Nature as a template for a new concept of extensive green roofs

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JOINT DOCTORAL THESIS:

NATURE AS A TEMPLATE FOR A NEW CONCEPT OF EXTENSIVE GREEN ROOFS

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"Our world is green.

Greener is the earth when more trees are planted.
Greener is the garden when nurtured by loving hands.
Greener is a tree with leaves on its branches.
Greener is the ground when seeds for grasses are sown.

Greener is human life when there's piece of land to toil.
Greener is life of man and women when trees, grasses and garden thrive best to serve mankind."

Green, Greener by Elizabeth Padillo Olesen (2013)

Four years of work, but also four years of collaboration, friendship and collegiality, that is how I can briefly summarize the period in which I wrote this thesis. How did I get involved in this? Well, after I obtained my Master in Biology at the University of Leuven, I had a pronounced desire to apply for a PhD scholarship. Partly because I wanted to do research in the first place, but also because I was looking for a challenge. After considering some opportunities at the Biology department, I decided to move from the fundamental research topics towards more applied research. I was very excited about the topics suggested by Prof. Hermy during our first encounter at the Division of Forest, Nature and Landscape (University of Leuven). One subject immediately caught my attention and afterwards became the base of this work. Green roofs where at that moment very unfamiliar to me, but as I started to explore the current knowledge on green roof technology, I found it very interesting. Six months later, I was unfortunately not able to persuade the jury of the Agency for Innovation through Science and Technology (IWT) to offer me a scholarship. Lucky for me, the University of Leuven offered me a scholarship so I could start my research in March 2011. I am therefore very grateful to the University of Leuven and to the Division of Forest, Nature and Landscape that they gave me the opportunity to start my research.

It is impossible to start a research without the expertise and consult of a supportive promotor. Thank you Martin, for suggesting the green roof topic to me in the first place. Because you are so committed to urban ecology, green roofs and green walls yourself, you were always able to point at interesting research options and eager to ask for my latest research results. We had very productive discussions after which I was always encouraged to continue.

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Je tiens aussi à remercier les doctorants à l'IUT. Adeline et Solène, vous étiez toujours présentes quand j'étais là pour quelques semaines. J'ai pu loger chez vous, manger chez vous, covoiturer avec vous… Ce fut un plaisir de vous aider, dans la Crau en cherchant le Saga pedo *à cinq heures du matin, ou en préparant les terrines pour tester la banque de graines. De retour, et ceci vaut également pour Jean-François, j'ai énormément apprécié votre aide pour l'installation de mon toit végétalisé. Je n'aurais ainsi pas pu réaliser ce travail toute seule.*

Many thanks to all my dear colleagues at BNL, for reminding me every single day that a PhD is not only about hard work. I really enjoyed our coffee breaks, the numerous treats, the sport activities during lunch break, the dinner evenings, the yearly lab day, barbecue and Christmas party, the 'Sinterklaas' preparations,… It almost seems impossible to have finished this thesis when listing all those activities! But just as Joana said ones: "There is proof that people become more productive when they are socially active" (or something like that). I think that applies to my work too.

Special thanks to Koenraad, who was more than just an office mate to me. We started together, worked together, and now we finish (almost) together. I could really ask you anything, from statistical stuff (you're really the best!) to personal stuff. I know I can be a disturbing chatting waterfall sometimes, but you never complained. To my other office mates with whom I spend a lot of my working hours: Hans, Wim (who actually stayed more in our office than in his own), and in the end Astrid and Ellen, thank you for the nice chats we had, the discussions, the jokes, the teasing,… I will never forget the nice working atmosphere I had thanks to you all.

I also like to thank my family and friends, for your interest in my work and your never ending support. I hope that after those four years, I convinced some of you about the importance of greening roofs.

Finally, thank you Jeroen, for sharing my enthusiasm, cheering me up when I was down, keeping my feet on the ground, being patient when I was annoying or stressed, practicing Flenglish (which was maybe not such a good idea), and so many other things. I really cannot wish for a better boyfriend!

I hope you all get inspired and enjoy reading this thesis!

Carmen

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Summary

1. Summary

In an era of urbanization, land use change, habitat loss and fragmentation, biodiversity is under pressure more than ever. This is an important issue as biodiversity is considered the major driver of ecosystem functioning and the provision of ecosystem services, and linked to that, our human well-being. Furthermore, urban areas face many environmental problems, including a risk of flooding due to a decrease in pervious surfaces, and above average temperatures related to building materials with higher heat storage capacity and lower albedo. Climate change is predicted to further enhance those problems, and the demand for sustainable strategies that can mitigate the situation is urgent. Urban green infrastructures, like street trees, parks, gardens, green walls and green roofs (GRs), comprise such a strategy. Offering a wide array of urban ecosystem services, including urban heat island effect reduction, stormwater management, habitat provisioning and aesthetic and amenity value, GRs have become an important tool for improving urban environmental quality. In essence, GRs are roofs with a vegetation layer on top. In this thesis we focus on the extensive GR type (EGRs, substrate depth < 20 cm) as these have a broad applicability and are more durable (i.e. less maintenance, self-sustaining).

Most expertise on EGRs is located in the temperate climate and cities in the Mediterranean are rather unfamiliar with the technique, which is probably due to the elevated temperatures and summer drought in these regions. In these regions, water is limited and climate change will lead to an even more severe water scarcity during summer. An irrigation system could help plant growth and survival, but it is perceived as an unsustainable and in some cases even impossible option. Therefore, more research is needed to select plant species suitable for Mediterranean unirrigated EGRs, and to adapt GR structure elements to meet the requirements of the selected plant species. As climate change will also lead to higher temperatures and erratic precipitation events in the temperate climate, these regions will also benefit from the resulting outcome of such research.

The main goal of this thesis is to elaborate and test a new concept for EGR design, comprising both plant selection and GR structure elements. The thesis includes a fieldwork study in southern France in which potential drought-adapted Mediterranean plant species were inventoried based on the habitat template hypothesis. In a GR context, this hypothesis states that natural habitats with similar characteristics as on EGRs should be targeted when searching for suitable plant species. Afterwards, the species list was screened for the most potential EGR plants making use of the plants' functional traits and utilitarian aspects. This screening procedure offered the scientific basis to construct an 'easy-to-handle' screening tool for optimal plant choice. As a case study, the tool was demonstrated on the Mediterranean plant list of the vegetation survey. In the following chapter, a subset of suitable Mediterranean plant species was tested for two years on experimental EGRs in both Belgium (temperate climate) and southern France (Mediterranean climate). The experimental setup included different substrate compositions (substrate depth 5 or 10 cm; presence/absence of a water retention layer) and exposition (exposed or sheltered). In a second experimental approach, the effects of different GR substrates on the growth of common GR plants were studied. The plots contained either a mineral substrate or one with additional organic material, and half of the plots were given a commercial arbuscular mycorrhizal inoculum. As the conducted experiments both focused on unirrigated EGRs, and observations pointed at severe plant stress during prolonged dry periods, results could probably be improved if regular irrigation had been provided. Therefore, a literature review was performed in order to highlight current irrigation techniques, possibilities to make the techniques more sustainable, and GR irrigation specifications in different climatic contexts. In a final chapter we looked at the biodiversity aspects of commercial GR systems. If we want to create a more sustainable urban environment, ecosystem services need to be improved. There is a consensus that ecosystem services can be predicted through functional (FD) and phylogenetic diversity (PD) of plant communities. In this chapter, currently available GR systems were analyzed in terms of FD and PD and two methods were proposed to select the species combination with maximal FD and hence ecosystem services value.

Based on the ecological and experimental knowledge obtained throughout the chapters of this thesis, a concept for EGR design in terms of vegetation and structure could be formulated. We conclude that Mediterranean vegetation can definitely inspire us as a source for development and improvement of EGR design, whether this is for the current Mediterranean climate itself or for the temperate climate under predicted climate change. Appropriate vegetation choice is essential, as well as the design in terms of sustainable irrigation techniques, appropriate substrate depth and composition, and water retention possibilities. Furthermore, many opportunities arise for additional GR research that will further contribute to more successful GRs with high biodiversity that are able to ensure and even improve ecosystem functioning and services under climate change.

2. Résumé

Au cours d'une ère dite Anthropocène et caractérisée par l'urbanisation, le changement d'affectation des terres, la perte d'habitat et la fragmentation provoquent des pressions très importantes sur la biodiversité. Il s'agit d'un problème important car la biodiversité est souvent considérée comme le principal moteur du fonctionnement des écosystèmes et comme une source de services écosystémiques, elle-même corrélée avec notre bien-être. De plus, les zones urbaines font face à de nombreux problèmes environnementaux, y compris le risque d'inondation du fait de la diminution des surfaces perméables et de l'augmentation des températures relatives aux matériaux de construction. Ceux-ci étant caractérisés par une capacité de stockage de chaleur plus élevée et un albédo plus faible. Le changement climatique devrait aggraver ces problèmes et augmenter la demande en stratégies durables afin d'atténuer cette situation. Les infrastructures vertes urbaines, comme les arbres, parcs, jardins, murs végétalisés et toits verts sont les composantes de cette stratégie. Offrant un large éventail de services écosystémique comme la réduction de l'effet d'îlot de chaleur urbain, la gestion des eaux pluviales, des habitats pour la flore et la faune locale ainsi qu'une certaine valeur esthétique; les toits verts sont devenus un outil important pour améliorer la qualité de l'environnement urbain. Ces toits verts sont essentiellement définis comme des toits avec une couche de végétation dessus. Dans cette thèse, nous mettrons notamment l'accent sur les toits verts dit "extensifs" (profondeur du substrat < 20 cm) car ils ont une gamme d'applications plus large et sont plus durables (car autonomes et nécessitant donc moins de maintenance).

La plupart des connaissances acquises sur les toits verts l'ont été en climat tempéré et peu de recherches ont été réalisées en climat Méditerranéen, probablement à cause de l'effet des fortes températures et de la sécheresse estivale. De plus, l'accès à l'eau y est limité et il le sera encore plus du fait du changement climatique qui occasionnera une pénurie d'eau encore plus grave au cours de la période estivale. La mise en place de systèmes d'irrigation pourrait alors aider en favorisant la croissance des plantes et leur survie, mais cet aménagement est souvent perçu comme une option non soutenable, voir impossible dans certains cas. Par conséquent, une augmentation du nombre de recherches menées sur ce sujet est nécessaire afin de sélectionner les espèces végétales les plus adaptées aux toits verts extensifs non irrigués de la région Méditerranéenne. Il est également nécessaire d'adapter les éléments structurels des toits extensifs pour mieux répondre aux exigences de ces plantes. Vu que les scénarios de changements climatiques prévoient également une augmentation des températures et des précipitations plus erratiques en climat tempéré, ces régions bénéficieront donc également des résultats d'une telle recherche.

L'objectif principal de cette thèse est d'élaborer et de tester un nouveau concept pour la réalisation de toits verts extensifs, comprenant notamment la sélection de la végétation et les éléments de structure de ces nouveaux aménagements comme le substrat. La thèse comprend une étude de terrain dans le Sud de la France, dans laquelle des espèces végétales méditerranéennes adaptées à la sécheresse ont été inventoriées sur la base de l'hypothèse de "l'habitat modèle". Dans le contexte des toits verts, cette hypothèse énonce qu'il faut cibler les habitats naturels possédant des caractéristiques similaires aux toits verts extensifs afin de trouver des espèces végétales les plus appropriées. La liste des espèces a ensuite été filtrée pour identifier les plantes qui possèdent le potentiel le plus fort pour être installées sur les toits verts extensifs. Ce filtre est basé sur l'utilisation des traits fonctionnels des plantes et de leurs aspects utilitaires dans ce contexte. Cette discrimination a permis la production d'une base scientifique pour construire un outil facile à utiliser pour choisir les plantes les plus favorables. A titre d'exemple, ce filtre a été appliqué à la liste des plantes méditerranéennes utilisé lors de l'étude de la végétation. Dans le chapitre suivant, un sous-ensemble des espèces méditerranéennes a été testé pendant deux ans sur des toits verts extensifs mis en place en Belgique (climat tempéré) et dans le Sud de la France (climat méditerranéen). Le montage expérimental comprend différentes compositions de substrats (profondeur 5 ou 10 cm avec ou sans couche de rétention d'eau) et différentes expositions (plein soleil ou ombre). Dans une deuxième approche expérimentale, les effets de différents substrats sur la croissance de plantes, appliqués généralement sur des toits verts ont également été étudiés. Les parcelles contenaient alors soit un substrat minéral, soit un substrat avec de la matière organique. La moitié des parcelles ont aussi fait l'objet d'une inoculation d'une souche commerciale de mycorhizes. Ces deux expériences ont été menées en l'absence d'irrigation et les résultats ont montré que les plantes étaient particulièrement stressées durant les périodes de sécheresse prolongée. En conséquence, une recherche bibliographique a été réalisée afin de mieux identifier les techniques actuelles d'irrigation utilisées, et les possibilités pour rendre ces techniques plus durables afin de proposer de meilleures techniques d'irrigation des toits verts pour des contextes climatiques différents. Dans un dernier chapitre, nous avons enfin examiné les aspects concernant la biodiversité des systèmes de toits verts extensif commerciaux. En effet, si nous voulons créer un environnement urbain plus durable, il faut en améliorer les services écosystémiques. Il y a de plus, un consensus croissant sur le fait que les services écosystémiques rendus pourraient être prévus en mesurant la diversité fonctionnelle (FD) et phylogénétique (PD) des communautés végétales. Des systèmes de toits verts écosystémisés ont donc été analysés en termes de FD et PD et deux méthodes ont alors été proposées pour sélectionner la combinaison d'espèces avec la FD maximale.

Basé sur les connaissances écologiques et expérimentales obtenues tout au long des chapitres de cette thèse, un nouveau concept pour la mise en place de toits verts extensifs (substrat; végétation; irrigation) pourrait maintenant être proposé. Nous concluons ainsi que la végétation méditerranéenne peut être une source d'inspiration pour le développement et l'amélioration de la conception de toits verts extensifs, que ce soit pour le climat méditerranéen actuel ou pour le climat tempéré sous l'effet futur des changements climatiques prévus. Un choix de plantes appropriées est alors essentiel, ainsi que la conception en termes de techniques d'irrigation durable, de profondeur et composition du substrat et des possibilités de rétention de l'eau. De plus, il existe encore de nombreuses voies pour la réalisation de recherches supplémentaires qui contribueront à la mise en place de toits verts avec une biodiversité plus forte. Ces toits verts seront alors en mesure d'améliorer de manière significative la qualité de vie des personnes dans les zones urbaines.

3. Samenvatting

In een tijdperk van verstedelijking, wijzigingen in landgebruik, habitatverlies en fragmentatie, staat biodiversiteit meer dan ooit onder druk. Dit is een beduidend probleem aangezien biodiversiteit beschouwd wordt als één van de belangrijkste drijfveren voor het functioneren van ecosystemen, het leveren van ecosysteemdiensten, en hieraan gelinkt het menselijk welzijn. Bovendien hebben stedelijke gebieden te maken met veel milieuproblemen, zoals een verhoogd overstromingsrisico door een toename aan verzegelde oppervlakte, en een verhoogde temperatuur gerelateerd aan bouwmaterialen met hogere warmte-opslagcapaciteit en verlaagd albedo. De klimaatsverandering zou deze problemen nog versterken, waardoor de vraag dringt naar duurzame strategieën die de situatie kunnen verbeteren. Stedelijke groene infrastructuurelementen, zoals straatbomen, parken, tuinen, groene muren en groendaken omvatten zo'n strategie. Groendaken zijn een belangrijk middel geworden om de stedelijke milieukwaliteit te verbeteren wegens hun breed aanbod aan ecosysteemdiensten waaronder reductie van het stedelijk hitte-eiland effect en vermindering van de afwatering. Ze bieden ook habitat voor lokale flora en fauna, esthetische waarde en gebruikswaarde. In essentie zijn groendaken daken met een vegetatielaag op. In dit doctoraat focussen we op groendaken van het extensieve type (substraatdiepte < 20 cm) omdat deze breed toepasbaar en duurzamer zijn (i.e. minder onderhoud, zelfvoorzienend).

De meeste expertise omtrent extensieve groendaken is gesitueerd in het gematigde klimaat, en steden in het Middellands-zeeklimaat zijn nog vrij onbekend met de techniek, onder meer door de verhoogde temperaturen en zomerdroogte in deze regio's. Water is hier gelimiteerd en de klimaatsverandering zal leiden tot een nog sterker watertekort in de zomer. Een bevloeiingssysteem zou plantengroei en overleving kunnen helpen, maar dit wordt vaak beschouwd als een niet-duurzame en in sommige gevallen zelfs onmogelijke optie. Daardoor is meer onderzoek nodig om geschikte plantensoorten voor mediterrane onbevloeide extensieve groendaken te selecteren, en om de structuurelementen zoals het substraat aan te passen aan de vereisten van deze geselecteerde planten. Aangezien klimaatsverandering ook zal leiden tot hogere temperaturen en onvoorspelbare neerslagmomenten in het gematigde klimaat, zullen deze gebieden ook voordeel halen uit resultaten van dergelijk onderzoek.

Het hoofddoel van dit doctoraat was het uitwerken en testen van een nieuw concept voor extensief groendak-ontwerp dat zowel plantenselectie als structuurelementen omvatte. Het doctoraat startte met een veldwerkstudie in Zuid-Frankrijk waarin potentiële droogte-aangepaste mediterrane plantensoorten werden geïnventariseerd op basis van de habitat sjabloon hypothese. In een groendak-context stelt deze hypothese dat natuurlijke habitats met gelijkaardige kenmerken als op extensieve groendaken als inspiratiebron kunnen dienen om geschikte plantensoorten te vinden. Vervolgens werd de soortenlijst gescreend voor de meest potentiële plantensoorten door gebruik te maken van hun functionele kenmerken en utilitaire aspecten. Deze screening procedure leverde de wetenschappelijke basis om een gebruiksvriendelijke methode te ontwikkelen voor optimale plantenkeuze. Als case studie werd de methode gedemonstreerd op de mediterrane plantenlijst uit het

veldonderzoek. In het volgende hoofdstuk werd een deel van de geschikte mediterrane plantensoorten gedurende twee jaar getest op experimentele extensieve groendaken in zowel België (gematigd klimaat) als Zuid-Frankrijk (Middellands-Zeeklimaat). De proefopstelling omvatte verschillende substraatcomposities (substraatdiepte van 5 of 10 cm en aan- of afwezigheid van een waterretentielaag) en exposities (onbeschut of beschaduwd). In een tweede experiment werden de effecten van verschillende substraten op de groei van algemene groendak-planten bestudeerd. De proefvlakken bevatten ofwel mineraal substraat of substaat met extra organisch materiaal, en aan de helft van de proefvlakken werd een commercieel inoculum met mycorrhiza toegevoegd. Beide experimenten waren onbevloeid, en de observaties leerden ons dat de planten stress ondervonden gedurende langdurige droge perioden. Betere resultaten hadden dus bekomen kunnen werdoen indien een bevloeiingsmechanisme voorzien was. Daarom werd een literatuurrevisie uitgevoerd om de huidige bevloeiingstechnieken te beklemtonen, om nadruk te leggen op mogelijkheden om deze technieken duurzamer te maken, en om specificaties voor bevloeiing van groendaken in verschillende klimaten voor te stellen. In een laatste hoofdstuk keken we naar de biodiversiteitsaspecten van commerciële groendak-systemen. Als we stedelijke omgevingen duurzamer willen maken, moeten ecosysteemdiensten verbeterd worden. Er bestaat een groeiende consensus dat functionele (FD) en fylogenetische (PD) diversiteit van plantengemeenschappen ecosysteemdiensten kunnen voorspellen. De FD en PD van huidige beschikbare groendak-systemen werden geanalyseerd en twee methoden werden voorgesteld om de soortencombinatie met de hoogste FD (en dus ook hoogste ecosysteemdienstwaarde) te bepalen.

Op basis van de ecologische en experimentele kennis verkregen doorheen de hoofdstukken van dit doctoraat kon een concept voor extensief groendak-ontwerp in termen van vegetatie en structuurelementen geformuleerd worden. We besluiten dat mediterrane vegetatie wel degelijk als inspiratiebron kan voor ontwikkeling en verbetering van extensieve groendaken, zowel in het huidige Middellands-Zeeklimaat als in het gematigd klimaat onder klimaatsverandering. Een geschikte vegetatiekeuze is essentieel, maar ook het ontwerp in termen van duurzame bevloeiingstechnieken, aangepaste substraatdiepte en compositie, en mogelijkheden voor waterretentie zijn belangrijk. We duiden eveneens op bijkomende onderzoeksmogelijkheden die zullen bijdragen tot het bekomen van goed functionerende groendaken met hoge biodiversiteit. Deze groendaken zullen in staat zijn om de levenskwaliteit van mensen in stedelijke gebieden aanzienlijk te verbeteren.

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List of abbreviations*

** Non standard abbreviations are given in full at first mentioning in every chapter*

A	Altitude
AAP	Average annual precipitation
AAT	Average annual temperature
AMF	Arbuscular mycorrhizal fungi
BL	Bryophyte + lichen layer
BS	Bare soil
C	Raunkiaer life form: Chamaephyte
ca.	Circa, approximately
CAM	Crassulacean acid metabolism
cf.	Confer, compare, see also
D	Depth of top soil
D_s	Simpson diversity index
DW	Dry weight
e.g.	Example given
EC	Electric conductivity
EGR	Extensive green roof (substrate depth 2-20 cm)
E_H	Shannon equitability
ET	Evapotranspiration
ETo	Reference evapotranspiration or pan evaporation
FAR	Floor-area ratio
FD	Functional diversity
FDMax1	Functional diversity maximization method 1, resulting in an ‘exact’ species list
FDMax2	Functional diversity maximization method 2, resulting in an ‘applicable’ species list
FDpg	Measure of functional richness of Petchey and Gaston (2002)
FEve	Measure of functional evenness of Villéger et al. (2008)
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (The Landscape, Research, Development and Construction Society of Germany)
FREQ	Frequency of use on extensive green roofs
G	Raunkiaer life form: Geophyte
GDD	Annual thermal sum in growing degree days
GR	Green roof
GRPL	Green roof plant list

H	Raunkiaer life form: Hemicryptophyte
H_s	Shannon diversity index
HL	Heat load
i.e.	In essence
I_{day}	Minimum daily summer irrigation requirement in l/m²
IGR	Intensive green roof (substrate depth > 20 cm)
ISA	Indicator species analysis
KW	Kruskal Wallis test
LEED	Leadership in Energy and Environmental Design
MEDLIT	Mediterranean plant list from literature
MEDPL	Mediterranean plant list
MEDVEG	Mediterranean plant list from vegetation recordings
MIE	Mycorrhizal inoculation effect
MIN	Mineral EGR substrate
MPD	Mean phylogenetic distance, measure of phylogenetic evenness of Webb et al. (2008)
MWU	Mann-Whitney U test
MYCO	plots with AMF inoculum
NA	Not applicable
NS	Not significant
OM	Organic matter
ORG	EGR substrate with additional OM
Ph	Raunkiaer life form: Phanerophyte
P	Precipitation (in mm)
PCA	Principal component analysis
PD	Phylogenetic diversity
PDf	Measure of phylogenetic diversity of Faith (1992)
PET	Potential evapotranspiration
P_{th}	Dryness threshold (in mm) for arid climates
r_s	Spearman rank correlation
RWH	Rainwater harvesting
s.s.	Sensu stricto, in the strict sense
SEGR	Semi-extensive green roof (substrate depth 12-20cm)
Sp.	Species (singular)
Spp.	Species (plural)
SR	Species richness
SS	Screening score
Th	Raunkiaer life form: Therophyte, annual species
T	Temperature (in °C)
UHI	Urban heat island
UK	United Kingdom
US	United States of America
USD	United States dollar
WHC	Water holding capacity
WRL	Water retention layer
WSUD	Water Sensitive Urban Design
$\chi 2$	Pearson Chi² analysis

Chapter 1. Introduction

1. Cities in the 21st century

According to the most recent World Urbanization Prospect of the United Nations, the world's population living in urban areas will reach 66% by 2050 compared to only 30% in 1950 (United Nations, 2014). The transition from rural to urban life styles has been marked by huge land use changes (e.g. increase in impervious surfaces), habitat loss and fragmentation (Antrop, 2004; Gill et al., 2007; Lundholm, 2011). Those factors have a severe negative impact on biodiversity in terms of local flora and fauna because many plant and animal species have difficulties to migrate or adapt to the novel conditions associated with urbanization (Lundholm, 2011). As biodiversity is considered the major driver of ecosystem functioning and the provision of ecosystem services, it also impacts our human well-being (Millennium Ecosystem Assessment, 2005). The demographic pressure in cities has also led to a decrease in green areas and hence pervious surfaces, which in turn reduces the infiltration rate and increases surface runoff during and after rainfall (Paul & Meyer, 2001). As a consequence, the risk of flooding has augmented (Kazmierczak & Cavan, 2011), causing both human tragedy and severe economic losses. Between 1998 and 2009, more than three million people have been affected by floods in Europe, leaving an economic damage of approximately 60 billion euro (EEA, 2010). In Western Europe, due to the huge economic costs and the increased flooding risk related to the predicted climate change, stormwater management is believed to be the most important environmental challenge in the 21st century (IPCC, 2013). Also in the United States, there have been significant floods during the 20st century, causing around 5 billion USD economic damage per year (O'Connor & Costa, 2003). Moreover, the urban heat island (UHI), the phenomenon that temperatures in city centres are generally 1-3°C higher compared to the surroundings because of building materials with higher heat storage capacity and lower albedo, is receiving considerable scientific attention (Saadatian et al., 2013; Li et al., 2014) because it lowers the quality of life in cities. The predicted climate change will further amplify both flooding and urban heat island problems, which is a cause for alarm and a trigger to implement more sustainable strategies in order to mitigate the urban environmental problems (cf. Gill et al., 2007; Semadeni-Davies et al., 2008; Harlan & Ruddell, 2011). A strategy that considers green space as a key to ecosystem service conservation and climate change adaptation is the implementation of a green infrastructure network (Gill et al., 2007). In an urban context particularly, the concept of green infrastructure comprises all the natural, semi-natural and artificial networks of multifunctional ecological systems in urban areas (Tzoulas et al., 2007; Naumann et al., 2011). Urban trees, parks, gardens, green walls and green roofs (GRs) are elements that fall under this definition. GRs are multifunctional engineered ecosystems that are increasingly popular in urban areas (Carter & Fowler, 2008). These elements are the main topic of this thesis and their significance will be brought to light in the following section.

2. A brief introduction to GR technology

By definition, a GR uses plants to improve the performance and appearance of a roof (Snodgrass & McIntyre, 2010). They are also often denoted as living roofs, vegetated roofs, or ecoroofs when the main goal is biodiversity conservation and little or no maintenance or irrigation is required (Spolek, 2008).

The first modern GRs emerged in the late 1950s in Germany. The environmental benefits associated with these structures were quickly acknowledged and in 1982, the first guidelines were published by the German Landscape, Research, Development and Construction Society (hereafter called FLL; the last version: FLL, 2008). Together with environmental policies, these guidelines made Germany the leading country in GR implementation and success (Oberndorfer et al., 2007) and the German GR technology is still considered a standard for GR construction all around the world.

Three main types of GRs can be distinguished based on substrate depth. Intensive GRs (IGR, substrate depth > 20 cm) can be considered as roof gardens, offering amenity value and habitat for a variety of flora and fauna. Evidently, this GR type poses constraints for the load bearing capacity of the building and usually demands a lot of maintenance (FLL, 2008). On the contrary, the extensive GR type (EGR) is characterized by a light and inorganic substrate and generally has a depth of 2 to 12 cm (Oberndorfer et al., 2007). It is easier and less expensive to design and build, requires little maintenance and is designed to be self-sustaining in the long term (Snodgrass & McIntyre, 2010). Between the IGR and EGR categories, a third category is often considered, namely the semi-extensive or simple intensive GRs (SEGR; substrate depth 12-20 cm; FLL, 2008; Theodosiou, 2009).

