth. To the latter, flow rate by the drainage layer is a function of the volume cleared via the drainage course, the surface area drained, the coefficient of discharge, maximum rainfall, altogether calculated as runoff width in meters (FLL, 2008: p. 51). Manufacturers must provide a runoff rate [L / (s * m)] characterizing the efficiency of the materials used in their drainage layers, presumably on the basis of industry standards.

6.1.3.3 Air content requirements

Total pore volume, described in the FLL guidelines as air content (at pF 1.8), should be no less than 10% volume when a substrate is at MWC (FLL, 2008: p. 62). To account for the water held in the fine pores at pF > 4.2, the volume of plant-available water can be calculated by subtracting around 10-15 % from the MWC. In the case of substrates with large pores (at pF 1.8), air content should be ≥ 20% volume. Dunnett and Kingsbury (2004) suggest EGR substrates should have 60-70% pore volume.

6.1.3.4 Permanent wilting point

When a plant cannot access enough water, either because there is not enough in the substrate, it is held too tightly, or it is too far from the roots to access it quickly enough, it begins to wilt permanently and if water is not supplied quickly enough it will begin to die (Handreck and Black, 2010). In testing scenarios, permanent wilting point is also defined as water content at 1.5 MPa suction pressure. Since green roof plants are typically drought tolerant and therefore have high wilting points, MWC for green roof substrates may be better explained by the nearest point to saturation (Miller, 2003), which is related to its field capacity.

6.1.3.5 Field/ container capacity

A soil is at field capacity when most of the drainage following irrigation or rain has stopped. The soil can hold this volume of water for some time provided that evaporation (from the soil surface) and transpiration (by the vegetation) are prevented. The smallest- and medium-sized pores, as well as capillary pores, retain water against the pull of gravity, and the particles forming large pores retain a film of water. Good soil structure gives soils more pores of the size that hold water against the pull of gravity, and texture is a useful guide to the ability of natural soils to hold water. The term ‘container capacity’ describes the similar circumstance of a soil or substrate that occur not over a subsoil but rather large pockets of air, like EGRs or golf greens. Beneath a multi-layered EGR system with a synthetic drainage layer (i.e., not a granular one), there is only one large pore – the whole of the atmosphere – and its surfaces do not exert any pull on the water retained in the substrate. Recalling that water is attracted to solid surfaces, and that small pores hold water more firmly than larger pores, soil structure and texture play a big role on how much water the substrate will hold. Container capacity can be illustrated by the example of placing a saturated sponge over a screen or a layer of gravel or sand. Unless it is sitting on an absorbent surface, a layer of saturation will remain at the bottom of the sponge because water can only drain under gravity or if there is a slight “head”, or weight, in the water above.

Container capacity is always greater than field capacity for the same soil, because the latter defines the water content at a suction pressure of 33.3 kPa. It’s interesting to note that the height of the saturation layer will be the same no matter what the height of the container, which means that a substrate in a shallow container will have a higher average water content (and a lower air-filled porosity) than the same substrate in a taller container (*ibid*). Factors that determine the field, or container, capacity of EGRs at any point in time include substrate depth, substrate physical properties and organic matter content, antecedent dry weather period and the weather conditions associated with this, rainfall intensity and duration, season, roof slope and orientation, roof area, number and type of system layers, and the types of plants used (VanWoert et al., 2005, Villarreal and Bengtsson, 2005, Stovin et al., 2012, Yio et al., 2013). In general, once the substrates’ retention (i.e., field or container capacity) is filled past about half of the maximum water holding capacity (MWC), the temporarily detained water will begin to run off (DeNardo et al., 2005).

6.1.3.6 Perched water table

A complication with shallow, contained media is the occurrence of perched water tables, which occurs when the air spaces at the bottom of the substrate are filled with water. This level of saturation destroys soil tubes, which prevents capillary action from pulling water from the soil to drain it (Boodley, 1998), and roots receive too few air voids (Bunt, 1988). In natural soils, a perched water table is an aquifer, or zone of saturation, located on top of an impermeable layer (e.g., clay pan), but below the soil surface. Ideally, perched water tables are small and short-lived, and any decent growing medium should balance water holding capacity with aerated pore space (Beattie and Berghage, 2004).

This phenomenon is often used in horticulture (with regards to container capacity) but also in the design of high-quality athletics turf, in particular cricket pitches and golfing greens. In fact, the United States Golf Association (USGA) has developed the very popular “perched or suspended water table method of construction” (Handreck and Black, 2010: p. 219), which is not unlike a green roof. In brief, below the rapidly-draining root zone (i.e., ≥ 90% sand content) lies a layering system of coarse sand/ fine gravel followed by a gravel drainage layer that incorporates a piped drainage system, and a shaped subgrade at base. Together, this system provides a firm surface ensuring continued high quality turf under intense use and aids drainage, thereby preventing soggy mud and maintaining good plant growth (Handreck and Black, 2010). In this context, the perched water table allows longer times between irrigations and gives turf a larger reserve of water to draw in hot weather (*ibid*: p. 224). With regards to EGRs, perched water tables can be considered in conjunction with the incidence of container capacity, specifically that the saturated depth (i.e., water vs. air content) will keep the same vertical height regardless of the depth of the system.

In multi-layered EGRs that use drainage boards filled with aggregate, this layer may behave as an 'anti-drainage' layer because it prevents percolation of water from the finer material above (Vesuviano, 2013). Water can only drain into the drainage layer from a soil with small pores after the soil has become completely saturated (Handreck and Black, 2010). The drainage layer therefore creates a sort of perched water table. The problem with perched water tables is they can induce anaerobic conditions within the root zone (Hillel, 1998). Maintaining such a layer of water on a green roof has been attributed to reducing heat flux and internal room temperatures into buildings (Niachou et al., 2001), and green roof systems that incorporate water retention into the drainage layer may increase the amount of water available for evapotranspiration (Hunter-Block et al., 2012). That being said, Vesuviano (2013) found that drainage layers without granular infill effectively separate the substrate from any stored water, such that the resulting air gap prevents capillary action so, unless this water transfers to the substrate by evaporation, it is not available to plants.

6.1.4 Research aims and questions

Soil is the foundation that determines the vegetation of terrestrial ecosystems, and this chapter evaluates the substrate properties and characteristics of the EGRs surveyed. As with mature green roof vegetation, little research has examined the substrates of old (versus newly installed) green roof substrates. Fortunately, a few German studies offer precedence. By characterising EGR substrates over the long-term, this research may help to elucidate the actual contribution that commercial EGRs can offer to urban ecology over the long-term.

- **Aim:** To characterise the substrate old EGRs (>20 years after installation).

- **Question:** do EGR substrates retain their recommended properties, as per FLL, over time?

- **Question:** if successional changes can be observed on EGRs, what are the main drivers and mechanisms?

6.1.4.1 Objectives of the chapter

In addition to its aim of characterising the physical and chemical parameters of the EGR substrate sampled, this chapter is interested in the possibility of soil ecological processes on these systems. Does soil formation, or pedogenesis, occur on EGR systems over time, or are the substrates too artificial and engineered, the conditions too harsh, and the soil biota too impoverished for processes like humus and crumb formation to occur? This chapter also complements the results of previous chapters for characterising EGR vegetation and determining the mechanisms driving natural succession and vegetation dynamics. Specific to this chapter, what happens to EGR substrate over the long-term, and how does this impact the growing conditions for plants? How do the physical and chemical properties of EGR substrates relate to the ecological dynamics deduced in previous chapters?

6.2 Methods

The pitched roof at Killesberg could not be sampled for soil, so eight of the nine roofs were sampled for substrate physical and chemical properties using a (10 cm) soil corer (Firma Schwab, Waidhofen). The samples were collected at the same time as the harvest of above-ground biomass in autumn 2010 and 2011. After all surface vegetation was removed, one or two soil cores were taken from the same quadrat area; any remaining plant biomass was removed thereafter. In the process of coring, care was given to avoid damaging the deeper layers of system, such as filter sheets or drainage boards. If ant nests were disturbed, the cores were carefully fit back into place and alternate cores taken. Before being bagged, core profiles were photographed beside a ruler for scale reference. Loose substrate was removed from the cored gap with a small shovel. Empty cores were re-filled with a commercially available green roof substrate, “Steinrosenflur.”

6.2.1 Data and analysis

A minimum of fifteen litres (15 L) substrate is required for physical and chemical analysis for a single roof (FLL, 2008). Cored samples were therefore united into a single sample for each roof, and these data are given as mean values per roof. Samples were analysed in adherence with the FLL standards by the University of Hohenheim LA-Chemistry laboratories. The FLL gives standardized testing procedures for evaluating the properties of EGR substrates, like the Proctor hammer compaction test as per DIN 18127 or ASTM D698 which replicates compression over time. To determine maximum water capacity, substrate samples were fitted into 150 mm cylindrical test samples, compacted, saturated and then left to drip freely for 2 hours (i.e., until container capacity). Air volume (% vol.) is the difference between total pore volume and water content at maximum water capacity. The amount of organic content (g/ L) in a green roof substrate is determined by ash content and loss due to burning, which is achieved by incinerating test samples at 550°C in a muffle oven until the weight readings have stabilized and no more loss is detected. The standard DIN 19684 method was used to measure soil pH whereby a 0.01 molar solution of $CaCl_2$ was added to the sample and measured using a pH-meter after three hours.

6.2.1.1 Biological component: ant survey

A thorough soil fauna survey was not possible, but one of the roofs (Pliensaufriedhof) was sampled on a sunny warm day in June 2014 to identify the species there. Ants were often seen traveling along the roof parapet, and the rounded mounds were evident. This roof was selected because it is easily accessible at short notice and because the one-off sampling was expected to be successful (low parapets, visible mounds, known populations). Dr. Sophie Evison from the School of Biology at University of Leeds provided materials and support on methods. For the parapet, five “honey baits” were placed along an evident travel route from which ants could be picked off with pincers; five individuals were collected per trap in vials of 90% ethanol. For the mounds, one free standing mound and one bordering the parapet were lifted and five individuals collected per nest. The samples were sent for identification to Dr. Bernhard Seifert, of the Department of Entomology at the Senckenberg Museum for Natural History in Görlitz. Similar to EIVs for plants, identifying ant species can infer information about the habitat conditions experienced by soil organisms, certainly on this roof and possibly on others.

6.3 Results and Discussion

The substrate results presented here endeavour to explain and understand soil-based processes on EGRs. Specifically, the most basic question inquires whether EGR substrates' recommended properties (as specified by the FLL) change over time.

6.3.1 Physical characteristics: water holding capacity, soil organic content

Three physical soil parameters for EGRs are defined by reference values specified by the FLL (2008): maximum water capacity (MWC) (vol. %); air content (vol. % at MWC); and water permeability (mm/ min). Of the eight roofs sampled, only two diverged from two of these recommendations (see bold italicised values in **Table 6.1**).

Table 6.1. Physical soil parameters from EGRs sampled in Stuttgart region (2010, 2011).

	Apparent density, dry (g/cm^3)	**Total pore volume (vol. %)**	**Maximum water capacity (vol. %)**	**Air content at MWK (vol. %)**	**Apparent density at MWK (g/cm^3)**	**Water permeability (mm/ min)**
Rathaus lower	1.18	54.00	38.00	16.00	1.57	N/A
Rathaus PV	1.17	55.00	32.00	23.00	1.49	N/A
FH Nürt.	0.88	66.00	53.00	13.00	1.41	0.70
Köngen	0.78	68.00	62.00	6.00	1.39	2.70
Tüb.	1.18	54.00	44.00	10.00	1.62	11.00
VB A1	0.54	79.00	44.00	35.00	0.98	N/A
VB A2	0.48	82.00	32.00	50.00	0.80	N/A
Pliensau	0.64	72.00	71.00	1.00	1.35	0.10
FLL guide:	none	none	≥ 35 ≤ 65	≥ 10	none	0.6-70

6.3.1.1 Maximum water holding capacity (MWC)

The FLL specifies that the substrates of multi-layered EGRs (in their compacted or installed state) should have ≥35% vol. maximum water capacity and, because of issues from water logging, no green roof system of any type should ever exceed 65% vol. maximum (FLL, 2008: 62). Other than the oldest roof, Pliensaufriedhof, which exceeded the recommended limit (71%), all the roofs sampled fell within or only slightly outside the prescribed range for MWC. The Römermuseum at Köngen was close to the limit (62%), and two roofs (VB A2, Rathaus PV) were slightly below the recommended minimum (both at 32%). Even though stormwater mitigation performance by these roofs is not known, these results imply that they probably perform fine for runoff detention and retention.

It's interesting that the roofs that were classified as "Species-poor Sedum roof" vegetation types had the highest MWC of all the roofs sampled, rather than the more floristically diverse roofs, as one might expect species requiring more moisture to exploit such opportunities and out-compete Sedums, which are susceptible to root rot in wet conditions. The cover by Sedum on these roofs was dense and vigorous, however, without any apparent competition by other growth forms nor symptoms of physiological stress by water-logging. The latter could be attributed to the drainage layers at both sites, and to the slope at Köngen. Considering how flat Pliensaufriedhof is, and the observations of earthworms and ants there, it is also possible that the engineering activities by these organisms regulates the water and air content in that roofs substrate (Wardle and Lavelle, 1997). This shall be considered in more detail later.

6.3.1.2 Air content at MWC (vol. %)

The air content at MWC is recommended by the FLL (2008) to be equal to or greater than 10% by volume, which was matched by all roofs except Köngen (6%) and Pliensaufriedhof (1%). This metric implies an unequal balance between air and water on those roofs, such that the roots do not receive sufficient air (recalls compacted soil, **Figure 6.1f**). This is not likely too grave a matter in Köngen since that roof is pitched, but Pliensaufriedhof at maximum water capacity must be at risk of saturation (recall **Figure 6.1b**). As mentioned, however, the Sedum vegetation there did not show any signs of stress in this regard, neither to waterlogging nor to competition by other growth forms. EGRs in Berlin were noted to have lower porosity in the early years after installation, but this increased significantly after about ten years, to the same total pore-volume as 100-year old TPG roofs (Köhler and Poll, 2010). Biological and physical processes may be responsible for these developments, as plant roots and soil biota create pore spaces through their activities while water flux and drought events also contribute to physical changes.

6.3.1.3 Soil organic content (C_{org})

The correlation analyses in Chapter 2 found that older roofs had more soil organic content (C_{org}) than younger roofs (*rho*=-.338, *p*<.000, *n*=118). Of the eight roofs sampled, half fell within and half were above the recommended limit for extensive greenings (≦65 g/L) (**Table 6.2)**. The paired roofs in Stuttgart and Esslingen, aged 21 and 25 years (respectively), fell within the FLL recommendation while the other roofs were in excess (**Figure 6.4**). Considering the variability of the measurements, even on the paired sets of nearly identical roofs in Stuttgart and Esslingen (i.e., same age, construction and location), roof age is not likely the sole factor influencing soil organic content. Of the Verkehrsbetrieb (VB) roofs in Esslingen, VB Area 2 had the lowest C_{org} record of all roofs surveyed (25 g/ L), followed by Rathausgarage PV (49 g/ L). The neighbouring counterparts of these two roofs – VB Area 1 and Rathausgarage lower – had C_{org} values at the upper limit of the FLL recommendation (60 and 61 g/L, respectively). When sampled, the substrate cores did not hold together the way that a topsoil would and seemed to comprise predominantly loose mineral aggregate.

Table 6.2. Soil organic content (C_{org}) for eight EGRs of various ages.

Roof name (in order of age)	**Roof age**	**C-org (g/L)**
Rathaus, lower	21	61.0
Rathaus, PV	21	49.0
FH Nürtingen	23	72.0
Köngen	23	126.0
Gärtnereihof Tübingen	24	79.0
Verkehrsbetrieb Area 1	25	60.0
Verkehrsbetrieb Area 2	25	25.0
Pliensaufriedhof	33	186.0

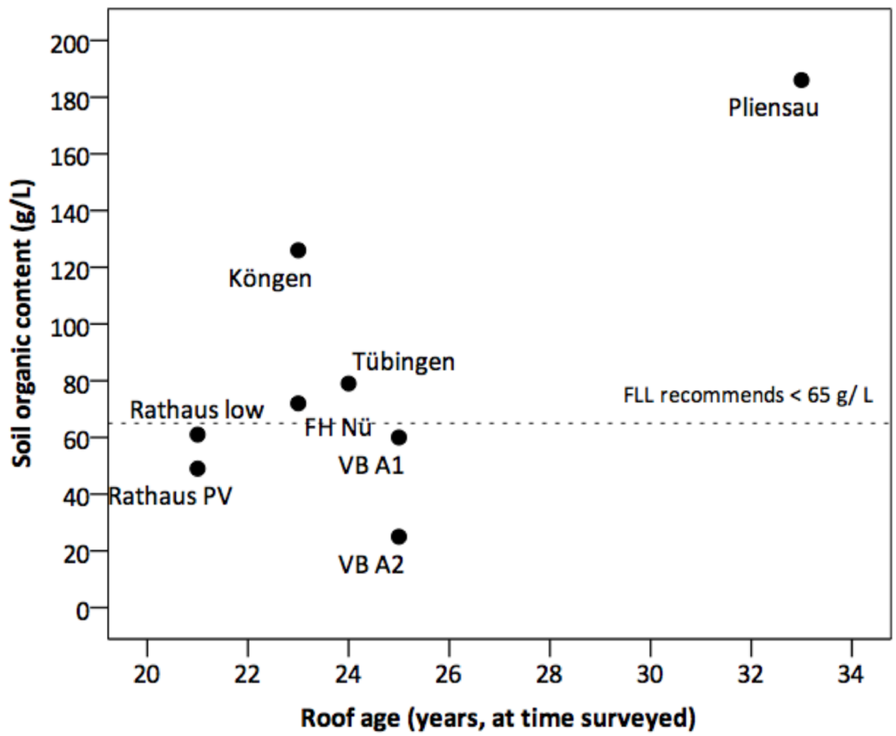


Figure 6.4. Mean soil organic content (C_{org}) for eight EGRs of various ages.

The EGR in Köngen had a high value for C_{org} (126 g/ L); this was likely owing to the 5 quadrats sampled from the north-facing roof which was shaded (two stories below) a neighbouring row of trees and had more herbaceous vegetation than the *Sedum*-dominated south-face. Since the soil samples from the north and south roofs had to be united into a single sample, it was not possible to separate the difference in C_{org} values for this building. The pitched roof in Tübingen also had excessive C_{org} (79 g/ L); the conditions leading to this might be similar to those in Köngen as the North-facing aspect in Tübingen also featured slightly less xeric vegetation and had an adjacent tree canopy. However, unlike the shading received at Köngen, the tree canopy in Tübingen is at roof-level so its influence (e.g., leaf litter, microclimatic effects) is limited to the edges of the roof immediately adjacent (which the quadrats did not sample). The floristically diverse Sedum meadow at FH Nürtingen also had C_{org} in excess of the FLL recommendation (72 g/ L). Notably, this roof had a number of thriving ant communities, whose mounded hills provided opportunities for deeper rooting grasses and forbs (though these were not sampled).

Of the four roofs exceeding the FLL guideline on soil organic content, the 189 g/ L at Pliensaufriedhof sets this roof well apart from the others, most likely reflecting the fact that it was installed as a simple intensive roof in the late 1970s. As a rule, this type of roof construction is the second of three green roof types, midway between “cheap” extensive green roofs and “complex” intensive systems (Krupka, 1992) (p. 142). Nevertheless, even multi-layered intensive green roofs are recommended to have ≤ 90 g/ L organic content (FLL, 2008: p. 61), which this roof exceeds two-fold. The substrate on this roof was a moist, dark humus with far fewer mineral components so apparent on the other roofs sampled. Given that it was installed prior to the publication of first edition of the FLL guidelines and that it is based by a system that is still used today, it is possible that the original blend aligned with the nascent FLL recommendations, even if engineered substrates were not yet available (Appl, 2014). It was interesting to note that several soil cores revealed large earthworms, as well as thriving ant communities.

6.3.1.3.1 <u>Physical characteristics: discussion</u>

Particle size wasn’t recorded here, but a number of early studies have noted changes to particle size distribution and pore size in EGR substrates over time, though these were conducted in order to verify the impact of installation by hydraulic blower trucks (Roth-Kleyer, 2006a, Roth-Kleyer, 2006b, Roth-Kleyer, 2002). From his survey of relatively young EGRs Buttschardt (2001) observed that particle size distribution had shifted beyond the FLL recommendations within four years. By 2002, 70% of EGR installations in Germany used blower trucks (Roth-Kleyer, 2002); hence the FLL (2008) recommends prescribing granulometric distributions with greater proportions of large particles.

Most of the ecological research of spontaneous roof vegetation has also examined the sandy-gravel growing substrate, in some cases with the simple intention of classifying (Buttschardt, 2001) or characterising it (Bornkamm, 1961, Darius and Drepper, 1983), though some have aimed to determine the occurrence of pedogenesis (Bossler and Suszka, 1988, Köhler and Poll, 2010, Schrader and Boening, 2006, Thommen, 1988). Unfortunately, as a result of the analytic method (i.e., loss on ignition at 550°C), it is impossible to know the constitution of the soil organic matter identified in these studies. To explain the high values for C/N ratio measured in Berlin, Köhler & Poll (2010) reported “a measuring fault of the C-N-Analyser which cannot differentiate between organic carbon (humus) and black carbon (likely originating in the chimney emissions)” (p. 727). In other words, because soil organic content is determined by ash content after incinerating the sample, organic content is a deceptive term that may indiscriminately include black carbon from chimney soot, biologically active humus, or undecomposed litter all under the same heading. Some of the studies referred to here use the term humus, but do not specify what this means. For the purpose of clarity, then, terminology used by the authors will be used and, beyond translation, no further interpretations will be made.

The accumulation of soil organic carbon seems to occur around 20 years after installation for all types of vegetated roof, although the lower substrate profiles of gravel roofs remain loose and skeletal, regardless of age (Bornkamm, 1961, Thommen, 1988, Köhler & Poll 2010). A survey of >thirty TPGs of various ages in Göttingen identified distinctive horizons resulting in the substrates of younger versus older roofs (Bornkamm, 1961). Soil organic content on younger roofs (i.e., renovated 1-8 years earlier) was typically higher in the lower layers of the substrate compared to the upper layers, though a couple young roofs presented exceptions (i.e., higher C_{org} in upper, rather than lower, layers). That study concluded that the first decade after TPG installation leads to varied humus development, but that it occurs mainly in upper horizons after ten years. Soil formation on those roofs was associated not with roof age, however, but more explicitly with its ongoing history, its vegetation, and the moisture regimes present. In Switzerland, a chronosequence of gravel roofs suggested an accumulation of humus over twenty years, to an average of 3% by fifty years (Thommen, 1988). That author noted that local microclimatic effects, like shading, had a significant impact on humus development and C_{org} accumulation (*ibid,* p. 35).

In Berlin, nutrient levels and organic content of twenty-four TPG roofs that had been undisturbed for at least 60 years, and ranging in depth from 20 to 240 mm, were likened to that of urban fallow land, although this was mainly to explain the ruderal character of the vegetation (Darius and Drepper, 1983: 68). These TPG roofs would not have included any nutrients at their point of installation, and the original substrate did not include organic content (just 50 mm sand, 100 mm gravel), yet a mean record of 6.3 kg/ m^2 organic content was assessed in 1982 (*ibid*). Twenty years later, soil organic content on those same roofs had not changed much, nor did the C/N-ratios (Köhler and Poll, 2010). The latter (which considered the results of green roof surveys starting in the 1980s) found that C_{org} (% vol.) on EGRs increased significantly between 1980 to 2008, from 2.5% to 4%, while TPG roofs remained just above 4% in that same timeframe (Köhler and Poll, 2010). On EGRs, soil organic content sank from 2.5% to 1.9% in the early years after being installed (possibly due to rapid decomposition, as observed by a study in Sweden) (Emilsson and Rolf, 2005), but had increased to significantly greater volume (3%) after twenty-five years (Köhler and Poll, 2010). The unique conditions and factors of each of the roofs in that survey may explain deviations in C_{org}, since grassy meadow assemblages (*Poa compressae anceptis*) produce more biomass than stress-tolerant vegetation of the *Sedo Scleranthetea* (Köhler & Poll, 2010). So, while C_{org} fluctuated more on the EGRs than the older TPGs, the roofs eventually all attained similar values.

In Karlsruhe, Buttschardt (2001) found that the EGRs sampled had "high to very high humus contents… to the magnitude of topsoil or humus-rich A horizons… [and] most of them exceeded the FLL guidelines" (p. 63). The substrate with the highest value in that study (51.6%) occurred on a 6 year-old, single-layered roof ($_{sy}$JTO) and was composed of red ash (*Rotasche*), a slag product with high proportion of carbon black (*Russ*). Interestingly, the spontaneous TPG roofs sampled had equally high values which did not differ significantly from the modern EGR roofs, although younger roofs had significantly less humus content. In a study of twelve roofs sampled after 12 or 16 years in northern Germany, increased soil organic content was correlated with declining pH and shallow, mineral substrates (Liesecke, 2006). Of the various roof constructions surveyed, the highest C_{org} concentrations were observed on the four single-layer EGRs featuring expanded shale, and the shallowest of those (50, 80 mm) had the highest C_{org} of all twelve roofs. In addition, after more than ten years, those single-layered EGRs retained considerably more water than the multi-layered systems (Liesecke, 2006). Similarly, a study in Michigan (USA) of variously pitched EGR platforms (all 60 mm depth) found that organic matter content nearly doubled after five years, as did water holding capacity (Getter et al., 2007). That study also noted greater values for porosity and more free space (macropores). The accumulation of organic matter, in the form of litter, on shallow mineral substrates (especially single-layer systems) may suggest that those conditions inhibit decomposition processes.

A study of five (90-year old) TPGs and three (20-year old) gravel roofs in Osnabrück found that organic content varied considerably between all roofs, regardless of roof type (Bossler and Suszka, 1988). The TPG roofs in that study were based by 80-150 mm sand with high skeletal proportions, in which the sand was darkly coloured by humic acid and the skeletal component consisted of sandstone, pieces of brick fragments, mortar chunks and marginal proportions of bitumen, and the gravel roofs (from the late 1960s) had 25-90 mm of predominantly medium-grade construction gravel. Both roof substrates showed pronounced soil structure, had high total pore volume (mean 53%) and poor water holding capacity (13.6 L soil water/ m^2 in 15 cm), and humus content ranged between 0.4 and 21.6%. After 90 years, the TPGs had developed distinct profiles through humus accumulation and the shifting of carbonates, leading the authors to define the vertical gradation as horizons (Y-Ah to YC, ending at the waterproofing) and defining TPG soils as sandy “para-rendzinas” (p. 221). By contrast, they classified the younger gravel roofs as “loose immature soil” according with the minimal accumulation of fine-earth component. Echoing the Berlin study of undisturbed TPG roofs (Darius and Drepper, 1983), these authors concluded that time and initial parent materials determined the different soil types that developed on the different roofs, and that the key factors to soil development over twenty years were precipitation and dust deposition, as well as the vegetation itself. Both of these studied agreed that these systems had established a steady state of litter production, humus formation and mineralization, although these processes were very slow because of the limited flora of the shallow depths (pioneering mosses and lichens).

As mentioned, the type and quality of organic material cannot be evaluated without a suitable testing mechanism, which inhibits the use of these analyses for ecological research on green roofs. Although Köhler & Poll (2010) suggest that the accumulation of soil organic content after twenty years on EGRs in Berlin indicates pedogenesis, or soil formation, Liesecke (2006) described the organic content from his samples as incompletely decomposed material, or litter. If the organic content that accumulates on EGRs over time is litter rather than humus, then there are several consequences of such developments.

Firstly, feedbacks associated with accumulated litter can influence plant establishment, growth and community composition via a range of interacting mechanisms (e.g., changes to light regimes and microclimate, nutrient immobilization) (Facelli and Pickett, 1991). Other repercussions for EGRs include enhanced water retention and associated increases in roof loading. Twelve years after installation, the shallow shale-based roofs in Hannover retained between 38.8 and 57 L/m^2 more water and were 42 to 76 kg/ m^2 heavier, with the shallowest depths nearly twice as heavy (Liesecke, 2006). This can obviously be problematic if the roof was not designed with sufficient structural capacity. No studies have addressed the changes in hydraulic performance of established green roofs (Li and Babcock, 2014), although some research has begun (Stovin et al., 2013).

6.3.2 Chemical characteristics: soil pH and nutrients

Soil reaction, or pH, determines the availability of nutrient elements to plants growing in mineral soils (Handreck and Black, 2010). The pH range recommended by the FLL (6.5-8.0) covers the greatest nutrient availability for macronutrients (N,P,K) and good availabilities of micronutrients (S, Ca, Mg, Fe, Mn) and trace elements (B, Cu, Zn, Mo). With reference to soil pH classifications by USDA (1998), the substrates surveyed ranged from “strongly acid” (5.2, Köngen) to “moderately acid” (Tübingen, the two Verkehrsbetrieb roofs and FH Nürtingen) to slightly acid (Pliensaufriedhof). Only the two youngest roofs (Stuttgart Rathausgarage roofs, both 7.2) fell within the recommended “neutral” range. Most roofs fell within the recommended range for nutrient concentrations, but Pliensaufriedhof had too much nitrogen (93 mg/ L, versus recommended limit of 80 mg/ L) and phosphorus levels in Tübingen were at the precise limit of the recommendations (50 mg/ L) (**Table 6.3**). The range of pH measured (pH 5.2 to 7.2) (**Figure 6.5**) indicates that nutrient availability for the essential macro- and micronutrients to the vegetation of the EGRs surveyed is potentially quite constrained (especially P, K, S, Ca, Mg) while trace elements become more available (and potentially toxic) (e.g., Fe, Mn, B, Cu, Zn).

Table 6.3. Chemical soil parameters for eight EGRs (in order of age) (bolded values fall beyond the FLL recommendation)

Roof name (in order of age)	**soil pH ($CaCl_2$)**	**N (mg/ L)**	**P_2O_5 (mg/ L)**	**K_2O (mg/ L)**	**Mg (mg/ L)**
Rathausgarage, low	7.2	53	11	71	120
Rathausgarage, PV	7.2	52	6	68	120
FH Nürtingen	6	62	< 5	130	N/A
Köngen	5.2	20	32	27	130
Gärtnereihof Tübingen	5.6	17	50	97	110
Esslingen VB Area 1	5.9	19	< 5	58	140
Esslingen VB Area 2	5.8	30	< 5	37	44
Pliensaufriedhof	6.3	93	7	88	150
FLL recommendation:	6.5-8.0	≤ 80	≤ 50	≤ 500	≤ 200

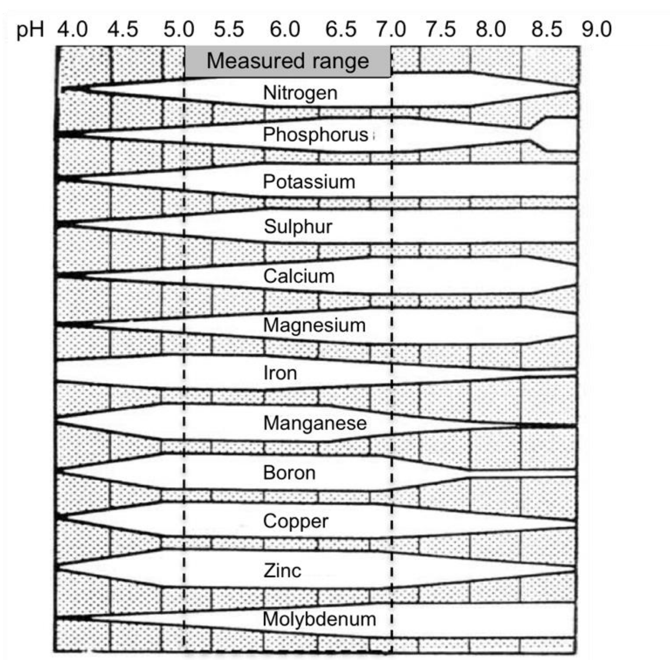


Figure 6.5. The availability of nutrient elements to plants in mineral soils varies with soil pH; the measured range for the EGRs surveyed is shown by the dashed lines (pH 5.2 to 7.2). Modified from Handreck and Black (2010).

The EGR at Gärtnereihof Tübingen was accompanied by documentation of a soil survey conducted six years after its installation, or seventeen years before it was surveyed for this research. The soil analyses by Sailer-Schmid (1993) report that soil pH on the Tübingen roof was at the lowest limit of the recommended range (6.5), while phosphorus and potassium concentrations were extremely high and magnesium concentrations were too low (**Table 6.4**)**.** This probably reflects that the roof had been over-fertilized; indeed, the Head Gardener's maintenance record reports annual fertilisation for the first seven years' after installation (Braun, 1992). Maintenance of this roof by the Department (including irrigation, weeding and filling in any gaps in the substrate or vegetation) apparently consumed 150-200 hours each year from 1988 until 1992, but in 1993 this was reduced to 60 hours and by 2000 hardly any maintenance took place. By 2005, roof maintenance had ceased altogether (Starke, 2010). This knowledge advises caution for sites that lack background information, as human involvement on easily accessible green roofs must be considered alongside ecological data.

Table 6.4. Nutrient analyses for Gärtnereihof Tübingen six years after installation show excessive levels of P, K and Mg.

Tübingen substrate	**1993**	**2010**	**Difference (16 years)**	**FLL reference**
pH	6.5	5.6	0.90	6.5-8.0
Phosphorus (P_2O_5)	41.70	50.00	-8.30	5-15 mg/ 100g
Potash (K_20)	38.00	97.00	-59.00	10-20 mg/ 100g
Magnesium (Mg)	26.00	110.00	-84.00	6-12 mg/ 100g

In Karlsruhe, Buttschardt (2001) found that plant available nutrients like phosphorus were in excessive concentrations on most of the EGRs sampled (**Table 6.5:** bold and italicised). The only roof that did not have excessive phosphorus levels (B7: Haid and Neustr.) was deficient, but the cause of this was attributed to the substrate manufacturer (Buttschardt, 2001: p. 67). Nitrogen was only measured for a few of the spontaneous TPG roofs in this study, of which the high concentrations recorded were associated with pigeons. Otherwise, perceptible levels of phosphorus and potassium only occurred on TPG roofs with deeper substrates and higher volumes of humus.

Table 6.5. Six of seven EGRs surveyed in Karlsruhe by Buttschardt (2001) had excessive phosphorus.

Roof #	Buttschardt EGRs in Karlsruhe (in order of age)	Roof age	P_2O_5 (mg/ L)	K_2O (mg/ L)	Mg (mg/ L)
B1	Forschungszentrum Umwelt	2	***80***	100	40
B2	Pavillon Waldorfschule	3	***230***	90	110
B3	Sparkasse Sophienstr.	4	***150***	120	30
B4	Jugendtreff Oststadt	5	***320***	50	150
B5	Klinikum OP	7	***390***	90	10
B6	Turnhalle RB	7	***70***	160	30
B7	Haid & Neustr.	7	10	190	70
B8	Garagen Rudolfstr. 6	7	N/A	N/A	N/A
		FLL recommendations:	≤ 50	≤ 500	≤ 200

6.3.2.1.1 Chemical characteristics: discussion

Other studies attribute differences in soil pH on EGRs to their variable carbonate amounts (Poll, 2008) and/ or to the varying carbonate levels in the recycled materials used by different substrate manufacturers (Buttschardt, 2001, Bossler and Suszka, 1988). A study in in Göttingen noted vertical gradation of pH, such that young roofs (renovated 1-8 years earlier) had equal pH values in upper and lower layers of the substrate, while older roofs (>10 years) had higher pH in the lower layers of the substrate (Bornkamm, 1961). Some studies reported relatively high concentrations of heavy metals in the substrates of various green roof types, including cadmium, lead and zinc (Bossler and Suszka, 1988, Poll, 2008).

Green roofs in Berlin – both EGR and TPG – were treated with lime in the 1980s in order to offset acid rain; by 2008 EGRs had declined from slightly alkaline (pH 7.4) to neutral (pH 7.1) while TPGs increased from slightly acidic (pH 6.4) to nearly neutral (pH 7.0) (Köhler and Poll, 2010). The TPG with the lowest pH from the 1983 surveys (pH 5.2) occurred on the only roof on which no mortar chunks were found in the substrate (Darius and Drepper, 1983), suggesting that the substrate of these Berlin roofs would have been far more acidic were it not for carbonate amendments (Poll, 2008). Both EGRs and TPGs had heterogeneous distributions of carbonate components and did not indicate any short- or long-term acidification (Poll, 2008). In Karlsruhe, old TPG roofs had a greater pH range (3.9 to 7.1) than modern EGRs (5.8 to 7.6) (Buttschardt, 2001). The TPG roofs were between 40 and 110 years old at the time surveyed (of which over half were >100 years old), so the large amplitude in soil pH would have occurred over a long and continuous period; indeed, Buttschardt (2001) reported a strong relationship between pH and roof age. The older TPGs surveyed had lower carbonate ($CaCO_3$) content than younger TPG roofs because they were based by dune sand and/ or sand that was decalcified at the time of extraction, while younger TPGs used sediment from the Rhine, which is derived from deeper layers that were never decalcified (Buttschardt, 2001, p. 62-63).

On the TPG roofs in Osnabrück, Bossler and Suszka (1988) also assessed neutral to slightly acidic pH, with a minimum record of pH 4.6 and maximum pH 7.5. These authors identified that carbonate ($CaCO_3$) from the mortar on TPG roofs influenced soil pH. One TPG roof (Nobbenburger Str.) had a full unit less pH than all others, which these authors attribute to the exhaustion of reactive carbonate reserves on that roof. The authors also proposed that aerial ash deposits from coal chimneys played a role to the acidification of the roofs sampled. At the time of that survey, acid rain and "Waldsterben" were familiar news: the annual value in 1982 for rain in Germany was pH 4.3, and Osnabrück itself recorded pH 4.6, whereas "normal" rain has a pH of 5.6 (Bossler and Suszka, 1988). These authors concluded that the volume, distribution and pH of rainfall influenced soil reaction, the rate of nutrient leaching, and plant-water relations, and thereby soil formation on the roofs. In Hannover, a comparison of EGR substrates on young (3-4 years after installation) versus older (8-12 years) roofs, all ca. 80 mm deep, revealed significant differences between the age classes owing to lower pH and higher organic content by the older roofs (Schrader and Boening, 2006). These authors suggest that the trajectories of acidification and the accumulation of C_{org} and nitrogen may themselves represent ongoing soil-formation processes on these systems, such that EGR substrates will develop towards states similar to those of natural soils, regardless of how artificial they may have initially been.

At FH Weihenstephan, a seven-year study of 23 mineral substrates (without organic content) were installed as single-layer systems at 80mm depth in 1.21 m^2 roof-top plots (with three replications). After seven years, pH had declined significantly from initial values and only four substrates still matched the FLL specifications (6.5-8.5) (Jauch and Fischer, 2000b). The same study found that crushed brick substrates were more stable than those based by lava or expanded clay and shale. Although the macronutrients on the roofs sampled fell within the recommended range, low pH can inhibit their availability to some plant species. This may partly explain the dominance by Sedum species on EGRs since they are stress tolerators [*sensu* Grime (1977)] which have the lowest nutrient requirements of any plant growth form (Grime, 2001). Indeed, a container study found that five species of *Sedum* produced the most dry weight in moderately to slightly acidic conditions, from pH 5.7 to 6.4 (Zheng and Clark, 2013). That study found that some species were exceptionally productive, in fact, for example *Sedum spurium* had 95 times more dry weight at pH 6.3 compared to pH 8.3 (*ibid*).

These observations recall concerns in Germany in the mid- to late 1990s regarding the accumulation of limescale (sintering) inside roof drains by the residue of poor-quality carbonate materials (Roth-Kleyer, 1996, Kolb, 1997). Those concerns were eventually calmed by results from FH Weihenstephan and FH Geisenheim which showed that sintering of roof drains could not be traced back to the EGR substrate, even when extremely high carbonate amounts were included (Jauch and Fischer, 2000a, Roth-Kleyer, 2002). As a result, even though some soil-based parameters were updated in the 1995 FLL guidelines (e.g., C/N ratio, absorption capacity), fixed targets or specifications for carbonate did not follow (Roth-Kleyer, 2002).

Many factors can lead to soil acidification, including cation leaching, acid deposition, and the accumulation of organic acids in soil organic matter during succession (Chapin et al., 2002). Changes in pH on green roofs (both TPG and EGR) are apparently influenced by substrate composition, but likely also to atmospheric deposition and other urban environmental conditions. While substrate composition on TPG roofs is very different from EGRs, it appears that climate and precipitation influence all green roof systems equally. The precedent works cited make it clear that acid buffering on green roofs over time is determined by the substrates material composition. The main reasons for concern regarding the acidification of EGR substrates over time relates to the effect of pH on plant nutrient uptake and any implications of nutrient leaching through runoff (Emilsson et al., 2007, Villarreal and Bengtsson, 2005, Teemusk and Mander, 2011), but it will also influence the vegetation and the ecological processes that can occur there. In parallel, declining pH and locked up nutrients may permit Sedum vegetation the conditions for competitive exclusion, creating feedback dynamics that maintain the vegetation as such. While it is straightforward to accept that vegetation is influenced by a soil's characteristics, it may be instructive to consider the opposite as well, namely the effects that the vegetation has upon the soil.

6.3.3 Biological component: ants and earthworms

Although green roof substrates are engineered and contrived compared to natural field soils, to some extent the biological principles of soil ecology must apply. Biological characterisation was not the remit of this research, but incidental encounters of ant nests and earthworms during soil sampling insinuated that biological activity was occurring on some of the roofs surveyed (**Figure 6.6**). Most soil development occurs in the presence of live organisms (Ugolini and Spaltenstein, 1992), so consideration of these observations was treated as significant to the aim of characterising EGR substrate development.

Figure 6.6. A few soil cores disturbed ant colonies, which appeared to be thriving given the visible abundance of eggs (this core is from Tübingen, T3Q4).

Mounded anthills were observed on Pliensaufriedhof and FH Nürtingen, and it is known that most green roofs support ant colonies (Mann, 1999a, Kadas, 2006, MacIvor and Lundholm, 2011, Madre et al., 2013). Ants influence plant communities by creating patchiness and potentially increasing plant species richness through activities such as central-place foraging, discarding of food remains around nests, soil-dumping and mound-building (Dean et al., 1997). The roof at Pliensaufriedhof visibly supported numerous thriving ant populations, in particular the conspicuous above-ground nests of *Lasius flavius*, whose tall mounds (↕ ca. 30 cm, ø ca. 80 cm) house both colony and root aphid farms (Ivens et al., 2012). The populations on that roof may be attributed to the rigid polystyrene foam of the drainage layer (Floratherm® WD 180), which is a useful building material for ants to build their nests (Seifert, 2014). The relative dryness of these mounds can give plants that are poor competitors an advantage in habitats that would otherwise favour grasses, but the activities of nest-mounds also influence soil nutrient status and soil pH (Dean et al., 1997). So, beyond the effect of providing deeper depths and heterogeneity to EGR vegetation, the presence of ants on EGRs could have further-reaching effects on EGR substrate and soil-based dynamics.

Pliensaufriedhof also supported ants that build subterranean nests (*Lasius niger* and *Formica cunicularia*), species which have been identified by green roof studies in Nova Scotia (MacIvor and Lundholm, 2011) and northern France (Madre et al., 2013). The latter, which surveyed three types of EGRs, found that ants comprised the majority (103) of the 163 hymenopterans sampled. A London study of green roof invertebrate diversity conceded poor results for ants due to inadequate sampling methods (Kadas, 2006). Closer investigation into ant populations on EGRs could help gain a better understanding of green roof ecology.

Little is known about the role of earthworms on EGRs, but a few of the roofs surveyed revealed worms during substrate sampling (Pliensaufriedhof, Rathaus-PV, and VB Area 1) (**Figure 6.7**). They probably arrived in the organic materials of the roof components (substrate and plants) or through the activities of birds. Since EGR substrates are relatively shallow and predominantly mineral systems with warm and dry growing conditions, it was remarkable to encounter these organism, and to consider that they have survived in these systems (at least generationally, if not individually). On green roofs, earthworms are believed to be limited to intensive systems (Schrader and Boening, 2006), although a study of 125 green roofs in southern Germany found that some EGRs with depths of 50 mm supported earthworms (Mann, 1999a). Considering the chance of an earthworm occurring in a random soil core, EGRs may support more worms than is thought. Worms are important to soil formation, as they alter the structure and function of decomposer food webs in natural soils (i.e., populations of fungi, nematodes, and microarthropods like springtails) (Lorenz and Lal, 2009). Given the importance of earthworms to soil ecology, their presence on green roofs could have tremendous implications for soil structure, soil formation and nutrient recycling, and far-reaching effects on the vegetation and on green roof performance for ecosystem services.

Figure 6.7. A few soil cores uncovered earthworms, such as this core from Rathaus-PV (Q4).

6.4 Conclusions

6.4.1 EGR substrate properties over time: FLL recommendations?

The roofs sampled would have aligned with the FLL recommendations when they were installed, so how did they line up more than 20 years later? The physical parameters of MWC and air content at MWC fell within the recommended ranges for most roofs; only the two “Species-poor Sedum roofs” (Pliensaufriedhof and Köngen) had insufficient air content and excessive MWC, while two “Sedum meadow” roofs (VB Area 2, Rathausgarage-PV) were slightly below the minimum recommendation for MWC. If the roofs that diverged from the recommendations are taken as a minority, then this work can conclude that the physical characteristics of EGR substrates over time are stable. Without measurements for particle size distribution, however, this is only speculation.

Most of the EGRs surveyed were near or above the limit for soil organic content, and all but the two youngest EGRs were too acidic, suggesting that the chemical characteristics are not as stable as the physical properties. With one exception (nitrogen on Pliensaufriedhof), the nutrients measured were within the recommended concentrations, but low pH probably inhibits their availability to plants, which could partly explain the vigorous Sedum dominance on these roofs. Incidental observations of ants and earthworms suggest biological characteristics of the substrates, thereby implying that soil formation on EGRs is possible. Although most studies have reported horizons on most vegetated roofs, some with colouration and textures suggesting humus formation, the substrates sampled did not hold together as would a topsoil and seemed rather skeletal, with weakly developed profiles, if any at all.

The studies referred to bring to light the important anthropogenic influence affecting EGR substrates, even decades or years after installation: just as soil pH may be related to substrate manufacture, lime amendments or atmospheric deposition, nutrient concentrations can be attributed to fertilisation by tenants, atmospheric deposition or soil processes. Without the documentation from Tübingen's Head Gardener, one might have been tempted to deduce that the high nutrient concentrations on that roof were due to the same circumstances leading to the high concentrations on the Karlsruhe roofs. The reverse might be true, however, as the documentation from Tübingen could equally suggest that the Karlsruhe roofs were diligently maintained in the early years after installation. So, unless a roof is known to have been inaccessible and its maintenance regime faithfully documented, human influence must be considered a lurking variable to all of the results reported here.

The guidelines developed by the FLL were designed to create a standard for quality in central Europe. The results from this and other studies suggests that numerous substrate parameters change over time, in particular increasing C_{org} and decreasing soil pH. The effect of these parameters, and of their variation of change over time, together with the possibility of decreasing substrate depth, undoubtedly have implications for EGR vegetation, and probably also for performance metrics like stormwater retention and loading. If floristic diversity and persistent biotic communities were desirable for EGRs, as would be assumed if they are to deliver urban ecosystem services, then these results suggest that those parameters must be taken into consideration. Promoting the conditions for complete decomposition of organic material into humus, for example, will obviously benefit the vegetation but can also facilitate nutrient recycling and create positive feedback mechanisms that maintain greater floristic diversity. This can be achieved by ensuring the pH does not become too acidic, and by creating habitat provisions for litter transformers like ants and worms, such as providing mounds and other forms of refuge from heat or frost. Of course, long-term monitoring programs are required in order to better understand the full potential of EGRs as ecosystems and for urban ecology.

6.4.2 Soil ecological processes on EGRs

To a certain degree, pH levels will direct nutrient availability and plant growth but also decomposition and other processes. Acidic soils may result in incomplete decomposition, and lead to accumulation of litter. Likewise, if plants growing in slightly acidic soils can access sufficient nutrients for strong growth, and if their litter is acidic, then this combination of vigorous plant growth and incomplete decomposition can lead to even more litter accumulation and continued or sustained acidification. Organic matter decomposition, as well as nitrogen mineralization, are affected by periods of extreme drought and the process of drying and rewetting (Denef et al., 2001). When soils become dry they can become hydrophobic (Handreck and Black, 2010); dried TPG substrates in Berlin did not absorb heavy downpours of rain because the water ran off as surface flow instead (Darius and Drepper, 1983). This presents problems of erosion and substrate loss. Intermittent water shortages were attributed to the enrichment of humus-rich soil components over the long-term on EGRs in Karlsruhe (Buttschardt, 2001). At the other extreme, perched water tables and incomplete drainage will also influence soil processes and vegetation. The dramatic increase in litter accumulation observed on shallow (Getter et al., 2007) and/ or single-layered EGRs (compared with multiple-layered systems) (Liesecke, 2006) implies that substrate depth plays an important role to decomposition processes. Thus, it appears that soil ecological processes and pedogenesis may occur on green roofs, but only very slowly.

6.4.2.1 *Hypothesis: soil-plant feedback cycles perpetuate acidification, litter accumulation and other trends.*

Vegetation can exert important influences on soil organic content through its effects on the soil biotic community, on the activities of soil micro-organisms and, accordingly, on litter decomposition rates (Boettcher and Kalisz, 1991, Saetre, 1998, Wardle, 2002). The macronutrients on the roofs sampled were in suitable concentrations, but low pH and incomplete decomposition inhibit their availability to some taxa (Handreck and Black, 2010). This may partly explain the floristic simplification described for these roofs over time, with the loss of most herbaceous species and grasses and dominance by Sedums. As stress tolerators [*sensu* Grime (1977)], Sedums have lower mineral nutrition requirements than taxa with other adaptive strategies (Grime, 2001). Indeed, a container study of five species of *Sedum* found that moderately to slightly acidic conditions (pH 5.7 to 6.4) yielded the most productivity, with *Sedum spurium* producing 95 times more dry weight at pH 6.3 compared to pH 8.3 (Zheng and Clark, 2013).

When slow-growing, stress-tolerant plants, like Sedums, dominate a site, decomposition rates are slower and nutrients are bound in complexes of low biological availability (Grime, 2001). Stress-tolerant plants often produce smaller, less photosynthetically active leaves with a higher content of structural carbohydrates and higher concentrations of secondary metabolites, like phenolics (Poorter and Bergkotte, 1992). Taken together, these properties make the leaf litter less favourable as a resource for the microflora and fauna and is therefore decomposed more slowly (Cornelissen, 1996). The two-way feedbacks between plants and soil seem to be important drivers of ecosystem properties and processes globally, though only few studies have explored the mechanisms [e.g., Hunt et al. (1988), Setälä and Huhta (1991)]. If feedbacks associated with litter influence plant establishment, growth and community composition (via a range of interacting mechanisms, like changes to light regimes and microclimate or nutrient immobilization) (Facelli and Pickett, 1991), then the dominance of Sedums on EGRs may be owing not only to tolerance of stressful rooftop conditions but perhaps also to competitive exclusion. Given that plants are the ultimate determinant of how the decomposer subsystem works (Wardle, 2002), it is reasonable to expect that different ecophysiological attributes and plant strategies are likely to influence the effects of plant species on ecosystem properties. Some soil scientists have suggested that species effects can be as or more important than abiotic factors (e.g., climate) in controlling ecosystem fertility (Hobbie, 1992).

6.4.2.2 Hypothesis: EGR substrates may approximate natural soil processes when they support persistent populations of soil macrofauna

Given the incidental encounters during substrate sampling of ant and earthworms, soil formation could be possible in EGR substrates since most soil development occurs in the presence of live organisms (Ugolini and Spaltenstein, 1992). Although these organisms were only encountered by chance, it is entirely possible that they have far-reaching effects on these systems. While some EGR studies refer to ants (Kadas, 2006, MacIvor and Lundholm, 2011, Madre et al., 2013), they do not consider the impacts of these taxa on vegetation or soil ecology. Earthworms have received little attention for EGR substrates, other than commentary that they would not likely survive there over the long-term (Mann, 1999b, Mann, 1996, Buttschardt, 2005, Schrader and Boening, 2006). This may be the first work that has observed earthworms on mature EGRs.

Since earthworms are effective litter transformers (Bardgett, 2005), their presence on EGR substrates over the long term could presumably alter the soil dynamics away from litter accumulation towards nutrient recycling, which would have knock-on effects with acidification, soil-plant feedbacks and any associated dynamics (Wardle, 2002). One study of 250 mm green roof microcosms observed the dramatic decline in biomass by an anecic earthworm (*Lumbricus terrestris*) after 28 days, owing to the conditions imparted by aggregate abrasion and shallow, mineral substrates (Scharenbroch and Johnston, 2011). For future investigations of earthworm habitat potential in such substrates, the latter authors suggest testing endogeic species (*ibid*). Although they were not identified, the presence of earthworms on the old EGRs sampled indicates that such organisms can persist over time, given the right conditions.

6.4.3 Recommendations

Some approaches for improving conditions for soil processes to occur on EGRs might include the addition of carbonate to the substrate blends in order to prevent acidification, whether at the point of installation or integrated into a maintenance regime(e.g., lime amendments every 5 years). If our hypothesis is true, that Sedum dominance is a response to acidification, then curtailing Sedum dominance can be accomplished both by maintaining neutral pH but also by ensuring a diverse seed bank or seed rain to support greater floristic diversity over time. This could be accomplished by sowing seed as part of a maintenance regime, perhaps together with lime amendments.

Given the proof that soil fauna can persist on EGRs over time, their contributions to soil ecological processes can be provided for in various ways. The provision of sufficient depths, whether across the roof or in mounded areas, can serve as valuable refuge for soil organisms and litter transformers from sun, wind, extreme temperatures and other hostile phenomena. Such provision could also benefit the conditions required for decomposition, nutrient recycling and humus formation. As well, inoculating the substrate with microbes and fungi, in particular mycorrhizal fungi, can promote the development of this essential community.

Of course, the monitoring of EGR substrates over time will advance our understanding of the soil ecological function of these systems, and of the yet-undiscovered potential that these results hint at. Given the great volumes required for substrate analysis, and the limitations of certain diagnostic methods (e.g., soil organic content), future work must develop alternative methods and will ideally arrange for replicated roofs as part of well-planned experimental design.

7 Proposing models for EGR vegetation development over time

The preceding chapters analyzed vegetation and substrate data from a small sample of some of the oldest extensive green roofs in southwestern Germany. The basic intent was to describe the biotic attributes, each roof an individual snapshot in time. The trend of species impoverishment appears to be associated with dominance by stress-tolerant species and prevalence of ruderals. Some of the key factors that influence EGR vegetation development include variable growing conditions that select species tolerant of warm temperatures, dry substrates, full sun, and limited nutrients. The acidification of the substrate, the accumulation of soil organic content and, potentially, the decrease in substrate depth are also important factors. Although the dataset was too small to make definite conclusions, a degree of confidence was gained by the corroborations from other studies and, where possible, by meta-analyses with other work. The causes, mechanisms and ecological processes that led to the results observed will be addressed in this chapter, with the broad goal of synthesizing these results with other works and ascertaining opportunities for practical application as well as theoretical developments.

7.1 Literature review: the role of models to ecological research

> *Every map is a simplification of a real landscape; nevertheless, maps are enormously helpful, and it is hard to imagine how we could get along without them.* (Raymo, 1991) (p. 147)

Due to their inherent complexities, ecological systems can only be observed and studied in the absence of complete information. Models are helpful because they can serve as simplified yet reasonably accurate representations of reality and because they can capture patterns in the data of individual variables that may not otherwise be obvious (Starfield and Bleloch, 1986). Fundamentally, "understanding is the overarching goal of any science, especially pluralistic and diverse disciplines like ecology, because understanding facilitates integration between sub-disciplines, divergent scales, causal alternatives, conceptual difficulties, etc." (Pickett et al., 1994) (p. 24). By definition, understanding is "an objectively determined, empirical match between some set of confirmable, observable phenomena in the natural world and a conceptual construct" (*ibid*, p. 28). It may also be referred to as "the degree of match between reality and theory, a match between what scientists observe and what they think" (*ibid*).

Ecological understanding has three components: observable phenomena, conceptual constructs, and the tools that relate these while facilitating dialogue. These tools, which relate the observable phenomena of nature with conceptual constructs, include causal explanation, generalization, and testing within a specific domain. However, ecological understanding can only be practical to the real world if it is integrated (i.e., with sub- and other disciplines) and if the conceptual constructs are updated through empirical developments. Such ongoing developments, by a diverse community of ecologists, are essential for such integration to develop. The value of theoretical models depends upon the extent to which they are able to explain phenomena and generate testable predictions (Grime and Pierce, 2012). Beyond the efforts of science, "the fruits of understanding can be applied… to management or policy concerns raised by society" (Pickett et al. 1994) (p. 28, Fig .2.1). This chapter shall engage in this spirit of inquiry with the basic aim of advancing ecological understanding to EGR research, design and implementation. A positive outcome of this goal might be integrating practical measures into green roof system design and installation, as well as education at the level of management and policy.

Theories and models are conceptual constructs that represent and simplify reality by showing the relationships between objects, the causal interactions, and the states of the system (Nagel, 1961, Suppe, 1977). Models are not the entirety of theory; instead theories can be considered as families of models (Thompson, 1989, Lloyd, 1988). There are different types of models and accordingly different uses for them. **Quantitative** models, based on statistical analysis of data, are useful for approximation and, therefore, for comparative ecology. Since quantitative models lack fine details, they are not useful for prediction but they can prompt questions and consideration of consequences. **Qualitative** models are descriptive, in the form of a narrative or diagram, and their simplicity has the benefit of making it easy to add more detail. The drawback of qualitative models, however, is that they may choose to include convenient rather than sufficient elements and that they may only represent matters of opinion (McCarthy, 2009). Models can cover an enormous range of descriptive/ predictive quality.

Organization of research and ideas is just as important as the ideas themselves, and conceptual frameworks are tools that help evaluate the state of a subject area (Pickett et al., 2007). Hierarchical structure shall be used in various parts of this chapter, as this can accommodate both specificity and comprehensiveness within a framework (Cadenasso et al., 2003). The higher levels of a framework are more abstract and therefore more generalizable, which helps identify the core concepts and processes to be addressed (Cadenasso et al., 2003). Accordingly, hierarchical structure also permits the disaggregation of high level, or general, causes into lower level, more specific mechanisms (Foxcroft et al., 2011).

7.1.1 Application of CSR triangle model for natural succession to EGRs

Previous chapters characterised certain components of EGR vegetation with CSR signatures, as this granted some insight into their ecological behavior and habitat preferences. The pressures of stress and disturbance, which are central to the theory (Grime, 1977), are clear and obvious influences on EGR vegetation. CSR theory is particularly useful for this work because it can explain trajectories of natural succession. These theories have both been introduced in previous chapters and will be elaborated upon here with regards to their applications in this chapter.

7.1.1.1 Successional trajectories using CSR triangle model

Natural habitats bearing environmental conditions similar to those occurring on EGRs and which have been studied under the lens of natural succession can complement the discussion on the processes of vegetation change occurring on EGRs. As stress-prone habitats featuring limited soil depth, highly mineral substrates, and exposure to the elements, rocky outcrops and dry grassland have served as habitat analogues for EGRs and as models for describing primary and secondary succession (Usher and Jefferson, 1990, Gibson and Brown, 1991, Gibson and Brown, 1992, Grime, 2001, Alard et al., 2005). The difference between primary and secondary succession can be seen as the difference in basic resource availability or in stress or climatic limitations: primary succession is slow because of low resource levels, while secondary succession is faster because the sites support more biological activity as a result of the higher resource levels (del Moral, 2007).

Primary succession on a rock outcrop begins from the initial basis of stress-tolerant colonizers, such as mosses and lichens, which have low biomass. As implied by the arrow in **Figure 7.1a**, after 100 years sufficient biomass and soil has accumulated to facilitate colonization by C-R strategists like small, slow-growing herbs and shrubs. These strategists produce more biomass than their predecessors (shown by the size of the circles); if undisturbed, the community will rest in this position (S/ C-S) for ca. 500 years. In addition to the minimal biomass of the rock outcrop, decomposition rates are also very slow; the coincident process of soil formation is a key factor driving this successional trajectory (Grime, 2001).

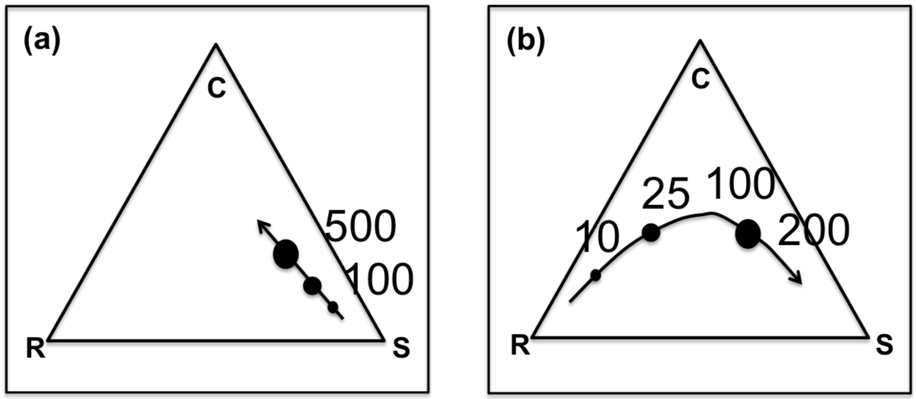


Figure 7.1. (a) Primary succession in a skeletal habitat such as a rock outcrop; **(b)** Secondary succession for a site of low fertility, such as unimproved calcareous grassland. Modified from Grime (2001).

Granted, EGRs are dramatically different from rock outcrops and, being planted with carefully selected species, they are subject to secondary, not primary, succession. Dry calcareous grassland, such as Xerobrometum, is an EGR analogue habitat that has been researched and applied in many parts of the world (Kolb et al., 1983, Choi and Dunnett, 2008, Macdonough et al., 2006). Knowledge of the factors and processes occurring on these semi-natural ecosystems are relevant for EGRs since both communities occur on special soils of limited profile, with limited plant available nutrients, and the relatively steady floristic character of both is strongly influenced by human intervention and stress. The intensity and form of stress that is integral to this ecosystem deflects competitive invasion by uncharacteristic species (which would lead to species-poor coarse grassland and woody encroachment) and helps maintain the characteristic species composition and diversity in a steady state (plagioclimax).