In line with the increased proportion of the human population that is living in urban areas, there is a growing awareness of the importance of ecosystem goods and services and biodiversity conservation (Kowarik, 2011; Gaston et al., 2013). Within an urbanized setting, the concept of novel ecosystems has gained momentum. These are, by definition, self-organizing systems originating from human interference and with actual altered biotic, abiotic and social components as compared to the prevailing historical ecosystems (Hobbs et al., 2013). Urban ecosystems, like GRs, parks and gardens, fall within this definition due to their novel elements but differ from traditional novel ecosystems because management is necessary (Lundholm & Richardson, 2010; Kowarik, 2011; Perring et al., 2013). Urban ecosystems are characterized by spatial and temporal heterogeneity, which makes them different from surrounding natural habitats (Kowarik, 2011; Gaston et al., 2013). Therefore, it has been suggested that urban ecosystems cannot be considered as a substitution for habitat lost in natural ecosystems. General biodiversity conservation strategies therefore focus on the preservation of remnant (semi-) natural habitats and restriction of urban sprawl to a minimum (Kowarik, 2011). However, this traditional conservation view is too narrow as evidence is growing that urban ecosystems can also significantly contribute to biodiversity conservation (Kowarik, 2011). Greening roofs for example, has gained wide international interest lately (Blank et al., 2013) due to the benefits that they offer, ranging from the building to the city scale and encompassing both ecological and economical aspects. The extent to which GRs can perform all these functions depends on many climatic and design factors like substrate depth, age, inclination and vegetation composition (Snodgrass & McIntyre, 2010; Saadatian et al., 2014). Here we give an overview of the main GR benefits:

- First of all, both vegetation and substrate have an important effect on thermal performance and hence contribute to climate regulation (Simmons et al., 2008; Lundholm et al., 2010; Cardinale et al., 2012). Buildings with a GR are cooler in summer (roof surface: 30-60°C cooler; interior: up to 20°C cooler) compared to conventional roofs due to evapotranspiration and higher albedo (Saadatian et al., 2013).
- Evapotranspiration and higher albedo also explain why GRs are effective in mitigating the UHI effect (Santamouris, 2014).
- The evapotranspirative capacity also contributes to stormwater management (Cardinale et al., 2012). GRs manage stormwater quantity, by reducing the runoff volume, reducing the peak discharge and releasing the runoff over a longer time period (Czemiel Berndtsson, 2010; Guo et al., 2014). The runoff quality can be enhanced by GRs as well, although caution must be taken when dissolvable fertilizers are used (Czemiel Berndtsson, 2010) or when pollution deposition is high (Rowe, 2011).
- Next to runoff quality, the vegetation is able to improve air quality (Rowe, 2011). This can be done through the vegetation directly by for example uptake of gaseous pollutants through stomata or interception of particular matter through leaves. Alternatively, indirect air pollution reduction can be attributed to lower building surface temperatures and hence reductions of photochemical reactions that produce pollutants like ozone. Also because of a reduced need for air-conditioning, there will be fewer emissions from power plants (Rowe, 2011).
- Considering biodiversity, GRs may serve as a habitat for local fauna and flora and support the pollination process (Brenneisen, 2006; Colla et al., 2009; Madre et al., 2014). They even have the potential to act as stepping stones for many high-mobility arthropod species (Braaker et al., 2014).
- The cultural service is determined by the GRs aesthetic and amenity value (Lindemann-Matthias et al., 2010; Dakin et al., 2013).
- Depending on their design, GRs can also be used to grow marketable products (Oberndorfer et al., 2007; Whittinghill & Rowe, 2011).
- As less daily temperature fluctuations occur on GRs, underlying structures are protected from harmful environmental conditions (e.g. ultraviolet radiation) and the life span of the roof membrane can hence be doubled

(average life span 40-55 years; Oberndorfer et al., 2007; Saadatian et al., 2013).

- Finally, GRs have been shown to significantly reduce the noise pollution in buildings (Rowe, 2011; Van Renterghem & Botteldooren, 2011).

It is important to conserve and enhance urban biodiversity as it is related to human well-being and because it is an important indicator of ecosystem health (Kowarik, 2011). Compared to homogenous species-poor habitats, urban ecosystems with high species richness (SR) are more resilient (Bengtsson et al., 2002), more resistant to invasions because of more efficient use of available resources (Loreau et al., 2002), and more productive (Tilman, 1997). Those healthy ecosystems are able to ensure normal ecosystem processes and functions, and are therefore essential for different aspects of human well-being and health (Tzoulas et al., 2007). Most of the benefits provided by GRs summarized above contribute to different ecosystem functions and services. Together with benefits not directly related to ecosystem functions and services, GRs contribute to both ecosystem and human health (Fig. 1.1; Tzoulas et al., 2007). It becomes clear that GRs have potential to conserve urban biodiversity and that conservation strategies should not only focus on remnant natural habitats but also include the range of urban ecosystems (Kowarik, 2011). Such a combined conservation approach can be considered as an adaptation to the ongoing urbanization process and a way to ensure the provision of ecosystem services in urban areas under global change (Kowarik, 2011).

All types of GRs have the same general structure, consisting of following components: a waterproofing layer on top of the roof deck and insulation layer; a drainage and root-permeable filter layer; a specialized GR substrate and finally the vegetation layer (Fig. 1.2). Sometimes, an additional water retention layer (WRL) is placed above or under the drainage layer. All the components have to be properly designed and work well together to ensure optimal GR performance (Snodgrass & McIntyre, 2010).

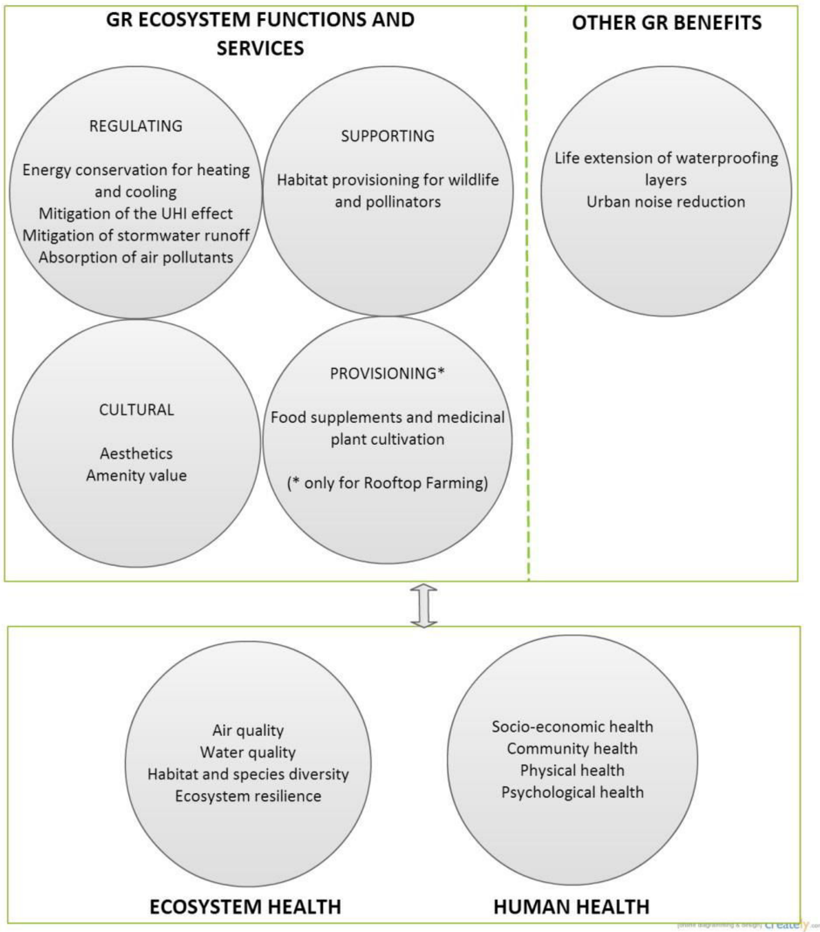


Fig. 1.1 Summary of GR benefits and the relation, either direct or indirect, to different aspects of ecosystem and human health. GR benefits are classified into the four ecosystem service categories (regulating, supporting, cultural and provisioning) and others. Adapted from Tzoulas et al. (2007).

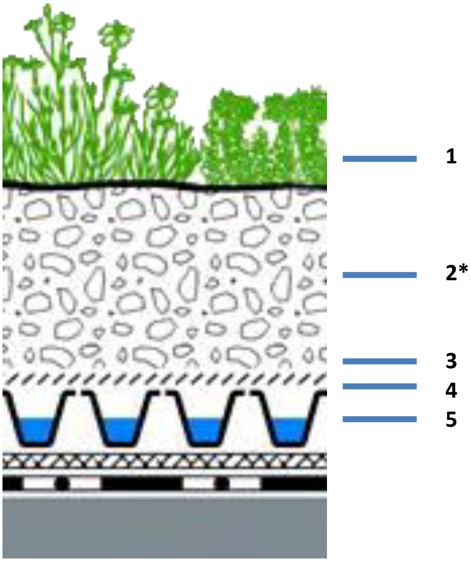


Fig. 1.2 Sketch of an EGR construction. 1: Vegetation layer; 2: Substrate or growing medium (*: an additional water retention layer can be placed under the substrate); 3: Drainage + root-permeable filter layer; 4: Waterproofing layer; 5: Roof deck, insulation [Source: ZinCo http://www.zinco-greenroof.com/; retrieved 10-2014].

The vegetation layer is the visual part of the GR system and must generally be aesthetically pleasing and meet the recreational or amenity requirements associated with the GR project. Indeed, people are still rather sceptical towards GRs which are not green all year round. It is not yet publicly accepted that EGRs can be dry and rather unattractive during summer due to the natural dynamics of the vegetation, while still being more interesting in terms of building insulation and stormwater management than traditional bitumen or gravel roofs. Plant selection depends on many factors, of which the most important ones are substrate depth and (micro) climatic conditions (Getter & Rowe, 2008b). The EGR vegetation generally consists of following plant communities (arranged according to increasing substrate depth): moss-*Sedum* (2-5 cm); *Sedum*-moss-herbs (5-10 cm); *Sedum*-grasses-herbs (10-12 cm); grasses-herbs (> 12 cm; FLL, 2008). On the shallowest EGRs, the substrate experiences faster desiccation rates and more temperature fluctuations, which make *Sedum* and moss communities the only vegetation types suitable for this GR type (Oberndorfer et al., 2007). For SEGRs (12-20 cm), vegetation options comprise grasses-herbs, perennials-shrubs and small bushes. On IGRs (> 20 cm), all types of plant species can be considered, including trees if appropriately accounted for in the design (FLL, 2008). Whatever plant community is selected, it is expected that plants should establish and cover the roof quickly and they should be long-living and stress-resistant (Getter & Rowe, 2008b; Snodgrass & McIntyre, 2010). Indeed, plants face many harsh conditions on roofs in contrast to habitats on ground level (e.g. limiting substrate depth and water availability, heat, frost and wind) and these stressful growing conditions limit the range of plants that can thrive on GRs in the long term. Fig. 1.3 illustrates how the GR vegetation is influenced by microclimatic variation on a carport. The sheltered and probably wetter part accommodates grasses and bulbs, in contrast to the exposed right part, which is dominated by water-stressed *Sedum album*. Due to the harsh GR conditions mentioned above, drought tolerance is considered one of the most essential characteristics for GR plant selection (Getter & Rowe, 2008b) and until recently, *Sedum spp.* were regarded as the most appropriate plantings for EGRs and SEGRs (Blanusa et al., 2013). They possess traits like CAM metabolism (i.e. closing their stomata during the day to save water), water storage in succulent leaves, very shallow rooting systems, compact growth form, quick ground covering capacity and easy propagation by fragmentation (Durhman et al., 2007). However, a GR only consisting of *Sedum spp.* has a rather low biodiversity value and its contribution to GR ecosystem services (e.g. cooling potential; stormwater retention) can be questioned (Cook-Patton & Bauerle, 2012; Blanusa et al., 2013). Some alternatives for *Sedum*, including grasses, perennials and small shrubs, have been investigated in different countries, but with variable success (e.g. Lundholm et al., 2010; Nagase & Dunnett, 2010; MacIvor & Lundholm, 2011; Blanusa et al., 2013).

Currently, a restricted list of 'tried and true plants' is used by GR companies around the world (Lundholm, 2006), but a tendency to increase GR biodiversity by including native plant material is noticeable in both scientific and GR designer circles (Butler et al., 2012). Including native plant species on a GR is indeed an interesting option, as these plants are assumed to be better adapted to local climatic conditions and because they would require less maintenance (Oberndorfer et al., 2007; Dvorak & Volder, 2010). GRs with native plant species could also offer an alternative new artificial habitat for other native flora and fauna whose natural habitats are endangered (Butler et al., 2012). For examples of studies and projects with a focus on GRs as natural habitat replacement, we refer to Brenneisen (2006). It has been shown that EGRs can offer suitable habitats for multiple and sometimes rare or endangered spider and beetle species (Jones, 2002; Kadas, 2006; Madre et al., 2013), rare birds like the Black Redstart (*Phoenicurus ochruros*; Frith & Gedge, 2000; Gedge, 2002), some ground-nesting birds (Brenneisen, 2003) and even endangered orchid species (Loudolt, 2001).

EGR performance could also be improved by increasing biodiversity in terms of plant characteristics (Lundholm, 2006; Wolf & Lundholm, 2008; Dvorak & Volder, 2010; Lundholm et al., 2010; Nagase & Dunnett, 2010; Butler & Orians, 2011). As stated earlier, biodiversity is considered the major driver of ecosystem functioning and provision of ecosystem services (e.g. Cardinale et al., 2012). There is also a growing consensus that one should rather improve biodiversity by increasing the range and value of the species' functional traits instead of increasing SR and evenness (e.g. Hooper et al., 2005; Lavorel et al., 2011). By increasing the functional diversity (FD) of a plant community, ecosystem functioning can be improved, through ecological processes like niche complementarity and facilitation (Lundholm, 2006). One could also look at and improve the phylogenetic diversity (PD) of the plant community, as it is considered a holistic diversity measure and accounts for the shared evolutionary history of genetically related species displaying similar traits (Cadotte et al., 2009; Devictor et al., 2010; Flynn et al., 2011; Srivastava et al., 2012). As PD accounts for species evolution, it hence encompasses many additional and often unmeasured traits that may be important to determine ecosystem functioning (Cadotte et al., 2009; Srivastava et al., 2012).

Fig. 1.3 An EGR installed on a carport in Flanders, Belgium. Micro variation in environmental conditions clearly influences vegetation composition [Picture: Frederik Lerouge; Division of Forest, Nature and Landscape; June 2013].

3. Problem statement

As highlighted in the previous section, GRs offer benefits and are in many aspects preferable to bitumen roofs in urban areas. However, the technique is relatively new and many questions still need to be resolved, especially in the context of expected climatic changes for the coming years. It is expected that the environmental challenges of urbanization will increase with climate change. Worldwide, temperatures are expected to increase by 0.1–0.4°C per decade (IPCC, 2007). By 2050, many large urban agglomerations will experience a minimum temperature increase of 2.5°C, as predicted through the Representative Concentration Pathway (RCP) 8.5 scenario in which unchanged current greenhouse gas emissions are assumed (Revi et al., 2014). Both changes in mean temperature and episodes of extreme temperatures will severely affect vegetation in many places on earth. Additionally, higher temperatures will increase the evaporative power of the atmosphere (reference evapotranspiration ET0), leading to higher plant evapotranspiration. Also precipitation patterns are predicted to change, with increases in annual precipitation of 1-2% per decade in Northern Europe. Winters are expected to become wetter (1-4% more precipitation per decade), but projections for summer precipitation are less unequivocal (Giorgi & Coppola, 2009). In Belgium (North-Western Europe), surface temperatures and winter precipitation are expected to increase while summers are predicted to be drier (Baguis et al., 2010; Vanuytrecht et al., 2014). In contrast, Southern Europe will experience a decrease in annual precipitation with 1% per decade, and even decreases of 5% are expected in summer (Parry, 2000).

Current annual weather patterns for Avignon (France, Mediterranean climate, Southern Europe) and Leuven (Belgium, temperate climate, Western Europe), two locations where this thesis focuses on, are given in Fig. 1.4. As a result of the above mentioned climate change predictions, temperatures in both locations will increase, which will also lead to an increased potential evapotranspiration (PET). Avignon already experiences 3-4 months of summer drought (0.5xPET > precipitation), and this period will extend as the PET increases and summer precipitation decreases. In Leuven, summer drought is currently not applicable, but can become a reality in upcoming decades, suggesting that average future climatic conditions will approach the current Mediterranean situation.

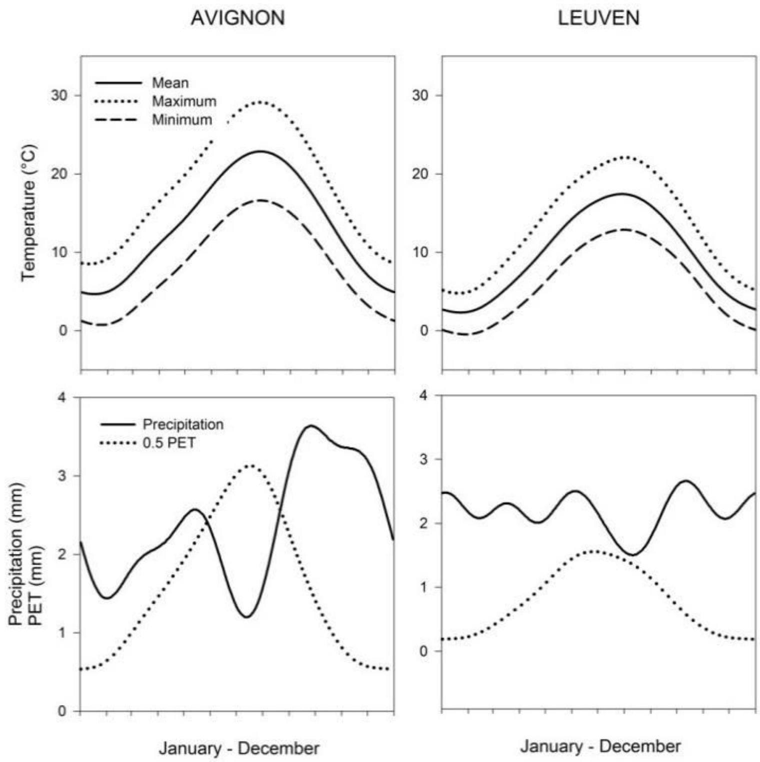


Fig. 1.4 Average annual weather patterns for the period 1970-2000 (temperature, precipitation and potential evapotranspiration PET) for Avignon (France, Southern Europe, Mediterranean climate) and Leuven (Belgium, Western Europe, temperate climate). Summer drought occurs when 0.5xPET (dotted line) > Precipitation (black line). Derived from New_LocClim v1.10 (FAO, 2005).

In the study of Vanuytrecht et al. (2014), vegetation drought stress and runoff for the near future (2050) were assessed for different GR types (grass-herb and *Sedum*-moss vegetation) under different climate change scenarios. With the projections of certain global climate models, which project substantial precipitation decreases and evapotranspiration increases in summer, relative runoff from grass-herb GRs was expected to decrease by approximately 50% in the future relative to the baseline period (1981-2010) and on *Sedum*-moss GRs by approximately 40%, whereas on bitumen roofs with the same climatic scenarios by only 30%. This observation, representative for extreme events, highlights the benefit of a GR in the future. Although runoff reduction will become more pronounced on grass-herb than on *Sedum*-moss GRs, grass-herb GRs proved to be more vulnerable to drought stress, a factor becoming more important under climatic scenarios. In the near future, GR designers will need to consider this trade-off between vulnerability to drought-stress and effectiveness to reduce runoff of different vegetation types. In conclusion, the GR industry will need to look for new plant species which are more adapted to the future climatic conditions.

As plant survival is essential to ensure any GR benefit, the most drought tolerant species should be considered. When looking for suitable GR plant species, it has been suggested to target natural ecosystems with similar characteristics as on GRs, a concept also described as the 'habitat template' (Lundholm, 2006). Species adapted to high temperatures, shallow mineral and free-draining soils, frequent drought and high wind speeds are supposed to be able to survive on EGR as well. Natural habitats demonstrating these conditions include limestone pavements, cliffs, scree beds and even dry grasslands (Sutton et al., 2012). The concept is very promising and is now increasingly adopted when looking for new potential EGR species (Williams et al., 2010; Butler & Orians, 2011; Sutton et al., 2012; Caneva et al., 2013). Selecting drought-adapted species for EGRs in both Mediterranean and temperate climates in order to prepare the GR industry for the predicted climate change is one problem that will be dealt with in this thesis. Based on the habitat template concept, plant species currently growing in the Mediterranean region may serve as representative, potentially suitable species, as many habitats match EGR conditions, and current average environmental conditions in that region approach the prospected future climatic situation in temperate climates.

Next to adaptation of species selection, the design in terms of GR structure can be adjusted. Increasing the substrate depth in order to retain more water for a longer time and hence facilitate plant survival is an obvious option (Getter & Rowe, 2008b; Razzaghmanesh et al. 2014), but not always possible because of the buildings' physical limitations. A deeper substrate may also increase the establishment of undesired vigorous weeds, which contribute to a more time-consuming maintenance procedure (Nagase et al., 2013). Alternatively, the effect of water retention additives on GR plant performance are now increasingly explored (Sutton, 2008; Farrell et al., 2013).

One could also add organic material (OM) or arbuscular mycorrhizal fungi (AMF) to the GR medium to support plant survival. In general, OM increases the substrates nutrient content and improves soil structure and water retention (Friedrich, 2005; Emilsson, 2008; Molineux et al., 2009). AMF are symbiotic fungi (Phylum *Glomeromycota*) that form mutualistic associations with plant roots of most plant species (Bonfante & Anca, 2009; Willis et al., 2013). Benefits for the plant include better phosphorus and nitrogen uptake and improved water uptake (Rillig, 2004; Veresoglou & Rillig, 2012). Both substrate additions could be of importance to increase the performance of EGR (cf. Busch & Lelley, 1997; Oberndorfer et al., 2007; McGuire et al., 2013), but although the benefits on plant growth and development are acknowledged in horticulture, there is hardly any evidence of the effects on GRs.

Because plants will experience more drought-stress, it may be expected that irrigation will become necessary on EGRs and SEGRs for species survival in summer (MacIvor et al., 2013; Vanuytrecht et al., 2014). However, in many cities, water scarcity is a yearly reoccurring problem, especially in regions with frequent droughts like Southern Europe and Australia (Coutts et al., 2012; Ascione et al., 2013), which has led to irrigation restrictions for GRs (Rowe et al., 2012). One should therefore look for alternative water sources and water conservation practices to make GR irrigation practices more sustainable (Moritani et al., 2013). The knowledge on irrigation practices and specifications for GRs in relation to different climates, is however still limited.

In conclusion, given that in particular the Mediterranean region is a hotspot in terms of plant diversity (Médail & Quézel, 1997), representing over 10% of the world's flora (Lavergne et al., 2006), we believe that there is a considerable amount of potential plant species available in nature that is able to offer solutions for better GR success. These species can be used to design more heterogeneous EGRs in terms of SR and FD, hence improving biodiversity value and associated GR ecosystem services. Heterogeneous GRs are also expected to be more resistant, persistent and resilient to climate change. Furthermore, because many of the potential species originate from natural habitats, the implementation of them on GRs is a step towards better biodiversity conservation in urban areas. Adaptations in GR structure design will alleviate the challenging environmental conditions on GRs and hence help survival of the GR plant species.

4. Research questions and chapter outline

The general aim of the thesis is captured in the title: 'Nature as a template for a new concept of EGRs'. The first part of the title 'Nature as a template' refers to the development of a detailed procedure for applying the habitat template concept. More specifically, potential EGR plant species (e.g. drought tolerant, shallow rooting system) originating from (semi-)natural Mediterranean habitats will be investigated. Knowledge collected during this part will then be used to elaborate and test a new concept for EGR design, comprising both plant selection and GR structure elements.

The main research questions can be formulated as follows:

1. What kind of vegetation can be found in (semi-)natural Mediterranean areas selected according to the habitat template concept of GRs? To what extent do the plants in the resulting Mediterranean plant list (MEDPL) offer new possibilities for use on EGRs?
2. How can the plants in MEDPL be ranked according to their potential use for EGRs by making use of their plant traits?
3. Next to theoretical evidence, can the potential of some Mediterranean plants for EGRs be confirmed experimentally? Do other factors including

climate, substrate depth, WRL and exposition affect the suitability of these plants?

Side questions also answered in this thesis include:

4. Plant performance can also be enhanced by adding OM and AMF to the growing medium. Is this also the case for plants developing under EGR conditions?
5. Based on previous research, plant performance is often believed to be enhanced by regular irrigation. What kinds of irrigation methods are commonly used on GRs? Can irrigation recommendations be made for different climates (including the Mediterranean) and are there sustainable methods that should be promoted?
6. Assuming that FD and PD of plant communities have a positive effect on ecosystem functioning, to what extend do different GR systems available on the market contribute to GR ecosystem functioning? Can FD and hence the ecosystem services of GRs be improved?

The flow chart in Fig. 1.5 gives an overview of the different Chapters that will provide answers to the above mentioned specific research questions. In this introduction part, it became clear that there is a need to adjust GR vegetation and design. This is because of the predicted climate change, which will result in longer dry periods that will pose an additional stress on EGR vegetation, and because EGRs are currently not very common in Mediterranean areas although they would be very beneficial here (Fig. 1.6)

The first research question will be the focus of **Chapter 2**. Natural habitats in the Mediterranean climate will be studied both in the field and from literature sources. Following the habitat template concept, we specially target habitats characterized by shallow, calcareous soils or pavements. This approach should result in a GR species pool which, given the high diversity of plant species in the Mediterranean region, probably will be an extensive list of Mediterranean plants (MEDPL). This list should be analyzed more thoroughly before eventual testing.

In **Chapter 3**, research question 2, i.e. how we can make use of the plant traits to find the most potential species for EGR application, will be addressed. This Chapter builds further on the MEDPL from the first chapter, together with a plant list of currently used GR plants (GRPL) as they are already considered ‘tried-and-true’ and hence serve as a reference. To be fully applicable we need a tool for screening potentially interesting species. This can be achieved by using functional plant traits related to drought tolerance and self-regulation (the key factors essential for survival on EGRs under dry conditions). But one might argue that more utilitarian aspects (like flower color, flowering period) are also important as these will determine the species that people like and which are or might be available from nurseries. Based on both functional traits and utilitarian aspects, it should be possible to deliver a screening tool in which species are scored and ranked according to their suitability for use on EGRs in regions with frequently occurring dry periods.

As the screening tool from Chapter 3 offers rather a theoretical evaluation, the performance of some Mediterranean species needs to be tested on outdoor GR experiments under varying conditions. **Chapter 4** will describe the approach and results of a two year experimental trial and will also discuss research question 3, i.e. if certain factors affect the suitability of those Mediterranean plants to be used on EGRs. More specifically, a subset of Mediterranean plants will be tested in two locations with different climates (cf. Fig. 1.4): Heverlee (Leuven, Belgium, temperate climate) and Avignon (France, Mediterranean climate). As it is impossible to test all possible GR conditions, three were selected playing an essential role in water balance of GRs (5 cm substrate; 5 cm substrate + WRL; 10 cm substrate + WRL). Also, the effect of two expositions (fully exposed and sheltered) will be tested. The results should also offer a first verification of the reliability of the screening tool from Chapter 3.

The focus of the antecedent chapters was on plant species and plant performance. However, GRs are more than just the vegetation layer. In Chapter 4, the effect of substrate depth was addressed as well. However, the substrate composition in all the plots was identical. In **Chapter 5**, the effects of addition of AMF and/or OM to the mineral GR substrate on initial development of EGR plants are studied. The plants originate from a commercial EGR seed mix and are installed as seeds. The results will be used to discuss research question 4.

Many scientific papers on both GR plant selection and Mediterranean GRs state that an irrigation system is necessary for plant survival on EGRs in regions with frequent dry periods. In both the experiments conducted in Chapter 4 and 5, an irrigation system was not installed for sustainability purposes. Vegetation hence relied on natural precipitation events to irrigate the experimental plot, but it became clear that this was often not enough to ensure plant survival in dry periods. In the literature, no exact information is available on different irrigation systems for GRs, or what kind of irrigation is advised in different climates. **Chapter 6** hence reviews the currently available information on (sustainable) GR irrigation. This will offer a response on research question 5.

Conform the approach in Chapter 3, a matrix of EGR species and relevant functional traits was created in **Chapter 7.** The species were derived from plant lists of GR systems currently available on the European GR market. Clustering techniques grouped the GR systems in different types according to their species composition. FD analysis of the resulting GR types was performed, as well as a PD analysis as PD is considered a valuable proxy for FD. The results give an answer on research question 6. It was found that there is room for improvement of FD, so in Chapter 7, two methods for maximization of FD will be applied and discussed.

In the conclusion part, **Chapter 8**, the highlights of all the Chapters will be brought together to answer to the main goal of the thesis, namely to formulate a new concept for EGR design and to propose new axes for further research on this subject.

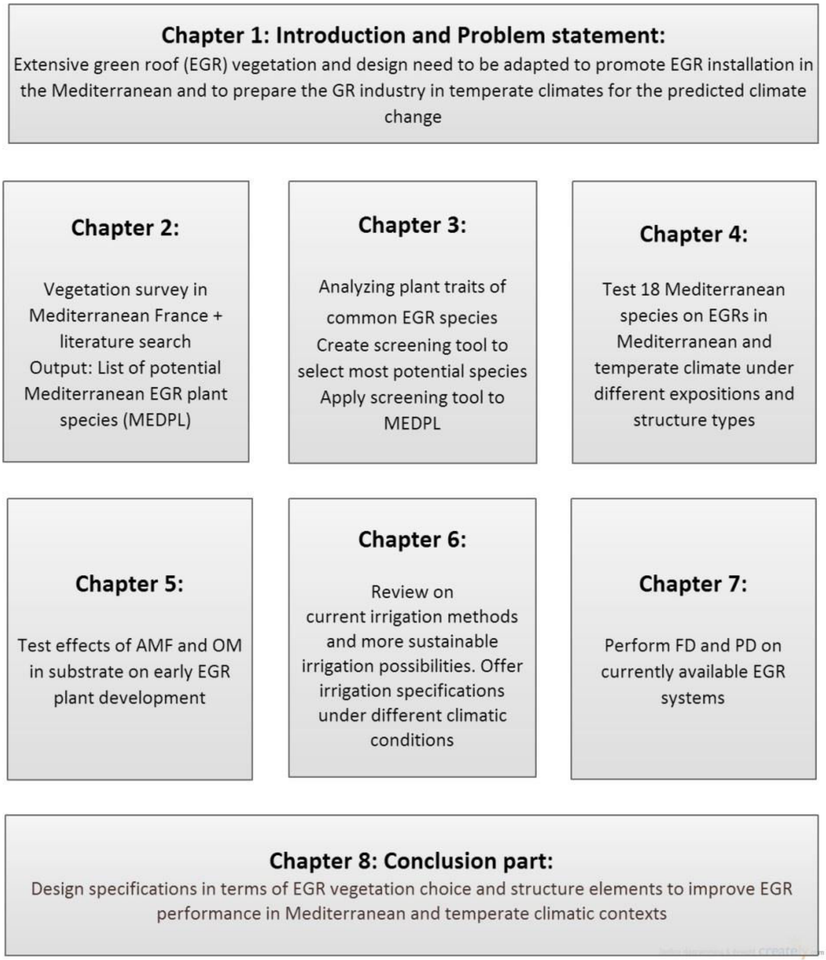


Fig. 1.5 Overview of the different chapters discussed in the manuscript.