Secondary succession in low nutrient habitats such as dry calcareous grassland develops as a shallow parabola across CSR space (**Figure 7.1b**), as the early deficiencies limit plant biomass and inhibits dominance by competitive species. (The successional parabola for high fertility sites reaches higher into the competitor corner of the model and features greater biomass.) After about 100 years, the course of secondary succession begins to deflect towards the stress-tolerator corner, beginning even when plant biomass is expanding appreciably. This occurs for both high- and low-nutrient sites and reflects a change in rates of resource capture and loss, particularly mineral nutrients, to one in which resources are efficiently retained in the biomass (Grime, 2001). This example would apply to EGRs that do not receive regular subsidies of nutrients.

Beyond the fact that plant ecology research on mature EGRs is rare, it is worth reflecting on the purpose of a model for EGR vegetation development. In a practical sense and for the short term, an applicable model can offer guidance to managers, policy-makers and designers interested in enhancing conditions for supporting biodiversity. As global biodiversity continues its downward spiral while urbanization and human population continue to grow, a model for long-term EGR vegetation development can help the EGR industry and designers to introduce measures that can augment the beneficial outcomes of their work. For example, integrating green roof installations or system designs with provisions for floristic diversity and below-ground biota (through policy requirements and other mechanisms) could maximize green roof potential for ecosystem services over the long-term, rather than simply maintaining the lowest denominator of engineered function (e.g., stormwater runoff).

This chapter therefore unites research with theories that are conceptually relevant to the urban environment and specifically for rooftops. For process-oriented models, succession theory is an obvious starting point since it examines mechanisms and dynamics over temporal scales. Although natural succession has been of interest on spontaneously vegetated gravel/ TPG roofs, other than a few German studies with access to EGRs (Poll, 2008, Schrader and Boening, 2006) this has only been applied to relatively young systems (<10 years) (Buttschardt, 2001, Dunnett et al., 2008, Rowe et al., 2012, Bates et al., 2013, Piana and Carlisle, 2014). Classification of EGR vegetation into adaptive strategies with CSR theory helps to relate EGR systems with the fundamental aspects of ecosystem function. Species with high S-coordinates, for example, tend to grow slowly even under favorable conditions, have long-lived leaves unpalatable to generalist herbivores and produce litter that decomposes very slowly (Grime et al., 1997, Diaz et al., 2004), which is the case of Sedum species (Stephenson, 1994). By contrast, species with low S-coordinates have the opposite characteristics (e.g., rapid growth rate, palatable) (Hunt et al., 2004). Such differences have major impacts upon ecosystem functions relating to nutrient recycling (Chapin et al., 2002).

7.1.2 Research aims and questions

This chapter unites the results from the research (i.e., observable phenomena) with ecological theories (i.e., conceptual constructs) in order to propose models at various degrees of detail (i.e., generalizations and practical use). Being the final chapter of the dissertation, it therefore determines the final conclusions for the various aims and questions underpinning this work.

- Aim: To propose models illustrating vegetation development on EGRs over time.
- Question: If successional change can be observed on EGRs, what are the main drivers and mechanisms?

7.1.2.1 Objective of the chapter

The objective of this chapter is to unite the findings from this research with precedent works and relevant ecological theories into a functioning model that can describe the mechanisms driving EGR vegetation change over time.

7.2 Methods

With reference to Grime's (1974, 1977, 2001) theoretical triangular scheme of competitor, stress-tolerator and ruderal plant strategies (CSR theory), a series of quantitative models shall locate the vegetation of individual roofs and of EGR vegetation types (as defined by the cluster analyses of Chapters 3 and 5) within CSR space. A conceptual model shall follow which proposes the trajectories of EGR vegetation (using adaptive strategies) over time, using original species lists where available and with reference to patterns from analogue habitats. These lead to the final model which integrates the general causes, specific mechanisms and ecological filters into a model of community assembly, specifically adapted for EGRs.

7.2.1 Methods for the quantitative model (EGR vegetation by CSR signatures)

The same methods and software tool (Hunt et al., 2004) that were used for characterising EGR grasses into CSR adaptive strategies in Chapter 3 are used here. In other words, each species was allocated with a CSR signature in order to depict the adaptive strategies present. The spreadsheet tool includes a list of ca. 1,000 species with their CSR allocations, which can be matched up with the species lists of the roofs surveyed. The standard coordinate values for the different signatures within CSR space range from 0 to 1 (**Table**

7.1). In cases where the species identified lack a nomenclatural match from that list, the first of three options was taken, namely substituting for the name of the species that of a presumptive CSR type with reference to taxonomic and ecological similarity. The other options were either not possible [calculating the CSR type by means of literary and laboratory procedure described by Hodgson et al. (1999)] or undesirable (grouping all unknowns under the single eliminator 'unknown'). Other databases (e.g., BiolFlor) were not used because knowledge of their existence arose too late, and the associated expense was prohibitive anyway. Although other methods and CSR tools have been developed (Hodgson et al., 1999, Pierce et al., 2013), this was deemed the best fit at the time of this work. It is encouraging that improvements to CSR classification methods using the same species in northern Italy (Pierce et al., 2013) were sufficiently accurate with the original predictions based on the Integrated Screening Programme from northern England (Grime et al., 2007).

Table 7.1. Standard coordinate values within CSR space (reference from spreadsheet tool).

	C	S	R
C	1.00	0.00	0.00
C/CR	0.75	0.00	0.25
C/CSR	0.67	0.17	0.17
C/SC	0.75	0.25	0.00
CR	0.50	0.00	0.50
CR/CSR	0.42	0.17	0.42
CSR	0.33	0.33	0.33
R	0.00	0.00	1.00
R/CR	0.25	0.00	0.75
R/CSR	0.17	0.17	0.67
R/SR	0.00	0.25	0.75
S	0.00	1.00	0.00
S/CSR	0.17	0.67	0.17
S/SC	0.25	0.75	0.00
S/SR	0.00	0.75	0.25
SC	0.50	0.50	0.00
SC/CSR	0.42	0.42	0.17
SR	0.00	0.50	0.50
SR/CSR	0.17	0.42	0.42
Corners have value 1, opposite sides have value 0, intermediates are equidistant from each parent, and C + S + R = 1			

The adjusted species list with allocations of CSR signatures (or nearest equivalent) reflects the proportionate cover of adaptive strategies on the roofs surveyed, and also includes the relative cover for each species calculated for all the roofs. Proportionate cover by adaptive strategies for EGR vegetation types or other lists will be given as required in the results sections that follow. The results therefore embody a range of detail, from species lists per roof to the proportionate groupings of strategies per EGR vegetation type. The amended species list is given in the results section.

Of the ninety-five (94) species identified in the roof surveys, nearly half (forty-three, or 45.7%) were listed in the "CSR lookup sheet" of the software tool. Of the species that were not listed, twenty-seven (28.7%) were confidently matched with the CSR signatures of other species on the basis of comparable genera, growth habits, and/ or habitat affinities. With reference to a variety of sources, species from the following genera were matched with confidence: *Agrostis, Allium, Carex, Crepis, Dianthus, Erigeron, Geranium, Hypericum*, *Linum*, *Nepeta, Poa, Sedum*, *Teucrium, Thymus* and *Veronica.* For example, only four of the ten Sedum species/ cultivars had allocated CSR signatures (*S. acre* = S/SR; *S. album* = S; *S. spurium* = S/SR; *S. telephium* = S/CSR), but most had the same habitat preferences and growth habits so the unlisted species were designated as S-strategists. Similarly, the single species of *Thymus* in the signature list (*T. polytrichus*) is a S-strategist, and the three species identified on the roofs bear the characteristics of successful stress tolerators so they were designated as such.

Twenty-four species (25.5%) were given CSR signatures based on educated guess, in other words through observation and literature. Most of these (seventeen) were cryptogams, which were designated as stress-tolerators (S), stress-tolerant ruderals (SR) or ruderals (R) on the basis of literature (Rogers, 1988) and on observation of their habitats and apparent strategies (During, 1979). The mosses found uniquely in the drip zone at FH Nürtingen or on the north-face of the roof at Köngen are pioneer species that occur in dry habitats like the other mosses, but have additional associations to wet habitats (e.g., *Calliergonella cuspidata*), woodland (*Eurynchium praelongum*), grassland and forested tracks (*Polytrichum juniperinum*) (Atherton et al., 2010), so they were designated as R/CSR strategists. The two *Petrorhagia* species were classified as stress-tolerant ruderals (SR) based on their ecological similarity with *Saxifraga tridactylites* (SR) and because they are stress tolerant but also behave like annuals (e.g., prolific seed production) (Kolb and Schwarz, 1986, Snodgrass and Snodgrass, 2006).

Once every species was designated a CSR signature, the software tool could calculate the position for the vegetation entered per sample, and then compare the vegetation of up to three roofs. The vegetation data from the clustered EGR vegetation types were used for the comparison. Since they were clustered according to site-specific attributes (species diversity, dominance, and habitat conditions or EIVs), evaluating the vegetation with CSR theory can offer further insight into the relations between stress and disturbance on EGRs. Mean cover proportions of the species surveyed for each roof cluster are thus corrected proportionally for total cover of 100% and then entered into the "Calculator" sheet of the spreadsheet tool which converts the floristic data to define a "nearest CSR vegetation type" for that sample. The output also provides a summary of the proportions of adaptive strategies per sample and a plot showing the position of the community's growth form composition within the triangular ordination of CSR space.

7.3 Results and Discussion

Using the CSR triangle diagram and output tables, the community composition for different roof samples is shown with resolution of the adaptive strategies defining the vegetation. Within the diagram, competition implies conflict over resources, stress implies any factors that place prior restriction on plant production, and disturbance implies factors causing partial or total destruction of plant biomass that has already been formed (Hunt et al., 2004).

7.3.1 Quantifying EGR vegetation types by adaptive life strategies (CSR)

The master species list, with total relative proportionate cover for all the roofs surveyed (**Table 7.2**) was entered into the software tool first, followed by the EGR vegetation types.

Table 7.2. Master species list with CSR signatures and relative total abundance per species.

Master species list (all roofs)	Blank = given in tool; Name = confident match; CSR = educated guess	Total abundance (all roofs) (%)	CSR type entered into tool
Acer campestre L.		0.006	SC
Acer pseudoplatanus L.		0.490	C/SC
Achillea millefolium L.		0.227	CSR
Agrostis stolonifera L.		1.356	CR

Agrostis tenuis Sibth.	*Agrostis canina*	0.138	CSR
Allium flavum L.	*Allium scorodoprasum*	0.502	S/CSR
Allium schoenoprasum L.	*Allium oleraceum*	2.027	S/CSR
Arrhenatherum elatius (L.) P. Beav. ex. J. & C. Presl.		0.334	C/CSR
Campanula rotundifolia L.		0.015	S/CSR
Carex flava L.	*Carex disticha*	0.361	C/CSR
Carex humilis Leyss.	*Carex disticha*	0.046	C/CSR
Carpinus betulus L.		0.046	SC
Cerastium arvense L., Sp. Pl. 438 (1753)		0.009	SR/CSR
Convolvulus arvensis L.		0.009	CR
Coronilla varia L.	*Securigera varia*	0.508	C/CSR
Crepis tectorum L.	*Crepis capillaris*	3.425	R/SR
Dactylorhiza fuchsii L.		0.024	SR
Dianthus carthusianorum L.	*Dianthus deltoides*	1.013	S/CSR
Dianthus deltoides L.		0.165	S/CSR
Erigeron annuus (L.) Pers.	*Erigeron acer*	0.021	SR/CSR
Festuca ovina L.		5.743	S
Festuca rubra L.		0.517	CSR
Fragaria vesca L.		0.080	S/CSR
Geranium spp.	*Geranium robertianum*	0.077	R/CSR
Geum urbanum L.		0.040	CR/CSR
Hieracium pilosella L.		3.288	S/CSR
Hypericum perfoliatum sensu Hayek pro parte, non L.	*Hypericum perforatum*	0.129	CR/CSR
Hypericum perforatum L.		0.422	CR/CSR
Lichen_Cladonia furcata (Huds.) Schrader	S	0.670	S
Lichen_Cladonia cf scabriscula (Huds.) Schrader	S	0.539	S
Lichen_Peltigera spp.	S	0.110	S
Linum perenne L.	*Linum catharticum*	1.494	SR
Lotus corniculatus L.		0.441	S/CSR
Medicago lupulina L.		0.113	R/CSR
Moss_Hypnum1	S	1.059	S
Moss_Hypnum2	S	0.796	S
Moss_Dicranum scoparium Hedw.	sr	0.098	SR
Moss_Eurhynchium praelongum (Hedw.) B., S. & F (stokesii)	r/csr	0.334	R/CSR
Moss_Scleropodium purum (Hedw.) M. Fleisch	sr	0.722	SR

Moss_Brachythecium rutabulum (Hedw.) Schimp.	sr	0.012	SR
Moss_Bryum1	sr	0.306	SR
Moss_Brachythecium cf. albicans1 (Hedw.) Schimp	sr	0.294	SR
Moss_Philonotis fontana (Hedw.) Brid.	sr	0.239	SR
Moss_Polytrichum juniperinum Hedw.	r/csr	0.135	R/CSR
Moss_Racomitrium elongatum Ehrh. ex Frisvoll	sr	1.053	SR
Moss_Brachythecium cf. albicans2 (Hedw.) Schimp	sr	0.214	SR
Moss_Brachythecium cf. albicans3 (Hedw.) Schimp	sr	0.205	SR
Moss_Bryum2	sr	1.172	SR
Moss_Calliergonella cuspidata (Hedw.) Loeske	r/csr	0.680	R/CSR
Moss_Ceratodon purpureus (Hedw.) Brid.	sr	0.490	SR
Moss_Starry yellow	sr	0.306	SR
Nepeta mussinii Sprengel ex Henckel	*Nepeta cataria*	0.150	C/CSR
Petrorhagia prolifera (L.) Ball & Heywood	SR	0.092	SR
Petrorhagia saxifraga (L.) Link.	SR	0.582	SR
Picris hieracioides L.		0.061	R/CSR
Pinus sylvestris L.	sc	0.009	SC
Poa angustifolia L.		0.024	SC/CSR
Poa compressa L.		2.452	SR/CSR
Poa pratensis L.		0.156	CSR
Potentilla argentea L.		0.021	S/CSR
Potentilla erecta (L.) Räuschel		0.119	S/CSR
Potentilla tabernaemontani Ascherson		0.970	S
Potentilla recta L.		0.300	C/CSR
Sedum acre L.		0.003	S/SR
Sedum album L.		0.070	S
Sedum album "Coral Carpet"	*Sedum album*	0.918	S
Sedum album "Murale"	*Sedum album*	1.956	S
Sedum kamtschaticum "Weihenstephaner Gold"	s	5.345	S
Sedum hybridum L.	s	17.688	S
Sedum rupestre L.	s	8.063	S
Sedum sexangulare L.	s	7.889	S
Sedum spurium Bieb.		5.682	S/SR
Sedum telephium L.		0.018	S/CSR

Sempervivum tectorum L.		0.003	S
Setaria viridis (L.) P.B	r	5.180	R
Solidago canadensis L.		0.012	C
Taraxacum officinale Weber		0.291	R/CSR
Teucrium chamaedrys L.	*Teucrium scorodonia*	0.070	S/CSR
Thymus praecox Opiz	s	1.941	S
Thymus pulegioides L.	s	0.049	S
Thymus serpyllum L.	s	3.187	S
Trifolium arvense L.		0.542	R/SR
Trifolium campestre Schreber		0.199	R/SR
Trifolium dubium Sibth.		0.046	R/SR
Trifolium pratense L.		0.055	CSR
Verbascum nigrum L.		0.006	C/CSR
Verbascum thapsus L.		0.003	SR/CSR
Veronica spicata L.	*Veronica arvensis*	0.471	SC
Vicia hirsuta (L.) S.F. Gray		1.194	R/CR
Vicia sepium L.		0.037	C/CSR
Vulpia myuros L. C.C. Gmel.		1.531	R/SR

On a whole, the master species list for all the roofs surveyed classified as S/SR vegetation (**Figure 7.2**). Seventeen types of adaptive strategies were present overall, with C-strategists a minority (0.05) relative to the other strategies, of which S-strategists dominated (0.74) and R-strategists had the remaining representative cover (0.21) (**Table 7.3**). According to the CSR model, the S-corner of the triangle diagram is typified by conditions of high stress and low disturbance (Grime, 1977). Climatic conditions were not monitored but earlier chapters have discussed and shown how widely it is known and accepted that EGRs are stressful environments for most forms of life. The slight pull towards the R-corner can be explained by the substrate results, as all the roofs (except one) had optimal mineral nutrient concentrations (N, P, K, Mg). Although this implies low disturbance in the context of CSR theory, the ruderal component on these roofs is not as strong as one might expect, probably because all (except the two youngest roofs) were slightly to strongly acidic. The consequent inhibition of nutrient availability, combined with the physical effects of the stressful roof environment, explains why the species list for all the roofs taken together classified as S/SR.

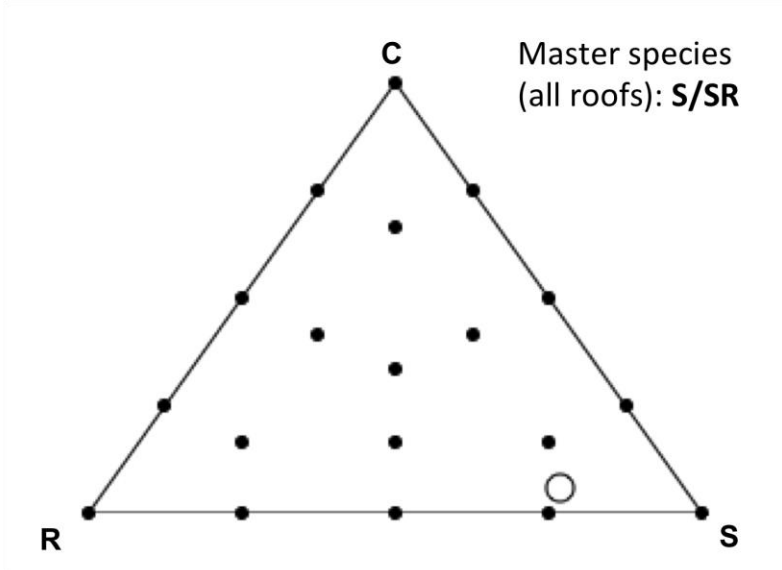


Figure 7.2. The master species list (from all roofs) in relative proportionate cover, classifies as a S/ SR community.

The results from this tool therefore make it clear that the vegetation of the EGRs surveyed is dominated by stress-tolerators, but that other adaptive strategists occur as well. By plotting the proportionate representation of each species' adaptive strategy, the tool illustrates the type of vegetation present on these EGRs after 20-30 years, while also elucidating the environmental conditions that direct vegetation composition. The sections that follow shall examine the vegetation of these roofs more closely, using the same CSR tool, starting with the five major EGR vegetation types (also **Table 7.3**). Similar to the output from the master species list, the EGR vegetation types (defined by the clustered roofs) are all located towards the S corner of the CSR triangle (**Figure 7.3**).

Table 7.3. Results for CSR proportions for the five EGR vegetation types, including master species list.

EGR vegetation types	Nearest type	# types	C	S	R
Master species (all species, all roofs)	S/SR	17	0.05	0.74	0.21
"Species-poor Sedum roof"	S	11	0.04	0.88	0.08
"Sparse Sedum meadow"	S/SR	15	0.03	0.73	0.24
"Sedum with Chives"	S/SR	11	0.04	0.85	0.11
"Pitched Sedum meadow"	S/SR	10	0.03	0.74	0.23
"Floristically-diverse Sedum meadow"	S/CSR	15	0.11	0.58	0.31

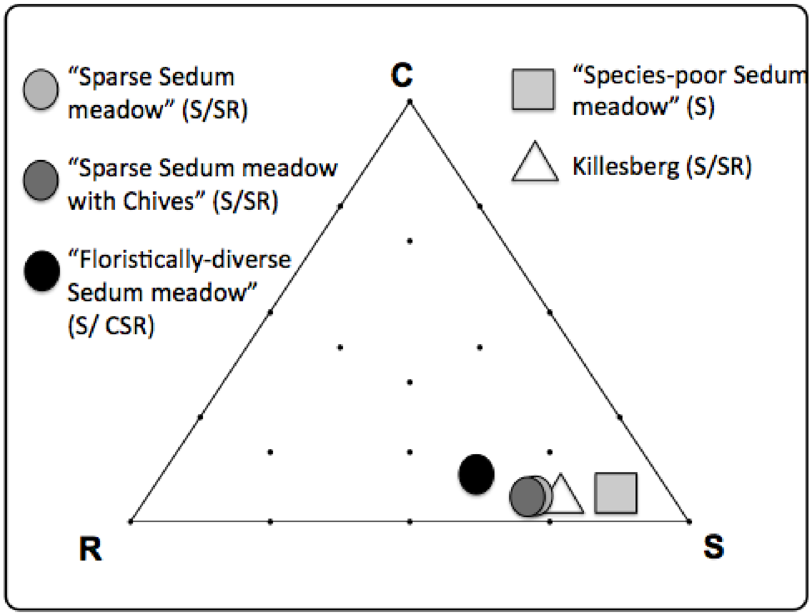


Figure 7.3. The clustered EGR vegetation types within CSR space.

The three EGR vegetation types described as different "Sedum meadow" roofs all classified as S/SR vegetation and positioned closely together in CSR space (overlapping circles and triangle icon). The triangle icon in this group represents the "Pitched Sedum meadow" of Killesberg roof. Although that roof stood alone in the cluster analysis, with respect to functional type composition it is nearly identically to the "Sparse Sedum meadow" and "Sparse Sedum meadow with Chives" (overlapping circles). These roofs all remain very low on the R-S axis, indicating that C-strategists had little influence. The "Species-poor Sedum roof" (square icon), located closest to the S-corner, is defined as pure S-community. The two roofs defining this vegetation type (Pliensaufriedhof and Köngen) had the fewest species of all the roofs surveyed, and their simple and homogeneous vegetation was dominated by only a few Sedum species. The "Floristically-diverse Sedum meadow" cluster (FH Nürtingen and Rathaus lower) classified uniquely as S/CSR, and is located slightly further from the S-corner towards the central CSR part of the triangle diagram (black circle icon).

7.3.1.1 S-vegetation

Stress can be defined as "the external constraints which limit the rate of dry matter production of all or part of the vegetation" (Grime, 2001) (p. 48), and the most frequent constraints on plant growth are related to shortages and excesses of solar energy, water, and mineral nutrients. Plant-induced stress can also arise, such as the shading and resource depletion that result from the accumulation of plant biomass, or through growth inhibitors secreted into the soil or produced by microbial decay (*ibid*). The severity of stress often varies from one growing season to the next, but is usually sufficient to restrict annual production to well below that achieved in habitats dominated by ruderals or competitive-ruderals (*ibid,* p. 124). Severe stress can occur in various types of habitat, such as arctic and alpine habitats, arid habitats, shaded habitats, nutrient-deficient habitats and urban habitats.

The general features of stress-tolerance employed by vascular plants exploiting various types of chronically-unproductive habitats include a range of adaptations that serve for endurance in unfavourable conditions (Grime, 2001). Some of these features are obvious in the Sedums used on green roofs, such as the long functional life of individual shoots and roots, and comparatively slow growth rate (Stephenson, 1994). Defense from physical damage is also important for plants of reduced stature and slow growth rates, so many S-strategists deter herbivory and palatability using physical mechanisms (e.g., hard or leathery texture, needle-like leaves) (Coley, 1983, Reader and Southwood, 1981) or allelopathic mechanisms (phytotoxic compounds) (Muller and Muller, 1956, Peng et al., 2004). Associated with low palatability, decomposition of litter from stress-tolerators is quite slow. This is true for particularly slow-growing evergreens of unproductive vegetation (Cornelissen et al., 1999, Cornelissen, 1996), and explains the deep accumulation of litter under many slow-growing woody species (*e.g., Calluna vulgaris, Fagus sylvatica, Rhododendron ponticum, Quercus petrea*) (Kubiena, 1953). This could also explain the high soil organic content on old EGRs (Buttschardt, 2001, Jauch and Fischer, 2000, Liesecke, 2006, Schrader and Boening, 2006).

7.3.1.2 S/SR vegetation

Species classified as stress-tolerant ruderals occur in habitats where moderate intensities of stress and disturbance coincide; the distinguishing point is that stress conditions are experienced during the period of growth rather than dormancy or other points in the life cycle (Grime, 2001). When climatic factors like low temperature and low rainfall inhibit plant productivity, they may be considered forms of stress but if the same factors disrupt plant growth and occur regularly, they can be considered an agent of disturbance (*ibid,* p. 81). Specifically, when climatic conditions encourage establishment but periodically become severe and interrupt plant growth, and neither competitors nor stress-tolerators can gain secure advantage then natural selection will favour fast-growing ephemerals. Ruderals are defined by their rapid life-cycles as a response to stress (Grime, 2001). Among the stress-tolerant ruderals, the two most strongly represented growth forms include bryophytes and small herbs, the latter consisting of small annuals and short-lived perennials as well as small geophytes (*ibid,* p. 125). Such species were indeed present within the vegetation of the roofs classified as S/SR vegetation, in combination with the dominant Sedum cover. The species lists for these vegetation types, with proportionate cover, and output from the CSR spreadsheet tool are given in the tables that follow.

Table 7.4 "Sparse Sedum meadow": species list with CSR signatures, proportionate cover and output from CSR calculator.

"Sparse Sedum meadow" (S/SR)	CSR signature	Abundance (mean %) Tübingen	Abundance (mean %) Rathaus-PV	Total abundance	Proportionate cover (%)
Acer campestre L.	SC	2		2	0.022
Acer pseudoplatanus L.	C/SC	1		1	0.011
Allium flavum L.	S/CSR		90	90	1.012
Arrhenatherum elatius (L.) P. Beav. ex. J. & C. Presl.	C/CSR	16		16	0.180
Crepis tectorum L.	R/SR	0	520	520	5.849
Dianthus carthusianorum L.	S/CSR	0	48	48	0.540
Dianthus deltoides L.	S/CSR	10	18	28	0.315
Festuca ovina L.	S	57	129	186	2.092
Festuca rubra L.	CSR	21	0	21	0.236
Fragaria vesca L.	S/CSR	26	0	26	0.292
Hieracium pilosella L.	S/CSR	6	87	93	1.046
Hypericum perforatum L.	CR/CSR	5	0	5	0.056
Lichen_Cladonia cf scabriscula (Huds.) Schrader	S		107	107	1.204
Lichen_Peltigera spp.	S		10	10	0.112
Linum perenne L.	SR		307	307	3.453
Moss_Hypnum1	S	0	163	163	1.834
Moss_Bryum2	SR	0	148	148	1.665
Moss_Starry yellow	SR	0	40	40	0.450
Nepeta mussinii Sprengel ex Henckel	C/CSR	0	49	49	0.551
Petrorhagia saxifraga	R/CSR	84	0	84	0.945

Picris hieracioides L.	R/CSR		3	3	0.034
Poa compressa L.	SR/CSR	0	9	9	0.101
Poa pratensis L.	CSR	18		18	0.202
Poa angustifolia L.	SC/CSR	1		1	0.011
Potentilla erecta (L.) Räuschel	S/CSR	0	39	39	0.439
Potentilla tabernaemontani Ascherson	S	0	122	122	1.372
Sedum album "Coral Carpet"	S	17		17	0.191
Sedum kamtschaticum "Weihenstephaner Gold"	S	543		543	6.108
Sedum hybridum L.	S	1204	474	1678	18.875
Sedum rupestre L.	S	35	1191	1226	13.791
Sedum sexangulare L.	S	612	342	954	10.731
Sedum spurium Bieb.	S/SR	410	0	410	4.612
Sedum telephium L.	S/CSR	0	4	4	0.045
Setaria viridis (L.) P.B	R	0	851	851	9.573
Taraxacum officinale Weber	R/CSR	0	21	21	0.236
Thymus praecox Opiz	S	550	0	550	6.187
Thymus serpyllum L.	S	0	50	50	0.562
Trifolium campestre Schreber	R/SR	0	51	51	0.574
Trifolium pratense L.	CSR	5		5	0.056
Veronica spicata L.	SC	0	39	39	0.439
Vicia hirsuta (L.) S.F. Gray	R/CR	355	0	355	3.993
	Nearest type	**# types**	**C**	**S**	**R**
	S/SR	15	0.028	0.732	0.24

Table 7.4. "Sparse Sedum meadow with Chives" (VB A1, A2): species list with CSR signatures, proportionate cover and output from CSR calculator.

"Sparse Sedum with Chives" (S/SR)	**CSR signature**	**Abundance (mean %)**		**Total abundance**	**Proportionate cover (%)**
		VB A1	**VB A2**		
Achillea millefolium L.	CSR	25	39	64	1.082
Agrostis tenuis Sibth.	SR/CSR	24	21	45	0.761
Allium schoenoprasum L.	S/CSR	65	597	662	11.196
Crepis tectorum L.	R/SR	4	86	90	1.522
Erigeron annuus (L.)	SR/CSR	7	0	7	0.118

Festuca ovina L.	S	1	12	13	0.220
Hypericum perforatum L.	CR/CSR	0	30	30	0.507
Lichen_Cladonia furcata (Huds.) Schrader	S	2	196	198	3.349
Moss_Hypnum2	S	80	180	260	4.397
Moss_Scleropodium purum (Hedw.) M. Fleisch	SR	236	0	236	3.991
Moss_Brachythecium rutabulum (Hedw.) Schimp.	SR	4	0	4	0.068
Moss_Brachythecium cf. albicans1 (Hedw.) Schimp	SR	0	70	70	1.184
Petrorhagia saxifraga (L.) Link.	R/CSR	1	105	106	1.793
Poa angustifolia L.	SC/CSR	0	8	8	0.135
Poa compressa L.	SR/CSR	0	86	86	1.454
Potentilla recta L.	C/CSR	3	59	62	1.049
Sedum album L.	S	16	7	23	0.389
Sedum kamtschaticum "Weihenstephaner Gold"	S	0	7	7	0.118
Sedum hybridum L.	S	994	1050	2044	34.568
Sedum sexangulare L.	S	333	174	507	8.574
Sedum spurium Bieb.	S/SR	570	33	603	10.198
Sedum telephium L.	S/CSR	0	2	2	0.034
Sempervivum tectorum L.	S	1	0	1	0.017
Taraxacum officinale Weber	R/CSR	9	1	10	0.169
Thymus serpyllum L.	S	597	164	761	12.870
Trifolium arvense L.	R/SR	5	0	5	0.085
Trifolium campestre Schreber	R/SR	9	0	9	0.152

Nearest type	# types	C	S	R
S/SR	11	0.039	0.847	0.114

Table 7.5. "Pitched Sedum meadow" (Killesberg): species list with CSR signatures, proportionate cover and output from CSR calculator.