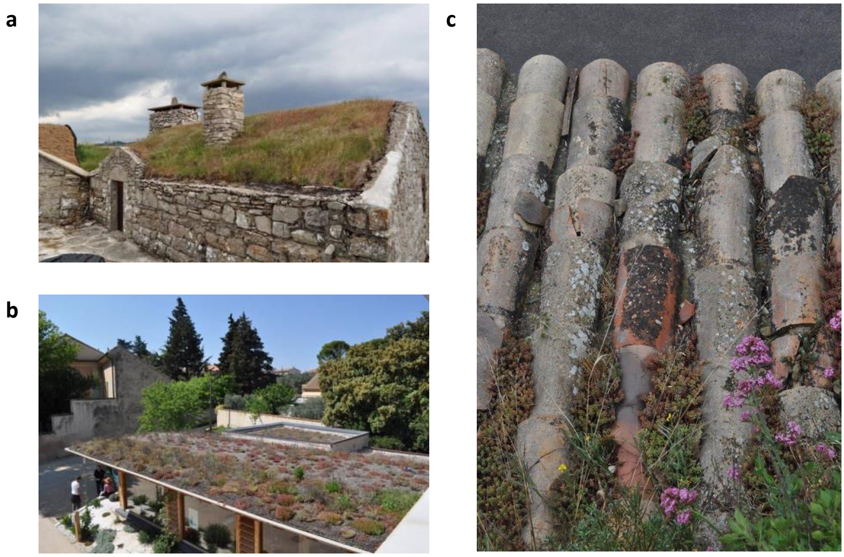


Fig. 1.6 Pictures illustrating installed and natural EGRs in a Mediterranean context. a) Grass roof on an old farmer's house on the Causse Méjean in the Parc National des Cévennes. The colder and humid local climate makes this kind of EGRs possible. b) EGR installed on the Naturoptère in Sérignan-du-Comtat as part of a sustainable building project. This EGR consists mainly of succulent species and is equipped with an irrigation system (sprinklers) that water the EGR every other day during summer at night for two times 15 minutes. The water comes from an underground rainwater harvesting (RWH) well (personal communication). c) Succulent species (mainly *Sedum album*, *S. acre* and *S. ochroleucum*) and grass species installed spontaneously on the roof of an old Mediterranean building. The plants are able to survive on the spots where water and OM accumulates [Pictures: Carmen Van Mechelen; June 2011].

Chapter 2. Mediterranean open habitat vegetation offers great potential for extensive green roof design

Adapted from Van Mechelen, C., Dutoit, T., Hermy, M. (2014) Mediterranean open habitat vegetation offers great potential for extensive green roof design. Landscape and Urban Planning, **121**, 81-91

1. Introduction

Urban regions are facing worldwide population and housing demand increases, causing a lot of environmental problems as building space becomes scarcer. New buildings replace green areas and make cities less attractive for living and working. In this respect, the application of green roofs (GRs) or ecoroofs proved that, by transferring vegetation to the top of buildings, major urban problems can be reduced (cf. Oberndorfer et al., 2007). In terms of sustainability, extensive GRs (EGR) are preferred over the intensive ones. The former offer stormwater control and thermal insulation without requiring substantial irrigation and maintenance. Furthermore, EGRs have a shallow substrate (< 20 cm) which makes them lightweight and suitable for wide application on new constructions and for renovation of old buildings (Oberndorfer et al., 2007). Although GRs are manmade, they can be part of nature restoration and even potentially help counteracting the destruction of (semi)natural habitats if local or regional species are used (Oberndorfer et al., 2007; Francis & Lorimer, 2011). The multitude of ecological and economic benefits, along with some non-negligible factors like psychological and aesthetic effects, makes GRs an important tool for improving urban environmental quality.

An exponential rise of interest in and implementation of GRs has been observed during the past decades particularly in temperate Europe and North-America (Köhler & Keeley, 2005; Dvorak & Volder, 2010; Williams et al., 2010). In 2007, GR coverage in Germany increased on average 13.5 million m² per year (cf. Oberndorfer et al., 2007). In France, EGR surface reached 1 million m² in 2011, and is expected to rise to ca. 1.5 million m² in 2015 (Lassalle, 2012). Modern GR technology is relatively recent and its origins lie in North-and Central Europe, with Germany as leading country.

Research and experience has led to the development of the German FLL guidelines for the planning, construction and maintenance of GRs (FLL, 2008), which serve as a model throughout the world. Implementation of these guidelines usually guarantees success in the temperate climate, but can pose problems in other ecoregions (Dvorak & Volder, 2010). In the Mediterranean area for example, plants often face severe water stress as a cause of frequent elevated temperatures and extended summer drought (Benvenuti & Bacci, 2010). When plant species commonly used for GR purposes are applied in the Mediterranean climate, they suffer from the additional stress factors, leading to poor GR performance and therefore discouraging both industry and government to promote this innovative tool (Dvorak & Volder, 2010; Williams et al., 2010). Despite these problems, scientists showed that GR advantages are also pronounced in the Mediterranean climate (Fioretti et al., 2010), therefore rendering investigations to overcome the poor GR performance very valuable. The incorporation of local or regional plant species can provide a solution to the problem, as they are more adapted to the Mediterranean climate (Oberndorfer et al., 2007). Evidence is provided that EGRs mimic habitats found in nature, a concept which is described as the 'habitat template hypothesis' (Lundholm, 2006). These natural template habitats comprise mostly rocky environments, free draining dunes, open areas on very shallow substrates, and limestone pavements. The Mediterranean region with its exceptional diversity of plant species (Médail & Quézel, 1997) contains a lot of these habitats, so we hypothesized that it should be possible to find drought-adapted, native plant species that could thrive on EGRs.

In this study, we aimed at:

1. describing and classifying the vegetation of open habitats on very shallow, stony soils and analyzing the variation in species composition in relation to environmental factors. A literature research on old vegetation surveys will further complement the potential plant species in the region. This delivers us a potential plant species pool for further analysis.
2. comparing the resulting species list with a list of currently used GR plant species in NW Europe and
3. highlighting the potential of the Mediterranean vegetation as a source of inspiration for development and improvement of EGR design, by considering some major plant traits.

2. Material and methods

2.1. Vegetation description

2.1.1. Study area

As the Mediterranean region is considered a biodiversity hotspot (Médail & Quézel, 1997) with approximately 25000 vascular plant species (ca. 7.8% of the number of species in the world), of which about 13000 are endemic to this region (Quézel, 1985), it was impossible to include the whole Mediterranean basin in this project. Therefore, we focused on the southern part of France, more specifically the departments Hérault, Gard, Bouches-du-Rhône, Vaucluse and Drôme in the regions Languedoc-Roussillon and Provence-Alpes-Côte d'Azur (Fig. 2.1), with a plant species richness (SR) of approximately 5880 taxa. According to the plant repartition section of Tela Botanica, this number accounts for 50% of the total amount of taxa on French territory (Association TELA BOTANICA).

The Mediterranean region is classified as 'shrub or treelike pseudo steppe and open forest in less dry climates' (Unesco-FAO, 1969). The climate is considered as intermediate between cold temperate and dry tropical. Summer temperatures and the number of sun hours are high, e.g. average of 30°C and 2835 sun hours a year in the Vaucluse region (Blondel et al., 2010). In general, summer drought lasts one to four months (Unesco-FAO, 1969) and precipitation is very irregular, with only a few intensive rainy days in summer, e.g. 80-90 mm in 12 days in Avignon, Vaucluse. On the contrary, rainfall is significantly higher in other seasons, with an average of 480 mm during winter, spring and autumn in Avignon (derived from the 'Local Climate Estimator' program and database New_LocClim v1.10 (FAO, 2005)). The whole region is very windy, with the '*mistral'* blowing from the north and the '*tramontane'* from the north-west, bringing glacial colds in winter and additional warmth in summer (Filippi, 2008; Blondel et al., 2010). The mountainous part in this region is dominated by coniferous forest but more to the Mediterranean sea, the vegetation changes in a mosaic of mixed forest (with amongst others *Pinus halepensis* and *Quercus ilex*), matorral such as *maquis* on acidic soils and *garrigue* on calcareous soils (David, 2006). The main blooming period of the vegetation occurs in spring. During summer drought, the aboveground part of many plants dies off, whereas the growth of evergreen shrubs just takes a halt. Altitudinal limits of the Mediterranean climate and flora and fauna is often situated at about 1000 m (Blamey & Grey-Wilson, 2004), although others (e.g. Blondel et al., 2010) do not recognize this limit. According to the latter, a good delimitation of the region should coincide with the 100 mm precipitation isohyets. We further describe our study area as (sub) Mediterranean.

2.1.2. Data collection

Given the specific conditions on EGRs, only non-forest vegetation on shallow soils and limestone pavements in the (sub) Mediterranean part of France was considered. The departments under study contain many stony calcareous habitats with a great diversity of plant species (Appendix 2.1). During the growing season of 2011 (April 22 - June 6), 20 locations in an area of 190 x 130 km were visited (Fig. 2.1; 2.2). Given the fact that local conditions on stony or rocky habitats may change over very short distances (Verrier, 1979), the vegetation was recorded in small plots of 1 m². Cover was estimated according to the decimal scale of Londo (Londo, 1976). In total, 253 plots were recorded with 12-20 plots per location. 372 species were found (Mediterranean plant list from vegetation recordings: MEDVEG), with on average 18 species per plot. Some in situ measurements of vegetation-related variables included an estimation of the amount of bare soil (BS) and % cover of lichen and bryophytes (BL).

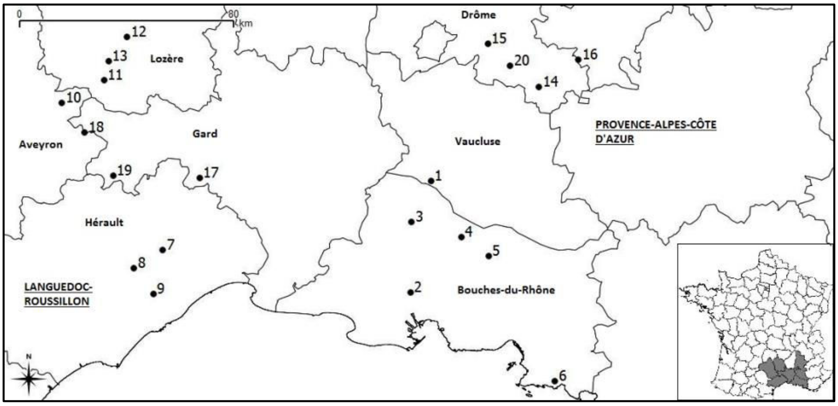


Fig. 2.1 Map of the study region in southern France with indication of the departments and the 20 locations. 1. Caumont-sur-Durance; 2. La Crau; 3. Plateau de Caume; 4. Lamanon; 5. Vernègues; 6. Calanques; 7. Mas Dieu; 8. Plateau d'Aumelas; 9. Plateau d'Artamon; 10. St. Pierre des Tripiers; 11. Saubert; 12. Cros Garnon; 13. Nivoliers; 14. Col d'Aulan; 15. Col Milmandre; 16. Montagne de la Chamouse; 17. Cuvette de Pompignan; 18. Causse Blandas; 19. Causse Bégon; 20. La Roche sur le Buis.

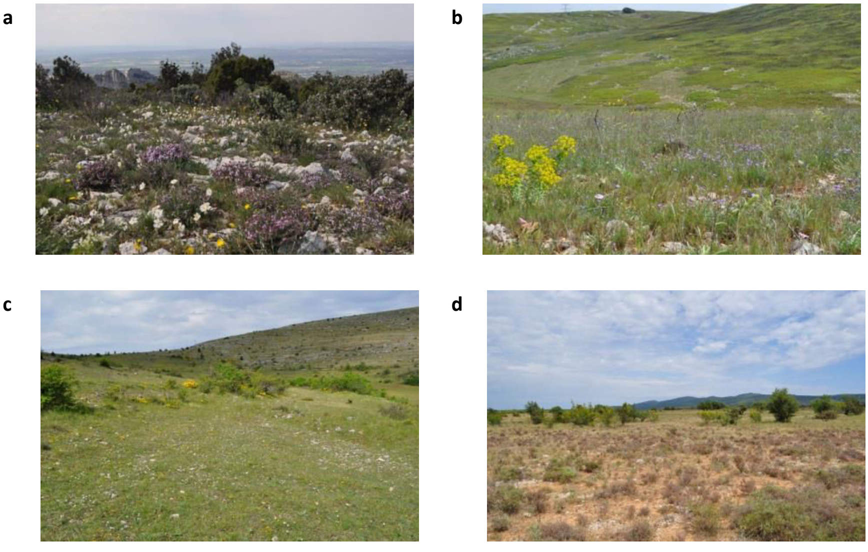


Fig. 2.2 Pictures of four of the study locations: a) Plateau de Caume; b) Plateau d'Aumelas; c) Nivoliers; d) Cuvette de Pompignan [Pictures: Carmen Van Mechelen; June 2011].

In every plot, a number of environmental variables were recorded as well (Table 2.1). Altitude (A), geographic coordinates (WGS 84 reference system) and aspect were measured with a GPS navigator (Garmin eTrex Vista HCx, Garmin Ltd 2007). The two latter variables, together with slope (angle in degrees measured with a clinometer), where used to calculate the heat load (HL) of the plot (Eq.1) with the formula presented by McCune and Keon (2002).

$$HL = 0.339 + 0.808 \times \cos(\text{latitude}) \times \cos(\text{slope}) - 0.196 \times \sin(\text{latitude}) \times \sin(\text{slope}) - 0.482 \times \cos(\text{folded aspect}) \times \sin(\text{slope}) \quad \text{(Eq.1)}$$

$$\text{Folded Aspect} = |180 - |\text{aspect} - 225||$$

The result of Eq.1 is a dimensionless index of the HL. The variables were all converted to radians prior to incorporation in the formula, and the aspect was folded in order to obtain the most accurate approximation, by shifting the equation from a maximum on south slopes to a maximum on southwest slopes and a minimum on northeast slopes.

A small one-piece drill was used to measure average top soil depth (D) and for soil sampling. In the lab, soil pH (H_2O) and electric conductivity (EC) were analyzed by means of a portable pH/EC/TDS/Temperature gauge (HI 991301, Hanna Instruments Inc.). This was done by inserting the calibrated electrode into a mixture of 25 ml deionized water and 10 g soil, after two shaking moments of 10 seconds (at start and after 30 minutes). A volumetric determination of organic matter (OM) was determined by the Walkley-Black procedure (Walkley & Black, 1934). The Coulter Principle was used for measuring the proportion of sand, silt and clay in the soil sample (LS 13320 Laser Diffraction Particle Size Analyser, Beckman Coulter Inc.).

Climate data were obtained by the FAO program New_LocClim v1.10, which uses interpolation methods to investigate the conditions at any possible location on earth. For our study region, the interpolation was done based on data from eight weather stations: Montpellier, Nimes, Marseille, Salon, Millau, Montélimar, Orange and Mont Ventoux. Average annual precipitation (AAP) and temperature (AAT), potential evapotranspiration (PET), the De Martonne Aridity Index, and dry period (days with precipitation < 0.5 PET) were calculated. The annual thermal sum in Growing Degree Days (GDD; Eq.2) is often used as a substitute for temperature and was calculated with the formula of Meunier et al. (2007):

$$GDD = \sum_{i=1}^{n} [(T_{i,\,max} + T_{i,\,min})/2 - 5] \quad \text{(Eq.2)}$$

Where $T_{i,\,max}$ and $T_{i,\,min}$ are the maximum and minimum daily temperatures for every *i*-day, i.e. day with mean temperature above 5°C, with exclusion of days in the dry period, as no growth can occur in these circumstances.

Table 2.1 Differences between four vegetation types (clusters) for all variables and Raunkiaer life forms. Significance of differences was tested using Kruskal Wallis test (KW). Average values and post hoc test results are listed for every cluster, with significant differences expressed by superscript letters. (*: $p < 0.05$; **: $p < 0.001$; NS: not significant)

Variable name	Abbrev.	Unit	KW	Average values			
Environmental			*significance*	*Cluster1Δ*	*Cluster2○*	*Cluster3 +*	*Cluster4●*
Altitute	A	m	**	232^{a}	153^{a}	977^{c}	812^{b}
Heat load	HL	-	*	0.91^{ab}	0.90^{ab}	0.90^{a}	0.92^{b}
Soil depth	D	m	*	0.09^{ab}	0.08^{a}	0.09^{ab}	0.1^{b}
Soil pH	pH	-	NS	7.95	8.02	8.04	8.01
Electric conductance	EC	mS	**	0.21^{a}	0.19^{a}	0.20^{a}	0.25^{b}
Organic matter	OM	%	**	7.2^{ab}	5.9^{a}	10.5^{c}	7.4^{b}
Sand (63-2000µm)	Sand	%	**	40.1^{a}	43.6^{ab}	52.2^{b}	46^{b}
Silt (2-63µm)	Silt	%	**	49.8^{c}	49.2^{bc}	41.4^{a}	45.7^{ab}
Clay (<2µm)	Clay	%	**	10.1^{b}	7.3^{a}	6.3^{a}	8.4^{ab}
Av. annual precipitation	AAP	mm	**	55.3^{b}	48^{a}	60.8^{b}	72.9^{c}
Av. annual temperature	AAT	°C	**	13.7^{c}	13.4^{b}	11.6^{a}	7.1^{a}
Pot. evapotranspiration	PET	mm	**	89.7^{b}	100.7^{c}	63.7^{a}	67.4^{a}
Aridity index	Aridity	-	**	28.8^{a}	25^{a}	34^{b}	56.4^{b}
Dry period	Dry	days	**	130^{b}	161^{b}	49^{a}	55^{a}
Growing degree days	GDD	GDD	**	1265^{a}	1190^{a}	1897^{b}	993^{a}
Vegetation-related							
Species Richness	SR	#	**	17^{a}	28^{b}	18^{a}	16^{a}
Cover (cumulative)	Cover	%	**	67^{b}	75^{b}	65^{b}	56^{a}
Bare soil	BS	%	**	22^{b}	7^{a}	6^{a}	20^{b}
Bryophytes + lichen	BL	%	**	8^{a}	51^{b}	7^{a}	4^{a}
Raunkiaer life forms							
Phanerophytes	Ph	#	NS	0	3	2	1
Chamaephytes	C	#	NS	7	3	2	3
Hemicryptophytes	H	#	**	37^{a}	32^{a}	46^{b}	42^{b}
Geophytes	G	#	NS	3	3	1	2
Therophytes	Th	#	**	29^{b}	71^{c}	2^{a}	7^{ab}

2.1.3. Data analysis

To achieve an accurate data analysis, all 19 variables were first checked for normality in SPSS 20.0 (SPSS Inc, Chicago, IL). As no single variable had a normal distribution (p-values of Kolmogorov-Smirnov test < 0.05), we further used non-parametric tests. Relations between variables and plots were studied using Principal Component Analysis (PCA), applied on the plot (n = 253)*variable (m = 19) matrix in PCord 6.0 (MjM Software, USA) and visualized with biplots.

To group the plots according to their species composition, the original plot (n = 253)*species (m = 372) matrix was imported in PCord 6.0. Species that only occurred in one plot (76 in total) were omitted as rare species complicate the data analysis and are not very useful in the context of GR application. After relativization by maximum and arcsin squareroot transformation of the resulting plot*species matrix, hierarchical clustering with flexible beta linkage method and Sörensen distance measure (to avoid space-distortion) was performed. Indicator Species Analysis (ISA) allowed determination of the optimum number of vegetation types (hereafter called 'clusters'; McCune & Grace, 2002).

Furthermore, the life form of every plant species was determined using the database Baseflor (Julve, 1998), for calculation of the Raunkiaer life form spectra in every cluster (Raunkiaer, 1934). Sörensen indices (Eq.3) were calculated to quantify and compare the similarity in species abundance between the emergent clusters. This is the shared species abundance divided by the total abundance, where C stands for the species in common between two clusters and A and B are the separate cluster species abundances (McCune & Grace, 2002).

$$QS = 2C/(A+B) = [2n\,(A \cap B)] / [n(A) + n(B)] \qquad \text{(Eq.3)}$$

The plot*variable matrix, supplemented with corresponding cluster numbers and life form categories, was imported in SPSS 20.0 to relate the variables to the emergent clusters by means of Kruskal Wallis tests (KW) and subsequent post-hoc tests.

The results of the hierarchical clustering and correlation analysis allowed an adequate description of the clusters. Assignment to a phytosociological class (i.e. a group of plant communities having the same diagnostic species) was based on a comparative description (Appendix 2.2; cf. Loisel, 1976).

2.2. Species lists comparison

For a more complete overview of the total SR in the selected habitats in southern France, an additional literature search was conducted resulting in four relevant sources: Molinier & Tallon, 1949; Van den Berghen, 1963; Loisel, 1976; Rieux et al., 1977 (see Appendix 2.2). The latter resulted in an additional list of species (MEDLIT). The literature data were not included in the vegetation analysis part of this study, as they had larger plot areas than the minimal area to detect vegetation homogeneity (about 20 m²) and hence contained internal small scale variation which might bias the results. Combining the two lists (MEDVEG and MEDLIT) yielded a total Mediterranean plant list, abbreviated as MEDPL. The MEDPL contained 633 plant species, from which 372 species originated from MEDVEG and 261 species from MEDLIT.

Next to the MEDPL, a list containing plant species commonly applied or spontaneously occurring on EGRs in NW Europe was compiled (GRPL). Seven key sources were used: five literature sources (Bornkamm, 1961; Krupka, 1992; Köhler, 1993; Kolb & Schwarz, 1999; Snodgrass & Snodgrass, 2006) and two species lists from international GR Companies (Optigreen Limited and Zinco Gmbh). The GRPL comprised 484 species (subspecies and varieties were not taken into account). Plant nomenclature followed The Plant List (The Plant List, 2010). The two lists (MEDPL and GRPL) are compared in terms of species similarity (Eq.3) and Raunkiaer life form distribution.

2.3. Potential of Mediterranean vegetation

A simple screening procedure was used to highlight the possibilities of Mediterranean vegetation for EGR purposes. A multitude of functional plant traits can be informative in this respect (cf. Cook-Patton & Bauerle, 2012), but as an extensive analysis is out of scope of this study, we focused on general traits associated with the survival on EGRs. For the MEDPL, information on ten plant traits (based on Oberndorfer et al., 2007) were derived from the TRY trait base (a global archive of plant traits, cf. Kattge et al., 2011). One of the used traits comprises the plant strategy types of Grime (Grime, 2001), in which plants are grouped into competitors, ruderals, stress tolerants or a combination of these categories. Only species having data for more than five plant traits were considered. Species were also omitted if they met one or more of the following obvious exclusion criteria (Table 2.2a): phanerophytic life form; plant height exceeding 1 m; root system deeper than 20 cm; no drought and/or stress tolerance. Finally, every remaining plant species gets a score of 1 for each trait where it meets the preferred condition as indicated in Table 2.2b. The total score (on 10) is adjusted to account for missing values, through division of the score by the number of traits for which the plant had data.

3. Results

3.1. Vegetation description

PCA results showed that five axes are significant in explaining the relationships between variables (p-value = 0.001). The first PCA axis (Fig. 2.3) explained 30% of the total variance and can be considered as a measure of the climatic variation in the studied sites. Climate variables (AAP, AAT, aridity, dry and PET) and altitude are strongly correlated, either positively or negatively, indicated in Fig. 2.3 by coincident or opposite vectors. Axis two explained 17% of the variance and was linked with soil-related variables. According to axis two, the % sand was negatively correlated with silt and clay, and OM and EC were positively correlated. The remaining axes account for 28% of the total variance. pH (H_20) and GDD correlated with PCA axis 3, although on Fig. 2.3, they are also partly explained by axis 2. The variables SR, Cover, BS, BL and HL have their highest eigenvector on axis 4. Again, the second highest eigenvalue of these variables can be found on axis 2. Finally, EC and D are expressed by axis 5. The main variation in species composition is hence determined by climate and soil related variables.

Table 2.2 Plant traits related to drought tolerance and self-sustainability, two key criteria for survival on EGRs. (a) traits and criteria used to exclude unsuitable species before scoring; (b) plant traits used for scoring. Plant traits were derived from the TRY initiative (Kattge et al., 2011).

(a) Plant traits for species exclusion	**Exclusion criteria**	**Reference**
Raunkiaer life form	P	Julve, 1998
Typical plant height	Tall plants (> 1 m)	Cornelissen, 1996; Diaz et al., 2004; Paula et al., 2004; Wright et al., 2004; Garnier et al., 2007; Kleyer et al., 2008; Green, 2009
Root depth	Deep rooting system (> 20 cm)	Paula et al., 2004; Green, 2009
Tolerance to drought	No drought tolerance	Green, 2009
Grime strategy	No stress tolerance	Kühn et al., 2004
(b) Plant traits for scoring step	**Preferable condition**	**Reference**
Grime strategy	Ruderal and/or stress tolerant	Kühn et al., 2004
Leaf phenology	Evergreen	Cornelissen, 1996; Wright et al., 2004; Cornwell et al., 2008; Kattge et al., 2009; Paula et al., 2009
Leaf shape	Small, acicular, needle-like leaves	Kühn et al., 2004; Paula et al.,2004
Maximum plant longevity	Annual or perennial	Diaz et al., 2004; Kühn et al., 2004; Moles et al., 2004; Green, 2009
Metamorphosis for storage	Succulence	Kühn et al., 2004
Photosynthetic Pathway	(facultative) CAM metabolism	Cornelissen, 1996; Diaz et al., 2004; Wright et al., 2004; Cornwell et al., 2008; Kattge et al., 2009
Raunkiaer life form	C, G and T preferred	Julve, 1998
Root depth	Shallow rooting system (< 20 cm)	Paula et al., 2004; Green, 2009
Tolerance to drought	Medium or high drought tolerance	Green, 2009
Typical plant height	Small plants (< 1 m)	Cornelissen 1996; Diaz et al., 2004; Paula et al., 2004; Wright et al., 2004; Garnier et al., 2007; Kleyer et al., 2008; Green, 2009

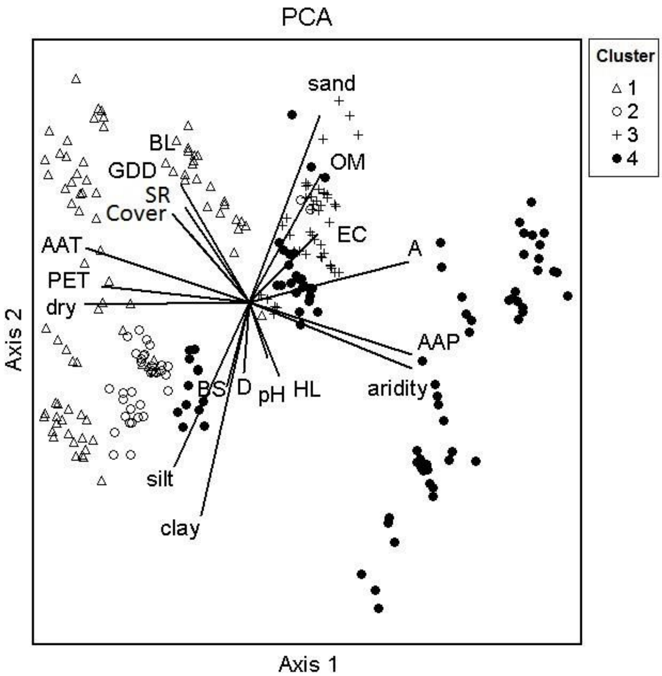


Fig. 2.3 Biplot of PCA results showing spatial plot- and variable distributions along the first two axes. Plots are indicated by symbols according to their respective group. Variable abbreviations are explained in Table 2.1. Axis 1 is primarily a measure of climatic variation, whereas axis 2 rather contains the soil-related measures.

Hierarchical clustering and ISA revealed an optimal division of the plots in four clusters (Fig. 2.3), as the lowest p-value of Monte Carlo permutation test ($p = 0.077$) was found for this cluster number. Table 2.3 shows a detailed description of the four clusters. KW tests revealed significant differences between the four clusters for all variables (p-value < 0.05), except for pH. The four clusters also significantly differed in life form distribution of hemicryptophytes and therophytes (or annuals; Table 2.1). In cluster 3 and 4, hemicryptophytes clearly dominate and annual species are very rare. Species with an annual life form are most pronounced in cluster 2 (Table 2.1). Sörensen indices showed the highest similarity in species abundance between clusters 1-2 (QS = 0.45) and clusters 3-4 (QS = 0.47).

We conclude that the four clusters (Table 2.3) can mainly be distinguished based on geographical and climatic factors. The vegetation in clusters 1 and 2 is typical for thermophilic limestone pavements. These species rich habitats contain a high amount of annuals and a mosaic of different biological types (cf. Loisel, 1976). Clusters 3 and 4 contain vegetation that occurs at higher altitudes, are more mesophilic and are scarce in annuals (cf. Van den Berghen, 1963; Loisel, 1976).