"Pitched Sedum meadow" (S/SR) (Killesberg)	**CSR signature**	**Abundance (mean %)**	**Proportionate cover (%)**
Acer pseudoplatanus L.	C/SC	146	3.680
Carpinus betulus L.	SC	15	0.378
Cerastium arvense L., Sp. Pl. 438 (1753)	SR/CSR	3	0.076
Dianthus deltoides L.	S/CSR	7	0.176
Festuca ovina L.	S	676	17.041
Lichen_Cladonia cf scabriscula (Huds.) Schrader	S	9	0.227
Lichen_Peltigera spp.	S	22	0.555
Linum perenne L.	SR	13	0.328
Moss_Calliergonella cuspidata (Hedw.) Loeske	CSR	67	1.689
Moss_Ceratodon purpureus (Hedw.) Brid.	SR	160	4.033
Moss_Starry yellow	SR	60	1.512
Opposite leaved herb	CSR	27	0.681
Potentilla argentea L.	S/CSR	7	0.176
Sedum album "Coral Carpet"	S	283	7.134
Sedum album "Murale"	S	639	16.108
Sedum rupestre L.	S	529	13.335
Sedum sexangulare L.	S	427	10.764
Setaria viridis (L.) P.B	R	246	6.201
Taraxacum officinale Weber	R/CSR	5	0.126
Thymus pulegioides L.	S	16	0.403
Trifolium arvense L.	R/SR	153	3.857
Veronica spicata L.	SC	10	0.252
Vulpia myuros L. C.C. Gmel.	R/SR	447	11.268
# types	**C**	**S**	**R**
10	**0.040**	**0.746**	**0.214**

7.3.1.3 S/CSR vegetation

The "Floristically-diverse Sedum meadow" vegetation type (FH Nürtingen and Rathaus lower) classified uniquely from the other roofs as S/CSR. Physically, the roofs of this cluster had the most protection of all the roofs surveyed, granted by adjoining walls and roofs, as well as mounds (which were not sampled) that supported higher statured plants and the associated seed rain. As such, the vegetation included the typical stress tolerators and stress-tolerant ruderals in the open roof expanses and along the xeric edges, while patches of more competitive perennials thrived in areas with some protection. Overall, the proportion of competitive species was 0.115, while ruderals had 0.303 and stress-tolerators had 0.582 cover (**Table 7.7**). Species classified as stress-tolerant competitors are associated with vegetation types that exhibit moderate productivity and experience very low intensities of disturbance, and are usually typified by herbaceous and woody plants (Grime, 2001). Some of the S/CSR species identified on these roofs include *Allium flavum, Campanula rotundifolia, Dianthus spp., Lotus corniculatus*. A number of competitive CSR species (C/CSR) were identified that did not occur on other roofs, like *Arrhenatherum elatius, Carex spp., Potentilla recta,* and *Verbascum nigrum*. This strategy is described as being proportionately composed of 0.1667 each C- and R-strategists and 0.667 S-strategists (Hunt et al., 2004).

Table 7.6. "Floristically-diverse Sedum meadow" (FH Nürtingen, Rathaus-low): species list with CSR signatures, proportionate cover and output from CSR calculator.

"Floristically-diverse Sedum meadow" (S/CSR)	**CSR signature**	**Abundance (mean %)**		**Total**	**Proportionate**
		FH Nürtingen	**Rathaus-low**	**abundance**	**cover (%)**
Acer pseudoplatanus L.	C/SC	12	1	13	0.1486
Agrostis stolonifera L.	CR	443	0	443	5.0652
Allium flavum L.	S/CSR	0	74	74	0.8461
Arrhenatherum elatius (L.) P. Beav. ex. J. & C. Presl.	C/CSR	93	0	93	1.0633
Campanula rotundifolia L.	S/CSR	5	0	5	0.0572
Carex flava L.	C/CSR	118	0	118	1.3492
Carex humilis Leyss.	SC	15	0	15	0.1715
Crepis tectorum L.	R/SR	0	509	509	5.8198
Dactylorhiza fuchsii L.	SR	8	0	8	0.0915
Dianthus carthusianorum L.	S/CSR	0	283	283	3.2358
Dianthus deltoides L.	S/CSR	19	0	19	0.2172
Festuca ovina L.	S	175	116	291	3.3272
Festuca rubra L.	CSR	148	0	148	1.6922
Geum urbanum L.	CR/CSR	11	0	11	0.1258
Hieracium pilosella L.	S/CSR	771	210	981	11.2166
Hypericum perfoliatum sensu Hayek pro parte	CR/CSR	103	0	103	1.1777
Lichen_Cladonia furcata (Huds.) Schrader	S	21	0	21	0.2401

Lichen_Cladonia cf scabriscula (Huds.) Schrader	S	45	15	60	0.6860
Lichen_Peltigera spp.	R	0	4	4	0.0457
Linum perenne L.	SR	0	168	168	1.9209
Lotus corniculatus L.	S/CSR	144	0	144	1.6465
Medicago lupulina L.	R/CSR	37	0	37	0.4231
Moss_Hypnum1	S	0	183	183	2.0924
Moss_Dicranum scoparium Hedw.	SR	32	0	32	0.3659
Moss_Eurhynchium praelongum (Hedw.) B., S. & F (stokesii)	R/CSR	109	0	109	1.2463
Moss_Bryum1	SR	0	100	100	1.1434
Moss_Brachythecium cf. albicans1 (Hedw.) Schimp	SR	0	96	96	1.0976
Moss_Philonotis fontana (Hedw.) Brid.	SR	78	0	78	0.8918
Moss_Polytrichum juniperinum Hedw.	R/CSR	44	0	44	0.5031
Moss_Racomitrium elongatum Ehrh. ex Frisvoll	SR	344	0	344	3.9332
Moss_Brachythecium cf. albicans3 (Hedw.) Schimp	SR	0	67	67	0.7661
Moss_Bryum2	SR	0	235	235	2.6869
Other small tree	R/CSR	5	0	5	0.0572
Petrorhagia prolifera (L.) Ball & Heywood	R/CSR	0	30	30	0.3430
Picris hieracioides L.	R/CSR	0	17	17	0.1944
Poa compressa L.	SR/CSR	664	42	706	8.0723
Potentilla tabernaemontani Ascherson	S	28	167	195	2.2296
Potentilla recta L.	C/CSR	0	36	36	0.4116
Sedum acre L.	S/SR	0	1	1	0.0114
Sedum hybridum L.	S	0	280	280	3.2015
Sedum rupestre L.	S	0	879	879	10.0503
Sedum sexangulare L.	S	546	143	689	7.8779
Setaria viridis (L.) P.B	R	0	595	595	6.8031
Solidago canadensis L.	C	4	0	4	0.0457
Taraxacum officinale Weber	R/CSR	13	18	31	0.3544
Thymus serpyllum L.	S	34	196	230	2.6298

Trifolium arvense L.	R/SR	19	0	19	0.2172
Trifolium campestre Schreber	R/SR	0	5	5	0.0572
Trifolium dubium Sibth.	R/SR	15	0	15	0.1715
Trifolium pratense L.	CSR	13	0	13	0.1486
Verbascum nigrum L.	C/CSR	0	2	2	0.0229
Veronica spicata L.	SC	0	105	105	1.2005
Vulpia myuros L. C.C. Gmel.	R/SR	0	53	53	0.6060
	Nearest type	**# types**	**C**	**S**	**R**
	S/CSR	**15**	**0.115**	**0.582**	**0.303**

7.3.2 Comparing EGR vegetation types by adaptive strategies

The second part of the spreadsheet tool (Hunt et al., 2004) compares the vegetation of up to three sites and calculates the proportionate difference in adaptive strategies between sites. This works very well here, since three major distinctions were identified by the cluster analysis: i) "Pitched Sedum meadow" (Killesberg); ii) "Species-poor Sedum roof" (Pliensau and Köngen); and iii) "Sedum meadows" (with three sub-divided clusters of two roofs each). Entering the results of the proportionate rankings for C, S, and R strategies present in each vegetation type into this part of the software tool reveals that the greatest dissimilarity between the vegetation types occurs between Species-poor Sedum roofs and the Sedum meadows (**Table 7.8**).

Table 7.7. Comparator tool output for three EGR vegetation types by CSR proportionate cover.

3 main EGR vegetation types	**C**	**S**	**R**
"Pitched Sedum meadow"	0.034	0.741	0.225
"Species-poor Sedum roofs"	0.036	0.884	0.080
"Sedum meadows" (3 types)	0.063	0.710	0.227
Measure between:	**Difference**		**Distance**
"Pitched Sedum meadow" **and** "Species-poor Sedum roofs"	C	0.002	0.1663
	S	0.143	
	R	-0.145	
"Species-poor Sedum roofs" **and** "Sedum meadows" (3 types)	C	0.027	0.1873
	S	-0.174	
	R	0.147	
"Pitched Sedum meadow" **and** "Sedum meadows" (3 types)	C	0.029	0.0344
	S	-0.031	
	R	0.002	

All three EGR vegetation types had negligible cover by C-strategists (0.034; 0.036; 0.063, respectively). The “Species-poor Sedum roof” had the greatest proportionate representation by S-strategists (0.884) and the lowest by R-strategists (0.080), probably because the two roofs in this cluster had the smallest species lists, of which the majority were Sedums. Few R-strategists were identified on that roof; the dense Sedum cover and lack of bare substrate clearly prevented opportunities for colonization. The other two vegetation types (“Pitched Sedum meadow” and “Sedum meadows”) had similar proportions of S-strategists (0.741; 0.710, resp.) and R-strategists (0.225; 0.227, resp.). These roofs supported more diverse vegetation than the “Species-poor Sedum roofs”, likely the result of gradients like microclimates issued by shade and shelter, as well as patches of bare substrate that supported small-statured ruderal species. The triangle diagram illustrating these results (**Figure 7.4**) shows that the roofs clustered as “Species-poor Sedum roof” occur close to the S-corner while the other two clusters defined as different sorts of “Sedum meadow” are a bit further from the S-corner in the direction of the R-corner. All three are located extremely low on the S-R axis.

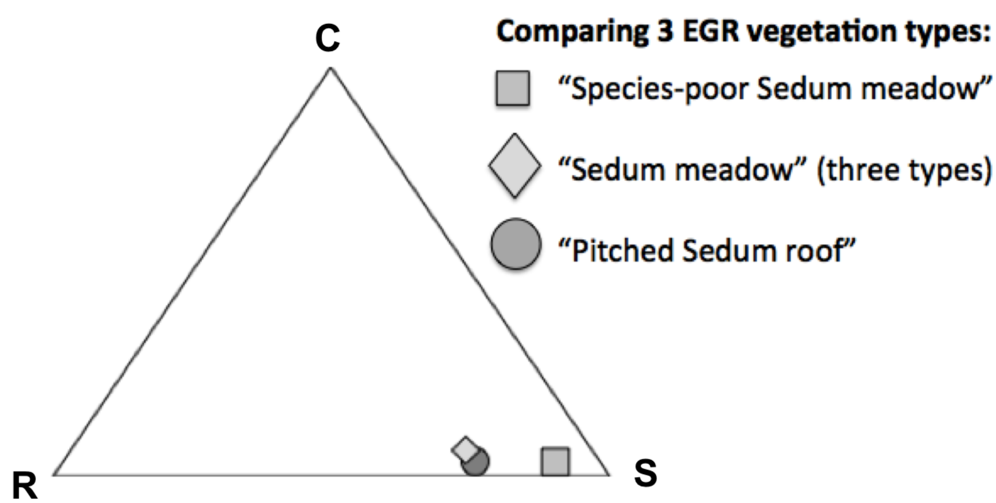


Figure 7.4. Comparative results of CSR classification for three roof types: Species-poor Sedum roof (S); Sedum meadows (S/SR); and Pitched Sedum roof (S/SR).

7.3.2.1 Discussion: EGR vegetation types in CSR space

This analysis confirms the observation that EGR vegetation largely comprises stress-tolerators (S) and stress-tolerating ruderals (SR), and reinforces other analyses from previous chapters that site-specific features (slope, aspect) and micro-climate (shade) permit a diversification of plant life strategies. Viewed from another perspective, the provision of gradients and a diversity of niches can shift EGR vegetation from “Species-poor Sedum roofs” in the S-corner to support a more diverse flora. This is hardly a new insight: ecology-oriented EGR research has consistently advocated the inclusion of topographic variation and heterogeneous substrates as essential for biodiversity (Mann, 1996, Mann, 1999, Buttschardt, 2001, Brenneisen, 2009, Kadas, 2011).

Another explanation for the strong S/SR classification of these old EGRs may reflect the properties of their growing substrates. The soil cores collected tended to be loosely bound aggregates whose particle cohesion was often similar to that of recently installed substrates, which makes them skeletal by definition (IUSS and WRB, 2014). Some ecological studies of green roofs have observed minimal horizon formation on mineral-based roof substrates (whether gravel, TPG or EGR roofs) decades to a century after installation (Darius and Drepper, 1983, Bossler and Suszka, 1988, Bornkamm, 1961, Köhler and Poll, 2010, Poll, 2008, Thommen, 1988). The skeletal nature of shallow rooftop substrates will affect any soil ecological processes with likely feedbacks with the vegetation. Indeed, many of the analogue habitats from which species were selected and then screened for green roofs are defined by free-draining, low nutrient soils (recall Chapter 1).

7.3.3 Quantifying EGR vegetation change over time

Successional trajectories showing how vegetation has changed over time can be accomplished using original species lists and the CSR triangle diagram. A few roofs surveyed had original species lists available, although the proportions were not given. Still, with reference to the few lists available, and to practical experience designing and installing green roofs, we can be confident that EGRs are typically planted/ sown with a variety of strategists and growth forms, including a substantial proportion of stress-tolerating succulent species.

The architectural section plans for the Stuttgart Rathausgarage roof complex (PV and lower roof) provides a species list of which many were identified in the 2011 surveys. The original species list for the extensive areas of these two roofs featured thirty-five species of which eleven were pure S-strategists, fourteen were S-intermediary strategists, and ten were intermediary strategists that did not include S-strategists (**Table 7.9**). Since proportions were not available, this classification is based on an equally proportioned species list, which is probably not realistic, but serves the purpose of illustration. According to the spreadsheet tool, the original Rathausgarage species list classified as S/CSR vegetation (**Figure 7.5**).

Table 7.8. Original species list for Stuttgart Rathausgarage roof complex (35 species, 12 CSR types)

Species/ cultivar	**CSR signature**	**Species/ cultivar**	**CSR signature**
Agrostis tenuis	CR	*Saxifraga aizoon*	S/CSR
Dianthus deltoides	S/CSR	*Sedum acre*	S/SR
Digitaria sanguinalis	SR	*Sedum album*	S
Festuca mairei	CSR	*Sedum album Coral Carpet*	S
Festuca ovina	S	*Sedum album Murale*	S
Hieracium pilosella	S/CSR	*Sedum floriferum "W. Gold"*	S
Inula hirta	SR/CSR	*Sedum hybridum*	S
Linum perenne	SR	*Sedum reflexum*	S
Nepeta musinii	C/CSR	*Sedum sexangulare*	S
Onobrychis sativa	CSR	*Sedum spurium*	S/SR
Plantago major	R/CSR	*Sedum telephium*	S/CSR
Poa compressa Reubens	SR/CSR	*Setaria viridis*	R
Poa nemoralis Enh.	SR/CSR	*Silene uniflora "Weisskehlchen"*	CSR
Polygonum aviculare	R	*Thymus pulegioides*	S
Potentilla argentea	S/CSR	*Thymus serpyllum*	S
Potentilla verna	S	*Trifolium arvense*	R/SR
Rumex acetosella	SR/CSR	*Veronica spicata*	SR
Saponaria ocymoides	C/CR		

Nearest type	**# types**	**C**	**S**	**R**
S/CSR	12	0.131	0.588	0.281

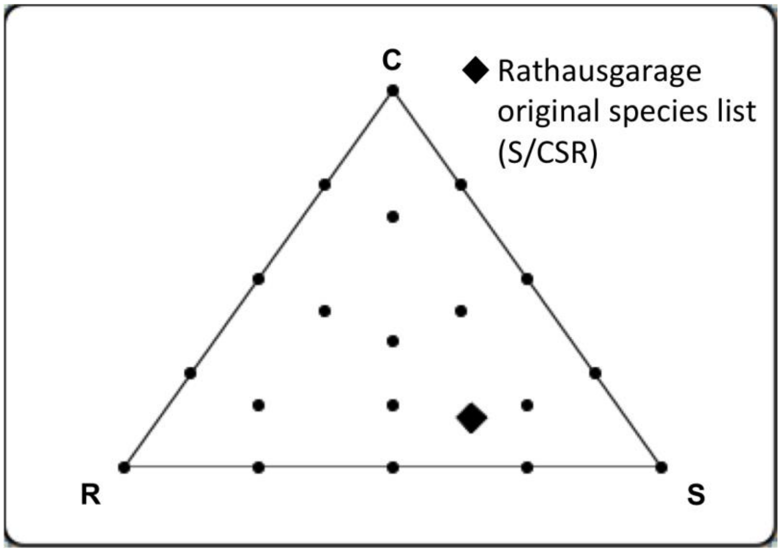


Figure 7.5. The original species list for Stuttgart Rathausgarage roofs classified as S/ CSR vegetation.

The two EGRs on this complex were apparently installed within days of each other and used the same materials, specifications and methods. Yet, on the basis of the 2011 surveys, the vegetation on each roof developed somewhat differently. The lower roof, which recorded thirty species, was classified as a “Floristically-diverse Sedum meadow” (together with FH Nürtingen), while Rathaus PV recorded twenty-six species and was clustered with Tübingen as “Sparse Sedum meadow”. Both roofs classified as S/SR vegetation (**Table 7.10**). Common to both roofs were *Linum perenne* (SR) and *Poa compressa* (SR/CSR). The majority of the pure S-strategists (four on PV; six on lower) were Sedum species but included other typical EGR species, too, like *Festuca ovina, Potentilla neumanniana* and *Thymus serpyllum.* The lower roof had eight pure R-strategists, of which seven were xeric bryophytes and one, *Setaria viridis*, was common to both roofs. This marks the divergence in vegetation character of the two roofs, as the more exposed PV roof had more S-strategists while the sheltered lower roof had more R-strategists. The roofs shall henceforth be described separately.

Table 7.9. Adaptive strategy proportions on the two Rathaus roofs after 21 years

Rathausgarage roofs	**C**	**S**	**R**	**Nearest type**
Original list (1990)	0.131	0.581	0.288	S/ CSR
Rathaus PV (2011)	0.011	0.657	0.332	S/SR
Rathaus lower (2011)	0.041	0.632	0.327	S/SR

The “Sparse Sedum meadow” on Rathaus PV was defined by S-strategists (seven species) followed by stress-tolerant ruderals (SR) as the next most abundant strategy (six species) (**Table 7.11**), of which the majority were bryophytes but also included two forbs that make a strong impression throughout summer, *Linum perenne* and *Veronica spicata*. The next most abundant grouping was S/CSR, of which the five species included typical EGR species like *Allium flavum, Dianthus carthusianorum, D. deltoides, Hieracium pillosella* and also *Potentilla erecta*. The two R/ CSR species included *Picris hieracioides* and *Taraxacum officinale*, both wind-dispersed weedy species. Finally, the two pure ruderals (R) on this roof comprised a xeric moss and the annual grass, *Setaria viridis.*

Table 7.10. The species composition for Rathaus PV in 2011 comprised seven CSR strategies.

Rathaus PV species list (S/SR)	Total abundance (%)	Proportionate abundance (%)	CSR strategy
Allium flavum L.	90	1.85	S/CSR
Crepis tectorum L.	520	10.69	R/SR
Dianthus carthusianorum L.	48	0.99	S/CSR
Dianthus deltoides L.	18	0.37	S/CSR
Festuca ovina L.	129	2.65	S
Hieracium pilosella L.	87	1.79	S/CSR
Lichen_Cladonia cf scabriscula (Huds.) Schrader	107	2.20	S
Lichen_Peltigera spp.	10	0.21	S
Linum perenne L.	307	6.31	SR
Moss_Hypnum1	163	3.35	S
Moss_Bryum2	148	3.04	SR
Moss_Starry yellow	40	0.82	SR
Picris hieracioides L.	3	0.06	R/CSR
Poa compressa L.	9	0.19	SR/CSR
Potentilla erecta (L.) Räuschel	39	0.80	S/CSR
Potentilla tabernaemontani Ascherson	122	2.51	S
Sedum hybridum L.	474	9.75	S
Sedum rupestre L.	1191	24.49	S
Sedum sexangulare L.	342	7.03	S
Sedum telephium L.	4	0.08	S/CSR
Setaria viridis (L.) P.B	851	17.50	R
Taraxacum officinale Weber	21	0.43	R/CSR
Thymus serpyllum L.	50	1.03	S
Trifolium campestre Schreber	51	1.05	R/SR
Veronica spicata L.	39	0.80	SR
# types	**C**	**S**	**R**
7	0.011	0.657	0.332

Although the vegetation of the Rathaus lower roof classified identically (S/SR) with its neighbour, the thirty species of this "Floristically-diverse Sedum meadow" encompassed four more adaptive strategies (**Table 7.12**). Following the dominant strategists as described above, Rathaus lower roof had three of the same R/CSR strategists (*Petrorhagia prolifera, Picris hieracioides, Taraxacum officinale*), two of the same R/SR species (*Crepis tectorum, Trifolium campestre*), as well as a third ruderal stress-tolerator (*Vulpia myuros*). Unlike PV, the lower roof had a number of C-intermediary strategists, likely owing to the more sheltered conditions here. The single C/SC strategist was an *Acer* seedling, and the two C/CSR strategists were *Potentilla recta* and *Verbascum nigrum*.

Table 7.11. The thirty species recorded at Rathaus lower roof (2011) comprises eleven life strategies.

Rathaus lower roof species list (S/SR)	**Total abundance (%)**	**Proportionate abundance (%)**	**CSR strategy**
Acer pseudoplatanus L.	1	0.022	C/SC
Allium flavum L.	74	1.598	S/CSR
Crepis tectorum L.	509	10.994	R/SR
Dianthus carthusianorum L.	283	6.112	S/CSR
Festuca ovina L.	116	2.505	S
Hieracium pilosella L.	210	4.536	S/CSR
Lichen_Cladonia cf scabriscula (Huds.) Schrader	15	0.324	S
Lichen_Peltigera spp.	4	0.086	S
Linum perenne L.	168	3.629	SR
Moss_Hypnum1	183	3.952	S
Moss_Bryum1	100	2.160	SR
Moss_Brachythecium cf. albicans1 (Hedw.) Schimp	96	2.073	SR
Moss_Brachythecium cf. albicans3 (Hedw.) Schimp	67	1.447	SR
Moss_Bryum2	235	5.076	SR
Petrorhagia prolifera (L.) Ball & Heywood	30	0.648	R/CSR
Picris hieracioides L.	17	0.367	R/CSR
Poa compressa L.	42	0.907	SR/CSR
Potentilla tabernaemontani Ascherson	167	3.607	S
Potentilla recta L.	36	0.778	C/CSR
Sedum acre L.	1	0.022	S/SR
Sedum hybridum L.	280	6.048	S
Sedum rupestre L.	879	18.985	S
Sedum sexangulare L.	143	3.089	S
Setaria viridis (L.) P.B	595	12.851	R
Taraxacum officinale Weber	18	0.389	R/CSR
Thymus serpyllum L.	196	4.233	S
Trifolium campestre Schreber	5	0.108	R/SR
Verbascum nigrum L.	2	0.043	C/CSR

Veronica spicata L.	105	2.268	SC
Vulpia myuros L. C.C. Gmel.	53	1.145	R/SR
# types	**C**	**S**	**R**
11	0.041	0.632	0.327

The lower Rathaus roof had a much stronger presence of intermediary R-strategists than the PV roof, yet the location of these two roofs within CSR space suggests that they are more similar to each other than to the vegetation with which they were both originally planted (**Figure 7.6**). This suggests a compositional shift from S/CSR vegetation towards the ultimate position of S/SR. The uncertainty of the original species list and its proportions may limit the degree of confidence in the universality of this shift. Still, given the results from the substrate analyses and substantiation from other studies (Buttschardt, 2001, Poll, 2008), not to mention personal observation and intuition, it is reasonable to expect that shallow EGRs in a climate like that of south-west Germany will shift to a more simple vegetation, dominated by stress-tolerant ruderal strategists, including colonising bryophytes.

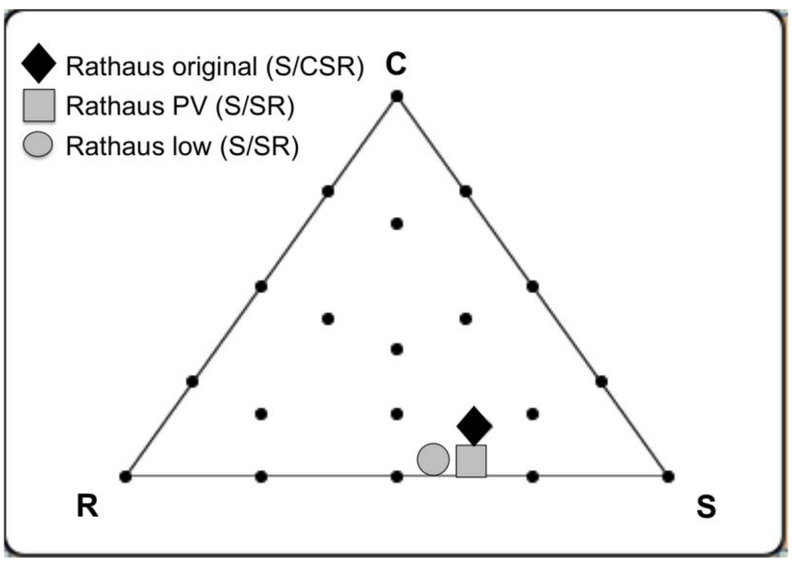


Figure 7.6. The vegetation surveyed in 2011 on Rathausgarage roofs can be described as S/SR vegetation, shifting from the S/CSR location of the original (though not proportional) list.

7.3.3.1 Discussion: successional trajectories on EGRs using CSR theory

The results from these analyses suggest that the EGR vegetation sampled here ranges between S- and S/CSR communities, but S/SR vegetation was the most prevalent vegetation observed. One of the aims of the research was to propose models illustrating and predicting vegetation change on EGRs over time, using plausible ecological theories, so this section will combine these results with different applications of ecological theory. Assuming that the initial species list for the Rathausgarage complex is not uncommon, and bringing together the results of this chapter thus far, **Figure 7.7** proposes a generalized successional trajectory that explains how EGR vegetation changes over time with reference to plant strategies. Initial vegetation is located in the S/CSR part of the triangle, and vegetation shifts to either of two main types: the "Species-poor Sedum roof" (S) or the "Sedum meadow" (S/SR), of which there are various types. The timeframe here is based on the observations made by this work, so twenty years or more after installation. It's possible, probably even likely, that smaller shifts continually occur throughout a growing season, and that the processes are much more dynamic.

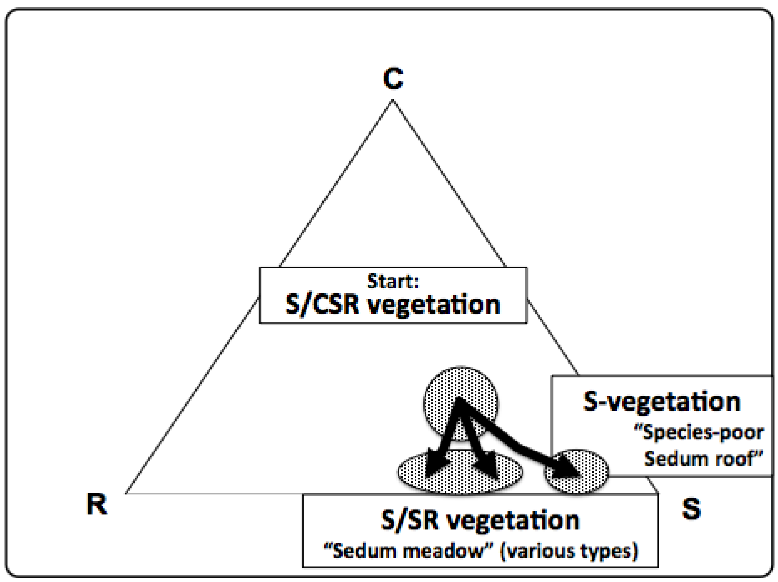


Figure 7.7. Proposed successional trajectories for Sedum-based EGR systems.

The successional trajectories that EGR vegetation take are influenced by various conditions and factors, as discussed in previous chapters, whether site specific (shade, aspect, slope) or owing to the system design and construction (substrate depth and composition). However, other factors that were not measured likely play a role as well, including mechanisms associated with persistence and regeneration, stress imposed by drought and the greater environment (irradiation, temperature, precipitation, pollution), or feedback mechanisms between vegetation and soil. Such factors could for example cause the vegetation of large and unshaded EGRs to deflect more steeply towards the S-corner, while EGRs with some provision of shade and shelter would tend towards S/SR character.

Building upon these results for various EGR vegetation types, green roof types were added into Gilbert's (1989) adaptation of the CSR model for urban habitats (**Figure 7.8**). The clear circles represent that author's allocations of different urban habitats into CSR space, and the additional green roof types are shaded. As per the results here, Sedum-based EGRs are located in the S-corner of the triangle and extend along the S-R axis. The "living roof" designed for Black Restarts, which is basically an EGR replicating brownfield habitat, was located more towards CSR since these systems are slightly richer than EGRs (Kadas, 2011). Recalling the Lake Water Filtration Facility near Zurich, "Swiss orchid roofs" were located towards the centre of CSR space since this mesic vegetation includes a variety of herbaceous perennials and bulbs (but no Sedums). This vegetation type is still closer to the S-R axis than either of the other two axes because the rooftop habitat is prone to disturbance and stress.

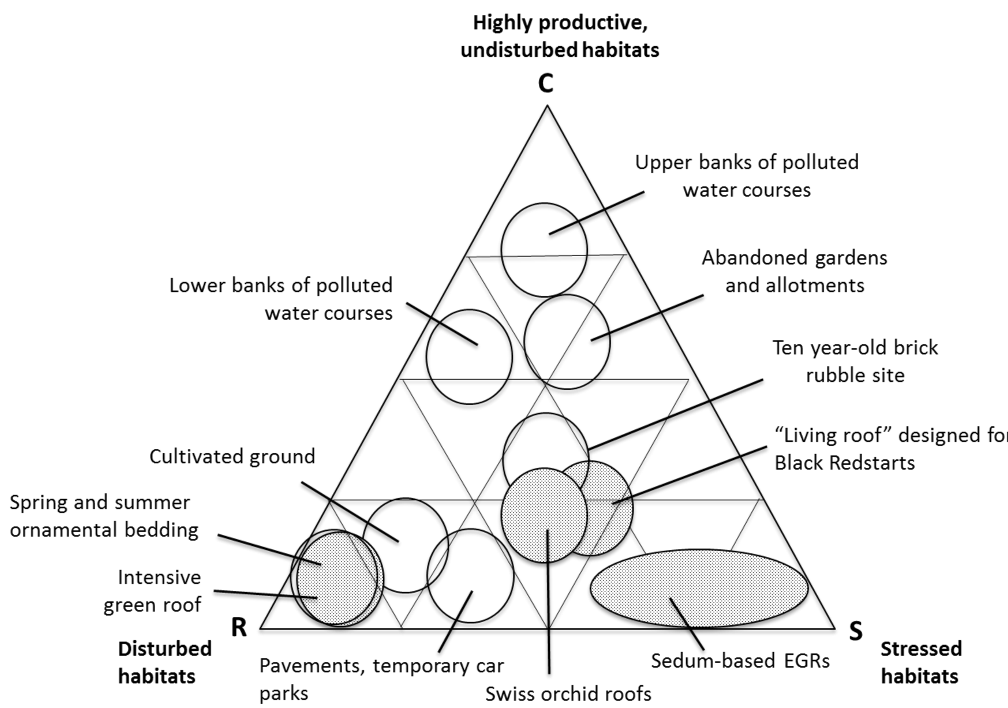


Figure 7.8. Compared with other urban habitats, extensive green roofs (EGRs) are among the most stressful with vegetation limited predominantly to S-strategists, or stress tolerators. Modified from Gilbert (1989) (p. 16).