3.2. Species list comparison

Of the 484 species in the GRPL, 19 species were noted in five or more of the seven key literature sources on EGRs in NW Europe, of which eight species were also noted in the MEDPL (Table 2.4). All except two species are hemicryptophytes. The other two are a bulbous geophyte (*Allium schoenoprasum*) and an annual species (*Erodium cicutarium*). Seven species in the list (36.8%) belong to the genus *Sedum*.

The species in the MEDPL showed some overlap with the GRPL (131 species in common), although a Sörensen index of 0.24 indicates a low species similarity. 79% of the species in the MEDPL is currently not applied on EGRs.

Fig. 2.4 indicates that hemicryptophytes are predominantly used on GRs (75.4%). The MEDPL also contained mainly hemicryptophytes (55%). Annuals are not applied frequently (13.8%) on EGRs, although they are particularly abundant in the MEDPL (28.4%), with a much higher percentage occurring in MEDVEG (36.3%) compared to MEDLIT (17.2%).

3.3. Potential of Mediterranean vegetation

Taking into account the ten main traits (Table 2.2), the MEDPL was analyzed. From the 633 species in the list, 330 species had to be omitted because only data for 1-4 traits could be found. Another 161 species were omitted for the following reasons: 21 for having a phanerophytic life form, 9 for exceeding 1 m in height, 60 because of a too deep rooting system, 2 because of complete lack of or weak drought tolerance and 69 due to unsuitable Grime plant strategy (i.e. no stress tolerance). The adjusted scores of the remaining 142 species ranged between 37.5 and 100%. Table 2.5 lists the species with potential for EGR application (adjusted score ≥ 60%). In general, 28 Mediterranean species (53%) are currently not used for EGR purposes in NW Europe. These species are promising and it would be interesting to further test them on experimental GR platforms. Species scoring the highest belonged to the genus *Sedum* and are already used on GRs. Six species had an annual life form and were not present in the GRPL. Other species all had a hemicryptophytic life form.

Table 2.3 Detailed description of vegetation types (clusters). Explanation of location numbers and variable abbreviations can be found in Fig. 2.1 and Table 2.1.

	Cluster 1 Δ	Cluster 2 ○	Cluster 3 +	Cluster 4 ●
Plots from locations	1, 3, 6-9	2, 4, 5	10-13	14-20
N° of plots	84	36	46	87
Characteristic plant traits				
low values	A, Sand, Aridity, BL	A, Aridity, OM, AAP, BS	Silt, PET, AAT, Dry, BS, BL	Silt, PET, AAT, Dry, BL, Cover, GDD
high values	Cover, BS, Silt, Clay, AAT, PET, Dry	Silt, AAT, Dry, Cover, BL, PET, SR	A, Cover, BS, Sand, Aridity, GDD	A, BS, Sand, EC, OM, AAP, Aridity
ISA results				
# species	76	112	53	55
# species significantly belonging to cluster	46	98	40	25
Indicator species	*Brachypodium retusum, Convolvulus cantabricus, Linum strictum, Euphorbia exigua, Dactylis glomerata, Phlomis lychnitis, Sedum sediforme*	*Poa bulbosa, Vulpia ciliata, Cerastium pumilum, Saxifraga tridactylites, Minuartia hybrida, Bromus madritensis, Helianthemum nummularium, Erophila verna, Brachypodium distachyon*	*Thymus praecox, Trinia glauca, Koeleria vallesiana, Festuca marginata, Galium pusillum, Potentilla neumanniana, Ononis striata, Anthyllis montana*	*Bromus erectus, Thymus serpyllum, Linum suffruticosum, Coris monspeliensis, Galium lucidum, Helianthemum italicum*
Phytosociology (Appendix 2.2)	Class *Thero-Brachypodietea*; Association *Brachypodietum ramosi*	Class *Thero-Brachypodietea; (la Crau: association Asphodeletum fistulosi)*	Class *Ononido-Rosmarinetea*; Association *Ononidion striatae*	Class *Ononido-Rosmarinetea*
Vegetative description	*Garrigue* vegetation, typical for thermophilic limestone pavements, with a high amount of therophytes and a mosaic of different biological types (Loisel, 1976)	Very species rich, dry and basophilic with many therophytes, mosses and lichens (Molinier & Tallon, 1949)	Typical for mesophilic, open calcareous grasslands and prairies with a low abundance of thero- and geophytes (Van den Berghen, 1963)	(Meso)xerophilous *garrigue* and dry grasslands, with a very low abundance of therophytes (Loisel, 1976, Van den Berghen, 1963)

Table 2.4 List of GRPL species that were noted in five of the seven key literature sources used to compile the list. The corresponding Raunkiaer life forms are indicated (abbreviations in Table 2.1), as well as the presence/absence in the MEDPL.

Species	Raunkiaer life form	MEDPL
Sedum album	H	x
Sedum rupestre	H	
Sedum sexangulare	H	
Allium schoenoprasum	G	
Hieracium pilosella	H	x
Phedimus spurius	H	
Achillea millefolium	H	x
Antennaria dioica	H	
Cota tinctoria	H	
Campanula rotundifolia	H	x
Erodium cicutarium	Th	x
Festuca ovina	H	x
Origanum vulgare	H	
Petrorhagia saxifraga	H	
Prunella grandiflora	H	
Sedum acre	H	x
Sedum kamtschaticum	H	
Sedum lydium	H	
Thymus serpyllum	H	x

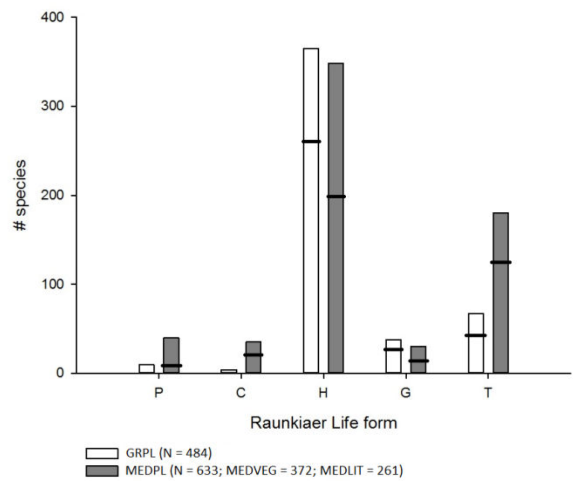


Fig. 2.4 Life form distributions of the species in the GRPL and the METPL. Categories are those of Raunkiaer (abbreviations in Table 2.1). Portions beneath the line segment in the GRPL and MEDPL bars indicate the amount of unique GR species (not comprised in the MEDPL) and the number of species from MEDVEG, respectively.

Table 2.5 Mediterranean species with good EGR potential (adjusted Score ≥ 60%). Calculations were based on 10 key criteria for survival on EGRs (cf. Table 2.2). The presence/absence in the GRPL, the original source (MEDVEG or MEDLIT) and the Raunkiaer life form (abbreviations in Table 2.1) are indicated. For species of MEDVEG which were used in the vegetation analysis, the cluster number is displayed as well.

Species name	Also in GRPL	Species list	Adjusted score (%)	Raunkiaer life form	Cluster n°
Aethionema saxatile		MEDVEG	67	H	2
Ajuga genevensis	x	MEDVEG	67	H	
Alyssum montanum	x	MEDVEG	71	H	3
Anacamptis pyramidalis		MEDLIT	63	H	
Arabis alpina		MEDLIT	63	H	
Arabis collina		MEDLIT	67	H	
Armeria arenaria		MEDVEG	67	H	4
Athamanta cretensis	x	MEDLIT	71	H	
Brachypodium distachyon		MEDVEG	67	T	2
Briza media	x	MEDVEG	63	H	3
Bromus rubens		MEDVEG	83	T	1
Campanula glomerata	x	MEDLIT	63	H	
Campanula persicifolia	x	MEDLIT	63	H	
Campanula rotundifolia	x	MEDVEG	63	H	
Carex alba		MEDLIT	63	H	
Carex mucronata		MEDLIT	63	H	
Ceterach officinarum		MEDLIT	71	H	
Crassula tillaea		MEDVEG	71	T	2
Crepis capillaris		MEDLIT	71	T	
Dianthus sylvestris		MEDVEG	63	H	2
Dittrichia viscosa		MEDLIT	67	H	
Filago pyramidata		MEDVEG	63	T	2
Galium boreale		MEDLIT	60	H	
Helianthemum nummularium	x	MEDVEG	71	H	2
Helleborus foetidus		MEDLIT	63	H	
Hieracium murorum	x	MEDVEG	71	H	1
Hieracium pilosella	x	MEDVEG	63	H	3
Hippocrepis comosa	x	MEDVEG	63	H	4
Linum tenuifolium		MEDVEG	71	H	
Minuartia hybrida		MEDVEG	71	T	2
Poa badensis	x	MEDVEG	63	H	
Polygala vulgaris		MEDVEG	63	H	3
Polypodium vulgare	x	MEDLIT	71	H	
Potentilla pusilla		MEDVEG	67	H	4
Primula vulgaris	x	MEDLIT	63	H	
Rubia peregrina		MEDLIT	67	H	
Rumex scutatus		MEDLIT	63	H	
Saponaria ocymoides	x	MEDVEG	71	H	3
Scabiosa columbaria	x	MEDVEG	63	H	4
Scrophularia canina		MEDLIT	67	H	
Sedum acre	x	MEDVEG	100	H	1
Sedum album	x	MEDVEG	100	H	2
Sedum dasyphyllum	x	MEDLIT	86	H	
Sedum ochroleucum	x	MEDVEG	100	H	2

Silene vulgaris	x	MEDLIT	63	H	
Succisa pratensis		MEDLIT	63	H	
Tanacetum corymbosum		MEDLIT	63	H	
Taraxacum sect. ruderalia	x	MEDVEG	71	H	1
Teucrium montanum	x	MEDVEG	83	H	3
Thymus praecox	x	MEDVEG	71	H	3
Thymus serpyllum	x	MEDVEG	71	H	4
Veronica chamaedrys		MEDLIT	63	H	
Viola reichenbachiana		MEDLIT	63	H	

4. Discussion

The results of the clustering and ordination analysis indicate that the plots, each containing their own specific (sub) Mediterranean vegetation, can clearly be separated into four vegetation types or clusters with distinct climatic, geographic and soil-related properties. The analysis of (sub) Mediterranean habitats and the assignment of species to a specific vegetation type contribute to a correct decision making regarding GR implementation. For instance, GRs in the southernmost part of Mediterranean France will benefit more from the selection of native species from clusters 1 and 2, like *Aethionema saxatile*, *Bromus rubens* and *Dianthus sylvestris*, as these species are most drought adapted: they are subjected to a short vegetation period during spring and autumn, extended summer drought, low AAP and high AAT (Table 2.3). In this case, the % OM and sand in the substrate should be relatively low (around 6.5 and 40% respectively) as these are the soil conditions in their natural habitats (Table 2.3). These percentages correspond with the composition range of the traditional EGR substrates (FLL, 2008). Alternatively, in higher locations with a longer vegetation period, lower AAT and higher AAP, species from clusters 3 and 4 should be preferred, and the substrate should contain higher values of OM. Some examples are *Alyssum montanum*, *Armeria arenaria* and *Potentilla pusilla*.

When the GRPL was compared to the MEDPL, two results need to be highlighted. First, we found that 79% of the species in the MEDPL were not yet applied on GRs and that *Sedum spp.*, succulents with a (facultative) CAM photosynthetic pathway (Durhman et al., 2006), are most frequently applied. Succulents are considered the best option for application on EGRs, as their shallow rooting system and efficient water use permits them to tolerate even the most extreme environmental conditions on the roof (e.g. Monterusso et al., 2005; Oberndorfer et al., 2007). However, some of these taxa could also pose problems due to slow colonization rates and frost sensitivity [e.g. *Hylotelephium cauticola* (Getter & Rowe, 2007); *Sedum rupestre* (Benvenuti & Bacci, 2010)]. Besides succulents, some herbaceous perennial plants, grasses and geophytes clearly are also capable to withstand drought [e.g. *Allium cernuum*, *Festuca glauca* (Getter & Rowe, 2008b); *Armeria maritima*, *Prunella vulgaris*, *Silene uniflora, Koeleria macrantha*, *Trisetum flavescens* (Nagase & Dunnett, 2010); *Poa compressa* (Wolf & Lundholm, 2008)]. Instead of using monocultures of succulents, mixtures of diverse life forms are more interesting (Dvorak & Volder, 2010) and have shown to optimize GR performance, by improving stormwater and cooling management (Wolf & Lundholm, 2008; Lundholm et al, 2010). Grasses and herbaceous species are less drought tolerant compared to succulents, but are more effective for evapotranspiration and thus stormwater retention (Wolf & Lundholm, 2008). Alternatively, succulents have been found to facilitate growth of herbaceous species under abiotic stress (Butler & Orians, 2011). Despite the promising features of species mixture implementation, a (partially) shaded roof with deeper growing substrate and irrigation is often suggested when successful establishment and survival of plant species on GRs in Mediterranean climates are considered (Getter & Rowe, 2008b; Benvenuti & Bacci, 2010; Williams et al., 2010; Nektarios et al., 2011). This is often not possible as most roofs are fully exposed and deeper growing substrates yield higher loads and thus special, costly building structure improvements. Furthermore, the eventual use of irrigation questions the sustainability of the whole EGR concept, especially in a region where water is very scarce during summer (cf. Filippi, 2008). The high amount of unused, local Mediterranean species with variable life forms comprises a potential source for urban GR purposes, although further screening and testing is required to see if they can thrive in shallow substrates without irrigation.

The second result of the species list comparison shows that hemicryptophytes constitute the major proportion of currently applied GR plants, and that very little attention has gone to the possibilities of annuals. We assume that the presence of annuals in the GRPL is mainly due to spontaneous colonization, as GRs comprise a dynamic system with seed input from surrounding vegetation and Bornkamm (1961) and Köhler (1993), which monitored vegetation on GRs, listed all species present on existing GRs and not only those that were introduced on them. In contrast to the low presence of annuals in the GRPL, this life form type is particularly abundant in the MEDPL, and contains promising features for EGRs. Many therophytes germinate, grow, flower and produce many seeds in a very short time period, whereupon they perish. Although they won’t be interesting during summer months, they may be attractive in spring and early summer for pollinators as well as having aesthetic value, due to their colorful flowers (cf. Filippi, 2008). Seed production is added to the seed bank, hence forming a buffer against eventual gap formation should other herbaceous plants die off. This property is a natural survival strategy which may guarantee GR performance in regions where weather conditions are very unpredictable (Madon & Médail, 1997). The incorporation of annuals in the design of EGRs can improve the EGR performance and should certainly be considered.

People are rather skeptical towards dehydrated GRs during summer (Dagenais et al., 2010). However, even when the GR vegetation is not very attractive in summer (except for evergreen succulents), GRs should still be the preferred option over bitumen or gravel roofs, as the substrate and other build-up layers are also effective in building cooling and stormwater retention. Outside the summer months, GRs can function optimally and offer a wide array of local drought adapted plant species, thereby increasing floral and faunal biodiversity. If people accept that non irrigated EGRs in the Mediterranean region will not be green all year round, which is in line with the general life cycles of the vegetation in this climate, more design possibilities arise which will greatly improve GR interest in the region.

Mediterranean vegetation definitely can thus inspire us as a source for development and improvement of EGR design. Many species were deleted due to a deep rooting system or lack of stress tolerance. Unfortunately also a lot of species (330 in total) had to be omitted as the plant traits were not sufficiently known (indicated by a confidential level below 50%). Therefore, possibly some interesting species have been omitted and Table 2.5 only brightens a small part of the immense possibilities that the Mediterranean vegetation offers. Alternatively, some species in the dataset can instinctively be described as 'not useful for EGR design' but are included because no information was available to argue their exclusion. An example is *Dittrichia viscosa*, without any information in the TRY database on rooting depth or other exclusion criteria. It is therefore included in the dataset, although experts would not recommend this species because rooting depth is not expected to be shallower than 20 cm. This is a recurring problem that has also been encountered in other studies (e.g. Mentens et al., 2006; Stadler et al., 2006), stressing the necessity to further complete and update available plant trait databases like the TRY Initiative.

Results in Table 2.5 indicated that *Sedum spp.* (of which some are already comprised in the GRPL) are also a good option for EGRs in the (sub) Mediterranean region. Other potential species not yet used on GRs in NW Europe include: *Bromus rubens*, a Mediterranean annual grass; *Ceterach officinarum*, a fern that likes sunny expositions and requires little or no humidity; *Linum tenuifolium*, a perennial that prefers sunny, dry and hot habitats on calcareous soil, and *Crassula tillaea*, an annual succulent that thrives in locations with strong summer drought because its short life cycle allows it to grow and flower before summer. Further plant types that need attention are mosses and lichens, as they are part of the vegetation (sometimes even exceeding 80% cover in the plots). Their value was already confirmed by certain authors also with respect to facilitation of establishment and survival of vascular plants in extreme conditions, improvement of water storage and carbon and nitrogen sequestration (e.g. Krupka, 1992; Anderson et al., 2010).

The approach of the EGR habitat template (Lundholm, 2006) applied in this study provided interesting outcomes. On one hand it was possible to describe the template vegetation in the study region, therefore pointing at some ecological requirements that need to be considered during GR design (like the incorporation of different life forms with special attention to annuals). On the other hand, this study highlighted the possibilities of (sub) Mediterranean vegetation for use on EGRs. However, the results do not offer scientific evidence that the species will effectively thrive on EGRs in the Mediterranean. Additional research is needed for a more thorough selection of plants in the provided species lists, for example by also using utilitarian plant traits (e.g. flower color, commercial availability) and then followed by testing them under different EGR conditions prior to commercialization.

5. Conclusion

GRs are an important tool to increase environmental quality in densely populated cities. The performance of GRs happens to be rather low in the (sub) Mediterranean region, as the currently applied species are more or less the same as in NW Europe and thus not very well adapted to the extreme environmental conditions in this region. This study used the habitat template concept to look at possibilities of native vegetation on shallow soils and rocky habitats in Mediterranean France. Four relevant vegetation types were identified, according to geographic, climatic and soil-related variables. A comprehensive list of species in the Mediterranean region of southern France with a potential for use on EGRs was compiled. Special attention should go to the incorporation of annual species, as they contain special features that can guarantee GR performance in regions where weather conditions are very harsh. This study provides evidence that natural habitats can inspire and improve the design of EGRs in the (sub) Mediterranean region.

Chapter 3. Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France

*Adapted from Van Mechelen, C., Dutoit, T., Kattge, J., Hermy, M. (2014) Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. Ecological Engineering, **67**, 48-59.*

1. Introduction

The life-quality-improving value of green roofs (GRs) in densely populated urban areas arouses the public interest for these novel urban ecosystems (Perring et al., 2013). GRs have the potential to mitigate urban temperatures to more comfortable levels through higher albedo and evapotranspiration from vegetation and substrate (cf. Oberndorfer et al., 2007). The evapotranspiration, together with water storage in the substrate, also leads to more effective stormwater management. Additionally, GR vegetation offers habitats and food sources that support a range of local invertebrate (Madre et al., 2013) and bird communities, therefore increasing biodiversity value (Oberndorfer et al., 2007; Madre et al., 2014). Other benefits include noise reduction, aesthetic and psychological value, a longer roof membrane longevity and substitution for lost space on ground level (Oberndorfer et al., 2007; Cook-Patton & Bauerle, 2012). In an era of climate change where more intense rainfall events and extended dry periods are predicted, the buffering capacity of GRs will increase their importance even further (Vanuytrecht et al., 2014). The focus here is on GRs of the extensive type (EGR; substrate depth < 20 cm) as these are widely applicable and their low-maintenance supports self-regulation which is an essential feature of these versatile systems

During the last decades, research and application of GRs have shown a remarkable rise in NW European and North American countries (e.g. Dvorak & Volder, 2010). However, knowhow and proper incentives are to some extent still lacking in a large part of the world (Dvorak & Volder, 2010; Fioretti et al., 2010; Williams et al., 2010). This is for instance the case in countries with a Mediterranean climate, where the beneficial effects of GRs would be similar or even more pronounced (Alexandri & Jones, 2008; Fioretti et al., 2010). However, environmental conditions on rooftops are very harsh, particularly in the Mediterranean during summer, and it is necessary to have a better understanding of drought tolerant vegetation that could survive and thrive in this challenging climate (Benvenuti & Bacci, 2010; Vanuytrecht et al., 2014).

Until recently, research exploring the suitability of various plant taxa has been limited. Succulent plants are generally considered the most appropriate plants to apply on EGRs, due to their shallow root systems, (facultative) crassulacean acid metabolism (CAM) and hence efficient water use and tolerance to extreme conditions of drought (Durhman et al., 2006; Benvenuti & Bacci, 2010). Butler and Orians (2011) highlighted the potential of succulents by indicating that *Sedum spp.* can facilitate the performance of neighboring plants, the so called 'nursery effect', by reducing soil temperature during dry weather conditions, thereby decreasing abiotic stress for other life forms. While the GR industries rely mainly on the use of succulent and some other 'tried-and-true' plants (i.e. plants tested and found capable for use on GRs), often applied in low species numbers or limited to only one life form, a range of unexplored herbaceous perennial and annual plants exists with the necessary drought adaptations (Dvorak & Volder, 2010; Nagase & Dunnett, 2010, Chapter 2). The use of different life forms has been shown to provide better ecosystem functioning and resistance to environmental stress, mainly due to niche complementarity and facilitation (Lundholm et al., 2010). Furthermore, highly diverse GRs have a higher survival probability and are more aesthetically pleasing even under dry conditions (Nagase & Dunnett, 2010).

In order to find potential species for urban greening projects (including GRs and green walls), the 'habitat template hypothesis' (Lundholm, 2006) is a highly interesting concept. In the case of EGRs, this hypothesis suggests that natural habitats with similar characteristics as those on this GR type, thus scree slopes, limestone pavements and calcareous grasslands on very shallow and nutrient poor soils, can inspire EGR design. Therefore, studying the native plant species composition in these habitats is useful. As a biodiversity hotspot, representing over 10% of the world's flora (Lavergne et al., 2006) and a lot of extreme habitats, the Mediterranean area offers a potentially interesting species pool for EGR application (see Chapter 2). With the habitat template hypothesis in mind, we described semi-natural vegetation in southern France in a previous study, and identified an elaborate list of species which do have some potential for use on EGRs (Chapter 2). Drawing attention to potential species is a starting point, but implementation of these species can still prove to be impossible, as there are also other factors besides drought adaptation to account for. For example, traits like plant size, growth potential, flowering duration, pollinator attractiveness and aesthetic value are factors that also need to be considered (cf. Benvenuti & Bacci, 2010). Detailed information on plant traits can offer insights into the typical characteristics of GR plants and therefore guide us to the most useful species for EGR application (cf. Lundholm et al., 2010). Because species selection can be a complex process when a wide range of criteria are involved (Reubens et al., 2011), the development of a decision support tool is a welcome instrument to assist GR developers toward an appropriate choice of native plants in GR projects.

The objective of this study was to provide an overview of plant traits that are crucial for survival of plants on EGRs in areas where dry periods are prominent, in particular in the Mediterranean climate. The most important plant traits will be incorporated in an easy to handle screening tool and it will be applied on a species list of a vegetation survey in Mediterranean France.

2. Material and methods

2.1. Species lists

For the analysis and case study, a matrix of plant species and corresponding traits was assembled. The species lists included a set of EGR plant species (GRPL), commonly used or spontaneously occurring on EGRs in NW Europe, and a Mediterranean plant species list (MEDPL) from a previous study of an extensive vegetation survey in southern France (Chapter 2). As drought tolerance and self-regulation are always important on all EGR systems, the GRPL is used as a reference data set.

For the GRPL, seven sources were used. These included five key literature sources of internationally recognized GR specialists or scientists (Bornkamm, 1961; Krupka, 1992; Köhler, 1993; Kolb & Schwarz, 1999; Snodgrass and Snodgrass, 2006) and two species lists of international GR Companies (Optigreen Limited, 2012; ZinCo Gmbh, 2012).The number of times a species is noted in these sources is considered a proxy to its frequency of use on EGRs (FREQ), which will be used to analyze the relation between frequency and plant traits. As plant traits were only available at the species level, the GRPL comprised 483 species, after exclusion of subspecies, varieties and hybrids. By this we assume that plant traits of infraspecific taxa are the same as for the species.

The MEDPL comprised the species of (sub) Mediterranean France observed in 2011 during an elaborate vegetation survey of open habitats on calcareous, shallow stony soils (for a full habitat description we refer to Chapter 2). These extreme habitat conditions are assumed representative for the conditions on EGRs. Additionally we added four literature data sources describing similar habitats (Molinier & Tallon, 1949; Van den Berghen, 1963; Loisel, 1976; Rieux et al., 1977). The vegetation in these literature sources was described as Mediterranean *matorral* (also called *garrigue*), typical for thermophilic limestone pavements of southern France, with high species richness (SR) and a mosaic of different biological types. Both our vegetation descriptions and the literature data together accounted for 633 species, from which 131 species also occurred in the GRPL. Plant nomenclature follows The Plant List (2010).

2.2. Trait selection procedure

The approach was based on both functional traits and utilitarian aspects, as actual species selection for EGRs will depend on both. Drought adaptation and self-regulation (e.g. regeneration strategy, presence of a seed bank, plant longevity) were considered key factors for survival and overall success on EGRs, which also holds for more arid environments (Getter & Rowe, 2008b; Vinson & Zheng, 2013). Relevant trait "groups", all related to drought adaptation and/or self-regulation, were identified through an extensive literature search. For the selection of utilitarian aspects, a similar approach was used, in which four GR publications were consulted. For a summary of the literature used, we refer to Appendix 3.1. Next, the TRY Initiative (Kattge et al., 2011; list of contributed authors in Appendix 3.2), a global archive of plant traits, was screened for plant traits related to the trait "groups" identified by the literature survey. A total of 67 traits (53 functional traits and 14 utilitarian aspects) were assembled for the 985 unique plant species. All species for which no information was available were omitted as they do not contribute to the analysis. This reduced the dataset to 696 plant species (316 in the GRPL and 507 in the MEDPL; 127 species occurring in both lists). Because we are only interested in Mediterranean species with a potential for EGRs, we then made a preselection based on some obvious exclusion criteria. Some traits (e.g. deep rooting system) may be considered an adaptation to drought, but since substrate depth on EGRs does not exceed 20 cm (cf. Krupka, 1992), all species having a larger rooting depth were omitted. Other exclusion criteria were: phanerophytic life form (in other words all trees); plant height exceeding 1 m (often shrubs); lack of drought tolerance and no stress tolerance according to the Grime strategy types. The final matrix for data analysis comprised 67 traits and 471 species (231 in the GRPL and 309 in the MEDPL; 69 species occurred in both lists; see Appendix 3.3 for the final species list).

2.3. Data analysis

To summarize the information in the species*trait matrix, a correlation analysis of plant traits was performed. As the goal was to highlight the most important traits for EGR plants and to use them for appropriate species selection, we first considered only the GRPL (n = 231 species). The analysis followed a hierarchy, first focusing on the ordinal variable frequency (FREQ), as we assumed plant traits associated with highly frequent species as more important and informative. Afterwards a more extensive correlation analysis was performed, to select other traits that are directly related to the traits resulting from the previous step. 31 traits (e.g. protein potential, leaf respiration, fire tolerance and moisture use) contained more than 90% missing values. To make the analysis more robust without further reduction of the amount of species, we only used the variables containing less than 75% missing values. This reduced the number of variables to 25: FREQ, 17 functional traits and 7 utilitarian aspects (Table 3.1). Exploration of the data suggested the use of non-parametric statistics, as all variables showed a non-normal distribution (p-value of Kolmogorov–Smirnov test < 0.05). Spearman rank correlation (r_s), Kruskal Wallis tests (KW) and Pearson Chi^2 analysis ($\chi 2$) were applied to test for relations between the variables. All analyses were performed in SPSS 20.0 (SPSS Inc, Chicago, IL). For the significant KW and $\chi 2$ results, post hoc tests were performed and results were presented with bar charts (Siegel & Castellan, 1988). For all the significant traits, 'scoring conditions' were calculated for further implementation in the screening tool. These are the average values (for scale variables) and main categories (for ordinal or nominal variables) of the most frequently used EGR species, defined as occurring in five or more of the seven sources used to compile the GRPL.

2.4. Screening tool and case study

Based on the results of the correlation analysis, a screening tool was constructed which can be considered as a hierarchical multi criteria scoring system weighted by trait importance (cf. Reubens et al., 2011). First before scoring, the exclusion criteria mentioned in the trait selection procedure were considered, to delete species that are obviously not suitable for EGR purposes. Then the traits significantly related to FREQ (hereafter called 'primary traits') are listed, followed by the traits that are significantly related to the primary traits. Species get a positive score for the traits (2 points for every primary trait and 1 point for every derived trait) when they meet the condition indicated in the screening tool. The final screening score (SS) is the sum of all the separate trait scores and can be considered as a measure of suitability for application on EGRs in the Mediterranean. As a case study, the screening score was applied to the MEDPL, indicating the most promising Mediterranean species for EGR purposes that merit further experimental tests.

Table 3.1 Overview of (i) 17 functional plant traits and (ii) 7 utilitarian aspects used for the correlation analysis, as they contained less than 75% of missing values. For the other we refer to Appendix 3.4. Variable types (scale: S, ordinal: O, nominal: N) are indicated and for scale variables, units are provided as well. Categories (for ordinal variables) and codes (for nominal variables) are listed. All variables are classified in a trait group. Authors (and corresponding reference) who contributed more than 10% of the trait data are also indicated.

(i) Functional traits	Var. Type	Unit	Categories/Codes	Trait group	Authors/ Reference
Leaf area	S	mm²		Leaf adaptation	Cornelissen, 1996; Kleyer et al., 2008; Siefert*
Leaf dry matter content per leaf water-saturated mass (LDMC)	S	g/g		Biomass	Garnier et al., 2007; Kleyer et al., 2008; Siefert*
Leaf nitrogen content per dry mass (LeafN)	S	mg/g		Nitrogen content	Ogaya & Penuelas, 2003; Garnier et al., 2007; Reich et al., 2009
Leaf phenology (LeafPH)	N		Evergreen; winter deciduous; summer deciduous	Leaf phenology	Kattge et al., 2009; Reich et al., 2009
Leaf shape (LeafSH)	N		Broad/full/simple; pinnate; palmate; digitate; needle-like/ ensiform; scale-like	Leaf adaptation	Kühn et al., 2004; Paula et al., 2009
Life form	N		Chamaephyte (C); hemicryptophyte (H): geophyte (G); therophyte (Th)	Life form	Julve, 1998
Maximum plant longevity (MaxPL)	N		Annual; annual/biennal; biennal; biennal/perennial; perennial ; indifferent	Plant longevity	Diaz et al., 2004; Kühn et al., 2004; Moles et al., 2004; Poorter **
Metamorphoses for storage (MetStor)	N		None; succulent; bulb; pleiocorm/primary storage root; rhizome; runner; tuft; root tuber/secondary storage root; shoot tuber	Reserves and storage	Kühn et al., 2004
Metamorphoses for vegetative dispersion (MetVD)	N		Fragmentation; bulb; pleiocorm; rhizome; runner; root/shoot; root tuber; shoot tuber; rhizome/ root/shoot; rhizome/runner	Regeneration strategy	Kühn et al., 2004
Photosynthetic	N		C3; C4; CAM; C3/CAM;	Photosynthesis	Kattge et al.,

pathway (PSP)			C4/CAM		2009
Plant strategy type (PlStrat)	N		S (stress tolerants); cs (competitor + stress tolerants); rs (stress tolerant ruderals); crs (competitive and stress tolerant ruderals)	Grime strategy	Kühn et al., 2004
Seed mass	S	mg		Seed mass and density	Dickie, 2008; Moles et al., 2004
Species reproduction (SpRepr)	N		Seed; veg; seed/veg	Regeneration strategy	Kühn et al., 2004
Specific leaf area (SLA)	S	mm²/mg		Leaf adaptation	Kleyer et al., 2008; Siefert*
Typical plant height (TypPH)	S	m		Plant height	Kleyer et al., 2008; Siefert*
Whole leaf dry mass (WLDM)	S	mg		Biomass	Kleyer et al., 2008; Siefert*
Woodiness (Wood)	O		0=non-woody; 1=semi-woody; 2=woody	High wood density	Kleyer et al., 2008
(ii) Utilitarian aspects					
Flower color (FlowC)	N		Yellow; red; blue/purple; white/pink; brown; green	Aesthetic appeal	Kühn et al., 2004
Flower pollinator (Poll)	N		Wind; insects; insects/wind	Ecosystem goods/service	Kühn et al., 2004
Flower type (FlowT)	N		Disc flowers; flower heads; lip flowers; pollen flowers; bell shaped flowers; funnel flowers; *Fabaceae*-type flowers	Aesthetic appeal	Kühn et al., 2004
Flowering duration (FlowD)	O		# months	Aesthetic appeal	Kühn et al., 2004 ; Garnier et al., 2007
Flowering period (FlowP)	O		1=early spring; 2=spring; 3=late spring; 4=early summer; 5=summer; 6=late summer; 7=early autumn; 8=winter	Aesthetic appeal	Kühn et al., 2004; Green, 2009
Pollinator reward (PollRew)	N		Nectar; pollen; deceit	Ecosystem goods/service	Kühn et al., 2004
Shoot growth form (ShGF)	N		Erect; ascending to prostrate/decumbent; prostrate: lianas/climbers	Aesthetic appeal	Kleyer et al., 2008

*: Herbaceous Leaf Traits Database Old Field New York (unpublished data)
**: Categorical Plant Trait Database (unpublished data)

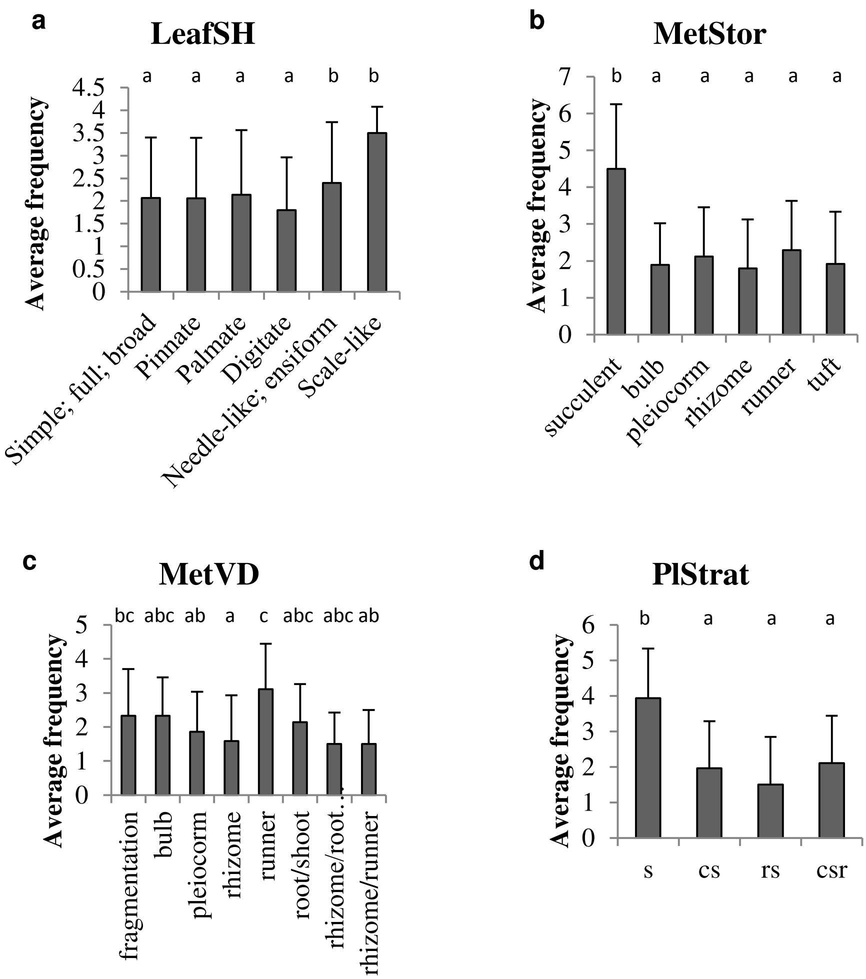
3. Results

3.1. Correlation analysis

FREQ is negatively correlated with leaf area ($r_s = -0.33$, $p < 0.001$), specific leaf area ($r_s = -0.33$, $p < 0.05$) and whole leaf dry mass ($r_s = -0.28$, $p < 0.05$) (Table 3.2i). Average values for highly frequent species (defined as occurring in 5-7 of the used GR sources) are for leaf area, specific leaf area and whole leaf dry mass lower than 368 mm^2, 18 mm^2/mg and 25 mg, respectively. The Kruskal Wallis test results in Table 3.2ii show a highly significant difference ($p < 0.001$) between FREQ and metamorphosis for storage (KW = 24.53) and plant strategy type (KW = 17.66). Leaf shape (KW = 12.86), metamorphosis for vegetative dispersal (KW = 18.71), and photosynthetic pathway (KW = 9.57) are also significantly correlated ($p < 0.05$) with FREQ. Fig. 3.1 illustrates the results of the post hoc tests. Frequently occurring EGR species are stress tolerant, have a CAM photosynthetic pathway, disperse through fragmentation or runners, store reserves through succulence and mostly have a scale-like or needle-like leaf shape. Most of the primary traits are correlated as well (e.g. leaf area and whole leaf dry mass; $r_s = 0.88$, $p < 0.001$). The primary traits show significant correlations or associations with following traits: Table 3.3i: seed mass, typical plant height, woodiness, flowering duration and flowering period; Table 3.3ii: seed mass, leaf phenology, pollinator reward, shoot growth form, flowering duration, flowering period and life form; Table 3.3iii: life form, species reproduction, flower color, flower type, pollinator and plant longevity. Fig. 3.2a–c show that trait categories associated with significant lower leaf area values are a decumbent shoot growth form, nectar as pollinator reward and evergreen leaf phenology. In Fig. 3.2d, plants with a low specific leaf area are mostly geophytes and those with a low whole leaf dry mass are generally therophytes. Fig. 3.3a indicates a seed mass of 0.13 mg and a flowering period in early summer for the plant strategy category ‘stress tolerance’. Fig. 3.3b–d show that average values of seed mass and flowering duration for the important leaf shape category ‘needle-like or ensiform’ are 2.78 mg and 1.75 months, respectively. Average values of seed mass and flowering duration for the metamorphosis for storage category ‘succulence’ are 0.03 mg and 1.92 months, respectively. For the categories ‘runner’ and ‘fragmentation’ of the trait metamorphosis for vegetative dispersal, average values are respectively seed mass of 0.66 and 4.54 mg and flowering duration of 1.09 and 1.13 months. As can be seen in Fig. 3.4, most species with a needle-like leaf shape are also pollinated by insects or wind and have yellow, blue or white disk flowers. Most succulent species also happen to be evergreen, are pollinated by insects and have disk flowers. Species dispersing through fragmentation or runners are mainly evergreen and are pollinated through insects or wind. CAM plants are mostly perennial. Stress tolerant species generally have a perennial longevity, are evergreen, are pollinated by insects and have disk flowers. All the important primary plant trait categories in Fig. 3.4 (except CAM plants) reproduce through seeds or vegetatively and have a hemicryptophytic life form.

Table 3.2 The relationship between plant traits and frequency of use on EGRs (FREQ). (i) Spearman rank correlations (r_s) together with their significance. (ii) Kruskal Wallis test results (KW) together with their significance. For abbreviations of plant traits see Table 3.1. (*: $p < 0.05$; **: $p \leq 0.001$; N: number of valid cases; df: degrees of freedom).

(i) Spearman rank		
Trait	N	r_s
LeafArea	128	-0.33**
LDMC	125	0.09
LeafN	79	-0.07
SeedMass	176	-0.03
SLA	139	-0.22*
TypPH	173	-0.10
WLDM	114	-0.28*
Wood	173	0.07
FlowD	156	0.05
FlowP	124	0.12
(ii) Kruskal Wallis test		
Trait	df	KW
LifeForm	3	6.06
LeafPH	2	0.86
LeafSH	5	12.86*
MaxPL	5	8.69
MetStor	6	24.53**
MetVD	8	18.71*
PSP	3	9.57*
SpRepr	2	0.14
PlStrat	3	17.66**
FlowC	5	5.73
FlowT	6	7.90
Poll	2	3.96
PollRew	1	2.15
ShGF	3	2.36



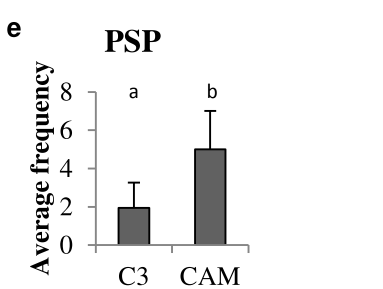


Fig. 3.1 Bar charts visualizing the significant relationship between nominal primary plant traits and the average frequency of species used on EGRs. a) Leaf shape (LeafSH); b) metamorphosis for storage (MetStor); c) metamorphosis for vegetative dispersal (MetVD); d) plant strategy (PlStrat); e) photosynthetic pathway (PSP). Significant differences between categories are indicated by different letters (Kruskal Wallis test cf. Table 3.2ii and post hoc tests). Error bars indicate the standard deviations.

Table 3.3 The relationship between the primary plant traits (P) and other plant traits. (i) Spearman rank correlations together with their significance. (ii) Kruskal Wallis test results together with their significance. (iii) Pearson Chi² test results of the nominal variables. For abbreviations of plant traits see Table 3.1. (*: p < 0.05; **: p ≤ 0.001; N: number of valid cases; df: degrees of freedom; NA: not applicable).

(i) Spearman rank (r_s)				
		LeafArea (P)	SLA (P)	WLDM (P)
LeafArea (P)		1	0.20*	0.88**
	N	128	125	114
LDMC		-0.05	-0.11	0.02
	N	120	124	113
LeafN		0.18	0.21	0.11
	N	64	74	57
SeedMass		0.43**	-0.06	0.45**
	N	114	121	102
SLA (P)		0.20*	1	-0.16
	N	125	139	114
TypPH		0.25**	-0.04	0.26**
	N	124	132	114
WLDM (P)		0.88**	-0.16	1
	N	114	114	114
Wood		-0.24**	-0.01	-0.22*
	N	118	125	109
FlowD		-0.01	0.19*	-0.07
	N	112	119	105
FlowP		-0.14	-0.19*	-0.08
	N	105	109	99

(ii) Kruskal Wallis Test (KW)											
		LeafArea (P)	LDMC	LeafN	SeedMass	SLA (P)	TypPH	WLDM (P)	Wood	FlowD	FlowP
LifeForm		6.4	0.3	0.8	22.5**	11.5*	0.4	11.8*	16.9**	14.2*	0.2
	df	3	3	2	3	3	3	2	3	3	2
LeafPH		11.5*	2.9	0.8	21**	3.4	6.4	14.4**	7.9	7.6*	3.4
	df	2	2	2	2	2	2	2	2	2	2
LeafSH (P)		16.2*	2.1	4.6	13.3*	19.7**	1.9	15.5*	8.2	20.8**	5.3
	df	5	5	4	5	5	5	5	5	5	5
MaxPL		5.4	0.2	2.6	4.6	8.8	0.8	7.7	1	6.9	6.4
	df	4	4	3	5	4	5	4	4	5	4
MetStor (P)		14.4*	12	11.3	25.2**	13.3*	3.7	14*	4.2	17.9*	10.5
	df	6	6	6	6	6	6	6	6	6	6
MetVD (P)		20.4*	18.7	11	26.7**	9.5	11	25.4**	9.2	17.6*	11
	df	8	8	8	8	8	8	8	8	8	8
PSP (P)		6.2	0.1	2.4	4.4	1.8	0.3	2.7	0.3	0.5	1.7
	df	3	2	1	3	3	3	2	3	2	2
SpRepr		1.6	0.1	1.6	0.5	0.6	1.5	1.1	3.8	3.8	0.4
	df	2	2	2	2	2	2	2	2	2	2
PlStrat (P)		16**	6.7	4.3	14.5*	8.2*	9.7	16**	1.5	0.8	9.6*
	df	3	3	3	3	3	3	3	3	3	3
FlowC		1.1	0	3.5	8.6	2	2.1	2	4.2	2.4	7
	df	5	5	4	5	5	5	5	5	5	5
FlowT		12	0	8.6	9.1	11.7	4	7.7	28.5**	2.5	8.2
	df	6	6	5	6	6	6	6	6	6	6

(ii) Continued. Kruskal Wallis Test (KW)											
		LeafArea (P)	LDMC	LeafN	SeedMass	SLA (P)	TypPH	WLDM (P)	Wood	FlowD	FlowP
Poll		2.7	10.5	5.2	0.4	0.2	4.4	2.7	2.9	18.9**	1.4
	df	2	2	2	2	2	2	2	2	2	2
PollRew		4.4*	0	0	0.4	0	1.4	3.3	2.9	3.8	0
	df	1	1	1	1	1	1	1	1	1	1
ShGR		12.4*	0.5	2.8	3.8	6.5	2.1	9.7*	26.4**	6	1.1
	df	3	3	3	3	3	3	3	3	3	3

(iii) Pearson Chi² (χ²)						
		LeafSH (P)	MetStor (P)	MetVD (P)	PSP (P)	PlStrat (P)
LifeForm		31.7*	94.7**	93.9**	0.7	138.7**
	N	164	153	115	132	162
LeafPH		17.5	29.5*	37.1*	3.1	49.9**
	N	152	135	109	102	152
LeafSH (P)		NA	93.9**	97.7**	3.2	47.1**
	N		146	115	106	162
MaxPL		21.8	16.7	22.8	22.2*	121.6**
	N	162	146	115	114	162
MetStor (P)		93.9**	NA	415.7**	98**	115.5**
	N	146		109	98	145
MetVD (P)		97.7**	415.7**	NA	4.9	38.0*
	N	115	109		74	115
PSP (P)		3.2	98**	4.9	NA	43.8**
	N	106	98	74		105
SpRep		60.0**	79.3**	57.4**	2.9	14.2*
	N	158	148	110	106	157
PlStrat (P)		47.1**	115.5**	38.0*	43.8**	NA
	N	162	145	115	105	
FlowC		47.3*	35.5	46.5	5.7	33.5*
	N	131	121	89	92	130
FlowT		71.6**	56.2*	25	4.6	33.0*
	N	125	115	83	84	124
Poll		33.8**	73.7**	61.9**	1.3	17.0*
	N	162	152	114	112	161
PollR		4	2.2	7.7	0.3	2.3
	N	119	109	81	80	118
ShGF		18.7	17.5	25.6	0.9	4.6
	N	149	137	106	117	148

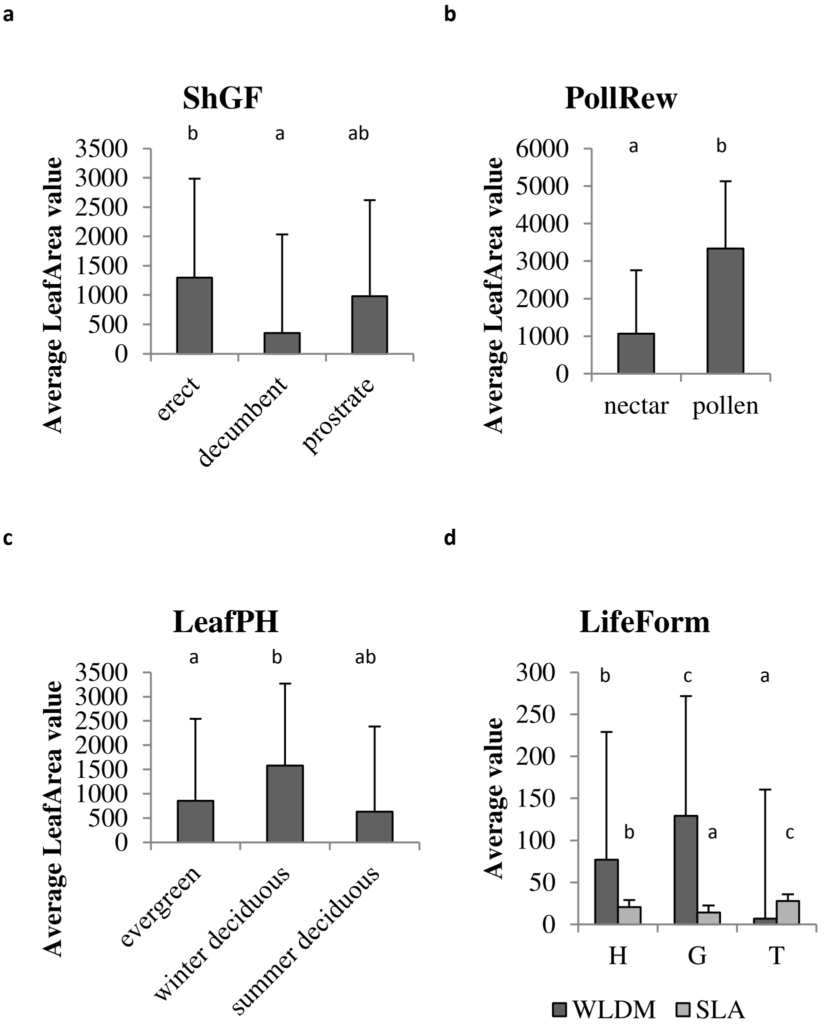


Fig. 3.2 Bar charts visualizing the significant relationship between primary and other traits of species used on EGRs. Average values and standard deviation for the primary trait leaf area for each category in: a) shoot growth form (ShGF); b) pollinator reward (PollRew); c) leaf phenology (LeafPH). d) The primary traits whole leaf dry mass (WLDM) and specific leaf area (SLA) for each category in life form. Significant differences between categories are indicated by different letters (Kruskal Wallis test cf. Table 3.3ii and post hoc tests).

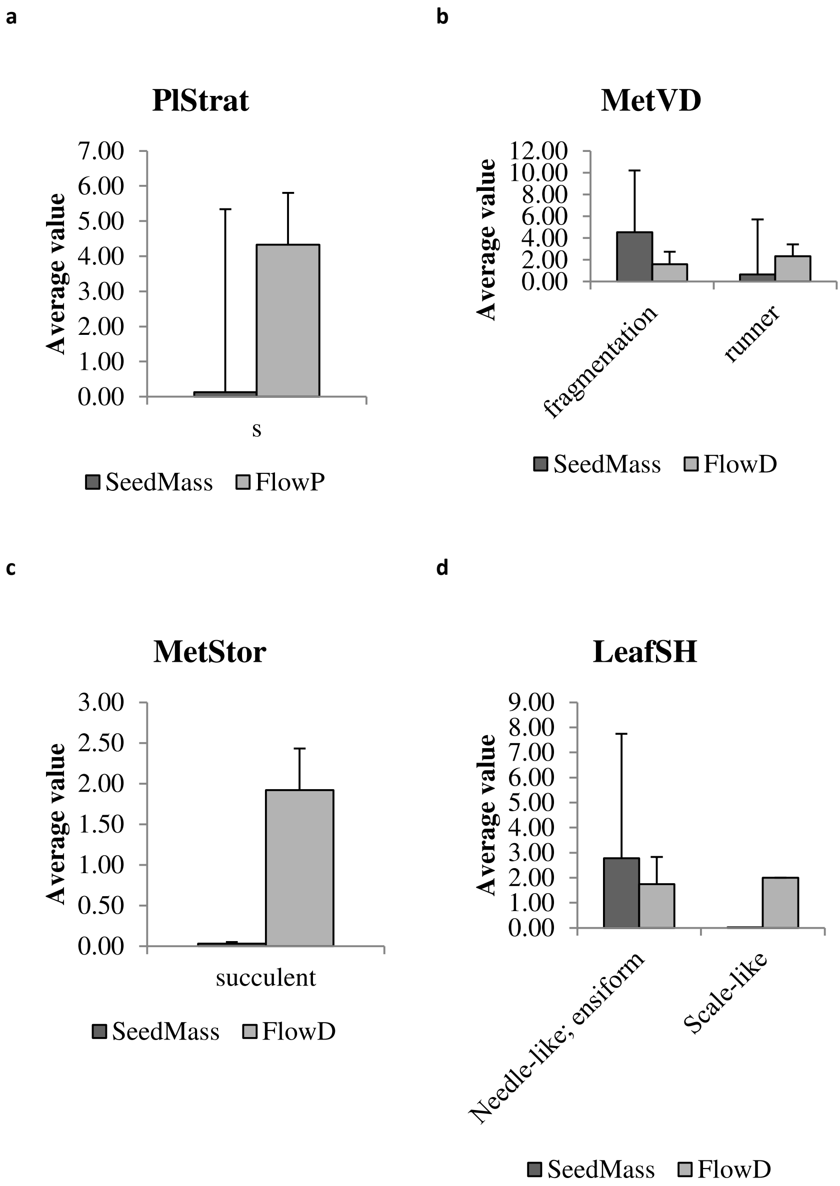
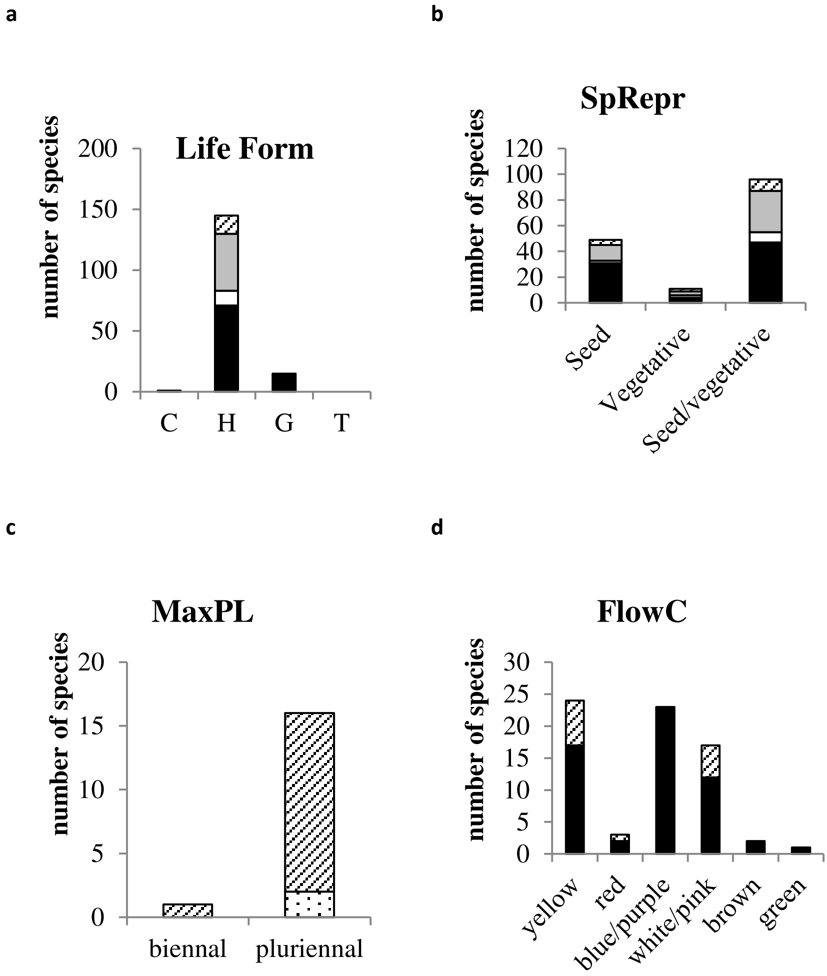
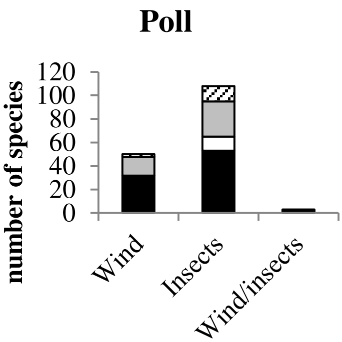


Fig. 3.3 Bar charts visualizing the significant relationship between primary and other traits of species used on EGRs. Average values and standard deviation for flowering period (FlowP), flowering duration (FlowD) and/or seed mass for the important categories of the primary traits: a) plant strategy (PlStrat); b) metamorphosis for vegetative dispersal (MetVD); c) metamorphosis for storage (MetStor); d) leaf shape (LeafSH).


a
Life Form
number of species
200
150
100
50
0
C
H
G
T
b
SpRepr
number of species
120
100
80
60
40
20
0
Seed
Vegetative
Seed/vegetative
c
MaxPL
number of species
20
15
10
5
0
biennal
pluriennal
d
FlowC
number of species
30
25
20
15
10
5
0
yellow
red
blue/purple
white/pink
brown
green

e



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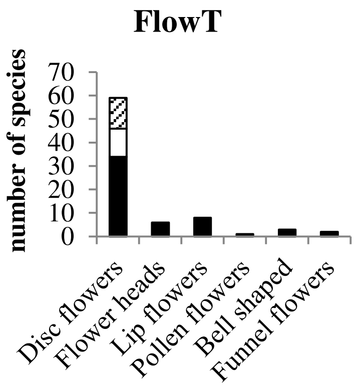

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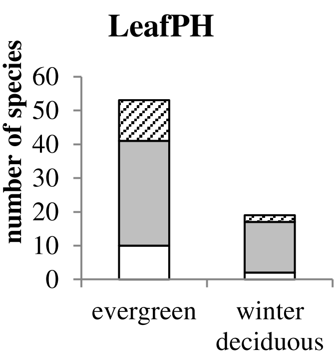

LEGEND

Leaf shape: needle or scale-like; ensiform

Metamorphosis for storage: succulence

Metamorphosis for vegetative dispersal: fragmentation; runner

Photosynthetic pathway: CAM

Plant strategy: stress tolerant

Fig. 3.4 Bar charts visualizing the significant associations of important primary plant trait categories (see legend) and other nominal plant traits of species used on EGRs (Pearson Chi² test cf. Table 3.3iii). a) life form; b) species reproduction (SpRepr); c) maximum plant longevity (MaxPL); d) flower color (FlowC); e) pollinator (Poll); f) flower type (FlowT); g) leaf phenology (LeafPH). Trait categories with a large number of species are important for EGR species performance.

3.2. Screening tool and case study

Table 3.4 shows the screening tool, in which all the significant results from the correlation analysis are incorporated. The traits species reproduction and pollinator type are excluded from the screening tool, as their important categories (seeds and vegetative for species reproduction; insects and wind for pollinator type) are the only categories for these traits, and incorporation in the screening tool will thus not be informative for species scoring. The 309 MEDPL species that passed through the exclusion step were submitted to the screening tool. In Table 3.5, the highest scoring Mediterranean species (61 species with SS ≥ 10, maximum SS = 28) are listed. 27 species in the list are already used on EGRs in NW Europe, and 34 species are currently unused. The average score in both groups is comparable (12 for the new species and 14 for the already used species). The highest scoring species are *Sedum album* and *Sedum acre*, both already frequently used on EGRs. We highlight that 35% of the species in the new potential species group recommended for use on EGRs in the Mediterranean region are therophytes.