At the opposite end of the green roof spectrum, highly maintained intensive green roofs were located in the R corner of the CSR triangle. Intensive green roofs that are used as roof gardens are probably just as "disturbed" as ornamental bedding, though they probably have much greater range than is proposed here. From the perspective of landscape management, cultivation is one of the most common forms of disturbance (Hitchmough, 1994), which explains why Gilbert (1989) allocated seasonal ornamental bedding to this corner.

7.3.4 Modeling successional change on EGRs over time: conceptual framework

The role of factors that could not be measured but which bear meaning to vegetation dynamics will be introduced in this final section which will propose a conceptual model of EGR vegetation change over time. Conceptual models on natural succession have continually built upon the classic Clementsian view and applied various methods for treating vegetation. This section shall more closely consider the causes and mechanisms that led to the results of the previous section, as well as filters that regulate species entry and exclusion into plant communities. The models proposed thereby combine the findings from this research with observations and findings from other works, and use theoretical constructs from plant ecology.

7.3.4.1 Framework of successional causes and mechanisms

The specific mechanisms that lead to changes in plant community composition occur both within and outside the system, and are due to different general causes. “Mechanism” in ecology connotes an interaction that is nested within the entity or system to be explained (Pickett et al., 1994), meaning it is a subtle driving force that can have varying degrees of impact on the processes of that system. The general causes can be organized hierarchically within a framework that allows the identification of different types of causes and relationships operating within the processes of change, while independently allowing consideration of varying levels of detail without compromising overview. A three-level hierarchical framework from contemporary process studies of succession by Pickett et al. (1987, 2009) was adapted to outline the general causes and specific mechanisms leading to vegetation change on EGRs (**Figure 7.9**). This arrangement emphasizes a mechanistic approach to understanding, rather than a focus on the net effects of species interactions (Pickett and McDonnell, 1989, Pickett et al., 2009). In order to clarify their role to vegetation change on EGRs, these will be introduced and then incorporated into a diagrammatic model of multi-layered processes.

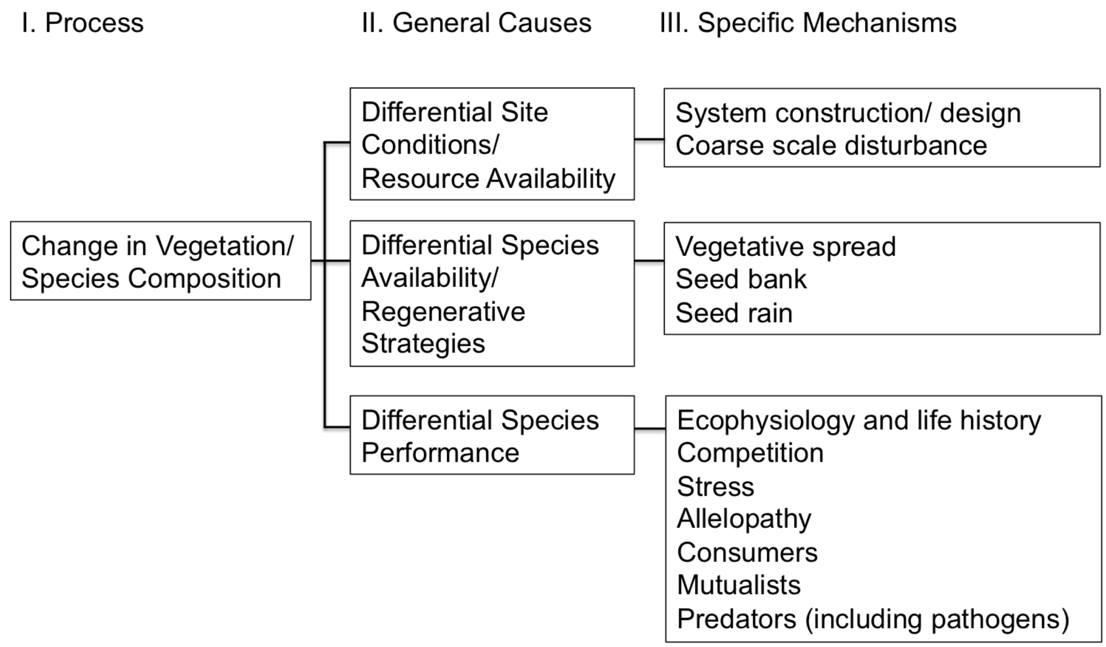


Figure 7.9. A hierarchical causal framework for EGR vegetation dynamics. Adapted from Pickett et al. (1987, 2009).

The first level in the framework (I. Process) specifies the most inclusive processes with the broadest, minimal defining phenomena. In other words, the process of interest here, natural succession, is specified as change in vegetation or species composition. The second level (II. General Causes) presents three major causes of natural succession, namely differential site conditions, differential species availability and differential species performance. The third level (III. Specific Mechanisms) consists of the particular mechanisms that determine the outcome of the three general causes, and are discernable or quantifiable at specific sites. Interactions may occur across all levels of this causal framework. For example, repercussions from the mechanisms of coarse scale disturbance will influence the other two general causes influencing vegetation change, the differential species availability and species performance. The causes of vegetation dynamics may each act independently or jointly in various combinations. Since these causes and mechanisms were not measured, they will be described in some detail before integrating them into a diagrammatic model of EGR successional change.

7.3.4.1.1 Differential site conditions

The basic resources available at a site and the incidence of coarse scale disturbance are two site-specific features that can direct the influence of differential site conditions on vegetation dynamics (Pickett et al., 2009). For green roofs, resource availability is determined by the system construction and design, in particular substrate composition and depth. Coarse scale disturbance on EGRs may be issued by slope, aspect, geographic location, maintenance frequency and intensity, and so on. Coarse scale disturbance influences vegetation when events like drought or extreme temperatures damage plant biomass or open the soil or substrate through cracking, erosion or scouring. The severity of the disturbance event, the area affected, the spatial heterogeneity within the site, the spatial relationship to other disturbed areas, and the temporal frequency of disturbances can all affect the conditions of the opened site (Pickett and White, 1985, Coffin and Lauenroth, 1989, Dale et al., 1998). Likewise, the availability of soil resources, especially nutrients and moisture, critically influences individual plant growth, population dynamics, competitive interactions, community structure, and successional change (Bazzaz, 1996).

i) *EGR system construction as mechanism of successional change*

The direction of vegetation change on EGRs can partly be attributed to their construction and the system used. Extensive green roofs are the product of decades of research and development, and the stable Sedum roof may well epitomize the low-maintenance, self-sustaining ideal. Commercial EGR systems regulate resource availability and disturbance intensity through the shallow, free-draining, mineral substrates and drainage elements. It is meaningful here to consider that alternative green roof constructions with the same loading constraints can support different flora. Experiments with wetland species have shown that green roofs can support mesic species (MacIvor et al., 2011, Song et al., 2013), and a few projects exemplify this potential, such as the wetland roof installed on the Victoria & Albert Museum in London (The Green Roof Consultancy, 2013). Orchids can also be cultivated on extensive green roofs given the appropriate conditions (Schneider, 2012). The Swiss technique of spreading hay from species-rich dry meadows onto extensive green roofs based by an organic substrate (100 mm water absorbent foam or straw and 50 mm natural topsoil) eventually comes to replicate the species composition of those meadows (Brenneisen, 2012). The species composition of those roofs may well be dominated by S-strategists, but lacking plant ecological studies limit this knowledge.

ii) *Coarse scale disturbance as mechanism of successional change*

Countless studies have observed that stress imposed by drought (and/ or lacking moisture) is the main controlling factor directing EGR species composition over time. There is mounting evidence that influence of drought on EGRs will vary depending on site productivity since species and phenotypes adapted for less fertile microhabitats are be more resilient in face of drought (VanWoert et al., 2005, Monterusso et al., 2005, Rowe et al., 2006, Durhman et al., 2007, Getter and Rowe, 2008, Nagase and Dunnett, 2010, Nagase and Dunnett, 2011, Schroll et al., 2011). Exposure is a source of coarse scale disturbance for green roofs, whether as direct solar radiation, unabated wind, or exposure to hail, intensive rainfall, or other. Shading provisions for reducing solar exposure can improve EGR plant cover and diversity (Köhler and Poll, 2010), particularly when combined with greater depths (80 vs. 100 mm) (Getter et al., 2009). Shelter from wind can reduce evapotranspiration rates, thereby helping to preserve water availability in the growing substrate (Bates et al., 2013).

Very severe environments with open and sparse plant cover do not show consistent patterns of vegetation change, presumably because autogenic influences and competition are minimal (Burrows, 1990). Even when vegetation in some extreme environments seem to be stable in the sense that the general composition is maintained on the same area of ground, this may be a result of the limited niche variety, combined with the relatively wide fundamental niches of species in those habitats. In other words, the vegetation of severe environments may be in a continual state of flux in terms of local changes, though the overall vegetation complex seems to be stable and resilient in face of disturbance. The limited range of species that can inhabit severe sites may therefore be attributed more to life history strategies, physiological specialization, vital attributes, etc. than to vegetation dynamics (Noble and Slatyer, 1980, Lavorel and Garnier, 2002, Chapin et al., 1994). Although no research has formally quantified coarse scale disturbance for EGRs, it seems that severe conditions do occur at least periodically (Rumble and Gange, 2013).

7.3.4.1.2 Differential species availability

Successional change can be simplified as the "dynamic balance between colonization and extinction" (Usher and Jefferson, 1990) (p. 149). A major insight into natural succession was that the disturbance that initiates change is often the very access point by which many individuals and species arrive (Pickett et al., 2009, Grime and Pierce, 2012). The second general cause of vegetation change on EGRs is therefore related to the species pool, or differential species availability and regenerative strategies. The propagules which give rise to plant communities are derived from immigrant and resident propagules, including vegetative parts but also seed rain and seed bank. Seeds are the primary means whereby plants colonize new sites, and also represent a stage in a plant's life cycle where it can resist unfavourable environmental conditions (Harper, 1977). Beyond vegetative spread, local seed bank and dispersal by seed rain are two specific mechanisms that determine differential species availability for EGRs.

The CSR successional models developed by Grime (1987, 2001) illustrate the role that abundantly dispersed propagules (*W*), vegetative spread (*V*), persistent seed bank (B_s) and persistent seedlings (B_{sd}) have on uninterrupted successional trajectories of certain habitats (**Figure 7.10**). In low fertility sites, like calcareous grassland, where succession is initiated by a disturbance, recolonisation usually involves species that produce an abundance of small, wind-dispersed seeds (*W*). As the vegetation attains dense cover, vegetative spread becomes more prevalent and those small, relatively fast-growing species must wait for renewed disturbance. Once resource limitation becomes the dominant selective force, the most successful regenerative strategy combines vegetative expansion (*V*) with a seed bank of persistent seedlings (B_{sd}), which are recruited from established populations (Grime, 2001). On skeletal sites, regeneration by *W* is not an effective mechanism of persistence and is replaced by perennial species that can expand vegetatively (*V*) and establish founder populations. This model predicts that a bank of persistent seedlings (B_{sd}) plays an inconspicuous but important role throughout primary succession.

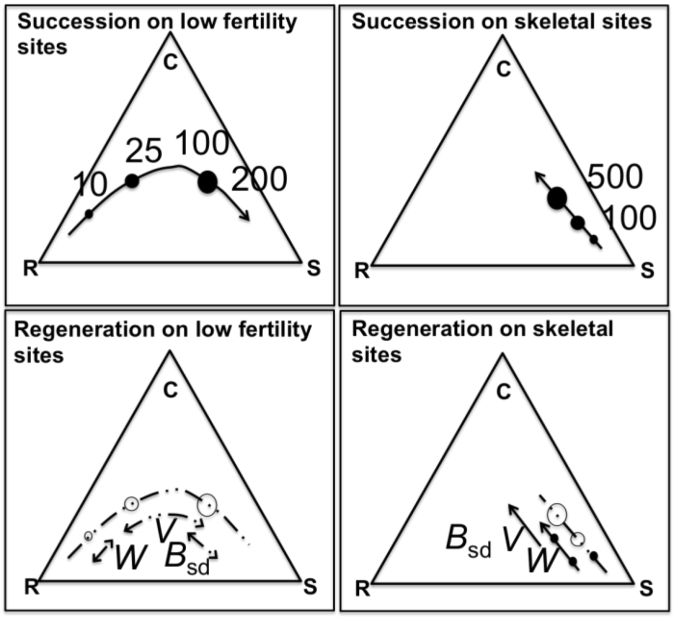


Figure 7.10. The role of regenerative strategies in the successional pathways of low fertility sites (left) and of skeletal habitats (right). *W* = numerous, small, widely dispersed propagules; *V* = vegetative spread; B_s = persistent seed bank; B_{sd} = persistent seedlings. Adapted from Grime (2001).

7.3.4.1.3 Differential species performance

Once the species are in place, the differential performance by those species further determines vegetation dynamics and change. Species, as well as individuals within a given species, often perform differently from one another (Pickett, 1976, Tilman, 1982), and species performance includes the responses of physiology, architecture, and life history to the environment (Grime, 1977, Noble and Slatyer, 1980, Connell et al., 1987, Pickett et al., 1987). In terms of growth, survival and reproduction, species performance will vary depending on resource availability (Grime, 2001), ecophysiology and life history (Chapin et al., 1994), competition (Grime, 1973), environmental stress (Desteven, 1991), allelochemicals (Peng et al., 2004), and by relationships with consumers, mutualists and predators (Chapin et al., 1994, Titus and Bishop, 2014). Differential species performance in this context can be exemplified by temporal offset when contrasting life cycles co-exist, such as the germination, growth and life cycle of annuals versus biennials. Also, different species can occupy the same space at different times when resource demands are contrasted, such as species requiring high levels of light dominating earlier in succession on infertile soils while those requiring high nitrogen occur later (Tilman, 1988, Bazzaz, 1996). “Floristically diverse Sedum meadows” demonstrate temporal co-existence well: grasses and forbs overshadow the Sedum ground cover when moisture is not limited, but die back in dry summers such that Sedums maintain the prevalent vegetation cover. Such species lists indicate the degree of climatic and ecological awareness to the region in which they were developed, and the intent of consistent plant cover on EGRs.

7.3.5 Ecological filters influencing EGR vegetation dynamics

Selective filters will further regulate entry and exclusion of species from a site and will complement this conceptual framework. Responsive with the dynamics of a site and occurring at all levels, filters operate generally, with regional factors modifying the relative strength of their effects (Williams et al., 2009). For example, seasonal drought and disturbances from climate can exert selective pressure that exclude unsuitable phenotypes from a site and permit some functional types to enter and persist (Woodward and Diament, 1991). Species that colonize and persist in urban habitats can be considered a subset of the regional species pool, from which successful traits are selected, or filtered, by urban environmental conditions and human preference (Williams et al., 2009). On extensive green roofs, disturbance and environmental stress are two obvious filters that determine whether a species or growth form can persist or colonise a roof. If the vitality of planted or sown species is compromised by drought, if they are outcompeted by more vigorous species, and/ or if their seeds or vegetative parts are not viable, then these species become filtered out of that plant community and make space for other species, such as colonisers with suited dispersal strategies. In other words, competition, stress and disturbance can be treated as ecological filters that determine the species and adaptive strategies that persist over time.

A key element from Universal Adaptive Strategy Theory (UAST), the **twin-filter model of community assembly** proposed by Grime and Pierce (2012) builds upon theoretical models of disturbance and community ecology (i.e., intermediate disturbance hypothesis and humped-back model). In the first part, the ***CSD filter*** determines the primary adaptive strategies that may enter a habitat from a species pool, which includes intentionally planted species and their seed bank as well as spontaneous colonisers. Successful establishment is limited to the subset of the strategists from that pool that can survive the CSD equilibrium prevailing in that habitat (**Figure 7.11**). Sites of varying productivity and disturbance will admit suitable strategies and exclude unsuitable ones. This filter selects on a day-to-day basis for convergence (similarity) in the general adaptive strategies that can survive locally, and is very important in early- to mid-successional stages (Grime and Pierce, 2012).

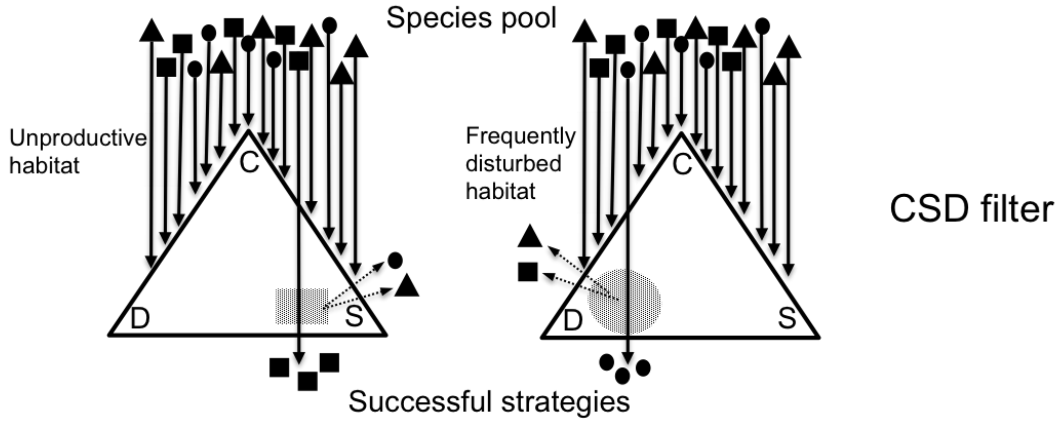


Figure 7.11. The CSD filter excludes adaptive strategies (represented by different geometric shapes) from niches characterized by contrasting levels of productivity and disturbance, sorting the local species pool into admissible and inadmissible strategies. Adapted and used with permission from Wiley & Sons, Ltd.

When individuals from the species pool have passed through the CSD filter, they are subjected to secondary pressures by the “proximal selection pressures filter”. This ***proximal filter*** represents the worldly conditions of a particular site because it is defined by innumerable factors, such as local pollinators or the presence of seed dispersal vectors. Notably, the traits of this filter are independent of CSR adaptive strategies. **Figure 7.12** details three possible scenarios of divergence determined by the proximal filter. In some cases, species (black arrow) cannot pass the filter because none of the individuals (white arrows) are suitably adapted (**Figure 7.12a**), while those individuals that are suitably adapted (e.g., by intraspecific trait variability) may enter and become established within the community (**Figure 7.12b**). Divergence occurs when two sub-populations with extreme trait values find suitable niches, while individuals with average traits do not (**Figure 7.12c**). To this end, the proximal filter selects intermittently against particular traits, rather than the strategy as a whole, and the resulting micro-evolutionary trait divergence has consequent implications for eco-evolutionary feedback, which may initiate sympatric and allopatric speciation and thus adaptive radiation. Single traits or small sets of traits differing between coexisting species with similar CSR strategies may represent subtle evolutionary differences that increase local biodiversity. United as a series of filters, the CSD equilibrium is a major determinant of ecosystem processes because it selects traits governing the movement of matter and energy (Grime and Pierce, 2012).

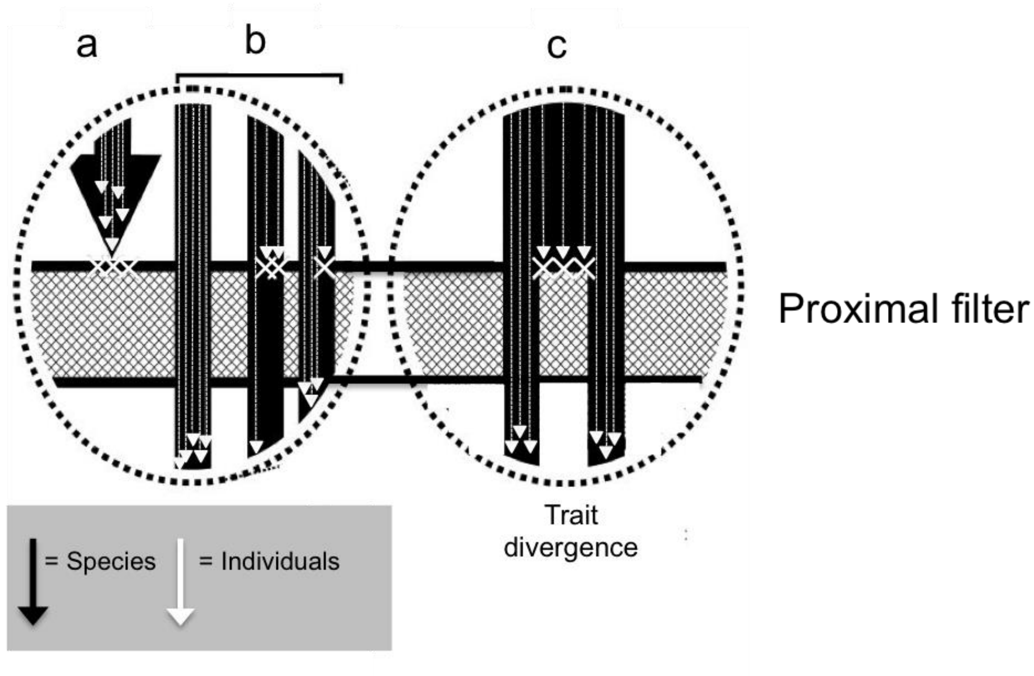


Figure 7.12. The proximal filter of community assembly, showing how species (black arrow) and individuals (white arrows) must pass through selection filters in order to enter a community. Adapted and used with permission from Wiley & Sons, Ltd.

7.3.6 Modeling EGR vegetation assembly over time

The causes and mechanisms driving successional change will combine in all sorts of relationships, but the twin filters (CSD and proximal filters) determine the final outcome of entry and exclusion into a community. This section integrates Grime and Pierce's (2012) twin filter model with the hierarchical causal framework for EGR vegetation dynamics outlined earlier in order to explain EGR vegetation dynamics, with particular reference to species availability and performance, disturbance issued by exposure, and stress caused by limited substrate depths and drought. These factors all exert pressures on the vegetation, independently and in combination, and across various scales of time. Interpreted through the model of the CSD filter, EGR vegetation after twenty years is located towards the S-corner of CSD equilibrium (the grey area in **Figure 7.13)**, having emerged as a result of general causes and specific mechanisms.

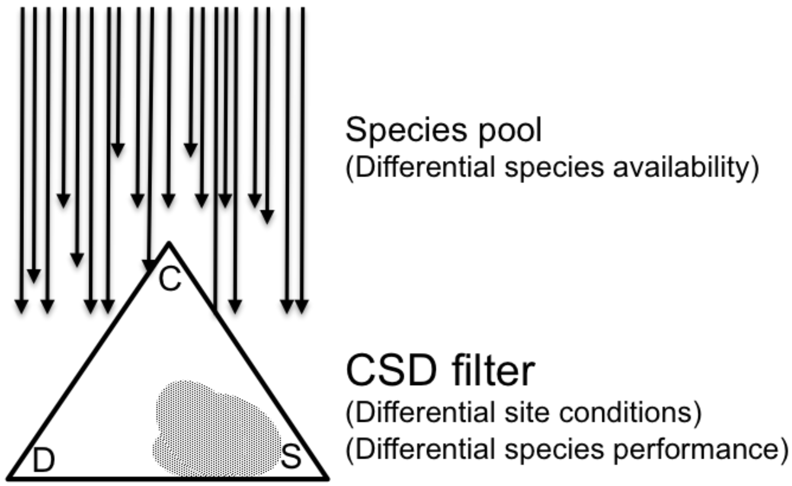


Figure 7.13. The CSD filter on EGRs leads to species composition predominated by S-strategists.

Beyond this general location in CSR space, the vegetation of the roofs surveyed was classified into several types, and their formation over time can be explained using the secondary, proximal filter (**Figure 7.14**). This filter is subject to the same causes and mechanisms as the CSD filter, but refines EGR species composition through exponentially more factors. These may include physical factors, like degree of maintenance (e.g., supplemental nutrition, frequency of weeding, elevation above the ground, or roof age); ecological factors (e.g., pollination, soil fauna populations, bird activity and associated fertilization); geochemical factors (e.g., atmospheric deposition, heat island effect, pollution), and any number of other effects. The factors represented by this filter are too numerous and interactive to itemize, but the obvious ones will be described in order to explain the divergence of trajectories.

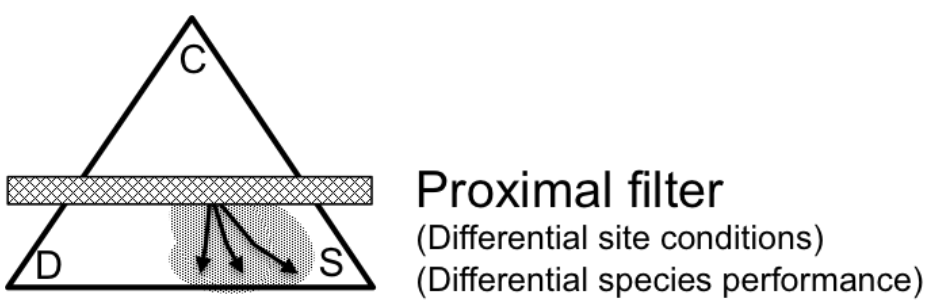


Figure 7.14. The proximal filter on EGRs leads to divergence in EGR vegetation types.

The realized communities defined for the EGR vegetation types identified can be explained by integrating the twin filter model with conceptual input from the hierarchical causal framework of vegetation change (**Figure 17.15**). As a simple example, the species composition of the "Species-poor Sedum roofs" (S-vegetation) was dominated by a few Sedum species/ cultivars. This vegetation had ostensibly attained dominant cover through vegetative spread, but likely also by other factors. The substrate on these two roofs, for example, probably played a key role in the vegetation dynamics over time; both roofs had the lowest records for air content at MWC and a few other parameters fell beyond the FLL guidelines maintained by the other EGRs surveyed. Even without assuming that the initial vegetation was more diverse, or located at S/CSR, Sedum dominance might be maintained on these roofs through feedbacks, whether from physical saturation of the species pool (by vegetative and sexual propagules) or by competitive regulation of entry and persistence of other growth forms (e.g., dense competitive spread, low pH, perhaps biochemical root exudates). By contrast, the more species diverse "Sedum meadow" variations were associated with more diverse site conditions and with greater availability of local seed rain as provided by deeper mounds in other parts of the roof.

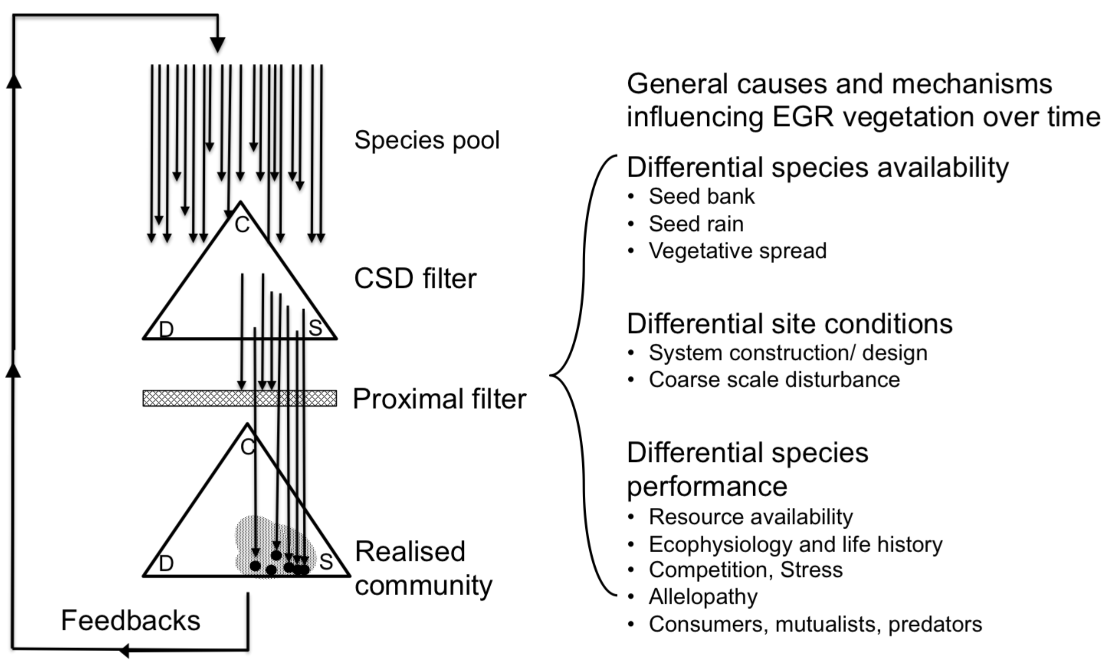


Figure 7.15. A series of ecological filters as well as feedback mechanisms determine species composition on EGRs over time.

The plant communities that emerge on EGRs after the succession of causes, mechanisms and filters will vary in accordance with the conditions and factors of the site and species. The dominant S-strategists maintain their dominance through their optimally suited strategies for surviving the recurrent stress and disturbance associated with shallow mineral substrates, high degrees of exposure and, possibly, through subtle competitive exclusion by feedbacks with substrate conditions, like low pH. On EGRs, the abandonment of roof maintenance may lead to the establishment of tree seedlings (C-strategists), though these rarely survive due to limitations like rooting depth (Buttschardt, 2001). When patches of particularly shallow substrates become cracked by drought or frost, only suitably adapted growth forms can establish (R-strategists) though persistence over the long term may be limited to stress tolerators (S-strategists).

7.4 Conclusions

7.4.1 To propose models illustrating and predicting vegetation development on EGRs over time

Vegetation change on EGRs over the long term was illustrated and predicted using a model that integrates a hierarchical causal framework of vegetation dynamics with a twin filter model for community composition. These two components were adapted from ground-level successional models, and the sources of reference have committed decades of rigorous science towards an improved and contemporary understanding natural succession and vegetation dynamics (Pickett, 1976, Grime, 1977, Pickett et al., 1987, Grime, 2001, Pickett et al., 2009, Grime and Pierce, 2012).

7.4.2 If successional change can be observed on EGRs, what are the main drivers and mechanisms?

The main drivers of vegetation change on EGRs relate to interactions between differential site conditions and resource availability, differential species availability and regenerative mechanisms, differential species performance, all of which are mediated by ecological filters. Numerous mechanisms are nested within the general causes of vegetation change. Resource availability is partly determined by EGR system construction and/ or design (e.g., substrate depth, substrate composition, system build-up), and coarse scale disturbances will influence the conditions for plant establishment, growth, colonization and persistence. While vegetative spread is an important mechanism by which stress-tolerators maintain dominant cover on EGRs, differential species availability hinges on the presence of seed bank and seed rain, specifically their species composition, proximity and quality, and viability for germination. Considering the prevalence of stess and disturbance on EGRs, some of the key mechanisms associated with differential species performance include ecophysiology and life history (e.g., germination requirements, growth rates, reproductive timing), although countless dynamics will also be generated by competition for resources (both within-community and predators), allelopathy (with respect to soil characteristics and microbes), community composition, patchiness, site history, microclimate, and so on. The twin ecological filters (CSD equilibrium and the proximal filter of worldly conditions) ultimately regulate species entry and exclusion onto EGR vegetation.