Table 3.4 Decision support tool to select species which are potentially interesting for use on EGRs in Mediterranean climates, based on functional (*) plant traits and utilitarian (+) aspects related to frequently applied EGR species. Three groups of selection criteria are shown: exclusion criteria, primary traits and derived traits. Species can be deleted in the first step using exclusion criteria, or get a weighted positive score for the traits for which they meet the condition indicated in the screening tool.

Exclusion criteria			
Trait	Condition	Action	
Rooting depth	> 20 cm	delete	
Tolerance to drought	None	delete	
Life form	Phanerophyte	delete	
Typical plant height	> 1m	delete	
Plant strategy type	No stress tolerance	delete	
Primary traits		**Derived traits**	
Trait	Scoring condition (2 points for each matching scoring condition)	Trait	Scoring condition (1 point for each matching scoring condition)
Low leaf area *	< 368 mm²	Low seed mass *	< 4.54 mg
Low specific leaf area *	< 18 mm²/mg	Low typical plant height *	< 0.2 m
Low whole leaf dry mass *	< 25 mg	High woodiness *	(Semi) woody
Metamorphosis for storage *	Succulence	Leaf phenology *	Evergreen
Plant strategy type *	Stress tolerance	Pollinator reward+	Nectar
Metamorphosis for vegetative dispersal *	Fragmentation or runners	Shoot growth form +	Decumbent
Photosynthetic pathway *	CAM	Short flowering duration+	< 2 months
Leaf shape *	Needle-like/ensiform or scale-like	Late flowering period+	Early summer or later
		Life form *	Geophytes, therophytes, hemicryptophytes
		Flower color+	Yellow, blue or white
		Flower type+	Disc flowers
		Maximum plant longevity *	Perennial
Sum of Scores:	/16		/ 12
Total screening score (SS):			/ 28

Table 3.5 Mediterranean species for potential EGR application and their screening score (SS ≥ 10) based on the screening tool in Table 3.4. The column 'New' indicates Mediterranean species that are currently not used on EGRs. Raunkiaer life forms (abbreviations in Table 3.1) are given as well.

Species	New	Life forms	SS
Sedum album		H	25
Sedum acre		H	23
Sedum dasyphyllum		H	19
Thymus praecox		H	18
Thymus serpyllum		H	18
Draba aizoides		H	17
Hippocrepis comosa		H	17
Silene otites	x	H	17
Alyssum montanum		H	16
Galium verum		H	16
Helianthemum nummularium		H	16
Sedum ochroleucum		H	16
Aster linosyris		H	15
Teucrium montanum		H	15
Petrorhagia prolifera	x	T	14
Plantago coronopus	x	H	14
Polygala vulgaris	x	H	14
Bupleurum falcatum	x	H	13
Centaurium erythraea	x	T	13
Euphorbia seguieriana		H	13
Galium boreale	x	H	13
Veronica chamaedrys	x	H	13
Allium sphaerocephalon		G	12
Alyssum alyssoides	x	T	12
Artemisia campestris	x	H	12
Briza media		H	12
Campanula persicifolia		H	12
Carex alba	x	H	12
Genista pilosa	x	C	12
Helictotrichon pratense	x	H	12
Hieracium pilosella		H	12
Linum catharticum	x	T	12
Linum tenuifolium	x	H	12
Minuartia hybrida	x	T	12
Allium oleraceum		G	11
Anthericum liliago		H	11
Cerastium pumilum	x	T	11
Chondrilla juncea	x	H	11
Filago pyramidata	x	T	11
Gymnadenia odoratissima	x	G	11
Scrophularia canina	x	H	11
Succisa pratensis	x	H	11
Torilis nodosa	x	T	11
Trifolium arvense		T	11
Biscutella laevigata	x	H	10
Campanula rotundifolia		H	10
Carex halleriana	x	H	10
Dianthus sylvestris	x	H	10
Erophila verna	x	T	10
Euphorbia cyparissias		H	10
Euphorbia segetalis	x	T	10
Hornungia petraea	x	T	10
Lavandula angustifolia		C	10
Myosotis ramosissima	x	T	10
Ophrys insectifera	x	G	10
Ornithogalum umbellatum		G	10
Peucedanum oreoselinum	x	H	10
Plantago maritima subsp serpentina	x	H	10
Saponaria ocymoides		H	10
Saxifraga tridactylites		T	10
Viola reichenbachiana	x	H	10

4. Discussion

4.1. Suitable habitats and plant traits for Mediterranean EGR plant selection

The habitat template hypothesis is a good starting point for finding potentially suitable plant species, whether this is for EGRs or other applications in urban greenery like green walls, parks and gardens (Lundholm, 2006; Perring et al., 2013). Environmental conditions in anthropogenic habitats such as EGRs indeed mimic circumstances also found in the field (Lundholm, 2006; Benvenuti & Bacci, 2010). Substrates of EGRs have in common with the sampled natural habitats that they are shallow, have a high draining capacity and are relatively calcareous (Lundholm, 2006; Perring et al., 2013). So only these vegetation communities were used here as a starting point (Molinier & Tallon, 1949; Van den Berghen, 1963; Loisel, 1976; Rieux et al., 1977). Natural habitats in the Mediterranean region have an extremely high diversity of plant species (Médail & Quézel, 1997) and these offer the potential for finding new species appropriate for EGRs (cf. Chapter 2). A particular assumption is that the traits (but not the trait values) that make plant species successful on NW European EGRs are the same as in Mediterranean Europe. Indeed, drought tolerance and variables which are important in self-regulating plant communities are also expected to be important on EGRs in other climatic regions, although the plant's drought tolerance properties are more essential in the Mediterranean (cf. Getter & Rowe, 2008b; Dvorak & Volder, 2010; Williams et al., 2010). So the primary and derived traits highlighted in this study should be particularly important for survival under a Mediterranean climate. It is not advised to implement the screening tool on species not native to the Mediterranean, as other factors could also influence species survival on EGRs in other regions. For example, if Scandinavian countries would be the target, the literature study should rather focus on tolerance to low temperatures and humid conditions, which would significantly alter the screening tool (cf. Emilsson, 2005).

4.2. Important EGR plant traits and design recommendations

Attributes characterizing frequently applied EGR species (Table 2.4) are a small leaf area, specific leaf area and whole leaf dry mass, needle-like/ensiform or scale-like leaves, CAM photosynthetic pathway (cf. Durhman et al., 2006), stress tolerance, dispersion through fragmentation or runners and storage of reserves through succulence. Other variables correlated to these primary traits extend the list of traits to be considered in the screening tool. An interesting result was that species with a low whole leaf dry mass were merely therophytes. These annual species contribute significantly to the vegetation of Mediterranean systems but their presence in the GR spectrum is until now limited (cf. Chapter 2), probably because of their short aboveground visibility per year, unreliable regeneration and poor ability to support perennial competition in more temperate climates. Also, as they are absent during summer months, the contribution to the cooling effect of the GR will be negligible during this period. Of the new potential Mediterranean species in Table 3.5, 35% are therophytes, indicating that many species with this life form meet the scoring conditions indicated in the screening tool. Therophytes have interesting properties, like short flowering time and production of many seeds, as explained in Chapter 2.

Their conservation value may also be important, certainly in Mediterranean areas where many annuals are threatened (Lavergne et al., 2006). The inclusion of 'annual life form' as a scoring condition for species selection shifts the traditional implementation of perennial and hemicryptophytic species to a more diverse and drought adapted design, which should improve the roofs value for biodiversity and ecosystem functioning.

Some of the primary traits, like CAM photosynthetic pathway, stress tolerance and succulence, already proved to be important for the success on GRs (Snodgrass and Snodgrass, 2006; Oberndorfer et al., 2007). The other leaf-related traits emerging from the plant trait analysis have gained much less attention in the literature (cf. Dunnett & Kingsbury, 2008; Cook-Patton & Bauerle, 2012). Therefore, the presence of these attributes in the screening tool offers some novel insights that reach beyond the usual considered water storage attributes. Next to important attributes, the potential species also have specific habitat requirements (e.g. pH, organic matter, nutrient content) and the GR substrate will need customization to ensure good plant health. This is however not an objective of this chapter, but a consideration for a later phase when the potential species are tested under EGR conditions.

Like other authors (e.g. Dvorak & Volder, 2010; Lundholm et al., 2010; Cook-Patton & Bauerle, 2012), we suggest to combine different life forms for EGR design, including *Sedum spp.*, annuals, geophytes and hemicryptophytes. *Sedum* and other succulent species could act as nursery plants for other herbaceous species when environmental conditions are harsh (Butler & Orians, 2011). By use of both novel or rarely used species (e.g. *Alyssum alyssoides*, *Dianthus sylvestris, Erophila verna, Filago pyramidata, Linum tenuifolium*) and already applied species (e.g. *Allium sphaerocephalon, Euphorbia cyparissias, Helianthemum nummularium, S. album, S. acre*), GR biodiversity can gradually be increased without risking failure. The EGR vegetation design recommended here should ensure EGR performance and sustainability, even under difficult climatic conditions, although further testing of the potential species is required.

4.3. Comments on the plant trait analysis

Although the plant trait based approach applied in this study offered insights in the ecological background of potential EGR vegetation, the results and the screening tool should be interpreted with caution, as some impediments could have influenced the results.

First, the most extended and complete data source currently available was consulted (TRY Initiative, Kattge et al., 2011), but still a large amount of missing values was encountered. To strengthen the analysis, species and variables with insufficient information (289 species and 43 variables, respectively) were deleted. In this way, potentially interesting species and traits could have been overlooked. Furthermore, substantial information was available for more general and common species (e.g. *Aster linosyris, Galium boreale, Hieracium pilosella, Hippocrepis comosa, Veronica chamaedrys*) but lacking for not well known local Mediterranean species (e.g. *Argyrolobium zanonii, Carthamus carduncellus, Teucrium aureum, Lysimachia linum-stellatum, Iris lutescens*). This problem manifested in the results of the case study, with a high amount of common species in the final species list (Table 3.5). Also, the screening tool (Table 3.4) appears quite conservative, as the exclusion criteria are severe. For example, all species with a rooting depth greater than 20 cm were excluded, although many species have the potential to spread roots laterally, suggesting that some species that could work on EGRs were not considered. We stress that this trait only contained information for 10.87% of the species, and that the consulted sources to obtain the trait values (Green, 2009; Paula et al., 2009) do not consider the possibility of lateral spread. Without this detailed information, it is better to be cautious when screening for appropriate species by leaving out all those that are doubtful. This is also why the lack of stress tolerance was added as an exclusion criterion, leaving out the species that are entirely competitive or ruderal. We believe that in our case the amount of missing traits and species is not a major issue, as the purpose was not to describe a plant community but to develop a recommendation system to screen appropriate species for EGRs in the Mediterranean. The lack of detailed information has been shown to be a common bottleneck in ecological research (e.g. Franzel et al., 1996; Diaz & Cabido, 1997; Reubens et al., 2011). A future intent of the TRY initiative is to develop algorithms to fill gaps in the TRY trait matrix, through machine learning techniques in combination with global databases (Shan et al., 2012).

Secondly, during the compilation of the GRPL, varieties, hybrids and subspecies were omitted because trait data were only available at species-level. This could also have caused deletion of potential information, but as mentioned before, the research objective was to find important plant traits and the analysis was based on 231 EGR species, so we believe the results are sufficiently substantiated. Another constraint when compiling the GRPL is that no information was available on whether or not the species on the EGR received irrigation. The consulted sources only list species commonly applied on EGRs, and generally, a minimal irrigation regime during dry periods is recommended. The drought tolerant capacities of the EGR species might therefore not be completely distinct, but this does not impose a big issue as the screening tool allows the deletion of species with unsuitable specific functional traits. A third potential problem with the GRPL is that many of the frequently occurring species are horticultural (except those occurring spontaneously), hence easy to propagate and widely available in nurseries. Many of these species belong to the genus *Sedum*, which are phylogenetically similar and have rather comparable functional traits. The plant trait analysis is therefore somehow biased toward these horticultural species, which is reflected in the outcome of the screening tool (Table 3.5) where many species already occurring on EGRs show the highest screening scores. This does not invalidate the proposed plant trait approach, but rather demonstrates the current GR situation where plants are often denoted as 'tried-and-true' (Dvorak & Volder, 2010; Nagase & Dunnett, 2010). We suggest that, after testing of the potential species under EGR conditions, nurseries should take the successful species into account in their supply, in order to diversify and improve the EGR's performance.

A last constraint is the non-consideration of the species habitat requirements, which resulted in some odd species propositions (Table 3.5), like *Gymnadenia odoratissima* and *Ophrys insectifera*, both orchids with a high conservation value (IUCN, 2013). Because of their trait values, they are marked as potential species, but their suitability for use in Mediterranean EGR installations is doubtful because of their non-Mediterranean climate and habitat affinities. Their inclusion in the list is a side effect of the used MEDPL, which targets appropriate natural habitats but in which some species are present that are actually not representative for the selected plots. This is for example the case for *Succisa pratensis*, which is actually a Mediterranean wetland plant, or *Peucedanum oreoselinum*, originally a mountain-forest border and gravel plant (Bernard, 2008). This constraint does not imply that the plant trait approach is not appropriate or successful, but the lack of 1:1 correspondence between traits and niches indicates that the screening tool should be applied with caution and sufficient knowledge of the species in the plant list.

5. Conclusion

The ultimate purpose of this study was to reveal the most important attributes of EGR plants by use of a plant trait analysis, i.e. a correlation analysis on an extended matrix containing EGR species and a list of their functional traits and utilitarian aspects. The screening tool created based on the results of the analysis is a useful framework for making substantiated decisions for appropriate EGR design in terms of vegetation choice, when sustainability and biodiversity are of major importance. The screening tool delivers a potential list, yet the ultimate prove will come from experimental outdoor trials. Although the adopted approach has some limitations, the plant trait based approach offers new possibilities for Mediterranean regions, and it can help GR companies in the temperate climate to adjust EGR design to cope with upcoming climate change. Parties and persons for whom this selection tool can be of interest (e.g. urban landscape designers, government, advisors, nurseries) would be surprised and inspired by the wide array of unknown species that point out to have potential for EGR purposes.

Chapter 4. Vegetation and structure recommendations for extensive green roofs in Mediterranean and temperate climates*

Adapted from Van Mechelen, C., Dutoit, T., Hermy, M. Vegetation and structure recommendations for extensive green roofs in Mediterranean and temperate climates. In preparation for Urban Forestry and Urban Greening.

1. Introduction

Some consequences of the current human population growth are land use changes, a decline of natural habitats and biodiversity loss (Gill et al., 2007). However, biodiversity is believed to be one of the major drivers of ecosystem services and therefore guarantees our human well-being (Tzoulas et al., 2007; Cardinale et al*.,* 2012). Biodiversity in urban areas should hence be maintained and enhanced, which can be done through application of green infrastructure elements (Tzoulas et al., 2007; Perring et al., 2013). Because rooftops offer a substantial amount of unused space, green roofs (GRs) are a suitable option (Dunnett & Kingsbury, 2008). Greening roofs is gradually becoming a common practice in urban landscapes due to their multi-functionality, including stormwater management, urban habitat provisioning, aesthetic and amenity value and even climate change mitigation (e.g. Oberndorfer et al., 2007; Lundholm et al., 2010). GRs that are lightweight, have a substrate depth of under 20 cm and require no or only little maintenance and irrigation are also referred to as extensive green roofs (EGRs; Oberndorfer et al., 2007). Their biotic and abiotic characteristics are comparable to xeric natural habitats which make them particularly interesting for reconciliation ecology (Lundholm & Richardson, 2010; Francis & Lorimer, 2011; Butler et al., 2012). These GRs are also examples of novel urban ecosystems, as they are self-organizing and originate from human interference (cf. Kowarik, 2011; Perring et al., 2013).

Pictures of the tested species can be found at the end of Chapter 4

Many regions with hot and dry climates, including the Mediterranean, are still unfamiliar with GR technology (Williams et al., 2010), which is mainly due to the challenging climate (i.e. summer drought and elevated temperatures) and therefore limited water availability. On roof-level, these features impose severe restrictions on plant growth and survival (Benvenuti & Bacci, 2010; Williams et al., 2010; Butler & Orians, 2011; Farrell et al., 2012). Plants are assumed not to survive in semi-arid climates on unirrigated GRs with substrate depths below 5 cm, especially not during summer drought or establishment (Getter & Rowe, 2006; Benvenuti & Bacci, 2010; Thuring et al., 2010; Williams et al., 2010). Furthermore, summer water scarcity is becoming a recurring problem in the Mediterranean, and climate change will lead to even more severe water scarcity, as a decrease in summer precipitation of 5% per decade is expected (Parry, 2000; Benvenuti & Bacci, 2010; Gill et al., 2007; Blanusa et al., 2013; Vanuytrecht et al., 2014). Also in temperate regions, water scarcity may pose an issue in a climate change context (cf. Baguis et al., 2010; Vanuytrecht et al., 2014). In Belgium for example, surface temperatures and winter precipitation are expected to increase while summers are predicted to become drier (Baguis et al., 2010; Vanuytrecht et al., 2014). It is hence estimated that by 2050, summer conditions in temperate regions will in some years be relatively similar to the current dry Mediterranean summers. This could, in the event that irrigation is needed, lead for irrigation to become an unsustainable or even a regulated and limited option. It is hence necessary in both regions to adjust plant species choice in order to suit unirrigated GR conditions (Williams et al., 2010; Butler & Orians, 2011; Vanuytrecht et al., 2014). Knowledge of the plants requirements, as well as their performance on site, are essential in this respect (Wolf & Lundholm, 2008; Williams et al., 2010; Nektarios et al., 2011; Butler et al., 2012). Mediterranean areas contain habitats rich in native plant species that have potential to be used on EGRs (see Chapter 2 and 3), because they are assumed to be better adapted to local climatic conditions and to require less maintenance (cf. Oberndorfer et al., 2007; Dvorak & Volder, 2010). From a biodiversity perspective one might even assume that GRs with these natives form an alternative new habitat for some Mediterranean plants whose natural habitats are endangered.

The performance of EGRs could also be improved by expanding the range of currently used plant species (Lundholm, 2006; Wolf & Lundholm, 2008; Dvorak & Volder, 2010; Lundholm et al., 2010; Nagase & Dunnett, 2010; Butler & Orians, 2011). Plant diversification, in terms of plant characteristics, can indeed offer better ecosystem functions due to niche complementarity and facilitation (Lundholm, 2006; Lundholm et al., 2010). *Sedum spp.* for example, can raise the survival probability of non-succulent species by buffering high soil temperatures during drought (Butler & Orians, 2011). This specific property has also been noted with bryophytes, which can colonize the substrate spontaneously and are appropriate to survive extreme drought (Anderson et al., 2010; Butler & Orians, 2011). Particularly in a Mediterranean climate, annual species are promising as well, as their short life cycle allows them to spend dry summer months as seeds and to germinate again after autumn rainfall, hence filling up gaps (see Chapter 2 and 3).

Without irrigation, plant selection mainly depends on the substrate depth of the GR system (Oberndorfer et al., 2007; Dvorak & Volder, 2010; Thuring et al., 2010). In semi-arid regions, roofs with deeper substrate depths may be required, ranging from

15 cm for succulents to over 30 cm for grasses and herbs (Williams et al., 2010). However, in practice there is a trade-off between substrate depth and weight, as building structures often cannot support excessive weight loads (Benvenuti & Bacci, 2010; Nektarios et al., 2011; Blanusa et al., 2013). Inclusion of a light weight water retention layer (WRL), in which plant-available water is stored for a longer time period, could be an alternative, although the effects on plant performance are still underexplored (Dvorak & Volder, 2010; Williams et al., 2010).

In this study, the performance of preselected Mediterranean plant species was monitored on unirrigated EGRs in two different climates: the Mediterranean (Avignon, southern France) and temperate climate (Heverlee, Belgium). The effects of substrate depth, additional WRL and exposition on plant performance were analyzed. The study period was two years and was assumed appropriate as it is primary the recruitment and early establishment phase, where seed germination takes place, which is critical for GR health in the long term (cf. Getter & Rowe, 2008; Nagase & Dunnett, 2013). After germination, plant performance was further monitored during two years (encompassing the growing season and period after the summer dry season) to study the GR dynamics. If plants survive during these two years and consequently also in dry seasons on these EGRs, it can be assumed that the EGR will remain functional during its lifetime. The results will help to inspire GR installation in the Mediterranean area, as well as adjust GR design in temperate regions in the light of climate change.

2. Material and methods

2.1. Experimental setup

The experimental EGRs were installed on existing flat roofs in September 2012, one at the University of Leuven in Belgium (Heverlee, 50°51’47’’N, 4°40’28’’E) and another at the Avignon Institute of Technology in France (43°54’36’’N, 4°53’19’’E). On both roofs (Fig. 4.1), one EGR was installed on the fully exposed south-side of the roof, in terms of sun and wind, and another one on the sheltered north-part of the roof. The bitumen roof was first covered with a root resistant waterproofing layer, a polyethylene foil with a thickness of 0.5 mm and density over 0.93 g/cm³ (Sopranature WF 50, SOPREMA nv). Above this layer, a drainage board with filter layer was placed (IBIC Drain 200, IBIC bvba). The drainage layer consisted of styrene and served to drain the runoff from the EGR while also protecting the roof. The filter foil of non-woven polypropylene prevented dirt accumulation in the drainage layer. Both layers together had a thickness of 12 mm, dry weight of 1.2 kg/m² and a compressive strength of 712 kN/m². On top of these layers, a wooden frame of untreated spruce (30 x 150 mm) was placed to delimit the plots of 1 m² which were surrounded by a 20 cm wide border to eliminate edge effects. Each plot represented one of the three following structure types (Fig. 4.1): (5) 5 cm substrate; (P5) 5 cm and (P10) 10 cm substrate on a WRL (Polygrow PG D1, Recticel BV). Characteristics of the EGR substrate used (LP24GREXORG1, Peltracom n.v.) are listed in Table 4.1. The 4 cm thick Polygrow WRL consisted of polyurethane foam and had flexibility, high pore content (98%) and stable structure as its main properties. Furthermore, the material had a bulk density of only 35 kg/m³, did not react with nutrients, was clean, and could absorb water even after complete drying. Depending on the type, the approximate weight of the plots ranged from 50-100 kg/m² when dry to 71.5-143 kg/m² when water-saturated. In summary, the experiment involved three factors (location, exposition and structure type) resulting in 12 treatments, which were each replicated three times.

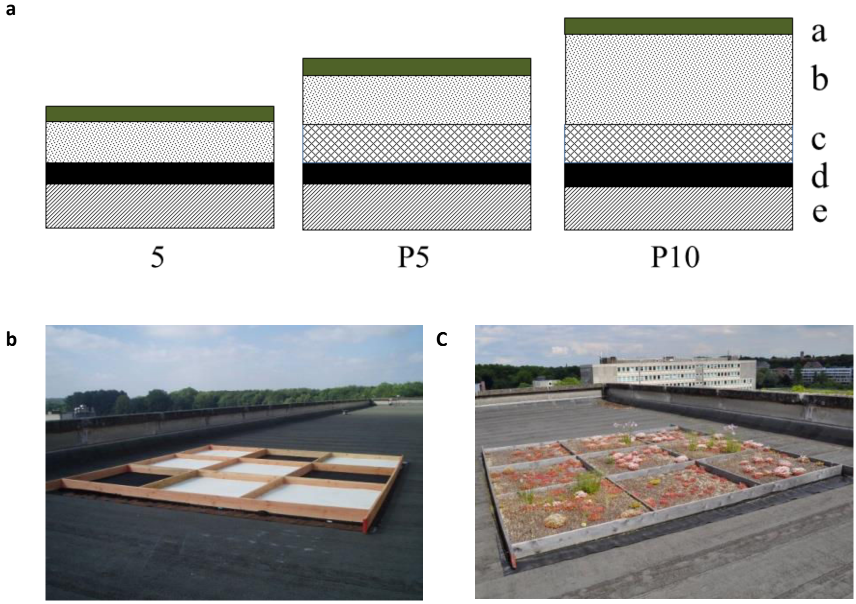

Fig. 4.1. Overview of the experimental setup. a: The three structure types of the experimental EGR. From left to right: (5) 5 cm substrate, no water retention layer (WRL); (P5) 5 cm substrate on a WRL; (P10) 10 cm substrate on WRL. a: vegetation layer; b: substrate layer; c: WRL; d: drainage + filter layer; e: roof deck covered with EPDM foil. b: EGR in Heverlee on exposed side of the roof, before addition of substrate and vegetation. In plots P5 and P10, the WRL (white) can be seen. c: Vegetation development on the same EGR during summer 2014 [Pictures: Carmen Van Mechelen, September 2012 and July 2014].

The used plants were a combination of species with different growth forms, selected after a vegetation survey and screening procedure in the French study region (cf. Chapter 2; Table 4.2). They were either novel or already used on GRs. Geophytes and succulents were pregrown in nurseries that were all located in southern France: Bulb d'Argence (Fourques), Pépinière Filippi (Mèze) and Pépinière Rouy (Saint Etienne du Grès). Seeds were supplied by B&T World seeds (Aigues-Vives, southern France), after collection in the country of origin. No information on region of provenance of the seeds was provided, but as all selected species naturally occur in the Mediterranean study region, and their chorology covers southern Europe, we believe the seeds were sufficiently adapted to the site conditions. Sowing of seeds and sprouts and planting of bulbs and rhizomes was done in October 2012. Sowing density of the plants applied as seeds was 5 g of seed mix per plot, in which approximately 150 seeds per species were present. This sowing density is in accordance with the FLL guidelines, which advise 5-10 g/m² (FLL, 2008), and is even higher than the sowing rates of 2 and 4 g/m² used by Nagase and Dunnett (2013a). Similar to Nagase and Dunnett (2013b), the geophytes *Allium sphaerocephalon* and *Iris lutescens* were planted at a density of 3 bulbs or rhizomes per plot. *Sedum spp.* were applied as sprouts at a density of 60 g/m², which is slightly higher than the sprout density of 30-50 g/m² advised by Kolb and Schwarz (1999). Prior to sowing on the experimental plots, the viability of the seeds was examined with a tetrazolium test (Baskin, 2001; see Appendix 4.1). The percentage of viable seeds ranged between 10 and 100%, but did not significantly affect the establishment, as shown by the non-significant Spearman rank correlation coefficients between % viable seeds and % germinated seeds during the first growing season (Appendix 4.1).

Table 4.1 Factory substrate specifications.

Peltracom LP24GREXORG1	FLL-norm	Analysis	Unit
Particle size distribution			
d ≤ 0.063mm	≤ 15	9	Weight %
d> 4mm	≤ 50	44	
Volume weight			
Dry	NA	1	g/cm³
Maximum water capacity	NA	1.43	g/cm³
Water/air distribution			
Total pore volume	35-65	62	Vol.-%
Maximum water capacity	≥ 10	42	Vol.-%
Air capacity at maximum water capacity	≥ 20	20	Vol.-%
Water permeability	0.6-70	27.9	mm/min
Chemical analysis			
pH ($CaCl_2$)	6.0-8.5	7.6	
Conductance	≤ 3.5	0.7	g>l
Organic material			
Organic material	≤ 65	32	g/l
Nutrients			
N	≤ 80	33	mg/l
P	≤ 200	180	mg/l
K	≤ 700	700	mg/l
M	≤ 200	120	mg/l

2.2. Monitoring

From September 2012 until November 2014, meteorological data, i.e. temperature (°C), precipitation (mm) and wind speed (m/s), were collected daily from nearby weather stations in Brussels (50°9'N; 4°53'E; elevation 58 m; 10 km from the study site in Heverlee) and Avignon-Caumont (43°9'N; 4°9'E; elevation 37 m; 1.5 km from the study site in Avignon). Temperature data and average wind speed, together with daily sunshine hours (derived from New_LocClim v1.10; Gommes et al., 2004; FAO,

2005) were imported in the program ETo Calculator (FAO, 2008) to calculate the reference evapotranspiration (ETo) using the FAO Penman-Monteith method. ETo and precipitation were plotted together with 0.5*ETo, which allowed determination of the summer drought period, i.e. when the precipitation bar drops below the 0.5* ETo curve (Fig. 4.2). To compare the ETo and precipitation during the study period with general local weather patterns, the average values for the period 1970-2000 from the FAO program New_LocClim were added to Fig. 4.2.

Plant performance surveys were done at seven moments: during the growing season (April, May and June 2013, and April and May 2014) and in autumn after summer drought (October 2013 and 2014). The cover of the total plot (overhead projection), the seeded species (categorized into annuals and herbs), the succulents *Sedum acre* and *S. album*, and bryophyte layer was estimated. The abundance in terms of number of individuals of the annual species, herbs and geophytes was recorded in each 1 m² plot as well. Also diversity in terms of species richness (SR) and Simpson diversity index (D_s; Eq. 1), which indicates the chance that two randomly selected individual plants belong to two different species, were calculated (Gotelli and Chao, 2013).

$$D_s = 1 - \sum_{i=1}^{SR} pi^{\,2} \qquad \text{(Eq. 1)}$$

In Eq.1, SR is the number of species present in the plot and p_i is the relative abundance of the *i*th species.

During the experimental period, some weeds established on the roof spontaneously (Appendix 4.2), of which the diversity measures SR and D were also calculated.

2.3. Data analysis

Cover data, abundance data and diversity measures were analyzed on four moments: the growing season and autumn period of 2013 and 2014, corresponding with monitoring periods 3, 4, 5 and 7. Because the data were nonlinear in time and did not meet the assumption of normality, distributions across the two locations were compared by means of Mann-Whitney U tests (MWU). For every location separately, differences in distribution between the two expositions and the three structure types were then examined with respectively MWU and Kruskal Wallis tests (KW). Furthermore, a Spearman rank correlation test (r_s) was performed to find relations between the bryophyte cover, the SR and D_s of the weeds and the other cover, abundance and diversity variables. The significance level was adjusted with a Bonferroni correction. All statistical tests were performed in SPSS 22.0 (SPSS Inc, Chicago, IL).

Finally, all the species were ranked according to their cover in the growing season and autumn period of 2013 and 2014 in both Avignon and Heverlee. Their relative cover was then calculated on a log-scale and the resulting rank-cover diagrams enable us to study the species composition development during the experimental period.

Table 4.2 List of species installed on the EGR, categorized according to their longevity and installation method. Pictures of the species can be found at the end of this chapter.

Scientific name	Common name	Chorology	Installed through	Current GR species
ANNUALS				
Alyssum alyssoides (L.) L.	Pale Madwort	Eurasia	Seeds [2]	no
Clinopodium acinos (L.) Kuntze	Basil Thyme	Europe	Seeds [2]	yes
Erophila verna (L.) DC.	Whitlow Grass	Eurasia	Seeds [2]	no
Lagurus ovatus L. *	Hare's-tail Grass	Mediterranean -Atlantic	Seeds [2]	yes
Linum bienne Mill.	Pale Flax	Mediterranean -Atlantic	Seeds [2]	no
Petrorhagia prolifera (L.) P.W.Ball and Heywood	Proliferous pink	Europe	Seeds [2]	no
Plantago afra L.	Black Psyllium	Mediterranean	Seeds [2]	no
Silene conica L.	Striated Catchfly	Eurasia	Seeds [2]	no
PERENNIALS				
Herbs				
Carthamus carduncellus L.	Distaff Thistle	Mediterranean	Seeds [2]	no
Dianthus superbus L.	Large Pink	Eurasia	Seeds [2]	no
Euphorbia cyparissias L.	Cypress Spurge	Eurasia	Seeds [2]	yes
Helianthemum nummularium (L.) Mill. **	Common Rockrose	Eurasia	Seeds [2]	yes
Lobularia maritima (L.) Desv.	Sweet Alyssum	Mediterranean	Seeds [2]	no
Sideritis hyssopifolia L.	Mountain Tea	S-European orophyte	Seeds [2]	no
Succulents				
Sedum acre L.	Biting Stonecrop	European	Sprouts [3]	yes
Sedum album L.	White Stonecrop	Eurasia	Sprouts [4]	yes
Geophytes				
Allium sphaerocephalon L.	Round-headed Leek	Eurasia	Bulbs [1]	yes
Iris lutescens (Lam.)	Crimean Iris	Mediterranean	Rhizomes [1]	no

Sources: (1) Bulb d'Argence; (2) BandT World seeds; (3) Pépinière Rouy; (4) pépinière Filippi
* grass species; ** evergreen shrub

3. Results

3.1. Climate data

The monitored precipitation patterns were rather divergent from the expected averages derived from the FAO (Fig. 4.2). Especially in Avignon, monthly precipitation was highly variable. The expected ETo derived from FAO followed the calculated ETo rather well in Avignon, but was approximately 0.5 mm/day lower during summer months in Heverlee. In Heverlee, the spring months of 2013 were very cold and dry, but the vegetation did not face summer drought. In contrast, the growing season of 2013 was characterized by a mild spring with plenty of rain in Avignon, followed by three months of summer drought. In 2014 however, little spring rains occurred in Avignon and summer drought started in March and lasted until the end of August. Also in Heverlee the start of the spring period was relatively dry with higher temperatures than usual but in May 2014 the average precipitation increased and July and August 2014 were even characterized by an exceptionally high amount of rain.

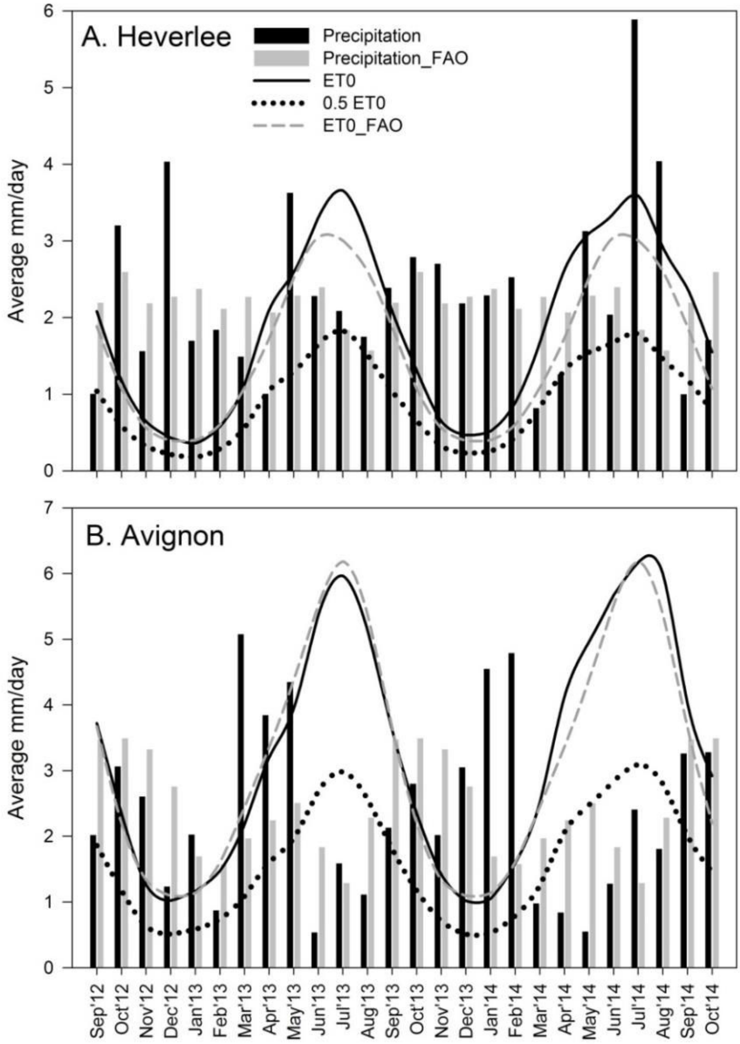

Fig. 4.2 Weather data for a) Heverlee and b) Avignon in terms of precipitation, reference evapotranspiration (ETo) and 0.5*ETo. For comparison, yearly averages for precipitation and ETo (grey bars and striped line) were derived from the FAO program New_LocClim.

3.2. General vegetation development

The total cover was significantly higher in Avignon compared to Heverlee in 2013, but was highest in Heverlee in 2014 (Table 4.3). Over the entire experiment, *S. acre* cover and the cover and abundance of annual species and herbs were significantly higher in Avignon compared to Heverlee. From the autumn of 2013 until the end of the experiment, *S. album* and bryophyte cover were significantly higher in Heverlee compared to Avignon. In 2014, the number of *I. lutescens* and *A. sphaerocephalon* were also highest in Heverlee.

In Avignon, the evolution in cover of the total plots, annual species, herbs, succulents and bryophytes was rather variable, with a pronounced increase in cover during the autumn periods after summer drought (monitoring times 4 and 7; Fig. 4.3a-f). The SR and D of the installed vegetation and the spontaneous colonized weeds were initially high but decreased over time and slightly increased again in autumn 2014 (Fig. 4.4a-d).

In Heverlee, total cover and *S. album* cover increased over time, but a decrease in *S. acre* cover was observed during 2014, and the cover values were much lower than those of *S. album* at the end of the experiment (on average 3% compared to 50%; Fig. 4.3a,d,e). Bryophyte establishment started in autumn 2013 and values up to 60% cover could be observed in sheltered plots with structure type 5 (Fig. 4.3f). The SR was initially low but increased over the growing season of 2013 after which it remained rather stable (Fig. 4.4a). Values for the D_s of the installed vegetation and the SR and D_s of the weeds were rather variable, with peaks observed during monitoring time 3 (Fig. 4.4b-d).

3.3. Exposition effect

For the majority of the monitoring periods and measured variables, no significant differences between exposed and sheltered plots could be detected. However, whenever significant, values for cover data, abundance data and diversity measures were generally higher in the sheltered plots in both locations (Table 4.4).

In Avignon, significantly higher values were found in the sheltered plots for the cover of *S. acre* over the entire experimental period, for the cover of *S. album* from autumn 2013 until the end of the experiment, and for the total cover during 2014 (Table 4.4a; Fig. 4.3d,e). The sheltered plots also resulted in higher abundance of herbs in the growing season of 2013, higher cover of annuals in growing season 2014, and higher cover of bryophytes and number of *I. lutescens* in autumn 2014. Only for the D_s of the weeds in growing season 2013 and the cover of the herbs in autumn 2014, the values were significant higher in the exposed plots.

In Heverlee, sheltered plots had significant higher values compared to the exposed ones for the following variables and periods (Table 4.4b): SR and D_s of the weeds in the growing season of 2013; *S. album* cover during 2013; bryophyte cover and number of *I. lutescens* during autumn 2013 and growing season 2014; total cover in the autumn periods of 2013 and 2014; D_s in the growing season of 2014.

Table 4.3 Mean values and standard errors for cover data, abundance data and diversity measures in Avignon and Heverlee in both the growing season and autumn period of 2013 and 2014. Significant differences between the locations are marked in grey and letters indicate the post-hoc results (Mann-Whitney U).

	Growing season 2013		**Autumn 2013**	
	Avignon	Heverlee	Avignon	Heverlee
Cover data				
Annuals	22.42 ± 2.9 b	3.03 ± 0.7 a	13.28 ± 1.5 b	1.50 ± 0.4 a
Herbs	10.17 ± 1.8 b	1.06 ± 0.2 a	48.06 ± 6.7 b	3.39 ± 0.7 a
S. acre	4.67 ± 0.4 b	1.61 ± 0.1 a	8.83 ± 1.2 b	4.06 ± 0.4 a
S. album	5.78 ± 0.5	7.11 ± 0.5	14.78 ± 2.7 a	28.44 ± 3.3 b
Bryophytes	0	0	0.42 ± 0.2 a	10.81 ± 3.1 b
Total	44.17 ± 4.5 b	13.61 ± 0.9 a	78.00 ± 4.9 b	41.83 ± 4.7 a
Abundance data				
Annuals	111.11 ± 8.0 b	12.50 ± 3.7 a	137.50 ± 14.8 b	28.39 ± 7.4 a
Herbs	58.17 ± 5.5 b	6.94 ± 1.7 a	285.17 ± 32.2 b	53.33 ± 10.5 a
Allium	2.61 ± 0.2	2.61 ± 0.2	2.61 ± 0.2	2.28 ± 0.2
Iris	2.56 ± 0.1	2.67 ± 0.1	2.33 ± 0.3	2.39 ± 0.2
Diversity measures				
SR	9.56 ± 0.2	8.83 ± 0.7	7.22 ± 0.2	7.22 ± 0.5
D_s	0.72 ± 0.0	0.61 ± 0.1	0.46 ± 0.0	0.45 ± 0.0
SR weeds	1.89 ± 0.3	2.22 ± 0.3	7.22 ± 0.2	7.22 ± 0.5
D_s weeds	0.31 ± 0.1	0.38 ± 0.1	0.11 ± 0.1	0
	Growing season 2014		Autumn 2014	
	Avignon	Heverlee	Avignon	Heverlee
Cover data				
Annuals	22.03 ± 5.0 b	8.22 ± 2.5 a	17.17 ± 3.2 b	0.72 ± 0.2 a
Herbs	1.33 ± 0.5	0.39 ± 0.2	6.56 ± 1.5 b	0.58 ± 0.2 a
S. acre	3.56 ± 0.7	3.50 ± 0.3	11.19 ± 2.5 b	2.33 ± 0.3 a
S. album	9.39 ± 2.5 a	34.44 ± 3.5 b	16.06 ± 5.0 a	51.67 ± 3.3 b
Bryophytes	0.17 ± 0.1 a	9.14 ± 3.5 b	8.78 ±2.4 a	28.11 ± 5.7 b
Total	32.50 ± 7.1 a	48.89 ± 5.5 b	61.11 ± 6.6 a	80.33 ± 3.3 b
Abundance data				
Annuals	127.33 ± 20.8 b	66.44 ± 12.7 a	212.39 ± 30.1 b	4.11 ± 1.6 a
Herbs	4.39 ± 1.8	6.56 ± 2.4	63.44 ± 11.4 b	6.44 ± 1.8 a
Allium	1.17 ± 0.3 a	2.56 ± 0.1 b	0.67 ± 0.2	0.22 ± 0.1
Iris	1.28 ± 0.3 a	2.39 ± 0.2 b	1.17 ± 0.3 a	2.22 ± 0.2 b
Diversity measures				
SR	6.39 ± 0.5	7.28 ± 0.4	6.44 ± 0.3	6.06 ± 0.8
D_s	0.39 ± 0.1	0.40 ± 0.1	0.48 ± 0.0	0.45 ± 0.1
SR weeds	0.50 ± 0.2	0.61 ± 0.2	0.72 ± 0.3	0.72 ± 0.3
D_s weeds	0.07 ± 0.1	0.11 ± 0.1	0.30 ± 0.2	0.53 ± 0.2

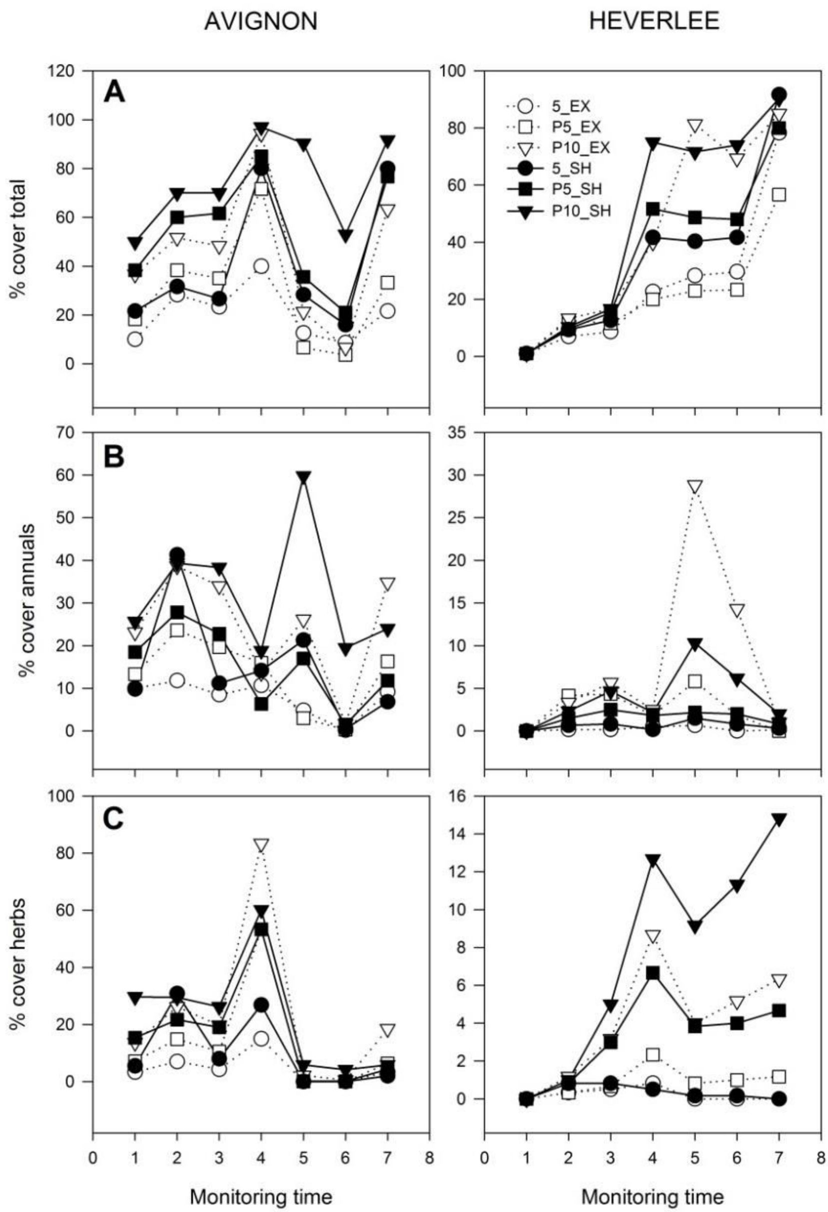

Fig. 4.3 Evolution in cover data in Avignon and Heverlee over the 7 monitoring periods. Percentage cover is given for a) the total plot; b) annual species; c) perennial herbs. Structure types 5, P5 and P10 are represented by different symbols and are either uncolored (exposed plots, dotted lines) or black (sheltered plots; full lines).

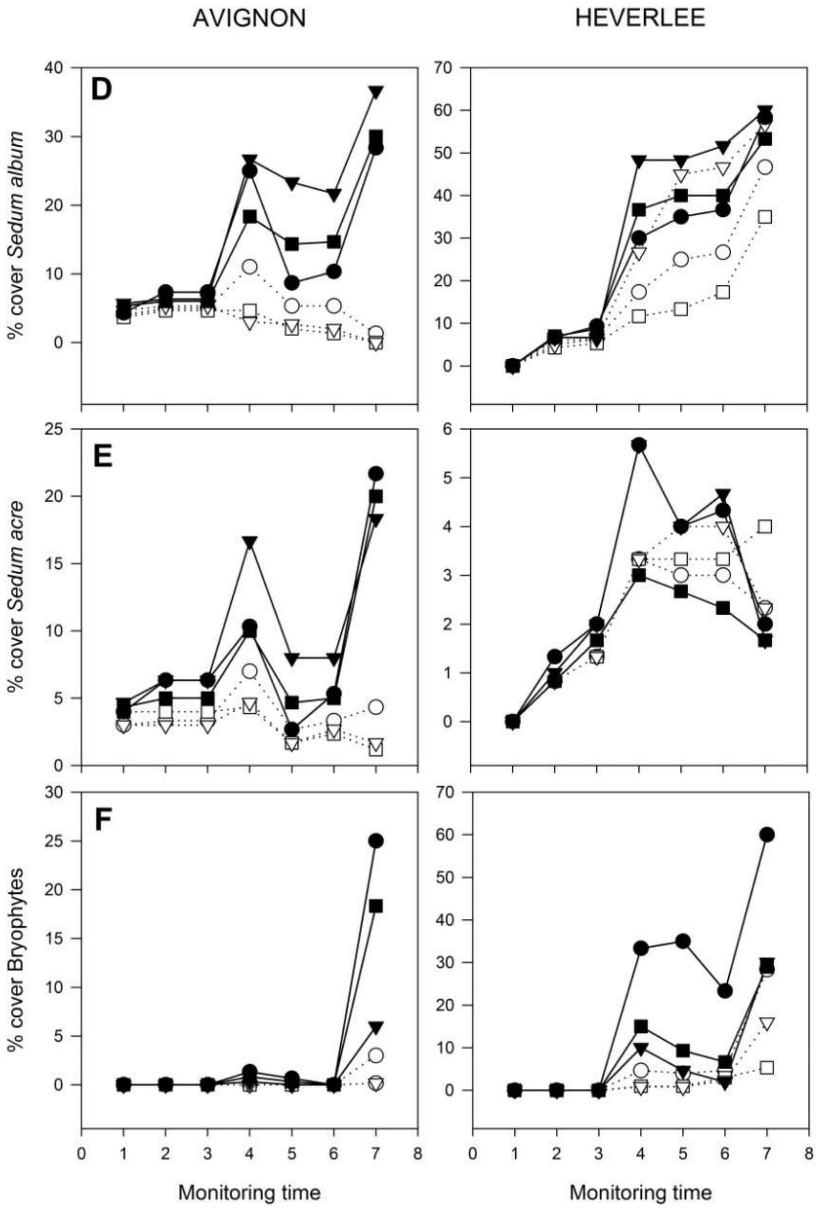

Fig. 4.3 Continued. d) *Sedum album*; e) *Sedum acre*; f) bryophytes. Structure types 5, P5 and P10 are represented by different symbols and are either uncolored (exposed plots, dotted lines) or black (sheltered plots; full lines).

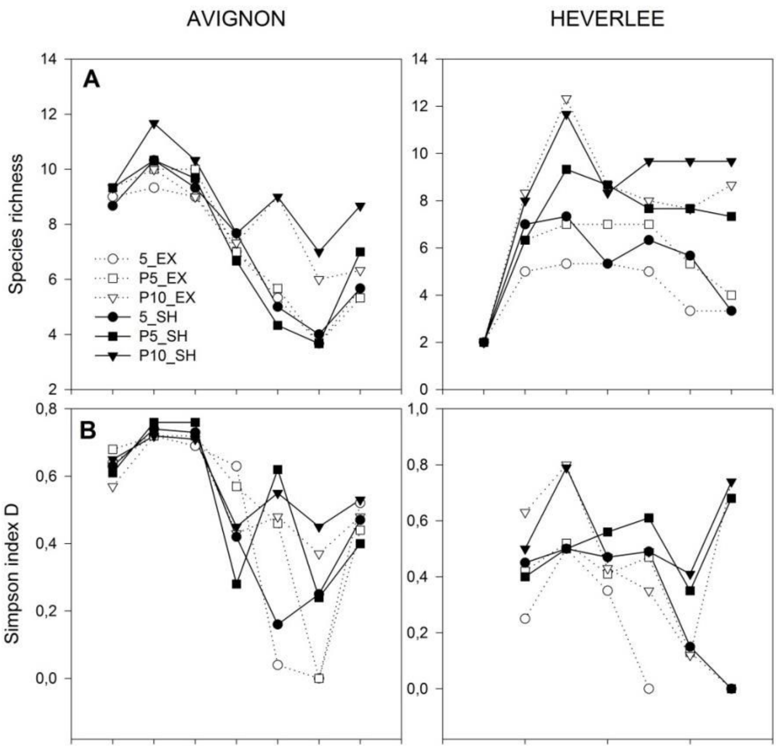

Fig. 4.4 Evolution in diversity measures in Avignon and Heverlee over the 7 monitoring periods. Information is given for a) Species richness SR and b) Simpson index D_s of the installed vegetation; c) SR and d) D_s of the spontaneously colonized weeds. Structure types 5, P5 and P10 are represented by different symbols and are either uncolored (exposed plots, dotted lines) or black (sheltered plots, full lines).

3.4. Structure type effect

Considering the structure types, the highest values were generally found in structure type P10, followed by P5, and lowest values were obtained in structure type 5 (Table 4.5).

In Avignon, some deviations from the general trend were observed. In the growing season of 2014 for example, the structure type P10 was significantly higher compared to both 5 and P5 for the abundance of annual species, the abundance and cover of herbs, and the SR and D_s. This was also the case for the total cover in autumn 2013. Structure type P5 had the lowest values for the cover of annual species in the growing season of 2014.

For Heverlee, following deviations from the general pattern were found. Structure types P5 and P10 were both significantly higher than structure type 5 for the number of *A. sphaerocephalon* in the growing season of 2013 and for SR in autumn 2013. Structure type P10 was significant higher compared to both 5 and P5 for the total cover in growing season 2014 and the D_s of the weeds in autumn 2014. Structure type P5 had the lowest values for *S. album* cover in the growing season of 2014 and both the total cover and SR of the weeds during autumn 2014. Finally, the cover and abundance of annual species were highest in structure type P5 during autumn 2013, and the bryophyte cover was highest in structure type 5 during 2014.

Table 4.4 Mean values and standard errors for cover data, abundance data and diversity measures in the exposed and sheltered plots of a) Avignon and b) Heverlee in both the growing season and autumn period of 2013 and 2014. Significant differences between the expositions are marked in grey and letters indicate the post-hoc results (Mann-Whitney U).

a) AVIGNON	**Growing season 2013**		**Autumn 2013**	
	Sheltered	Exposed	Sheltered	Exposed
Cover data				
Annuals	24.11 ± 4.3	24.72 ± 4.1	13.11 ± 2.7	13.44 ± 1.5
Herbs	11.72 ± 2.6	8.61 ± 2.5	45.56 ± 8.2	50.55 ± 11.1
Sedum acre	5.89 ± 0.5 b	3.44 ± 0.3 a	12.33 ± 1.6 b	5.33 ± 0.6 a
Sedum album	6.56 ± 0.9	5.00 ± 0.5	23.33 ± 3.3 b	6.22 ± 1.5 a
Bryophytes	0	0	0.83 ± 0.4	0
Total	52.78 ± 7.2	35.56 ± 3.8	87.33 ± 2.7	68.67 ± 8.5
Abundance data				
Annuals	115.56 ± 10.9	106.7 ± 12	124.8 ± 26	150.2 ± 14.4
Herbs	70.67 ± 6.4 b	45.7 ± 6.9 a	337 ± 43.0	233.3 ± 43.3
Allium	2.55 ± 0.3	2.67 ± 0.2	2.78 ± 0.2	2.44 ± 0.3
Iris	2.33 ± 0.2	2.78 ± 0.2	2.22 ± 0.4	2.44 ± 0.4
Diversity measures				
SR	9.78 ± 0.2	9.33 ± 0.2	7.33 ± 0.3	7.11 ± 0.2
SR weeds	1.56 ± 0.2	2.22 ± 0.6	0.67 ± 0.2	0.56 ± 0.2
D_s	0.73 ± 0.0	0.71 ± 0.0	0.38 ± 0.1	0.54 ± 0.0
D_s weeds	0.19 ± 0.1 a	0.46 ± 0.1 b	0.1 ± 0.1	0.12 ± 0.1
	Growing season 2014		Autumn 2014	
	Sheltered	Exposed	Sheltered	Exposed
Cover data				
Annuals	32.72 ± 7.7 b	11.3 ± 3.9 a	14.22 ± 3.4	20.11 ± 5.6
Herbs	1.94 ± 0.9	0.72 ± 0.4	3.78 ± 1.0 a	9.33 ± 2.7 b
Sedum acre	5.11 ± 1.1 b	2.00 ± 0.3 a	20.00 ± 2.5 b	2.39 ± 0.7 a
Sedum album	15.44 ± 4.0 b	3.33 ± 0.6 a	31.67 ± 6.6 b	0.44 ± 0.3 a
Bryophytes	0.33 ± 0.2	0	16.44 ± 3.1 b	1.11 ± 0.7 a
Total	51.44 ± 10.8 b	13.6 ± 2.8 a	82.78 ± 3.2 b	39.44 ± 7.5 a
Abundance data				
Annuals	161.33 ± 26.9	93.3 ± 28.6	197.2 ± 30.3	227.6 ± 53.7
Herbs	7.00 ± 3.4	1.78 ± 1.0	41.78 ± 7.5	85.11 ± 19.4
Allium	1.11 ± 0.5	1.22 ± 0.2	0.44 ± 0.2	0.89 ± 0.4
Iris	0.56 ± 0.2 a	2.00 ± 0.3 b	1.89 ± 0.4 b	0.44 ± 0.2 a
Diversity measures				
SR	6.11 ± 0.8	6.67 ± 0.6	7.11 ± 0.5	5.78 ± 0.3
SR weeds	0.67 ± 0.3	0.33 ± 0.2	1.11 ± 0.5	0.33 ± 0.2
D_s	0.45 ± 0.1	0.32 ± 0.1	0.47 ± 0.0	0.48 ± 0.0
D_s weeds	0.12 ± 0.1	0	0.53 ± 0.2	0

Table 4.4 Continued

b) HEVERLEE	**Growing season 2013**		**Autumn 2013**	
	Sheltered	Exposed	Sheltered	Exposed
Cover data				
Annuals	2.67 ± 1.0	3.39 ± 1.1	1.39 ± 0.7	1.61 ± 0.4
Herbs	1.5 ± 0.3	0.61 ± 0.2	2.89 ± 1.1	2.89 ± 0.9
Sedum acre	1.89 ± 0.2	1.33 ± 0.2	4.78 ± 0.6	3.33 ± 0.3
Sedum album	8.22 ± 0.6 b	6.00 ± 0.7 a	38.33 ± 3.6 b	18.56 ± 3.1 a
Bryophytes	0	0	19.44 ± 4.5 b	2.17 ± 0.7 a
Total	14.89 ± 0.9	12.33 ± 1.5	56.11 ± 5.3 b	27.56 ± 3.8 a
Abundance data				
Annuals	13.44 ± 16.7	11.56 ± 3.8	19.44 ± 8.8	37.33 ± 11.7
Herbs	10.00 ± 2.8	3.89 ± 1.3	44.67 ± 15.9	62.00 ± 14.1
Allium	2.78 ± 0.1	2.44 ± 0.3	2.78 ± 0.2	1.78 ± 0.4
Iris	2.89 ± 0.1	2.44 ± 0.2	2.89 ± 0.1 b	1.89 ± 0.4 a
Diversity measures				
SR	9.44 ± 1.0	8.22 ± 1.1	7.44 ± 0.8	7.00 ± 0.6
SR weeds	3.11 ± 0.5 b	1.33 ± 0.3 a	0.33 ± 0.2	0.33 ± 0.2
D_s	0.60 ± 0.1	0.62 ± 0.1	0.51 ± 0.1	0.40 ± 0.1
D_s weeds	0.55 ± 0.1 b	0.17 ± 0.1 a	0	0
	Growing season 2014		Autumn 2014	
	Sheltered	Exposed	Sheltered	Exposed
Cover data				
Annuals	4.67 ± 1.8	11.78 ± 4.4	1.06 ± 0.4	0.34 ± 0.2
Herbs	0.72 ± 0.3	0.06 ± 0.1	0.89 ± 0.4	0.28 ± 0.2
Sedum acre	3.56 ± 0.4	3.44 ± 0.3	1.78 ± 0.2	2.89 ± 0.4
Sedum album	41.11 ± 3.2	27.78 ± 5.4	57.22 ± 4.3	46.11 ± 4.4
Bryophytes	16.33 ± 6.2 b	1.94 ± 0.6 a	39.67 ± 9.3	16.56 ± 4.2
Total	53.56 ± 5.6	44.22 ± 9.7	87.33 ± 2.3 b	73.33 ± 5.3 a
Abundance data				
Annuals	54.56 ± 16.6	78.33 ± 19.4	6.44 ± 3.0	1.78 ± 1.0
Herbs	11.44 ± 4.3	1.67 ± 0.7	8.89 ± 3.1	4.00 ± 1.8
Allium	2.56 ± 0.2	2.56 ± 0.2	0.11 ± 0.1	0.33 ± 0.2
Iris	2.89 ± 0.1 b	1.89 ± 0.4 a	2.67 ± 0.2	1.78 ± 0.3
Diversity measures				
SR	7.89 ± 0.6	6.67 ± 0.6	6.78 ± 1.2	5.33 ± 0.9
SR weeds	1.00 ± 0.3	0.22 ± 0.2	1.11 ± 0.5	0.33 ± 0.2
D_s	0.53 ± 0.0 b	0.27 ± 0.1 a	0.60 ± 0.1	0.32 ± 0.2
D_s weeds	0.14 ± 0.1	0.0 ± 0.0	0.70 ± 0.3	0.19 ± 0.2

3.5. Species-specific performance

Fig. 4.5 shows the rank-cover distributions of the installed species in the two locations for the growing season and autumn period of 2013 and 2014. For the relative cover data for every species under the different treatments over the seven monitoring periods we refer to Appendix 4.3. *S. album* and *S. acre* were always part of the dominant species in both locations on all monitoring moments. Next to those succulent species, *Silene conica* and *Lobularia maritima* were the species with the highest cover in Avignon in the growing season of 2013, followed by *Alyssum alyssoides*, *Dianthus superbus* and *Lagurus ovatus.* In Heverlee, high cover values were found for *I. lutescens, A. sphaerocephalon* and *A. alyssoides.* In the autumn of 2013, the SR decreased in Avignon from maximum 11 to 10 species and in Heverlee from maximum 14 to 12 species (Fig. 4.5a). In Avignon *L. maritima* became very dominant together with *S. album*, which resulted in steeper lines in Fig. 4.5a. There was also a high cover compared to the other species of *L. ovatus* and *A. alyssoides* in Avignon and *L. maritima, I. lutescens* and *A. sphaerocephalon* in Heverlee. In the second growing season, the maximum SR increased to 11 in Avignon but decreased to 11 in Heverlee (Fig. 4.5b). *S. conica* became the dominant species again in Avignon, followed by *L.ovatus* and the succulents. In Heverlee, besides the succulents, *S. conica, A. sphaerocephalon, I. lutescens* and *D. superbus* covered a high portion of the plots as well. In autumn 2014, the SR decreased in Avignon to a maximum of 10 species and increased in Heverlee to a maximum of 12 species. Together with the succulents, *S. conica* remained the dominant species in Avignon, followed by *L. maritima*. In Heverlee, *D. superbus* and *I. lutescens* had the highest average cover values next to the succulents.