Our understanding of natural succession has evolved quite dramatically since the concept was first introduced, so its use for green roofs and urban ecology may benefit from more contemporary terminology. The term “climax” is encumbered with history and fraught with problems (Burrows, 1990), but many alternative terms have been proposed over the years. For example, Selleck (1960) proposed “most advanced stages”, while Bray (1958) and Park (1970) advocated “steady state”, by which they meant a “temporary state of dynamic equilibrium in an open system” (Burrows, 1990). Odum (1971) and others used the term “mature”. More recently, Pickett et al. (2009) suggest that “vegetation dynamics” more realistically portray the nature of plant community change, but recommend that “succession” as a term acknowledges the conceptual development of this theme. This research concedes with the practicality of the latter.

8 Concluding summary

This concluding chapter summarises the main points made by this research, proceeding methodically through the research aims with reference to the research questions outlined at the beginning of the dissertation.

8.1 Aim: To characterise mature EGR vegetation in terms of growth form cover and species diversity.

As a growth form, succulents were the most prevalent with the greatest cover on the roofs surveyed, and behaved contrarily to the other growth forms on most measures. Unlike the other growth forms, species richness of succulents did not correlate to their cover abundance, which reflects the fact that Sedum-dominated roofs can be extensively covered by just two or three species. Cover by succulents correlated negatively with the diversity of other growth forms, except for bryophytes. Of all growth forms, succulents showed the weakest response to roof age and substrate depth. The succulents identified classify as stress tolerators according to Grime (1977), which may partly explain why this growth form was notably immune to some of the factors that influenced the other growth forms.

In addition to the prevalence of stress tolerators, ruderals also formed an important component of long-term EGR vegetation. In the context of CSR theory, species with annual life cycles and the capacity for rapid recovery and easy colonisation indicate the degree of disturbance that EGRs sustain. This characterizes the vegetation of these old EGRs as combining both hardy and stress tolerant components together with a dynamic component of opportunistic colonizing ruderals.

One of the research questions asked whether emergent community characteristics result with time, such that roofs with similar properties end up with similar species composition/ abundance/ diversity after a period of decades. The analyses of Chapters 3 and 5 concluded that green roof vegetation is not static and that it converges over time with subtle divergences into different vegetation types.

Based on site-specific attributes for the roofs surveyed (species diversity, dominance, and ecological indicators given as Ellenberg Indicator Values), two broad EGR vegetation types were identified:

1. "Species-poor Sedum roof" (typically less than 12 species, mainly Sedums)
2. "Species-rich Sedum meadow" (typically more than 12 species, with a base cover of Sedums) of which three sub-types were described:
    2.1. "Floristically-diverse Sedum meadow"
    2.2. "Sparse Sedum meadow"
    2.3. "Sparse Sedum meadow with Chives"

With the consideration of EGRs as novel ecosystems that support anthropogenic plant communities, and recalling that phytosociological efforts of spontaneously vegetated TPG roofs could only manage very general classifications, this work hypothesises that EGRs with identical starting points, constructions, and conditions will probably converge at certain points of similarity, but not to the point of the emergence of identical and recurring species compositions. Although the classifications here were limited to nine roofs, this work reveals how previous efforts of classifying EGR vegetation have been either too simplistic (Krupka, 1992, FLL, 2008, Madre et al., 2014) or too specific (as per phytosociology but also Van Mechelen et al. 2015). Suggestions for future research are proposed in section **8.4.3**.

8.2 Aim: To characterise EGR substrate development > 20 years after installation.

This research substantiates other studies that the substrate of EGRs decline in soil pH over time and increase in soil organic content. Depth may also decrease over time, though insufficient samples with original documentation inhibit strong conclusions. Anthropogenic influence through unreported maintenance efforts was deemed a lurking variable that could influence nutrient concentrations and pH. Incidental observations of ants and earthworms suggest biological activity in the substrates and imply that soil formation processes on EGRs are possible. Still, the acidic conditions of the substrates may prevent the decomposition of organic content, which is an important soil process.

Assuming that the roofs sampled aligned with the FLL recommendations when they were installed, one of the research questions sought to establish how the physical and chemical parameters lined up with those values more than 20 years later. The physical parameters of maximum water content (MWC) and air content at MWC fell within the recommended ranges for most roofs; only the two “Species-poor Sedum roofs” (Pliensaufriedhof and Köngen) had insufficient air content and excessive MWC, while two “Sedum meadow” roofs (VB Area 2, Rathausgarage-PV) were slightly below the minimum recommendation for MWC. Most of the EGRs surveyed were near or above the limit for soil organic content. Except for the two youngest EGRs, the pH of all the roofs sampled was acidic, and below the FLL recommendations. The nutrients measured were within the recommended concentrations in all but one exception (Nitrogen, Pliensaufriedhof).

Given the lack of published research or long-term observations of EGR substrates after installation, the suggestion that substrate depth decreases over time cannot be ruled out. This is especially pertinent for regions with emerging green roof movements where the materials and methods for installation are new, and where the intuition and common sense advised by the FLL with regards to green roof design is not culturally inherent. Less substrate depth on EGRs basically means a simpler flora, dominated by stress tolerators and species with annual life cyles. Proponents stating that green roofs can support diverse vegetation and habitat for organisms would therefore be advised to take this time-based phenomenon into account, which has not otherwise been considered.

Based on the previously unknown German research, the soil organic content of old EGR substrates is probably undecomposed litter (rather than humus). Coupled with the vegetation results, this work hypothesises that the floristic simplification observed on the roofs surveyed could be at least partly due to soil-plant feedback cycles. Unlike most species, Sedums perform well in acidic conditions and, by perpetuating acidification through their litter, can become increasingly dominant over time. Although more observations are required, this work also hypothesizes that EGR substrates could potentially come to approximate natural soil processes when they support persistent populations of soil macrofauna.

8.3 Aim: To identify plausible ecological theories or models which describe the processes that occur on EGRs over time

Conceptually, the ecological models of fragmentation, island biogeography and metapopulation theory resonated with the interests of this work, but natural succession, disturbance theory, and CSR theory were deemed most relevant for describing the processes occurring on EGRs since they focus on vegetation change and are site-level processes. With its emphasis on environmental stress and disturbance, CSR theory was useful for connecting up individual species' functional traits and adaptive strategies with community level perspective, including successional change. As alluded to already, the application of CSR theory for characterising EGR species was useful for describing the vegetation of the roofs surveyed.

One of the research questions asked whether successional changes could be observed and, if so, what might be the main drivers and mechanisms. The results suggest that EGR species diversity and composition over the long term are influenced by substrate variables (depth, composition, nutrient status, pH, C_{org}) and site conditions (e.g., aspect and slope), and that feedbacks may be involved. Initial species selection (with reference to strategies for persistence and self-regeneration) and species recruitment (including possibilities in seed bank and proximity to wind-dispersed propagule sources) are important factors, too. This work agrees with general consensus from green roof practice and research that substrate depth should not be less than 100 mm, both for species richness and green roof function. The prospect of declining soil pH and depth over time should be examined through monitoring.

8.4 Aim: To propose models illustrating and predicting vegetation development on EGRs over time.

Integrated with the hierarchical causal framework outlining various levels of detail for EGR vegetation dynamics, the modification to Grime and Pierce's (2012) twin-filter model was adapted to explain why some species or growth forms may persist on EGRs over time better than others. The CSR triangle diagram proved useful for characterising EGR vegetation components according to adaptive strategies, and provided a dynamic approach for considering the processes of EGR vegetation assembly over time. It is noteworthy that the twin-filter model advances the unification of ecology with evolutionary biology and provides the basis for a mechanistic model of the dominant forces shaping evolution across the spectrum of ecological situations (Grime and Pierce, 2012). To the author's knowledge, the application of natural succession and CSR theory to novel ecosystems like green roofs is unprecedented.

8.5 Future research

This research can be viewed from two perspectives. On the one hand, it can be seen as one of the few examples of plant ecology oriented green roof research; in other words, as a minority within an area of research that has otherwise been led largely by engineering, architecture and construction (Blank et al., 2013). In this light, a preliminary understanding of long-term plant ecological development on EGRs can help establish a foundation for EGR research within the context of urban ecological studies. On the other hand, this work can be viewed as a preliminary attempt at urban ecological research using EGRs as a particular type of novel ecosystem within the built environment. Just as the green roof movement is due to refresh its ecological goals and mandates, similarly the discipline of urban ecology has yet to integrate the potential of living architecture into its program.

8.5.1 EGRs and urban ecological research

To date, EGRs have been treated as engineered systems whose implementation rests largely in the domain of policy-makers and industry. Ecological investigation of EGRs, and consideration by ecologists in general ,have been hampered by inaccessibility. Now that urban ecology is a more firmly established discipline (Pickett et al., 2004) and greater rigor is being encouraged for urban ecological research (McDonnell and Hahs, 2013, Felson et al., 2013), green roofs could serve as discrete experimental systems for all sorts of ecological research. Further to vegetation dynamics and soil processes of novel ecosystems, applied research projects on actual roofs could facilitate interactions between ecologists and other disciplines and offer ecologists access to the design process of urban areas. Such collaborations with architects, landscape architects and urban designers could offer the additional benefit of infusing designed experiments into the goals and monitoring approaches of projects (Felson and Pickett, 2005). Since EGRs are very closely tied to socio-economic systems, their integration with ecological models and with socio-economic and physical systems will help to better understand the importance of different processes in different locations (Grimm et al., 2000, McDonnell et al., 2009, McCarthy, 2009).

Given the ground that urban ecology continues to gain, and considering how the EGR industry is expanding to all regions of the world, this work can benefit the pragmatic and intellectual development of both disciplines. The abandonment of antiquated philosophies, in exchange for contemporary- and future-oriented views, can help us approach human habitats more intelligently (Groffman et al., 2014). Ecological research on EGRs can aim towards supporting urban ecological research through the collaborative development and improvement of methods, along with clarification of factors to be monitored and quantified. The establishment of coordinated research programs in different parts of the world would help to enhance the quality of output from EGR ecological research. The implementation of permanent plots on newly installed EGRs, with monitoring devices installed from the start, can build synoptic datasets. Research into soil processes on EGRs would greatly advance our understanding of these systems and of their ecological potential, with attention to nutrient cycling, soil fauna, physical compression, nitrification and humification. Still, though comparative studies are of great value, estimates of the size of effects being studied and measured must be clearly provided, and the precision of any estimates duly reported, as these are crucial for providing suitable data for meta-analysis (McCarthy, 2009).

8.5.2 EGRs and urban soil ecology

Interesting questions raised here that could be addressed by future research might ask whether soil ecological processes on EGRs are more, or less, dynamic at different periods in time (e.g., early years after installation or after twenty years). Establishing methods and metrics to determine the quality of soil organic content, will be crucial if distinctions between litter and humus are to be made. Clarifying ecological relationships, such as plant-soil feedbacks, the role of ecosystem engineers like ants, and the effects of episodic phenomena, like extreme stress, can help to understand EGRs as novel ecosystems. Research into soil processes on EGRs would greatly advance our understanding of these systems and of their ecological potential, with attention to nutrient cycling, soil fauna, physical compression, nitrification and humification.

Future-oriented land use planning must integrate opportunities for soil carbon sequestration and enhancement of nitrogen sinks, even in cities (Lorenz and Lal, 2009), and strategies that strengthen soil ecological functions (e.g., retention of nutrients, hazardous compounds and water) can help to improve ecosystem services, but little work has examined the enhancement of EGRs for carbon sequestration (Getter et al., 2009). The soil-based processes of individual EGRs are undoubtedly affected by the effects of urbanization, like increased concentrations of reactive nitrogen and atmospheric CO_2 (Brown et al., 2005, Kaye et al., 2006), or changes to global biogeochemical cycles (Grimm et al., 2000), but this has never been measured or quantified.

8.5.3 EGRs and plant ecological research

An improved understanding of EGR ecology and function, including responses, feedbacks and processes, is essential if green roofs are to be treated as novel ecosystems and/ or as meaningful components of green infrastructure. A greater number of roofs that can be sampled over short-and long-terms, and accompanied by consistent and reliable information (on installation, materials, construction, etc.), will help develop our understanding of the processes influencing EGR vegetation over time. Such replicability could also serve to test fundamental questions of plant ecology, such as the vegetation dynamics that occur over time with regards to stress and disturbance, but also to novel and urban influences. The emerging trend of research that examines functional (and phylogenetic) diversity within EGR vegetation may lead towards the enhancement of green roofs' potential for ecosystem services.

In terms of viability, the commercial success of EGR implementation could be a real support for such research, since long-term research would benefit from commencing at the point of installation and especially in circumstances where blocks of identical buildings are installed with green roofs around the same time. This would require skillful communication and effective coordination between ecologists and researchers with town planners, building owners, contractors and other stakeholders. A forum or network of international researchers with resources or interests in such work would facilitate the progress of such work, including the means by which potential collaborators can find each other.

8.5.4 EGRs for testing theories and generating hypotheses

The application of CSR theory and its contemporary offshoots (CSD equilibrium and Universal Adaptive Strategies Theory) may be of value for the treatment of EGR vegetation, and vice versa. A recently developed method for designating vegetation with CSR strategies (Pierce et al., 2013), as an improvement to the laborious plant screening trials conducted in the UK, appears to hold promise for a variety of applications, including the rapid description of vegetation and ecology of entire landscapes, from local to continental scales (Pierce et al., 2013), the remote sensing and mapping of vegetation at local scales (Schmidtlein et al., 2012), and four-dimensional representations of global vegetation showing ecological changes in response to large-scale anthropogenic disturbances such as deforestation, species invasions, nitrogen deposition or climate change (Pierce et al., 2013). Instilling plant ecology with greater predictive power at local, regional and global scales can offer better insights for better practices.

8.6 Possible implications for the research

The integration of green roof and urban ecological research will have no meaning unless it is connected in partnerships that facilitate the transfer of knowledge to application, including the EGR industry, policy, planning and the design disciplines. Increased calls for environmental remediation, ecological health and biodiversity suggests the need to re-imagine urban futures (Mostafavi and Doherty, 2010). Although EGRs are becoming increasingly common in cities, dynamic progress in research and the implementation of well-thought-out policies is essential if they are to become integral parts of urban green infrastructure strategies (Henry and Frascaria-Lacoste, 2012). While research is accruing which affirms that EGRs can deliver ecosystem services when designed in certain ways (Lundholm et al., 2010, Connelly and Hodgson, 2013, MacIvor and Lundholm, 2011, MacIvor et al., 2011, Madre et al., 2014, Rowe et al., 2012, Getter et al., 2011, Getter et al., 2009, Van Mechelen et al., 2015), their actual contribution to biodiversity and ecosystem function falls under scrutiny (Williams et al., 2014).

Green roofs are central to one of the future scenarios proposed by the Millennium Ecosystem Assessment (2005) – the TechnoGarden – yet the form and construction type proposed are as vague as the assumptions this is based upon. In order for green roofs to claim this noble position – one which benefits both human well-being and the natural world – this work suggests reviewing the industry standards and the FLL guidelines that are exported to other parts of the world. While the Sedum meadow is an excellent climatic match for south-western Germany, the rigid adherence to of the physical specifications of commercial systems (e.g., depth, system construction) to other climates and bioregions inherently misses the great opportunity that green roofs implicitly provide. If biotic homegenisation is to be avoided, and local biodiversity to be supported, then the involvement and imagination of local ecologists is required. Mechanisms such as Biodiversity Action Plans, in the UK, have proven beneficial to enhancing the ecological potential of commercial EGR systems.

This work presents evidence that green roof systems from the 1980s have successfully achieved their original vision of low-maintenance, self-sustaining vegetation. It observes that ecological processes do occur on EGR systems, but that they are inhibited by disturbance, stress and other mechanisms associated with these systems and the urban environment. With respect to current issues of global climate change, increasing urbanization and declining biodiversity, this work reflects that the original vision from the 1980s no longer align with contemporary issues and future-oriented projections, and that these system constructions may be inadequate for the pressing challenges and needs of the present and future. Particularly when so many other options are possible (e.g., orchid roofs, dry meadow or wetland roofs), the apparent trend of species impoverishment and dominance by stress tolerators suggests lost opportunities.. After thirty years of market development, and with a globally burgeoning industry, the green roof movement has a decisive opportunity to help turn the trend on declining biodiversity and ecosystem services.

8.7 In closing

This thesis was written during the Decade on Biodiversity and soon after the Millennium Ecosystem Assessment's call for concerted efforts on slowing the decline of biodiversity, and therefore hopes to inspire greater involvement of ecological disciplines in the roof domain.

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Appendix 1. Roof details

Stuttgart Killesberg Year installed/ background: Installed in July 1991, this steeply-sloped green roof was built as part of the International Garden Show (IGA), which occupied the site for one year. The City moved into the site after the IGA left, and the Dept of Gardens, Cemeteries and Forests occupied the building since then. John Döveling, landscape architect for the city, worked here and kept a close eye on the vegetation from the start. John also developed and managed the green roof incentive program for the City from 1986 until 2009.	
Type:	Pitched Sedum meadow
Size (m2):	450 m^2
Location:	Gartenbauaumt, Maybachstr. 3, 7000 Stuttgart
Slope/ Aspect:	30° pitch, exact N-S gradient
Shading:	none
Original depth:	80 mm at time of installation (according to plan)
Construction:	Soil: 40% compressable fill; 40% sieved topsoil; 20% screened gravel (16/32 particle size); nutrient- and humus-poor blend styrofoam (120 mm) Protection mat Root-resistant waterproofing
Description:	This is not a ZinCo roof. The S-facing vegetation is xeric with horizontal cracks (from erosion?), covered mainly by drought- and stress tolerators. The N-facing roof is dense with grass and flowering herbs, Sedums are in the understory.
Vegetation type:	S-face: extensive Sedum-Moss cover N-face: grassy sward (F. ovina, P. pratensis, H. perfoliatum, S. hybridum)
Sampling method:	Stratified random along systematic transects

Substrate results (Killesberg)
No details on physical and chemical properties

Killesberg documentation (2 pages)

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Postfach 161

7000 Stuttgart 1

LANDESHAUPTSTADT STUTTGART
–GARTENBAUAMT–
Eing.: 23 FEB. 1990
Tgb.Nr.

1	2	3	4	5	IGA		
zErl	zU	sS	zR	zSt	zK	uR	zA

Dr-sc 21.02.1990

Erweiterung Betriebshof Stuttgart Killesberg

Sehr geehrter Herr Döveling,

bezugnehmend auf unsere Besprechung vom 20.02.1990 teile ich Ihnen die Zusammenstellung der Saatgutmischung sowie der Pflanzentragschicht mit:

Saatgutmischung "CE":

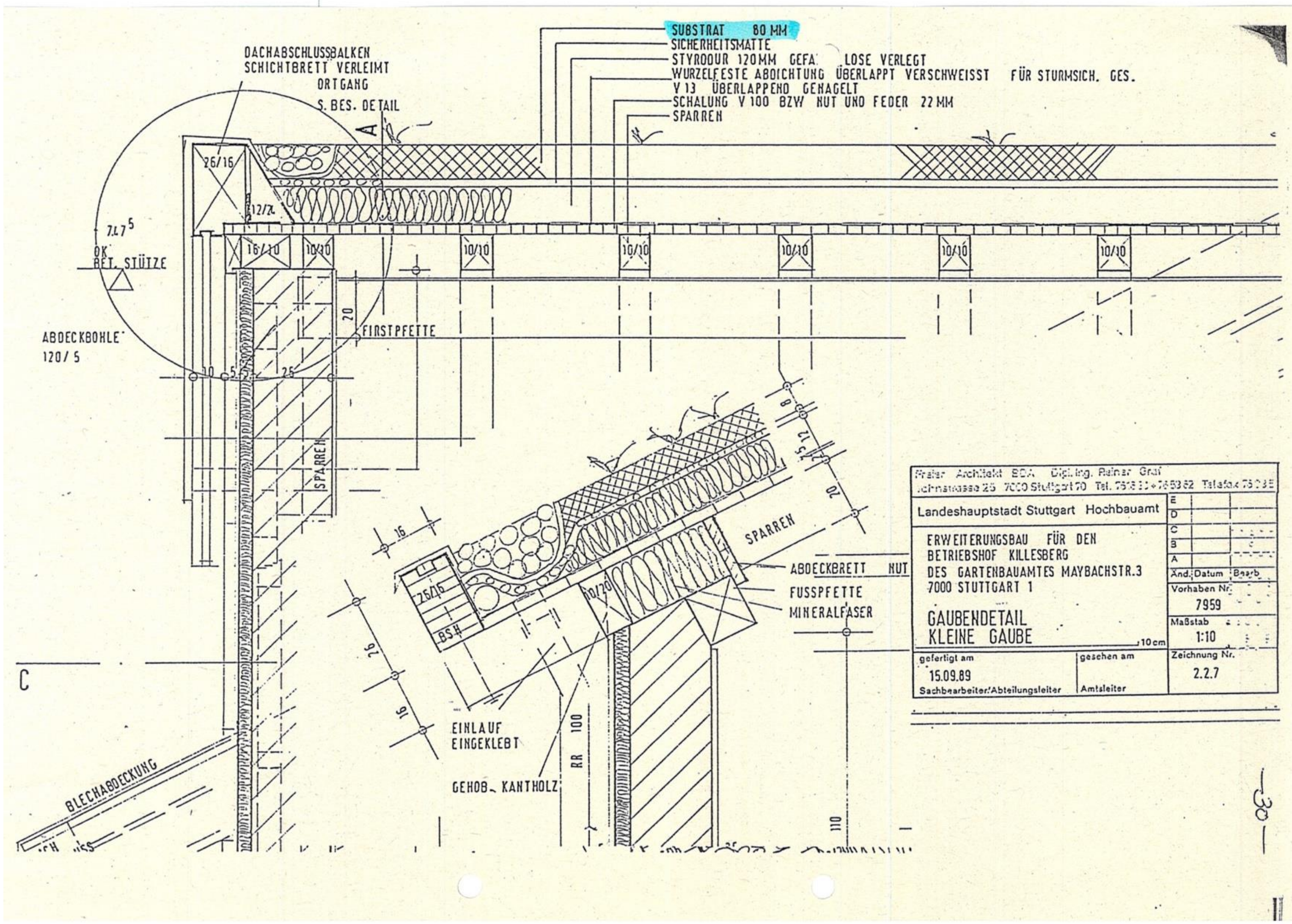
Sedum acre
Thymus pulegioides
Digitaria sanguin.
Polygonum aviculare
Setaria viridis
Trifolium arvense
Hieracium pilosella
Plantago major
Nepeta mussinii
Potentilla verna
Linum perenne
Rumex acetosella
Dianthus deltoides
Inula hirta
Potentilla argentea
Saponaria ocymoides
Veronica spicata
Agrostis tenuis highland
Festuca Ovina
Onobrychis Sativa
Poa compressa reubens
Poa Nemoralis enhary
Festuca Ovina Dur. Crystal

Aussaat
Juli 1991

Pflanzentragschicht:

ohne Leichtzuschläge
40 % verdichtungsfähiger Füllboden
40 % gesiebter Oberboden
20 % Siebkies 16/32 Körnung
nährstoff- und humusarme Mischung

e landschaftsschutz- und deponiebau



SUBSTRAT 80 MM
SICHERHEITSMATTE
STYRODUR 120MM GEFA. LOSE VERLEGT
WURZELFESTE ABDICHTUNG ÜBERLAPPT VERSCHWEISST FÜR STURMSICH. GES.
V 13 ÜBERLAPPEND GENAGELT
SCHALUNG V 100 BZW NUT UND FEDER 22 MM
SPARREN
DACHABSCHLUSSBALKEN
SCHICHTBRETT VERLEIMT
ORTGANG
S. BES. DETAIL
A
26/16
12/24
16/10
10/10
OK BET. STÜTZE
FIRSTPFETTE
ABDECKBOHLE 120/5
SPARREN
ABDECKBRETT NUT
FUSSPFETTE
MINERALFASER
25/16
BSH
10/20
EINLAUF
EINGEKLEBT
GEHOB. KANTHOLZ
RR 100
BLECHABDECKUNG
C
110
Landeshauptstadt Stuttgart Hochbauamt
ERWEITERUNGSBAU FÜR DEN
BETRIEBSHOF KILLESBERG
DES GARTENBAUAMTES MAYBACHSTR.3
7000 STUTTGART 1
GAUBENDETAIL
KLEINE GAUBE
gefertigt am
15.09.89
gesehen am
Sachbearbeiter/Abteilungsleiter
Amtsleiter
Änd. Datum Bearb.
Vorhaben Nr.
7959
Maßstab
1:10
Zeichnung Nr.
2.2.7
-30-

Stuttgart Rathausgarage - lower roof Year installed/ background: Installed spring/ summer 1990 as pilot project. Maintenance contract handed over to municipality in Oct 1991 (the 1-yr warranty had expired).	
Type:	Sedum meadow
Size (m^2):	ca. 1,100 m^2
Location:	Eichstraße 7, 70173 Stuttgart
Slope/ Aspect:	none
Shading:	none
Original depth:	100 mm
Construction:	ca 100 mm "Dachgartenerde, flächig" Nora-Drain Mat (30 mm) with filter fleece; Protection layer SSM 45 Waterproofing: PE-Folie 0.2 mm/ 2-layered
Description:	This is not a ZinCo roof. A central circular island defines this lower roof, which is also vegetated both on top and up the sides with climbers. Far less *Allium* cover on this roof as on PV roof, and six more species (*Dianthus* deltoides, 3 mosses, Poa compressa, Potentilla erecta, Sedum sexangulare, Setaria viridis, Vulpia myuros)
Vegetation type:	Extensive *Sedum-Thyme-Dianthus* moss meadow with ruderal grasses
Sampling method:	Stratified random

Substrate results (Rathaus-lower)			
Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion of slurry-forming components (d < 0.063 mm)	mass %	8.5	≤ 15
Proportion gravel (d > 4mm)	mass %	54	≤ 50
Apparent density, dry	g/cm^3	1.18	no requirement
Apparent density, at mWK	g/cm^3	1.57	no requirement
Total pore volume (GPV)	vol. %	54	no requirement
Maximum water capacity (mWK)	vol. %	38	≥ 35 ≤ 65
Air content at mKW	vol. %	16	≥ 10
Water permeability mod. kf	mm/ min	-	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	7.2	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.3	≤ 3.5
Organic content	g/ L	61	≤ 65
Nitrogen (N) (in CAT)	mg/ L	52	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	6	≤ 50
Potash (K2O) (in CAT)	mg/ L	68	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	120	≤ 200

Stuttgart Rathausgarage - PV roof Year installed/ background: Installed spring/ summer 1990 as pilot project. Maintenance contract handed over to municipality in Oct 1991 (the 1-yr warranty had expired).	
Type:	Sedum meadow
Size (m^2):	ca. 1,300 m^2
Location:	Eichstraße 7, 70173 Stuttgart
Slope/ Aspect:	none
Shading:	only from PV panels, but vegetation beneath was not sampled
Original depth:	100 mm
Construction:	ca 100 mm "Dachgartenerde, flächig" Nora-Drain Mat (30 mm) with filter fleece; Protection layer SSM 45 Waterproofing: PE-Folie 0.2 mm/ 2-layered
Description:	This is not a ZinCo roof. Some construction as lower roof.
Sampling method:	Stratified random

Substrate results (Rathaus-PV) Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	10	≤ 15
Proportion gravel (d > 4mm)	mass %	60	≤ 50
Apparent density, dry	g/cm^3	1.17	no requirement
Apparent density, at mWK	g/cm^3	1.49	no requirement
Total pore volume (GPV)	vol. %	55	no requirement
Maximum water capacity (mWK)	vol. %	32	≥ 35 ≤ 65
Air content at mKW	vol. %	23	≥ 10
Water permeability mod. kf	mm/ min	-	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	7.2	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.4	≤ 3.5
Organic content	g/ L	49	≤ 65
Nitrogen (N) (in CAT)	mg/ L	53	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	11	≤ 50
Potash (K2O) (in CAT)	mg/ L	71	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	120	≤ 200

Stuttgart Rathausgarage documentation (2 pages)

Landeshauptstadt Stuttgart PROD 110 vom 18.3.92
Gartenbauamt (67-3).1 Nebenstelle 5451

67-Ü

Projektnummer

An
67-4.1

Verteiler bei 67: [x] Archiv [x] 67-1.20 [x] 67-4. [x] 67-4.1 [x] 67-4.7 [x] 67-3.1

Sonstige: [x] 62 [ ] 70

Mitteilung über die Fertigstellung

[x] eines Neubauvorhabens
[ ] einer Veränderung

Art der Plananlagen:
[x] Aufmaßplan [ ] Baum-Änderungsblatt [ ] ______ [x] Übergabeplan

Art der Bauvorhaben:
[ ] Fremdamt ______ [ ] Grünanlage [ ] Kinder-spielplatz [ ] Grün im Straßenraum G K L B

Lage/Bezeichnung:
S-Mitte, Rathausgarage - Dachbegrünung -

Bebauung ausgewiesen als	Flurstück Nr.	m²	Flurstück Nr.	m²
Dachbegrünung	126/27	1.714,60		
Stadt ~~Stuttgart~~ (verwaltendes Amt) 66				

Bauabnahme am	Fertigstellung bis	Übernahme und Verkehrssicherungspflicht ab
12.3.92	4.10.91	4.10.91

Bauausführung: - Gewährleistung nach BGB/VOB -

	m²	Beginn	Ende	beauftragter Unternehmer
Wege- und Platzflächen	61,14	→ (505)		Fa. A. Fides-Kahl
Rasenflächen				
Gehölzflächen				
Staudenflächen	1.653,46	→ (300)		"
	5 m²	→ (950)		

Gesamtfläche 1.714,60 Abrechnungssumme: 282.476,05 DM = 164,75 DM/m²

Darin entsiegelte Flächen: 1653,46 m²

Sachgebiet Neubau
Datum, Unterschrift
20.3.92 [signature]

Sachgebiet Unterhaltung
Datum, Unterschrift
24.3.92 [signature]

Übernahme ist erfolgt
Abt.-Leiter/-in der Pl.
Datum, Unterschrift
27.3.92 [signature]

Abt.-Leiter/-in der U.
Datum, Unterschrift
26.3.92 [signature]

67-301-291V

(Species list as excerpt on construction plan)

Dachbegrünung Rathausgarage

PFLANZENLISTE

Pos.	Pflanze	Stck
4040	Hedera helix	16
4044	Parthenocissus tric.Veitchii	16
4060	Saxifraga aizoon	200
4064	Silene marit.Weißkehlchen	200
4066	Thymus serphyllum Cocc.	200
o.P.		
4018	Festuca mairei	30
	Sedum telephium	300

AUSSAAT FLÄCHIG: Mischung TYP 'CE` -Blumenhügel-

Sedum acre	Thymus pulegioides
Digitaria sanguinalis	Ploygonum aviculare
Setaria viridis	Trifolium arvense
Hieracium pilosella	Plantago major
Nepeta musinii	Potentilla verna
Linum perenne	Rumex acetosella
Dianthus deltoides	Inula hirta
Potentilla argentea	Saponaria ocymoides
Veronica spicata	Agrostis tenuis H.
Festuca ovina	Onobrychis sativa
Poa compressa Reubens	Poa nemoralis Enh.
Festuca ovina dur.Crystal	

AUSSAAT DURCH SEDUMSPROSSEN:

Sedum acre	Sedum hybride
Sedum album	"Immergrünchen"
Sedum album Coral Carpet	Sedum reflexum
Sedum album Murale	Sedum sexangulare
Sedum floriferum	Sedum spurium
"Weihenstephaner Gold"	"Purpurteppich"

FH Nürtingen Year installed/ background: Installed and planted autumn 1986; dead/ missing plants replaced in autumn 1987. Until 1992 maintenance was frequent and regular; this was reduced to annual mowing (late summer). In 2000, orchids and anthills appeared; by 2010 this had expanded to 30 individuals. The edges of the green roof were renovated in autumn 2010, after sampling.	
Type:	Sedum meadow
Size (m^2):	258 m^2
Location:	Neuffenerstr. 139, 7440 Nürtingen
Slope/ Aspect:	flat, roof facing North but protected by 1.5 m parapet
Shading:	yes, edges beside walls receive shade from 11:00
Original depth:	90 mm centre, 20 mm along edges (initial interest to see what happens)
Construction:	Soil blend: expanded shale with Floraperl, humousy (top?)soil 50 mm Floradrain with filter fleece; Protection layer; Root-resistant PE layer atop bituminous waterproofing
Description:	Protected on the south- and west-sides by walls, and contained by parapet on the other sides. The north edge is very xeric, while the south edge seems rather damp (supports orchids and lush mosses.)
Vegetation type:	Edges = Sedum-Moss-Lichen; Central area = meadow vegetation (Poa compressa, Hypericum perforatum, Campanula rotundifolia)
Sampling method:	Stratified random with transect grid: roof divided into transects every 4m, quadrats every 3m = 12 quadrats total

Substrate results (FH Nürtingen)

Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	1.4	≤ 15
Proportion gravel (d > 4mm)	mass %	39	≤ 50
Apparent density, dry	g/cm^3	0.88	no requirement
Apparent density, at mWK	g/cm^3	1.41	no requirement
Total pore volume (GPV)	vol. %	66	no requirement
Maximum water capacity (mWK)	vol. %	53	≥ 35 ≤ 65
Air content at mKW	vol. %	13	≥ 10
Water permeability mod. kf	mm/ min	0.7	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	6	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.5	≤ 3.5
Organic content	g/ L	72	≤ 65
Nitrogen (N) (in CAT)	mg/ L	62	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	< 5	≤ 50
Potash (K2O) (in CAT)	mg/ L	130	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	160	≤ 200

FH Nürtingen documentation (5 pages)

EINGEGANGEN
29. JAN. 87
Erl. ....

Metall Dachtechnik GmbH

Metall- und Dachtechnik GmbH · Postfach 2068 · 7440 Nürtingen

☎ 0 70 22/60 03-0 · Tx 7 267 412

Bauleitung der
Fachhochschule Nürtingen
z. H. Herrn Romeike
Neuffener Str. 139

7440 Nürtingen

Rechnung

Rg.-Nr. 8507-86
(Bitte bei Bezahlung angeben)

BV-Nr. 5999

Datum (28.01.1987)
31.12.1986
Es schreibt Ihnen
H. Matschiner/hy
Telefon-Durchwahl
0 70 22/60 03- 63
Unser Angebot

Ihr Auftrag

Unsere Bestätigung

Bauvorhaben: Nürtingen, Fachhochschule
Lehr- und Versuchsanlage

Menge	Bezeichnung	EP DM	Betrag DM
	Sie erhielten lt. Lieferscheine Nr. 756, 771, 785, 778 und Nr. 3626 von der Fa. Fischer:		
50 Sack	Erdsubstrat	17,10	855,00
260 qm	Filtervlies	1,75	455,00
46 Sack	Blähschiefer u. Floraperl	19,85	913,10
2,24 to	Moränesand	56,20	125,89
			2.348,99
	+ 14 % Mehrwertsteuer		328,86
			2.677,85

Die Materialien wurden Ihnen zugefahren!

Es gelten ausschließlich unsere
umseitig abgedruckten Geschäfts-
und Montagebedingungen 11.85.

sachlich richtig
gepr. Betrag DM 2677,85

Anlage
Kopien der Lieferscheine

Fachhochschule Nürtingen
Fachbereich Landespflege
05.02.87
Schnitzler

Zahlbar innerhalb 30 Tagen ohne Abzug. Bei verspäteter Zahlung werden die üblichen Verzugszinsen belastet. Beanstandungen können nur innerhalb 8 Tagen berücksichtigt werden. Die Ware bleibt bis zur vollständigen Bezahlung, auch in verarbeitetem Zustand, unser Eigentum. Es gelten unsere umseitig abgedruckten Geschäftsbedingungen.
Werk: Industriestraße 21 · 7441 Unterensingen · Autobahnausfahrt Wendlingen · Bahnstation Nürtingen

Geschäftsführer: Walter Zink
Registergericht: Nürtingen HRB 770

Kreissparkasse Nürtingen BLZ 612 500 30 Kto. 48 913 290
Volksbank Nürtingen BLZ 612 901 20 Kto. 880

Metall
Dachtechnik
GmbH

Metall- und Dachtechnik GmbH · Postfach 2068 · 7440 Nürtingen

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Dachgärten + Dachbegrünungen
Metalldächer + Fassaden
Flachdach-An- und Abschlüsse

Bauleitung der
Fachhochschule Nürtingen
z. Hd. Frau Schnitzler
Neuffener Str. 139

7440 Nürtingen

Ihre Nachricht / Ihr Zeichen	
Unsere BV-Nr.	
Es schreibt Ihnen	Frau Schaich
Datum	05.03.1987
Telefon-Durchwahl	07022/6003- 30

OFFENE RECHNUNG
===============

BV.: Nürtingen Fachhochschule

Sehr geehrte Frau Schnitzler

bezugnehmend auf das heutige Telefongespräch mit Ihrem Herrn Mangold erhalten Sie anbei eine Kopie unserer Rg.-Nr. 8507-86 vom 31.12.86/28.01.87, da diese Ihnen nicht vorliegt.

Somit dürfte der Bezahlung unserer oben genannten Rechnung nichts mehr im Wege stehen.

Mit freundlichen Grüßen

Metall- und Dachtechnik GmbH

i. A. Schaich

Schaich

Anlage
Kopie Rechnung Nr. 8507-86
Kopie Lieferscheine zu Rg.

erledigt Rechnung wurde von H. Mangold angewiesen 22.05.87 Sk

F.Nr. 50 32. 11.85

Werk: Industriestraße 21 · 7441 Unterensingen · Autobahnausfahrt Wendlingen · Bahnstation Nürtingen
Banken: Kreissparkasse Nürtingen (BLZ 612 500 30) Nr. 48 913 290 · Volksbank Nürtingen (BLZ 612 901 20) Nr. 880
Geschäftsführer: Walter Zink · Handelsregistereintragung: HRB 770

Metall Dachtechnik GmbH

Metall- und Dachtechnik GmbH · Postfach 2068 · 7440 Nürtingen

☎ 0 70 22/60 03-0 · Tx 7 267 412

Bauleitung der
Fachhochschule Nürtingen
z. H. Herrn Romeike
Neuffener Str. 139

7440 Nürtingen

Rechnung

Rg.-Nr. 8507-86
(Bitte bei Bezahlung angeben)

BV-Nr. 5999

Datum (28.01.1987)
31.12.1986

Es schreibt Ihnen
H. Matschiner/hy

Telefon-Durchwahl
0 70 22/60 03- 63

Unser Angebot

Ihr Auftrag

Unsere Bestätigung
12000 / 8107

Bauvorhaben: Nürtingen, Fachhochschule

GEBUCHT 31. Dez. 1986 № 97

Menge	Bezeichnung	EP DM	Betrag DM
	Sie erhielten lt. Lieferscheine Nr. 756, 771, 785, 778 und Nr. 3626 von der Fa. Fischer:		
50 Sack	Erdsubstrat	17,10	855,00
260 qm	Filtervlies	1,75	455,00
46 Sack	Blähschiefer u. Floraperl	19,85	913,10
2,24 to	Moränesand	56,20	125,89
			2.348,99
	+ 14 % Mehrwertsteuer		328,86
			2.677,85

Die Materialien wurden Ihnen zugefahren!

Es gelten ausschließlich unsere umseitig abgedruckten Geschäfts- und Montagebedingungen 11.85.

Anlage
Kopien der Lieferscheine

Zahlbar innerhalb 30 Tagen ohne Abzug. Bei verspäteter Zahlung werden die üblichen Verzugszinsen belastet. Beanstandungen können nur innerhalb 8 Tagen berücksichtigt werden. Die Ware bleibt bis zur vollständigen Bezahlung, auch in verarbeitetem Zustand, unser Eigentum. Es gelten unsere umseitig abgedruckten Geschäftsbedingungen.

Werk: Industriestraße 21 · 7441 Unterensingen · Autobahnausfahrt Wendlingen · Bahnstation Nürtingen

F.Nr. 50.33.11.85

Geschäftsführer: Walter Zink
Registergericht: Nürtingen HRB 770

Kreissparkasse Nürtingen BLZ 612 500 30 Kto. 48 913 290
Volksbank Nürtingen BLZ 612 901 20 Kto. 880

ZinCo Metall- und Dachtechnik GmbH
744 Nürtingen-Unterensingen
Postfach 2068

ZinCo [redacted]

7441 Unterensingen
Industriestraße 21
Telefon (070 22) [redacted]
Telex 7-267 324

Anschrift

ab 1.10.85
07022/6003-0

Lieferschein № 771 Datum 8.8.86

Ihr Auftrag Nr. vom

Kom./BV

Wir liefern Ihnen per Bahnfracht / Eilgut / Expreß / Spedition / Post / Lkw
oder durch .... unfrei / frei *

Filtervlies 168 / 42

F-Nr. 60.25.08.75

Obige Lieferung richtig
erhalten bestätigt: Datum

Es gelten ausschließlich unsere Geschäftsbedingungen. Die Rechnung ist zahlbar innerhalb 30 Tagen ohne Abzug. Bei verspäteter Zahlung berechnen wir Ihnen die üblichen Verzugszinsen. Beanstandungen können nur innerhalb 8 Tagen nach Empfang berücksichtigt werden. Die Ware bleibt bis zur vollständigen Bezahlung, auch in verarbeitetem Zustand, unser Eigentum. Erfüllungsort für beide Teile ist Unterensingen. Gerichtsstand Nürtingen.

* Nichtzutreffendes streichen

ZinCo Metall- und Dachtechnik GmbH
744 Nürtingen-Unterensingen
Postfach 2068

ZinCo [redacted]

7441 Unterensingen
Industriestraße 21
Telefon (070 22) [redacted]
Telex 7-267 324

Anschrift

Fachhochschule
Nürtingen

ab 1.10.85
07022/6003-0

Lieferschein № 756 Datum

Ihr Auftrag Nr. vom

Kom./BV

Wir liefern Ihnen per Bahnfracht / Eilgut / Expreß / Spedition / Post / Lkw
oder durch .... unfrei / frei *

50	Sack Erdsubstrat 80 Liter
8	Sack Floraperl 60 Liter
60	qm Filtervlies
14	Sack Blähschiefer gebr. 80 Liter

F-Nr. 60.25.08.75

Obige Lieferung richtig
erhalten bestätigt: G. Powelke Datum

Es gelten ausschließlich unsere Geschäftsbedingungen. Die Rechnung ist zahlbar innerhalb 30 Tagen o[hne] Abzug. Bei verspäteter Zahlung berechnen wir Ihnen die üblichen Verzugszinsen. Beanstandungen kön[nen] nur innerhalb 8 Tagen nach Empfang berücksichtigt werden. Die Ware bleibt bis zur vollständigen Bezahl[ung], auch in verarbeitetem Zustand, unser Eigentum. Erfüllungsort für beide Teile ist Unterensingen. Geric[hts]stand Nürtingen.

* Nichtzutreffendes strei[chen]

ZinCo Metall- und Dachtechnik GmbH
744 Nürtingen-
Unterensingen
Postfach 2068

ZinCo

[redacted]
7441 Unterensingen
Industriestraße 21
Telefon (070 22) [redacted]
Telex 7-267 324

Anschrift

ab 1.10.85
07022/6003-0

Lieferschein № 778 Datum

Ihr Auftrag Nr. vom

Kom./BV

Wir liefern Ihnen per Bahnfracht / Eilgut / Expreß / Spedition / Post / Lkw
oder durch .... unfrei / frei *

A. Rowcike

F-Nr. 60.25.08.75

Obige Lieferung richtig
erhalten bestätigt: Datum

Es gelten ausschließlich unsere Geschäftsbedingungen. Die Rechnung ist zahlbar innerhalb 30 Tagen ohne Abzug. Bei verspäteter Zahlung berechnen wir Ihnen die üblichen Verzugszinsen. Beanstandungen können nur innerhalb 8 Tagen nach Empfang berücksichtigt werden. Die Ware bleibt bis zur vollständigen Bezahlung auch in verarbeitetem Zustand, unser Eigentum. Erfüllungsort für beide Teile ist Unterensingen. Gerichtsstand Nürtingen.

* Nichtzutreffendes streichen

ZinCo Metall- und Dachtechnik GmbH
744 Nürtingen-
Unterensingen
Postfach 2068

ZinCo

[redacted]
7441 Unterensingen
Industriestraße 21
Telefon (070 22) [redacted]
Telex 7-267 324

Anschrift

Fachhochschule
Nürtingen

ab 1.10.85
07022/6003-0

Lieferschein № 785 Datum 29.09.86

Ihr Auftrag Nr. 5999 vom

Kom./BV

Wir liefern Ihnen per Bahnfracht ~~/ Eilgut / Expreß / Spedition / Post / Lkw~~ RKW
oder durch .... ~~unfrei~~ / frei *

7 Säcke gebr. Blähton a 60 ltr.

F-Nr. 60.25.08.75

Obige Lieferung richtig
erhalten bestätigt: Schmitter Datum

Es gelten ausschließlich unsere Geschäftsbedingungen. Die Rechnung ist zahlbar innerhalb 30 Tagen ohne Abzug. Bei verspäteter Zahlung berechnen wir Ihnen die üblichen Verzugszinsen. Beanstandungen können nur innerhalb 8 Tagen nach Empfang berücksichtigt werden. Die Ware bleibt bis zur vollständigen Bezahlung auch in verarbeitetem Zustand, unser Eigentum. Erfüllungsort für beide Teile ist Unterensingen. Gerichtsstand Nürtingen.

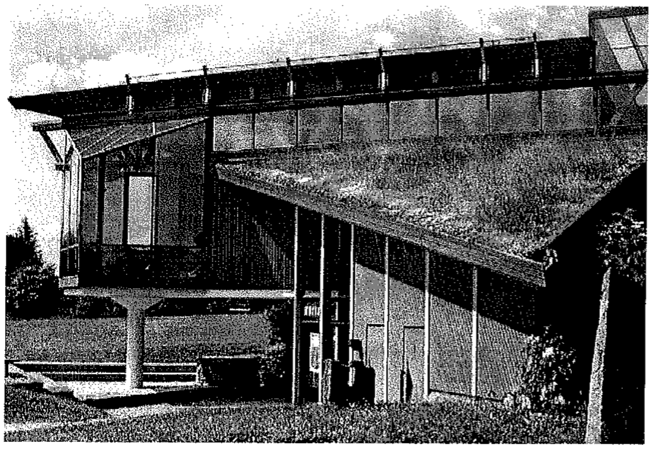
* Nichtzutreffendes streichen

Römermuseum Köngen Year installed/ background: Installed over 7 days in 1987, including construction of erosion barriers (50 mm) (sloped roofs were new territory). Sown with herb-grass mix, plus cuttings. Substrate was an “early version" of Steinrosenflur. Regular maintenance by municipal crews.	
Type:	Species-poor Sedum roof
Size (m^2):	S-facing roof: 230 m^2, N-facing roof: 120 m^2.
Location:	Römerpark, south-west Köngen
Slope/ Aspect:	S-facing roof: 17°, N-facing roof: 15°
Shading:	Some shade from trees at north-west edge of roof
Original depth:	70-80 mm at installation (Hövekamp)
Construction:	Soil: 39% exp-shale, 23% rice husks, 23% bark compost, 15% lava-clay Floraset FS 100 with filter fleece Protection layer SSM 45 Root-resistant waterproofing
Description:	This is one of ZinCo's earliest pitched roofs. The S-facing roof is mainly Sedum, with a patch of *Coronilla*, a *Verbascum* and some grass. The smaller N-facing roof is dense with grass. Mosses form a consistent undercover.
Vegetation type:	S-face: extensive Sedum-Moss cover N-face: grassy sward (F. ovina, P. pratensis, H. perfoliatum, S. hybridum)
Sampling method:	Stratified random with transect grid: 13 quadrats on S-face, 5 on N-face.

Substrate results (Köngen) Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	10	≤ 15
Proportion gravel (d > 4mm)	mass %	10	≤ 50
Apparent density, dry	g/cm^3	0.78	no requirement
Apparent density, at mWK	g/cm^3	1.39	no requirement
Total pore volume (GPV)	vol. %	68	no requirement
Maximum water capacity (mWK)	vol. %	62	≥ 35 ≤ 65
Air content at mKW	vol. %	6	≥ 10
Water permeability mod. kf	mm/ min	2.7	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	5.2	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.3	≤ 3.5
Organic content	g/ L	126	≤ 65
Nitrogen (N) (in CAT)	mg/ L	20	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	32	≤ 50
Potash (K2O) (in CAT)	mg/ L	27	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	130	≤ 200

Köngen documentation (6 pages)

Objektbericht — Römermuseum, Köngen



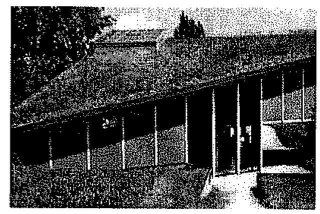
Das Römermuseum in Köngen, das 1987 begrünt wurde (Foto von 2007).

Objektdaten

Fläche:	ca. 350 m²
Baujahr:	1987
Architekten:	Rutschmann + Partner, Stuttgart
Ausführung:	Metall- und Dachtechnik GmbH, Unterensingen
Begrünungsaufbau:	Floraset® FS 100 mit Sedumsprossen und Kräuter- und Gräsereinsaat
Sonstiges:	Dachneigung ca. 17°
Koordinaten:	48°40'39.01"N 9°21'33.48"E

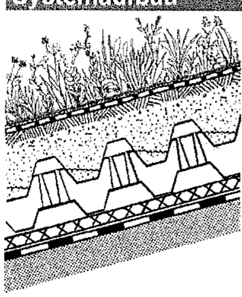
Konzeption

Der Römerpark Köngen wurde in den Jahren 1986 bis 1988 auf dem Gelände des ehemaligen Römerkastells angelegt, dessen ursprüngliche Dimensionen sich in der Anlage und Bepflanzung des Parks wiederspiegeln.
Der Museumspavillon mit seiner außergewöhnlichen Form entstand 1988. Die Idee des Architekten war dabei, dass die beiden Dachflächen eine „angehobene Erdscholle" darstellen sollen, um so einen Einblick in die römische Vergangenheit zu ermöglichen.
Die Dachflächen haben eine Neigung von je 17° und wurden mit Sedum-Sprossen und einer Kräuter- und Gräsermischung einheitlich begrünt.
Auf der Nordseite haben sich durch die klimatischen Bedingungen die Gräser und Kräuter stärker durchgesetzt, während auf dem nach Süden ausgerichteten Dach die Sedum-Arten dominieren.



Auf dem nach Süden ausgerichteten Dach dominieren Sedum-Arten und Kräuter...

Systemaufbau

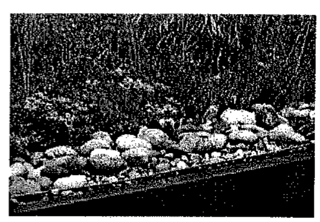


Pflanzebene „Kräuter- und Gräsermischung" und „Sedum-Sprossen"
Systemerde „Steinrosenflur"
Floraset® FS 100
Speicherschutzmatte SSM 45
Dachaufbau mit wurzelfester Abdichtung

...während auf dem Nord-Dach auch zahlreiche Gräser zu finden sind.

Zwei hochgeklappte Gründächer sollen Einblicke „unter die Grasnarbe" ermöglichen.

Im Wandel der Jahreszeiten - das Römermuseum im Winter.



Der Dachrand mit dem schmalen Streifen aus Grobkies.

ZinCo GmbH • Grabenstr.33 • 72669 Unterensingen • Tel. 07022 / 6003-0 • Fax 07022 / 6003-300
www.zinco-greenroof.com • e-mail: contact@zinco-greenroof.com

Vegetations-schicht	Dachgärtnererde	ZinCo

EINSATZGEBIETE

Substratmischung auf Blähschiefer - Ton - Kompost - Basis für intensive Dachbegrünungen und Trogbegrünungen, sowie bei Extensivbegrünungen als Mulchlage und für Anhügelungen.

Bei größeren Schichtdicken (ab ca. 20 cm) kann die Dachgärtnererde auch im Verhältnis 1:1 mit gutem Oberboden gemischt werden (höheres Gewicht beachten!).

Eine Sackung von 15-20 % ist einzukalkulieren.

ZUSAMMENSETZUNG

KENNWERTE

Luftporen (wassergesättigter Zustand)	ca.	36	Vol.-%
Wasserverfügbarkeit	ca.	27	Vol.-%
Feststoffe	ca.	37	Vol.-%
Trockengewicht	ca.	530	Vol.-%
Feuchtgewicht	ca.	800	kg/m^3
Wasserdurchlässigkeit (nach Einbau) mod k*		0,1	cm/s
Wasserdurchlässigkeit (wassergesättigt)		0,066	cm/s
Bodenreaktion	pH	6,2-6,7	
Salzgehalt als KCL		1,19	g/l
Nährstoffe:	Stickstoff:	116	mg/l
	Kalium:	410	mg/l
(nach Prüflabor Pätzold Osnabrück)	Phosphor:	186	mg/l
	Magnesium:	217	mg/l

LIEFERFORM

50 l- oder 80 l-Säcke
1,5 m^3 Bigbag
offene Ware im Kipper

ZinCo Dach-Systeme GmbH · Postfach 20 69 · 7440 Nürtingen · Werk: 7441 Unterensingen · Tel. 0 70 22 / 60 03-0

Metall Dachtechnik GmbH

Metall- und Dachtechnik GmbH · Postfach 2068 · 7440 Nürtingen ☏ 07022/6003-0 · ✆ 7267412 · Fax 07022/600312

Dachgärten + Dachbegrünungen
Metalldächer + Fassaden
Flachdach-An- und Abschlüsse

An die
Gemeinde Köngen
Postfach 11 53

7316 Köngen

Gemeinde
Eing.: 18. APR. 1989
Köngen

Ihre Nachricht / Ihr Zeichen

Unsere BV-Nr.

Es schreibt Ihnen
Herr Pillasch/uz

Datum	Telefon-Durchwahl
17.04.1989	07022/6003- 62

Betr.: Dachbegrünung BV. ~~Neubau Museumspavillon~~ Römerpark, Köngen
- Pflege- und Wartungsangebot -

Sehr geehrte Damen und Herren,

an der im Betreff genannten Baumaßnahme haben wir 1987 die Dachbegrünungsarbeiten für Sie durchgeführt.

Auch bei extensiv begrünten Dächern ist es ratsam, regelmäßig eine Wartung und gegebenenfalls eine Pflege durchzuführen.

Durch regelmäßige, fachkundige Begehung und Wartung werden mögliche Mängel frühzeitig erkannt und können in der Regel mit wenig Aufwand beseitigt werden. Dabei handelt es sich nur in den seltensten Fällen um solche Mängel, die an einen Dritten weiterbelastet werden können. Der Ursprung liegt oft in Umwelteinflüssen, die der Eigentümer selbst zu vertreten hat.

Wir empfehlen Ihnen, unser weit verzweigtes Mitarbeiternetz zu nutzen und einen Wartungsvertrag abzuschließen. Einen Vertrag fügen wir bei. Gerne sorgen wir dafür, daß Sie an der Dachbegrünung auch in Zukunft noch viele Jahre Freude haben.

Mit freundlichen Grüßen

Metall- und Dachtechnik GmbH

Pillasch Hövekamp

Herr Bosler,
1. In die jährliche Kontrolle der Fachgärtner mit einbeziehen
2. z.d.A.
18.04.89

Anlage
Wartungsvertrag 2fach
Dachgärtnerrichtlinien

F.Nr.5032.01.89

Übertrag: DM ..17.160,-

3. Dachbegrünung

3.1 2 Lagen Speicherschutzmatte Nr. 45 aus verrottungsfesten Fasern in Rollen von 2 m Breite stumpf gestoßen verlegt. Nähte versetzt. Beide Lagen Speicherschutzmatten sind an den Dachrändern hochgeführt über den First zu legen oder wenn nicht vorhanden, mit einem Klemmprofil vor dem Abrutschen zu sichern.

Fabrikat Zinco oder gleichwertig, angeboten: ....

bereits beim Wurzelschutz enthalten

ca. 300 qm á DM ...-..... DM ...-.....

3.2 Klemmprofil aus Aluminium stranggepreßt, gelocht, ... mm hoch, 5 m lang mit nichtrostendem Befestigungszubehör fluchtgerecht montieren. Sämtliche Lagen Wurzelschutzfolie und Speicherschutzmatte sind am aufgehendem Bauteil hochzuführen und anzupressen, einschließlich dauerelastischer Kittfuge auf Thiokolbasis einschl. Voranstrich liefern und herstellen.

ca. 120 m á DM ...26,20.. DM ..3.144,-

3.3 Systemaufbau bestehend aus Floratherm-Elementen TH 100 mit Dämmwirkung aus PS-Hartschaum, ausgestattet mit umlaufendem Hakenfalz, oberseitig eingeformter Querrippung zur Aufnahme des Erdschubes und der Wasserbevorratung, Lochrasterung zum Ablauf des Überschußwassers und Diffusionsausgleiches, sowie unterseitigen Drainagekanälen liefern und nach den Verlegerichtlinien vollflächig verlegen.

Fabrikat Zinco oder gleichwertig, angeboten ....

Übertrag DM ..20.304,-

Übertrag: DM ..20.304,-..

ca. 300 qm á DM ..19,60... DM ..5.880,-

3.4 m Drainage entlang der Traufe aus Drainerohren DN 100 liefern und nach Verlegeanleitung einbauen.

Fabrikat Zinco oder gleichwertig,
angeboten..Teilsickerrohr.
Strasil

ca. 120 m á DM ....4,60... DM 912,-

3.5 m Verfüllung mit gewaschenem Kies, Körnung 16/32, ca. 8 cm hoch, zur Sicherung des Überschußwasserablaufs, liefern und einbringen.

ca. 120 m á DM ....8,40... DM ..1.008,-.

3.6 m Filtervliesbahn 50 cm breit, entlang des Firstes über den Floratherm-Elementen zur Abdeckung der Schnittfuge liefern und mit Stoßüberdeckung verlegen.

Fabrikat Zinco oder gleichwertig.

ca. 50 m á DM ...4,20... DM ....210,-.

3.7 Holzgerüst ab 15 Grad Dachneigung aus nicht imprägnierten Holzlatten als Rost zusammengefügt liefern und über den Florathermelementen als Abrutschsicherung für die Vegetationsschicht einbauen.

ca. 300 qm á DM ..13,60... DM ...4.080,-

3.8 Dachgärtner-Substrat auf Ton-Lava-Kompost-Basis, pH-Wert 5,7, in Säcken zu 80 l, liefern und über dem Filtervlies aufbringen und einebnen, Schichtdicke ca. 5 cm einschl. 20% Sackung.

Übertrag DM .32.394,-

Übertrag: DM .32.394,-

Fabrikat Zinco oder gleichwertig,
angeboten ....

ca. 300 qm á DM ...27,75... DM ..8.325,-

3.9 Herstellen einer Pflanzebene durch Einsaat einer geeigneten Gräser-Kräutermischung mit zusätzlicher Einsaat von Wildstauden und versch. Sedumarten, einschl. Lieferung des Saatgutes, sowie aller erforderlichen Nebenarbeiten, wie Bodenbearbeitung, Saataufbringung, Einigelung und Walzung der Oberfläche. E

ca. 300 qm á DM ....4,60.... DM ..2.280,-

3.10 ~~Alternativ:~~

~~Grasfläche mit geeigneten Rollrasenmatten aus einer wartungs und pflegearmen Gräser-Kräutermischung lieferung, fachgerecht aufbringen und vor dem Abrutschen sichern.~~

~~ca. 300 qm á DM~~ ..15,20... alternativ DM ....

3.11 Keim- und Erosionsschutz gegen Abschwemmungen und Windabtrag herstellen durch Aufbringen eines Jutegewebes, Maschenweite ca. 3 cm, als Rollenware ...m Breite mit Stoßüberdeckung nach den Verlegerichtlinien verlegen einschl. Befestigung mit Haften. Fabrikat: Zinco o. gleichwertig

ca. 300 qm á DM ...7,40... DM ...2.220,-

3.12 Fertigstellungspflege vor Übergabe einschl. Bewässerung

ca. 300 qm á DM ...1,40... DM 420,-

Übertrag DM .45.639,-

Gärtnereihof Tübingen Year installed/ background: Installed in May 1986, this was the first pitched extensive green roof in sw-Germany. The City wanted a grass roof, but ZinCo arranged to restrict grass to the north-face, and use drought-tolerant species for the south-face (cuttings, seeds, and 4 plugs/ m^2). The turf didn't survive; gaps from die-off were replaced by species from the south-face. Maintenance (by garden staff) was considerable in the first 7 years; by 2000, all maintenance had ceased.	
Type:	Pitched Sedum roof
Size (m^2):	2,160 m^2
Location:	Europastr. 30, (south-west) Tuebingen
Slope/ Aspect:	ca. 15°
Shading:	only at the very edges (NW) where tree canopies come close to roof
Original depth:	unknown
Construction:	unknown
Description:	This was ZinCo's earliest pitched roofs. The south facing aspect was mainly Sedum interspersed with *Thyme, Festuca, Petrorhagia*, etc. While the N-facing roof is similar but has more grass. Mosses formed a consistent undercover but were not recorded as this was one of the first roofs surveyed.
Vegetation type:	S-face: extensive Sedum; N-face: extensive Sedum with more grasses
Sampling method:	Stratified random along systematic transects

Substrate results (Tübingen)			
Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	2.7	≤ 15
Proportion gravel (d > 4mm)	mass %	71	≤ 50
Apparent density, dry	g/cm^3	1.18	no requirement
Apparent density, at mWK	g/cm^3	1.62	no requirement
Total pore volume (GPV)	vol. %	54	no requirement
Maximum water capacity (mWK)	vol. %	44	≥ 35 ≤ 65
Air content at mKW	vol. %	10	≥ 10
Water permeability mod. kf	mm/ min	11	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	5.6	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.4	≤ 3.5
Organic content	g/ L	79	≤ 65
Nitrogen (N) (in CAT)	mg/ L	17	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	50	≤ 50
Potash (K2O) (in CAT)	mg/ L	97	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	110	≤ 200

Tübingen documentation (7 pages)

Correspondence between Tübingen and FH Nürtingen regarding green roofs (3 pages)

Fachhochschule Nürtingen
Die individuelle Hochschule.

Landespflegerische Lehr- und Versuchsanlagen Braike, Tachenhausen
Prof. Dipl.-Ing. Eberhard

Fachhochschule Nürtingen Postfach 1349 D-7440 Nürtingen

Neckarsteige 6-10
7440 Nürtingen
Telefon 07022/701-1
Telefax 07022/701-303

Schelmenwasen 4-8
7440 Nürtingen
Telefon 07022/404-0
Telefax 07022/404-166

Außenstelle Geislingen
Bahnhofstraße 62
7340 Geislingen
Telefon 07331/22-481
Telefax 07331/22-480

Grünflächenamt Tübingen
z.Hd. Herrn Mang
Poststr. 10

7440 Tübingen

Universitätsstadt Tübingen
Grünflächenamt
Poststraße 10
18. MAI 1992
4 | M

Datum: 14.05.92
Ihre Zeichen:
Ihre Nachricht:
Unsere Zeichen:
Durchwahl: /47360

Fax 07022-404166

Betr.: Informationen über Schrägdachversuch

Sehr geehrter Herr Mang,

bezüglich unseres Telefonats Ende April sende ich Ihnen diese Anfrage. Herr Prof. Eberhard interessiert sich, wie ich Ihnen bereits mitteilte, für den Schrägdachversuch Ihres Amtes.
Konkret geht es dabei um folgende Fragen:

1. Welcher Dachaufbau wurde verwendet?
   evntl. Skizze oder Bezeichnung des Systems (Unterlagen von Zinko liegen uns vor)
2. Wie ist die Artenzusammensetzung?
   wenn möglich in Form einer Liste (Sedum und Grasdach)
3. Werden regelmäßig Beobachtungen durchgeführt und wenn ja, welche?

An der Fachhochschule soll in diesem Jahr in der Landespflegerischen Lehr- und Versuchsanlage Abtl. Braike ein Dachgartenversuch gestartet werden. Es handelt sich um eine kleinere Dachfläche mit mehreren Unterteilungen. In jedem Feld stellt eine Firma ihren Aufbau für eine Bepflanzung mit Sempervivum vor.
Wenn Ihrerseits Interesse besteht, können wir Sie gerne darüber informieren.
Anbei für Sie wie besprochen die beiden aktuellen Programmpunkte der FH Nürtingen.
Vielen Dank im voraus

Mit freundlichen Grüßen

B. Schnitzler
Betriebsleiterin, LVA
Schnitzler B.

Fachbereiche mit Studiengängen Betriebswirtschaft, Landespflege, Landwirtschaft

Bankverbindung: Volksbank Nürtingen eG
Konto-Nr. 507 373 006 BLZ 612 901 20

Entwurf

BÜRGERMEISTERAMT
DER UNIVERSITÄTSSTADT TÜBINGEN

Bürgermeisteramt Tübingen · Postfach 2540 · 7400 Tübingen

Sprechzeiten:
Montag - Freitag 8.00 - 11.30 Uhr
Ordnungsamt zusätzlich
Dienstag 14.00 - 17.00 Uhr

Sachbearbeitende Dienststelle
Grünflächenamt
Poststr. 10

Gesch. Zeichen
67

Sachbearbeitung
Herr Braun

An die
Fachhochschule Nürtingen
z.H.H.Prof.Dipl.Ing.Eberhard
Postfach 1349

D-7440 Nürtingen

Anlagen	Datum und Zeichen Ihres Schreibens	Telex 7 262 864 stue d Telefax 07071 / 204777 ☎ (0 70 71) 204 -575	Datum
2	14.5.92 /47360		26.06.1992

Betrifft:

Ihre Anfrage vom 14.05.1992,
Information über Schrägdachbegrünung
Südseite Stauden/Nordseite Gräser,
Fertigstellung im Sommer 1986

Sehr geehrter Herr Professor Eberhard,

Zu Frage 1: Siehe Skizze

Zu Frage 2: Siehe Artenliste, heute geändert. Gräser infolge Trockenheit abgestorben - vorwiegend im oberen Dachbereich, da hier die Austrocknung zuerst beginnt. Entleerung der Kavernen aufgrund der Neigung. Kahlstellen werden mit Stecklingen der bezeichneten Stauden aufgefüllt. Im Ansiedlungsversuch: Eriophyllum lanatum, Helianthemum, noch nicht ausgewertet.

Zu Frage 3: Ein zu begrünendes Schrägdach ist schwieriger zu erhalten als ein Flachdach (Trockenheit, Abschwemmgefahr des Pflanzstoffes, wenn aus Kostengründen vollbewachsene Elemente nicht zur Verfügung stehen; Ansiedlung von Beikräutern auf den noch nicht bewachsenen Flächen - vom Wind angetragen, aus dem Pflanzstoff u. d. Vögel).

Aufwand zur Wildkräuterbekämpfung und Bewässerung in Tübingen 1989 = rd. 180 Std.

Nach unseren Erfahrungen ist mind. während der Herstellungspflege das Bewässern unerläßlich, wobei es das System ZinCo erfordert, daß etwa die obere Hälfte des Daches (zum First) intensiver zu bewässern ist als die untere. Die untere Hälfte profitiert vom längerandauernden Wasserabfluß Richtung Dachrinne. Es zeigte sich anfangs relativ starke Moosbildung im unteren Dachbereich bei Außerachtlassung dieser Erkenntnisse. An heißen Sommertagen betrug die Temperatur unmittelbar auf der Oberfläche 47 ° C. Diesen Verhältnissen waren z. B. Dianthus alpinus, Hieracium und Achillea nicht gewachsen. Sempervivum ist außerstande rasch Flächen zu schließen - es leidet auch stark, wenn es durch das Abschwemmen des Substrates, auch nur leicht überhöht, angedeckt wird.

Deswegen bekamen wir als nicht gerade willkommene (weil sehr fruchtbar), aber sehr dekorative Staude, Tunica saxifraga irgendwie in die Fläche rein. Nach dem Verblühen wurden die Samenstände abgeschnitten sowie bei den Säuberungsgängen versucht, Pflanzen zu entfernen, was bei der starken Wurzelballen-Bildung nicht immer möglich ist. Bis heute ist die Dachfläche zu ca. 85 % mit gewolltem Bewuchs bedeckt.

<u>Düngung:</u> Luzian-Urgesteinmehl ca. 50 g/qm
N+P+K-Dünger, 12/12/17,
ca. 10 g/qm im April

Mit freundlichen Grüßen
Im Auftrag

(Krommes)

Species list for pitched roofs (1 page)
(this appears to be a generic list that was recommended/ used for the Tübingen roof)

ZinCo

Pflanzen für Schrägdachbegrünung ; hier: Gärtnerhof, Europastr. 30
7400 Tübingen 1

Stauden:

Achillea millefolium – Schafgarbe
Dianthus alpinus – Alpennelke
Dianthus deltoides – Heidenelke
Doucus carota – Wilde Möhre
Hieracium pilosella – Habichtskraut
Hieracium pilosella – Kleines Habichtskraut
Matricaria chamomilla – Echte Kamille
Origanum vulgare – Majoran
Sedum reflexum – Tripmadam
Sempervivum – Hauswurz
Sedum album – Weißer Mauerpfeffer
Sedum cauticolum – Fetthenne
Sedum floriferum "Weihenstephaner Gold" – Fetthenne
Sedum sexangulare – Milder Mauerpfeffer
Sedum acre – Scharfer Mauerpfeffer
Sedum hybridum "Immergrünchen" – Fetthenne
Sedum spurium "Coccineum" – Fetthenne

Gräser:

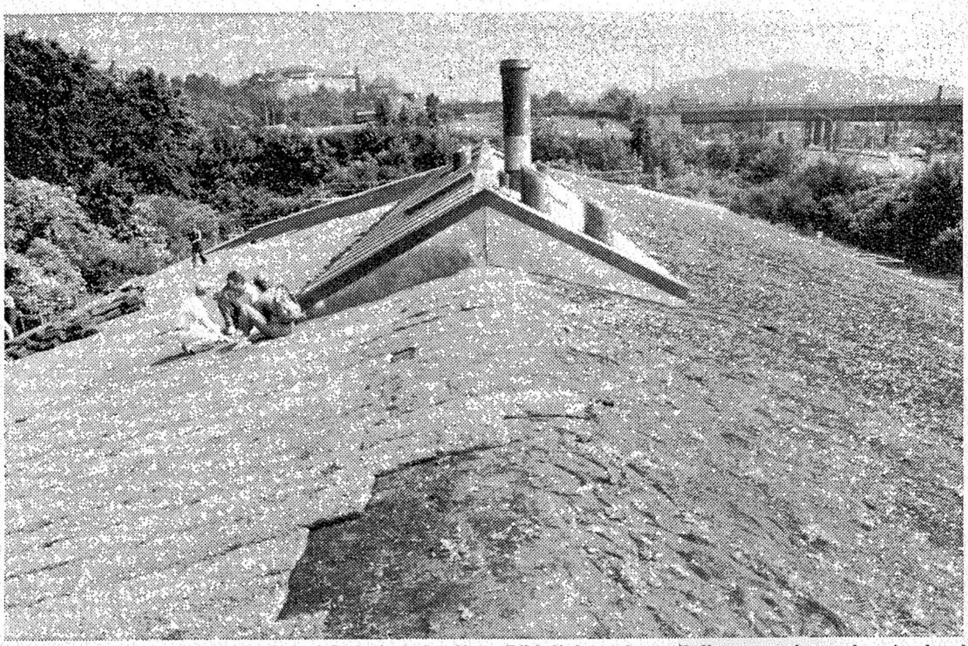
Festuca ovina duriusenta SCALDIS – Rotschwingel
Festuca rulra commutata ATLANTA – Rotschwingel
Festuca rubra rubra PERNILLE – Rotschwingel
Festuca rubra trichophylla ARTIST – Rotschwingel
Poa pratensis BARON – Wiesenrispe
Agrostis tenuis TRACENTA – Straußgras
Lolium perenne MAJESTIC – Weidelgras

Stand: Mai 1986

ZinCo Dach Systeme GmbH · Industriegebiet · 7441 Unterensingen · Telefon 0 70 22/60 03-0 · Telex 7 267 324

Newspaper article about the green roof at Gärtnereihof Tübingen (1 page)

25 Juni 1984



Die Unterschiede zwischen Nord- und Südseite zeigt dieses Bild: links verlegter Rollrasen, rechts noch weitgehend sichtbare Erdschicht mit den jungen Stauden und Kräutern. Bilder: Metz

Für den Gärtnereihof ein pflegeleichtes Dach:

Mit Gras und Stauden gedeckt

Unterschiedlicher Bewuchs für die Nord- und die Südseite

TÜBINGEN (-ger). Das größte bepflanzte Steildach in Europa wurde in den vergangenen Tagen auf dem neuen Gärtnereihof der Stadt Tübingen angelegt. Mit den 1500 Quadratmetern Grasdach will die Stadt nach Auskunft von Baubürgermeister Klaus A. Blanke zum einen den „problematischen Standort" vor Tübingens ältester (Linden-)Allee weitgehend in die vorhandene Parksituation einbinden, zum anderen Erfahrungen „unter ökologischen Aspekten" mit Grasdächern überhaupt sammeln.

Die Überlegungen für einen neuen Gärtnereihof reichen zurück bis in die frühen sechziger Jahre. Gemeinderat und Verwaltung taten sich schwer bei der Standortsuche. Bis das Restgrundstück an der L 370 (zwischen neuer Europabrükke und SV-03-Stadion) akzeptiert wurde, gingen Jahre ins Land. Mitentscheidend für diesen Standort war schließlich auch, daß im Bereich südlich des Schloßbergs das Haupteinsatzgebiet der Stadtgärtnerei liegt. Daß sich das große Gebäude – es faßt vom Herbst an (bis dahin soll der Bau bezogen werden) die bisher über die Stadt verteilte Gärtnerei unter einem Dach zusammen – **in die Umgebung einpassen sollte, stand von Anfang an außer Zweifel, schließlich prägt die wohl**

gen von Wurzeln in eben die Wärmedämmung verhindern wird, dann die Speichermatten, die zum einen Wasser aufnehmen, zum anderen überschüssiges Naß gleichmäßig in Richtung Kandel abfließen lassen. Darüber eingebaut sind schließlich die Pflanzelemente, aufgefüllt mit Blähton und Substraten.

Soweit sind beide Dach-Seiten gleich. Darüber aber beginnt der Unterschied. Während die schattigere Nordseite mit einem Rollrasen belegt ist, wird die Südseite einmal durch blühende Stauden ein aufgelockertes Bild bieten. Pro Quadratmeter sind vier Stauden eingepflanzt, darunter verschiedene Sedum-Arten. Dazwischen wurden noch Pflanzen ausgestreut, die

Ziegeldach rund 255000 Mark auszugeben.

Die Dach-Grünzone erfährt übrigens am westlichen Haupteingang zum Gärtnereihof noch eine Ergänzung. Ein Pflanzen-Rankgerüst, das knapp über die Dachfirsthöhe hinausreicht, wird mit attraktiven Rankpflanzen wie der Glyzinie, vielleicht einer Clematis oder einer großblättrigen Winde zu einer Visitenkarte der Stadtgärtnerei. Und entlang der Holzverschalung entlang der südlichen Dachunterkante, ist nach den Worten von Hochbauamts-Chef Dr. Rolf Nill auch noch eine gärtnerische Gestaltung vorgesehen.

Junge Handwerksmeister

POLTRINGEN/TÜBINGEN. Vor den Prüfungsausschüssen der Handwerkskammer Reutlingen haben aus dem Kreis Tübingen die Meisterprüfung bestanden: Jürgen Cerfontaine aus Poltringen als Gas- und Wasserinstallateur und Anne Schissler aus Tübingen als

Results from soil analyses of Tübingen roof (2 pages)

Dipl. Geogr.
A. SAILER-SCHMID
WIRTSÄCKERSTRASSE 14
7406 MÖSSINGEN

ANGEWANDTE
GEOÖKOLOGIE - BODENKUNDE
FELD- UND LABORUNTERSUCHUNG
SUBSTRAT - MATERIALPRÜFUNG

BÜRGERMEISTERAMT DER UNIVERSITÄTSSTADT TÜBINGEN
26. MAI 1993

Bürgermeisteramt Bauamt
26. MAI 1993

Universitätsstadt Tübingen
Grünflächenamt
Poststraße 10
28. MAI 1993

Stadt Tübingen
Grünflächenamt
z.Hd. Herrn Braun
Poststraße

7400 Tübingen

Mössingen, den 25.05.1993

UNTERSUCHUNGSBERICHT

Auftraggeber	:	Stadt Tübingen, Grünflächenamt Herr Braun
Art des Auftrages	:	Untersuchung eines Dachgartensubstrates hinsichtlich pH-Wert und Nährstoffversorgung
Probenahme	:	Mitarbeiter des Grünflächenamtes
Entnahmeort	:	Tübingen
Probeneingang	:	18.05.1993
Untersuchungsbeginn	:	18.05.1993
Aktenzeichen	:	T-313-05-93-S

Der Untersuchungsbericht umfaßt 2 Seiten

ANDREA SAILER-SCHMID, DIPLOM-GEOGRAPHIN, WIRTSÄCKERSTRASSE 14, 7406 MÖSSINGEN
TEL. (0 74 73) 2 33 44, FAX 2 58 08, BANKVERB.: KREISSPARKASSE TÜBINGEN (BLZ 641 500 20) 442 015

1. L A B O R E R G E B N I S S E

Dachgartensubstratprobe
Extensive Begrünung

1.1 Untersuchung aus dem Original

Wassergehalt	7,90 %
Trockensubstanz	92,10 %

1.2. Untersuchung aus der Trockensubstanz

pH-Wert nach $CaCl_2$ Eluat
Phosphat,Kalium nach CAL-Eluat, Magnesium nach $CaCl_2$-Eluat

		Meßwert	empfohlene Werte FLL extensive Begrünung
pH-Wert	(1)	6,5	6,5 - 8,0
Phosphat (P205)	(mg/100g)TS	41,7	5 - 15
Kalium (K20)	(mg/100g)TS	38,0	10 - 20
Magnesium (Mg)	(mg/100g)TS	26,0	6 - 12

1.3. Beurteilung

Der Beurteilung legen wir die Richtlinien für die Planung, Ausführung und Pflege von Dachbegrünungen der FLL zugrunde.

Die hier untersuchte Substratprobe liegt hinsichtlich ihres pH-Wertes im angegebenen Toleranzbereich der Richtlinie.
Die Nährstoffe Phosphat, Kalium und Magnesium liegen über den empfohlenen Werten. Eine Düngung mit diesen drei Nährstoffen ist im Augenblick nicht zu empfehlen.

Sailer-Schmid

Dipl.-Geogr. A. Sailer-Schmid

Verkehrsbetrieb Esslingen, Area 1 Year installed/ background: Thomas Hövekamp's first green roof construction site, installed May-June 1986. Over 3,000 styrofoam Floraterra boxes were pre-grown with *Sedum, Thyme* (these were over-due by installation). It had clearly not been maintained for some time, judging from the large Rose, clogged drains, exposed membrane, shredded bits of filter cloth and debris.	
Type:	Sedum meadow with Floraterra modules every m^2
Size (m^2):	1,860 m^2
Location:	Heilbronner Straße 70, east of Esslingen centre
Slope/ Aspect:	none
Shading:	none
Original depth:	100 mm plus 10-20 mm organic substrate
Construction:	As described above (expanded clay looked like Leca or lava); Floraterra modules interspersed every 1 m^2, flush with surface; 2 protection layers
Description:	Area 1 is dominated by 5 light shafts, each ca 50 m long. The vegetation between the shafts is mainly Sedum and Thyme, while that in the more open area to the west supports grasses. Floraterra boxes could not be avoided in sampling, but their vegetation was similar to that of the other parts of the roof.
Vegetation type:	Extensive Sedum-Moss cover with *Allium schoenoprasum, Thymus.*
Sampling method:	Stratified random

Substrate results (VB A1) Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	0.5	≤ 15
Proportion gravel (d > 4mm)	mass %	68	≤ 50
Apparent density, dry	g/cm-3	0.54	no requirement
Apparent density, at mWK	g/cm-3	0.98	no requirement
Total pore volume (GPV)	vol. %	79	no requirement
Maximum water capacity (mWK)	vol. %	44	≥ 35 ≤ 65
Air content at mKW	vol. %	35	≥ 10
Water permeability mod. kf	mm/ min	-	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	5.9	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.2	≤ 3.5
Organic content	g/ L	60	≤ 65
Nitrogen (N) (in CAT)	mg/ L	19	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	< 5	≤ 50
Potash (K2O) (in CAT)	mg/ L	58	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	140	≤ 200

Verkehrsbetrieb Esslingen, Area 2 Year installed/ background: Installed May-June 1986, same as Area 1.	
Type:	Sedum meadow with Floraterra modules every m^2
Size (m^2):	2,064 m^2
Location:	Heilbronner Straße 70, east of Esslingen centre
Slope/ Aspect:	none
Shading:	none
Original depth:	100 mm plus 10-20 mm organic substrate
Construction:	10-20 mm organic substrate and 100 mm expanded clay (looks like Leca or lava); Floraterra modules interspersed every 1 m^2, flush with surface; 2 protection layers
Description:	Area 2 is more open than Area 1, with 12 evenly spaced light shafts Gravel paths connect the light shafts with each other and with the gravel edges of the roof. Floraterra modules are evenly spaced, too.
Vegetation type:	Extensive Sedum-Moss cover with *Allium schoenoprasum, Thymus,* and some grasses.
Sampling method:	Stratified random

Substrate results (VB A2)

Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	2.3	≤ 15
Proportion gravel (d > 4mm)	mass %	77	≤ 50
Apparent density, dry	g/cm-3	0.48	no requirement
Apparent density, at mWK	g/cm-3	0.8	no requirement
Total pore volume (GPV)	vol. %	82	no requirement
Maximum water capacity (mWK)	vol. %	32	≥ 35 ≤ 65
Air content at mKW	vol. %	50	≥ 10
Water permeability mod. kf	mm/ min	-	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	5.8	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.3	≤ 3.5
Organic content	g/ L	25	≤ 65
Nitrogen (N) (in CAT)	mg/ L	30	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	< 5	≤ 50
Potash (K2O) (in CAT)	mg/ L	37	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	44	≤ 200

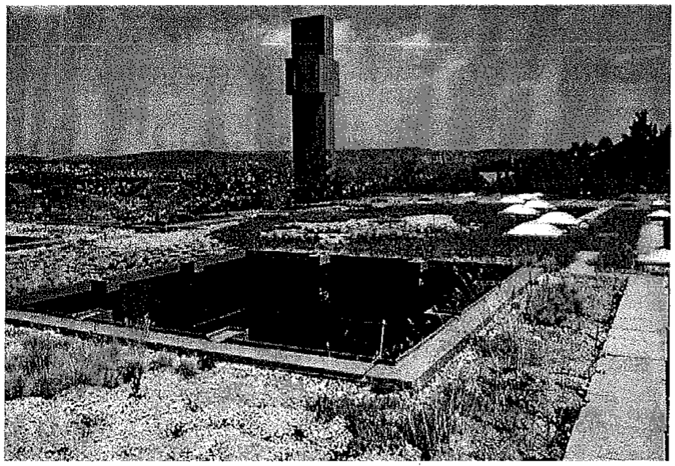
Pliensaufriedhof, Esslingen Year installed/ background: The only information is from a ZinCo product sheet which describes the concept and site; the illustrated system cross-section does not specify substrate depth. Maintenance was apparently considerable, as gardening staff in the building below have easy access to the roof via permanent ladder.	
Type:	Species-poor Sedum roof
Size (m^2):	~ 500 m^2
Location:	Eichendorfstrasse, 73732 Esslingen am Neckar
Slope/ Aspect:	none
Shading:	large *Pinus sylvestris* at east end of the roof
Original depth:	unknown
Construction:	Soil: "Systemerde Dachgarten" Floratherm WD 180 with system filter SF; Water storage, ca. 70 mm; Protection layer ISM 50; Root-resistant waterproofing
Description:	Perhaps the happiest Sedum roof in the world, the plants are lush and not bothered by competition of any sort, it seems. Just the odd herb in between and the odd pine sapling. A few distinct patches of *Teuchrium* and *Festuca* were avoided as best possible in the sampling.
Vegetation type:	extensive Sedum-Moss cover
Sampling method:	Stratified random, total 15 quadrats distributed over homogeneous vegetation

Substrate results (Pliensau)

Physical properties	**Unit**	**Result**	**FLL reference value**
Proportion slurry-forming components (d < 0.063 mm)	mass %	1.3	≤ 15
Proportion gravel (d > 4mm)	mass %	24	≤ 50
Apparent density, dry	g/cm-3	0.64	no requirement
Apparent density, at mWK	g/cm-3	1.35	no requirement
Total pore volume (GPV)	vol. %	72	no requirement
Maximum water capacity (mWK)	vol. %	71	≥ 35 ≤ 65
Air content at mKW	vol. %	1	≥ 10
Water permeability mod. kf	mm/ min	0.1	0.6-70
Chemical properties	**Unit**	**Result**	**FLL reference value**
pH value (CaCl2)	-	6.3	6.0-8.5
Salt content (KCl) (water extract)	g/ L	0.6	≤ 3.5
Organic content	g/ L	189	≤ 65
Nitrogen (N) (in CAT)	mg/ L	93	≤ 80
Phosphorus (P2O5) (in CAT)	mg/ L	7	≤ 50
Potash (K2O) (in CAT)	mg/ L	88	≤ 500
Magnesium (Mg) (in CAT)	mg/ L	150	≤ 200

Pliensaufriedhof documentation (1 page)

Objektbericht Pliensaufriedhof, Esslingen



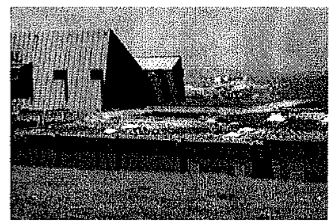
Das Gebäude am Esslinger Pliensaufriedhof ist auch Sitz des städtischen Gartenbauamts.

Objektdaten

Fläche:	ca. 500 m²
Baujahr:	1977
Bauherr:	Stadt Esslingen/Neckar
Ausführung:	Metall- und Dachtechnik GmbH, Unterensingen
Koordinaten:	48°43'41.30"N 9°17'42.79"E

Konzeption

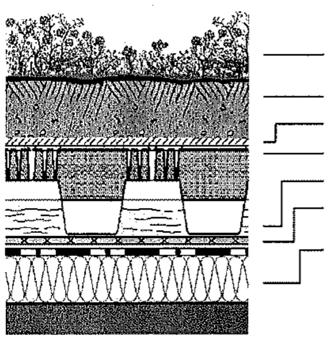
Das mit einer einfachen Intensivbegrünung versehene Dach auf dem städtischen Gebäude am Esslinger Pliensaufriedhof bildet nach wie vor nicht nur einen wohltuenden Kontrast zum smogverhangenen Neckartal, sondern es war auch aus konstruktiver Hinsicht eine kleine Revolution. Durch den wärmedämmenden Begrünungsaufbau entstand nämlich aus einem konventionellen Warmdach ein bauphysikalisch günstiges DUO-Dach, welches nach wie vor bestens funktioniert.



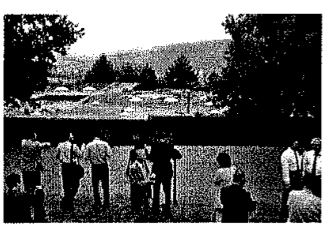
↑ Das Objekt fotografiert 1984...
... und im Jahr 1999. ↓

Auch heute, nach 25 Jahren, sind Dach und Begrünung voll funktionsfähig.

Systemaufbau



- Pflanzebene mit Sedum, Stauden und Gräsern
- Systemerde „Dachgarten“
- Systemfilter SF
- Floratherm® WD 180
- Wasseranstau, ca. 7 cm
- Isolierschutzmatte ISM 50
- Dachaufbau mit wurzelfester Abdichtung Grundwärmedämmung



Das inzwischen 25-jährige Gründach findet Interesse bei Besuchern aus nah und fern.

Wege aus Betonplatten erleichtern Kontroll- und Wartungsgänge.

Auch im Herbst bietet das begrünte Dach sehenswerte Farbaspekte.

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Appendix 2. Master species list (including intentional species and EIVs)

Master species list Species name	Intentional (1) or colonising (0)	Ellenberg Indicator Values					
		L	T	C	M	R	N
Acer campestre L.	0	5	6	4	5	7	6
Acer pseudoplatanus L.	0	4	0	4	6	0	7
Achillea millefolium L.	1	8	0	0	4	0	5
Agrostis stolonifera L.	0	8	0	5	0	0	5
Agrostis tenuis L.	1	7	0	3	0	4	4
Allium flavum L.	1						
Allium schoenoprasum L.	1	7	0	7	0	7	2
Arrhenatherum elatius (L.) J. et C. Presl.	0	8	5	3	5	7	7
Campanula rotundifolia L.	1	7	5	0	0	0	2
Carex flava L.	1	8	0	2	9	8	2
Carex humilis Leyss.	1	7	6	5	2	8	3
Carpinus betulus L.	0	4	6	4	0	0	0
Cerastium arvense L.	1	8	0	5	4	6	4
Convolvulus arvensis L.	0	7	6	0	4	7	0
Coronilla varia L.	0	7	6	5	4	9	3
Crepis tectorum L.	0	8	6	7	4	0	6
Dactylorhiza fuchsii	0						
Dianthus carthusianorum L.	1	8	5	4	3	7	2
Dianthus deltoides L.	1	8	5	4	3	3	2
Erigeron annuus (L.) Pers.	0	7	6	0	6	0	8
Festuca ovina L.	1	7	0	3	0	3	1
Festuca rubra L.	1	0	0	5	6	6	0
Fragaria vesca L.	0	7	0	5	5	0	6
Geranium spp.	0						
Geum urbanum L.	0	4	5	5	5	0	7
Hieracium pilosella L.	1	7	0	3	4	0	2
Hypericum perforatum L.	0	7	6	5	4	6	3
Hypericum perfoliatum L.	0						
Lichen_Cladonia furcata	0						
Lichen_Cladonia cf scabriscula	0						
Lichen_Peltigera	0						
Linum perenne	1	7	0	6	3	8	2
Lotus corniculatus L.	1	7	0	3	4	7	3
Medicago lupulina L.	0	7	5	0	4	8	0
Moss_Hypnum1	0						
Moss_Hypnum2	0						
Moss_Dicranum scoparium	0	5	0	5	4	4	
Moss_Eurhynchium praelongum	0	6	4	5	6	5	

Moss_Scleropodium purum	0	6	4	5	4	5	
Moss_Brachythecium rutabulum	0	5	x	5	4	x	
Moss_Bryum1	0						
Moss_Brachythecium_cf_albicans1	0	9	3	5	2	x	
Moss_Philonotis fontana	0	8	0	6	7	2	
Moss_Polytrichum juniperum	0	8	2	?	4	3	
Moss_Racomitrium elongatum	0	8	3	6	9	5	
Moss_Brachythecium_cf_albicans2	0	9	3	5	2	x	
Moss_Brachythecium_cf_albicans3	0	9	3	5	2	x	
Moss_Bryum2	0						
Moss_Calliergonella cuspidata	0						
Moss_Ceratodon purpureus	0						
Moss_starry_yellow	0						
Nepeta racemosa	1						
opplved herb	0						
Other small tree	0						
Petrorhagia prolifera (L.) Ball. U. Heyw.	0	8	7	3	3	5	2
Petrorhagia saxifraga (L.) Lk.	1	9	7	4	2	7	1
Picris hieracioides L.	0	8	0	5	4	8	4
Pinus sylvestris L.	0	7	0	7	0	0	0
Poa angustifolia (L.) Gaud.	0	7	5	0	0	0	3
Poa compressa L.	1	9	0	4	2	9	2
Poa pratensis L.	1	6	0	0	5	0	6
Poa pratensis angustifolia	1	7	6	0	0	0	3
Potentilla argentea L.	1	9	6	3	2	3	1
Potentilla erecta L.	0	6	0	3	0	0	2
Potentilla neumanniana	1						
Potentilla recta	0	9	7	5	3	5	2
Sedum acre L.	1	8	6	3	2	0	1
Sedum album L.	1	9	0	2	2	0	1
Sedum album Coral Carpet	1						
Sedum album Murale	1						
Sedum floriferum	1						
Sedum hybridum	1						
Sedum rupestre	1	7	5	4	2	5	1
Sedum sexangulare L. emend. Grimm	1	7	5	4	2	6	1
Sedum spurium	1	8	6	4	3	5	3
Sedum telephium L.s.str.	1	7	6	0	4	7	0
Sempervivum tectorum L.	1	8	0	2	2	4	0
Setaria viridis (L.) P.B	1	7	6	0	4	0	7
Solidago canadensis L.	0	8	6	5	0	0	6

Taraxacum officinale Web.	0	7	0	0	5	0	7
Teucrium chamaedrys L.	1	7	6	4	2	8	1
Thymus praecox Opiz	1	8	6	5	3	8	1
Thymus pulegioides L.	1	8	0	4	4	0	1
Thymus serpyllum L.	1	7	6	5	2	5	1
Trifolium arvense L.	1	8	6	3	3	2	1
Trifolium campestre Schreb.	0	8	6	3	4	6	3
Trifolium dubium Sibth.	0	6	6	3	5	6	5
Trifolium pratense L.	0	7	0	3	0	0	0
Unknown herb	0						
Verbascum nigrum L.	0	7	5	5	5	7	7
Verbascum thapsus L.	0	8	0	3	4	7	7
Veronica spicata L.	1	7	7	6	3	7	2
Vicia hirsuta (L.) S.F. Gray	0	7	6	5	4	0	4
Vicia sepium L.	0	0	0	5	5	6	5
Vulpia myuros L. C.C. Gmel.	0	8	7	3	2	5	1