Over the entire experimental period, 33 species colonized spontaneously in the 1 m² plots, of which 18 in Avignon and 13 in Heverlee (Appendix 4.2). In general, most abundant weeds were the phanerophyte *Celtis australis* and the annuals *Erigeron canadensis* and *Veronica arvensis* in Avignon. *E. canadensis* was also the most abundant weed in Heverlee, followed by *Acer pseudoplatanus* and *Cerastium fontanum* subsp. *vulgare.* When a species was present in 2013 and 2014, it was not the same individual plant, as the colonized weeds from 2013 died rather quickly when a hot-dry or cold-wet period started. The SR of weeds in both locations was positively correlated with the cover and abundance of annual species and herbs in the plots, but not with the cover of succulent species (Table 4.6). The SR of the weeds was also positively correlated with the SR and D_s of the installed vegetation. In Avignon, the bryophyte cover was negatively correlated with the SR and D_s of the installed vegetation. In both locations, a positive correlation was found between bryophyte cover and the total cover and cover of *S. album* and *S. acre*.

Table 4.5 Mean values and standard errors for cover data, abundance data and diversity measures in the structure types 5, P5 and P10 in a) Avignon and b) Heverlee in both the growing season and autumn period of 2013 and 2014. Significant differences between the structure types are marked in grey and letters indicate the post-hoc results (Kruskal Wallis).

a) AVIGNON	**Growing season 2013**			**Autumn 2013**		
	5	P5	P10	5	P5	P10
Cover data						
Annuals	9.83 ± 0.8 a	21.25 ± 2.6 ab	36.17 ± 3.1 b	12.42 ± 2.6	11.17 ± 3.0	16.25 ± 2.0
Herbs	3.33 ± 0.4 a	10.25 ± 2.6 ab	16.92 ± 2.7 b	20.83 ± 4.4 a	53.33 ± 9.2 ab	70.00 ± 10.3 b
Sedum acre	4.83 ± 0.8	4.50 ± 0.6	4.67 ± 0.9	8.67 ± 1.5	7.17 ± 1.3	10.67 ± 3.1
Sedum album	6.17 ± 0.7	5.33 ± 1.0	5.83 ± 1.1	18.00 ± 3.3	11.50 ± 4.9	14.83 ± 6.1
Bryophytes	0	0	0	0.67 ± 0.5	0.42 ± 0.3	0.17 ± 0.2
Total	25.00 ± 1.3 a	48.33 ± 6.9 b	59.17 ± 5.5 b	60.00 ± 9.0 a	78.33 ± 5.7 a	95.67 ± 1.3 b
Abundance data						
Annuals	77.67 ± 6.1 a	113 ± 10.1 ab	142.67 ± 9.7 b	138.50 ± 28.8	126.67 ± 30.8	147.33 ± 20.1
Herbs	40.00 ± 8.9	62.67 ± 7.1	71.83 ± 8.4	175.17 ± 31.1 a	291.67 ± 49 ab	388.67 ± 51 b
Allium	1.83 ± 0.4	3.00 ± 0.0	3.00 ± 0.0	3.00 ± 0.0	2.00 ± 0.5	2.83 ± 0.2
Iris	2.17 ± 0.3	2.67 ± 0.2	2.83 ± 0.2	3.00 ± 0.0	2.00 ± 0.5	2.00 ± 0.6
Diversity measures						
SR	9.17 ± 0.2	9.83 ± 0.3	9.67 ± 0.3	7.33 ± 0.3	6.83 ± 0.2	7.50 ± 0.3
SR weeds	0.67 ± 0.2 a	2.67 ± 0.7 b	2.33 ± 0.4 b	0.50 ± 0.2	0.33 ± 0.2	1.00 ± 0.4
D_s	0.71 ± 0.0	0.74 ± 0.0	0.71 ± 0.0	0.52 ± 0.1	0.43 ± 0.1	0.44 ± 0.1
D_s weeds	0 a	0.44 ± 0.1 b	0.39 ± 0.1 b	0	0	0.25 ± 0.1
	Growing season 2014			Autumn 2014		
	5	P5	P10	5	P5	P10
Cover data						
Annuals	13.08 ± 5.5 ab	10.00 ± 4.4 a	43.00 ± 8.2 b	8.00 ± 0.7 a	14.08 ± 2.7 ab	29.42 ± 7.0 b
Herbs	0.00 ± 0.0 a	0.08 ± 0.1 a	3.92 ± 0.9 b	2.67 ± 0.3	5.33 ± 1.1	11.67 ± 3.7
Sedum acre	2.67 ± 0.4	3.17 ± 1.1	4.83 ± 1.7	13.00 ± 4.4	10.58 ± 5.0	10.00 ± 4.2
Sedum album	7.00 ± 0.9	8.17 ± 4.5	13.00 ± 6.1	14.83 ± 6.2	15.00 ± 8.1	18.33 ± 12.0
Bryophytes	0.33 ± 0.2	0.17 ± 0.2	0	14.00 ± 5.1	9.25 ± 4.3	3.08 ± 1.4
Total	20.50 ± 4.6	21.17 ± 8.8	55.83 ± 15.8	50.83 ± 13.1	55.00 ± 10.9	77.50 ± 8.4
Abundance data						
Annuals	79.00 ± 24.7 a	80.00 ± 28.6 a	223.00 ± 15 b	109.67 ± 5.9 a	214.8 ± 34.4 ab	312.67 ± 63 b
Herbs	0 a	0.17 ± 0.2 a	13.00 ± 3.5 b	30.83 ± 4.7 a	58.33 ± 10.5 ab	101.17 ± 26 b
Allium	1.33 ± 0.4	0.50 ± 0.3	1.67 ± 0.5	0	0.67 ± 0.3	1.33 ± 0.6
Iris	1.83 ± 0.5	0.83 ± 0.4	1.17 ± 0.5	0.50 ± 0.3 a	0.83 ± 0.4 ab	2.17 ± 0.4 b
Diversity measures						
SR	5.17 ± 0.3 a	5.00 ± 0.4 a	9.00 ± 0.5 b	5.67 ± 0.2 a	6.17 ± 0.5 ab	7.50 ± 0.6 b
SR weeds	0 a	0.33 ± 0.2 ab	1.17 ± 0.3 b	0 a	0.33 ± 0.2 ab	1.83 ± 0.5 b
D_s	0.10 ± 0.1 a	0.54 ± 0.1 b	0.52 ± 0.0 b	0.50 ± 0.0	0.42 ± 0.0	0.51 ± 0.1
D_s weeds	NA	0	0.10 ± 0.1	NA	0	0.43 ± 0.2

Table 4.5 Continued

b) HEVERLEE		**Growing season 2013**			**Autumn 2013**	
	5	P5	P10	5	P5	P10
Cover data						
Annuals	0.50 ± 0.3 a	3.42 ± 1.1ab	5.17 ± 1.2 b	0.33 ± 0.1 a	1.83 ± 0.4 b	2.33 ± 0.9 ab
Herbs	0.50 ± 0.1 a	0.83 ± 0.3 ab	1.83 ± 0.3 b	0.58 ± 0.2 a	3.00 ± 0.8 ab	6.58 ± 0.7 b
Sedum acre	1.67 ± 0.2	1.50 ± 0.2	1.67 ± 0.3	4.50 ± 0.6	3.17 ± 0.3	4.50 ± 0.9
Sedum album	7.83 ± 1.2	7.00 ± 0.9	6.50 ± 0.6	23.67 ± 4.3	24.17 ± 6.4	37.50 ± 5.4
Bryophytes	0	0	0	19.00 ± 7.5	8.00 ± 3.4	5.42 ± 2.4
Total	10.67 ± 1.4 a	13.50 ± 1.4 ab	16.67 ± 1.1 b	32.17 ± 5.5	35.83 ± 7.5	57.50 ± 7.9
Abundance data						
Annuals	1.67 ± 1.0 a	9.83 ± 2.3 ab	26.00 ± 8.7 b	5.50 ± 2.1 a	47.33 ± 15.2 b	32.33 ± 12.1 ab
Herbs	1.50 ± 0.4 a	5.50 ± 2.4 ab	13.83 ± 2.5 b	18.67 ± 9.0 a	47.17 ± 12.8 ab	94.17 ± 17.3 b
Allium	2.00 ± 0.4 a	2.83 ± 0.2 ab	3.00 ± 0.0 b	1.67 ± 0.6	2.50 ± 0.3	2.67 ± 0.2
Iris	2.83 ± 0.2	2.33 ± 0.2	2.83 ± 0.2	2.67 ± 0.3	1.83 ± 0.5	2.67 ± 0.2
Diversity measures						
SR	6.33 ± 0.8 a	8.17 ± 1.2 ab	12.00 ± 0.4 b	5.33 ± 0.3 a	7.83 ± 0.7 b	8.50 ± 0.7 b
SR weeds	1.67 ± 0.6	1.83 ± 0.4	3.17 ± 0.7	0.17 ± 0.2	0.33 ± 0.2	0.50 ± 0.2
D_s	0.50 ± 0.1 a	0.51 ± 0.1 ab	0.80 ± 0.0 b	0.40 ± 0.1	0.49 ± 0.1	0.45 ± 0.1
D_s weeds	0.55 ± 0.1	0.26 ± 0.1	0.40 ± 0.1	0	0	0
		Growing season 2014			Autumn 2014	
	5	P5	P10	5	P5	P10
Cover data						
Annuals	1.08 ± 0.2 a	4.00 ± 1.4 ab	19.58 ± 4.5 b	0.25 ± 0.2 a	0.42 ± 0.3 ab	1.50 ± 0.5 b
Herbs	0	0.58 ± 0.3	0.58 ± 0.3	0 a	0.50 ± 0.3 ab	1.25 ± 0.4 b
Sedum acre	3.50 ± 0.3	3.00 ± 0.4	4.00 ± 0.6	2.17 ± 0.4	2.83 ± 0.7	2.00 ± 0.3
Sedum album	30.0 ± 5.0 ab	26.67 ± 6.7 a	46.67 ± 2.5 b	52.50 ± 5.4	44.17 ± 4.9	58.33 ± 5.9
Bryophytes	19.50 ± 8.9 b	5.17 ± 3.1 ab	2.75 ± 1.5 a	44.17 ± 10.4 b	17.17 ± 8.9 a	23.00 ± 7.8 ab
Total	34.33 ± 5.2 a	35.83 ± 7.1 a	76.50 ± 2.4 b	85.00 ± 4.1 ab	68.33 ± 6.7 a	87.67 ± 1.9 b
Abundance data						
Annuals	17.50 ± 4.8 a	65.50 ± 21.3 ab	116.33 ± 14.0 b	1.50 ± 1.3 a	1.50 ± 1.1 ab	9.33 ± 4.0 b
Herbs	0.17 ± 0.2 a	7.67 ± 5.1 ab	11.83 ± 4.4 b	0 a	5.17 ± 2.9 ab	14.17 ± 2.4 b
Allium	2.17 ± 0.3	2.67 ± 0.2	2.83 ± 0.2	0	0.33 ± 0.2	0.33 ± 0.3
Iris	2.67 ± 0.3	1.83 ± 0.5	2.67 ± 0.2	2.33 ± 0.3 ab	1.67 ± 0.5 a	2.67 ± 0.2 b
Diversity measures						
SR	5.67 ± 0.3 a	7.33 ± 0.7 ab	8.83 ± 0.4 b	3.33 ± 0.2 a	5.67 ± 1.3 ab	9.17 ± 0.8 b
SR weeds	0.67 ± 0.5	0.50 ± 0.2	0.67 ± 0.3	0.17 ± 0.2 ab	0 a	2.00 ± 0.6 b
D_s	0.24 ± 0.1	0.53 ± 0.1	0.42 ± 0.1	0 a	0.27 ± 0.2 a	0.74 ± 0.0 b
D_s weeds	0.20 ± 0.2	0	0.15 ± 0.1	0	NA	0.63 ± 0.3

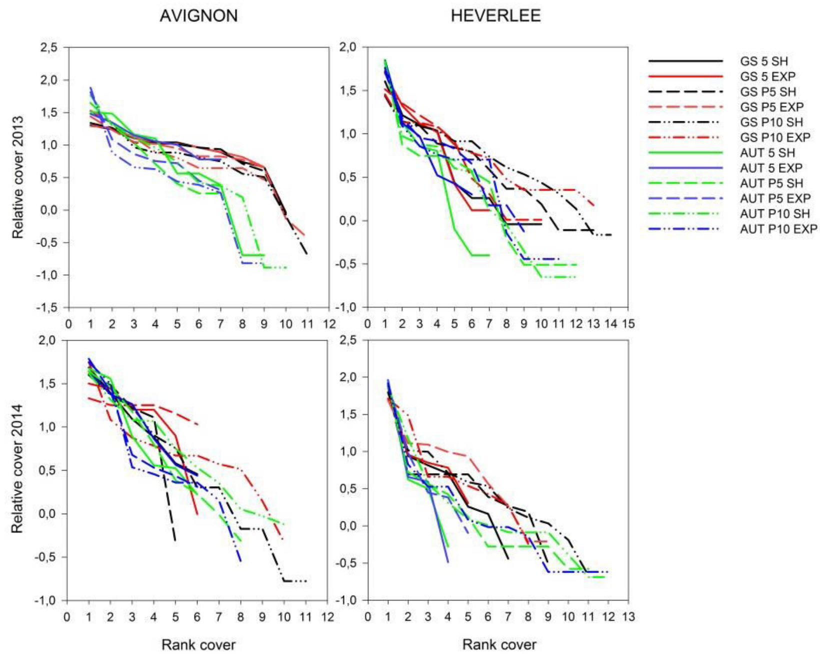

Fig. 4.5 Rank cover diagram of the species in Avignon and Heverlee for a) 2013 and b) 2014. Expositions and structure types 5, P5 and P10 are represented by line types in different colors. Both species present during the growing season (GS) and in autumn (AUT) were considered. Relative species cover is represented on a log-scale.

Table 4.6 Spearman rank correlation coefficients and significance between the bryophyte cover, the SR and D of the weeds, and the cover data, abundance data and diversity measures. (*: p < 0.004; **: p < 0.001; NS: not significant; NA: not applicable).

	AVIGNON			HEVERLEE		
	Cover bryophytes (N=126)	SR weeds (N=126)	D_s weeds (N=76)	Cover bryophytes (N=126)	SR weeds (N=126)	D_s weeds (N=76)
Cover data						
Annuals	-0.45	0.55**	0.19	0.06	0.44**	-0.17
Herbs	-0.45	0.47**	0.07	0.14	0.35**	0.21
Sedum acre	0.37**	0.03	-0.07	0.66**	0.06	-0.11
Sedum album	0.34**	-0.03	0.06	0.83**	0.07	-0.05
Bryophytes	NA	-0.23	-0.16	NA	-0.08	-0.16
Total	0.35**	0.25	-0.15	0.82**	0.13	-0.07
Abundance data						
Annuals	0.19	0.30*	0.08	0.21	0.32**	-0.24
Herbs	0.11	0.34**	-0.09	0.17	0.38**	-0.01
Diversity measures						
SR	-0.27*	0.77**	0.36*	0.11	0.58**	0.16
SR weeds	-0.23	NA	0.83**	-0.08	NA	0.99**
D_s	-0.35**	0.62**	0.32*	-0.13	0.47**	0.35
D_s weeds	-0.16	0.83**	NA	-0.16	0.99**	NA

4. Discussion

4.1. EGR performance

As expected, the vegetation developed differently in both locations, which can be attributed to the differences in weather conditions. The effects of summer drought, spring and autumn rains are expressed in the cover data graphs of Avignon (Fig. 4.3). The growing season of 2013 was favorable for germination and plant growth in Avignon (especially the annuals and herbs), whereas in Heverlee the vegetation only started to develop in May. No summer drought occurred in Heverlee, hence allowing the vegetation to grow further during the summer months while the vegetation in Avignon dried out. The 2013 autumn rainfall in Avignon led to a germination boom of seeds originating from the wilted plants from the first growing season. The winter and subsequently dry second growing season did not allow survival of most of these plants and the vegetation started to wilt early in 2014. Also in Heverlee, the first spring months were relatively dry, but vegetation (especially *S. album* and bryophytes), developed further after the precipitation events in May, resulting in a higher total cover in Heverlee in 2014 compared to Avignon. However, in Avignon, there was a general decrease in SR and D_s after the first growing season (Fig. 4.4), a trend which has also been observed in a study of Dunnett et al. (2008). This trend was most remarkable in Avignon, where some species (first *L. maritima* and in 2014 *S. conica* and *L. ovatus*) became dominant. As weather conditions vary from year to year and EGRs are dynamic systems, we expect for the following years that the vegetation will behave similar like the past two years, which were already quit contrasting. A further monitoring could of course add extra detail to the future development of the installed plant communities.

Whenever significant, the performance of the EGRs was generally better in the sheltered plots. Total cover for example was significantly higher when sheltered in both locations. Also cover of the succulents in Avignon and cover of *S.album* and bryophytes in Heverlee were higher in the sheltered plots. The plants take advantage of the increased humidity after summer drought and the less elevated temperatures in the sheltered exposition. In contrast, the D_s of the weeds was higher in the exposed plots in the first growing season in Avignon, which could be due to the low cover of the plots together with mild weather conditions which favor the installation of ruderal species.

The factor structure type had a more pronounced effect on the EGR performance than the factor exposition, as a higher number of significant differences in distribution were found. Throughout the course of the experiment, the EGRs generally performed best under structure type P10. Structure type 5 generally had the lowest cover, abundance and diversity values, but in some cases there was a shift where the lowest values could be attributed to P5. Therefore, deeper substrates (min 10 cm) together with an additional WRL are preferred for EGRs in any climate. Using substrate depths of 5 cm or less without a WRL or provision of an irrigation system is not advised, at least not for the species tested in this study, if good performance and biodiversity value of EGRs need to be ensured. Other studies focusing on EGRs in semi-arid climates (Benvenuti & Bacci, 2010; Thuring et al., 2010; Williams et al., 2010), come to the same conclusion.

Next to an additional WRL, which proved a useful addition to the EGR setup in this experiment, bryophytes have been suggested to carry out this function (Anderson et al., 2010). Although the bryophyte layer was considered as a whole in this experiment, it was noticed that most of them were acrocarps and that multiple species were present in the layer, e.g. Silky Forklet-moss (*Dicranella heteromalla (Hedw.) Schimp*.), Redshank (*Ceratodon purpureus (Hedw.) Brid.),* and Umbrella liverwort (*Marchantia polymorpha L*.). The very wet summer of 2014 in Heverlee favored the establishment and growth of bryophytes, where the highest cover was reached in structure type 5. This could be explained by a stronger competition effect in the P5 and P10 plots due to higher vascular plant cover. Bryophytes are also poikilohydric and their water content hence depends on the water potential of their environment. It could hence be possible that the WRL in P5 and P10 resulted in quicker water flow to deeper layers, whereas the water remained at the surface of the shallowest substrate where it favored bryophyte establishment. Indeed, compared to P5 and P10, the substrate surface of structure type 5 generally seemed to remain moist over a longer time period after rainfall. Furthermore, there was a positive correlation with the cover of succulents, which also benefit of superficial substrate moisture. However, in Avignon, bryophyte cover was negatively correlated with the SR and D_s of the plot, hence indicating that bryophyte establishment is less likely when the biodiversity of the EGR is high. Regardless of the exposition and structure type effects, bryophytes need to be able to establish and develop spontaneously, which was counteracted on EGRs in the Mediterranean and on exposed EGRs in temperate climates mainly due to climatic conditions. Therefore, if bryophytes are not considered as a part of the vegetation composition from the beginning of an EGR project, the use of a WRL like polyurethane foam is recommended instead.

Next to bryophytes, 33 weedy species also colonized spontaneously (Appendix 4.2). For comparison, 35 colonizing species were identified by Nagase et al. (2008) on a GR over six growing seasons. In contrast to the bryophytes, weed establishment in the experimental plots was not correlated with the cover of succulents, but there was a positive correlation with the cover and abundance of annual species and herbs, and the SR and D_s of the installed vegetation. Although the relation between bryophyte cover and SR and D_s of the weeds was not significant in this experiment, Zamfir (2000) and Emilsson (2008) found that the presence of a bryophyte layer may oppose weed establishment. The weeds were mainly native or exotic ruderal annuals also present in the environment surrounding the EGRs. Like the annual species installed on the EGRs, the weed development dynamics follow the weather patterns of summer drought, autumn and spring rains (cf. Emilsson, 2008). *E. canadensis*, *Epilobium hirsutum, Crepis sancta, Sonchus oleraceus* and *Trifolium campestris* established the first growing season on the EGRs, produced seeds and reappeared the next year, hence illustrating the ecological phenomenon of the founder effect. Similar to Emilsson (2008), some tree species also germinated but they all died quickly as expected when temperature and drought increased.

4.2. EGR design recommendations for Mediterranean and temperate climates

Of the species that are already used on GRs, we confirm that all, except *Helianthemum nummularium* and *Clinopodium acinos* which did not germinate or died after the first growing season, are suitable for use on EGRs (Appendix 4.3). These two species could have resulted in better germination and performance if seed quality was better or if plug plants were used. Indeed, good seed quality needs to be ensured or installation as plug plants should be considered in all cases. *L. ovatus* germinated and flowered abundantly in Avignon, but was not present in Heverlee. This species is therefore recommended for EGRs in the Mediterranean. *Euphorbia cyparissias* can be used in temperate climates on EGRs with 5 or 10 cm substrate depth and a WRL, although this species is not expected to reach a high cover. In Avignon, this species was only noticed in structure type P10 at the end of the experiment. The succulents *S. album* and *S. acre* survived very well in the sheltered plots in Avignon. In Heverlee, the cover of *S. album* increases throughout the experiment, but cover values for *S. acre* remained rather low although still higher than many other seeded species. Similar results for *S. album* and *S. acre* were found in the experiment of Emilsson (2008) in Sweden. We recommend considering *Sedum spp.* as part of every EGR vegetation composition because of their high cover and because it was observed that the small, annual species survived in proximity of *Sedum* patches. This nursing effect has also been demonstrated by Butler and Orians (2011). Other studies (e.g. Boivin et al., 2001; Farrell et al., 2012) also point at the importance of succulent species on GRs. In general, *A. sphaerocephalon* grew and flowered well the first year but in 2014, only few new stems reappeared from the bulbs in substrate types P5 and P10. *A. sphaerocephalon* is a summer flowering accent plant with a high regeneration capacity if the substrate is deeper than 5 cm.

This is in accordance with Oberndorfer et al. (2007), who recommend the use of geophytes when the substrate has at least 7 cm of depth.

Of the species that are not yet used on GRs, only *Carthamus carduncellus* is not recommended in any of the locations based on its low germination rate and bad performance. We like to advise *A. alyssoides, L. maritima* and *S. conica* for use on EGRs in both locations. In Avignon, *Linum bienne* is a small annual plant that can be considered for biodiversity reasons in sheltered plots with structure type P10. The other seeded species are not advised here, as they did not germinate (*Erophila verna, Petrorhagia prolifera*) or did not reappear in 2014 (*Plantago afra, D. superbus, Sideritis hyssopifolia*). In Heverlee, next to *D. superbus, S. hyssopifolia* and *L. bienne* are good performing species in structure types P5 and P10, although their cover remained rather low. *E. verna* did only perform well in the sheltered plots with structure type P10, and *P. prolifera* did only germinate at the end of the experiment. Like *A. sphaerocephalon*, *I. lutescens* is advised as an aesthetically appealing early flowering accent plant, although the combination of prolonged drought and shallow substrate on exposed EGRs can pose a regeneration problem.

In both the Avignon and Heverlee experiment, only for some variables and periods, the EGR performance appeared better in the sheltered plots. Placing the EGR in a sheltered location is hence not a major requirement to obtain a successful EGR. The structure type on the other hand appeared of much higher importance. In order to ensure a well-functioning EGR in both Mediterranean and temperate regions, one should best opt for a substrate depth of minimum 10 cm together with an additional WRL during the design phase. Opting for a shallower substrate with a WRL (structure type P5) may result in better or worse EGR performance compared to structure types 5 and P10, and is therefore a risky option. A very shallow substrate without a WRL (structure type 5) is only the best option if one wants to establish an EGR dominated by a bryophyte layer, and this is more certain to succeed in the temperate climate. In all circumstances, an irrigation system should be considered in order to keep the vegetation alive as long as possible if GRs are expected to be aesthetically pleasing (i.e. have a green appearance) throughout the major part of the year. Irrigation could also prevent the vegetation from wilting too early before having set seed, hence reducing the maintenance time and cost of reseeding the next year if no seed has been produced and in the absence of a permanent soil seed bank of the annual sowed species.

5. Conclusion

The discussed design and species recommendations for both Mediterranean and temperate climates shed some light on the possibilities for EGR design in regions with yearly summer drought and regions facing climate change. They can be applied immediately in the respective regions. As future summer conditions in the temperate climate are expected to be comparable to the current Mediterranean summer climate, the Avignon experiment gives an indication of how EGR vegetation could shift in the temperate climate in the next decades. As biodiversity conservation is becoming a priority on political agendas in developed countries all over the world, the promotion of urban infrastructure and especially the installation of EGRs should be supported, as it is an attainable way to counteract some of the negative effects of biodiversity loss. Even when EGRs do not appear very attractive during part of the year when the vegetation is dry, their value as a habitat for local flora and fauna cannot be neglected (cf. Brenneisen, 2006; Madre et al., 2014), as well as their other benefits including stormwater retention and mitigation of the urban heat island effect.

Intermediate section. Plant species used in the experiment described in Chapter 4

Annual species

Alyssum alyssoides (L.) L.

Pale madwort

[Picture: Carmen Van Mechelen]

***Clinopodium acinos (L.) Kuntze* Basil thyme**

[Picture: Hortipedia.com]

Erophila verna (L.) DC.

Whitlow grass

[Picture: Carmen Van Mechelen]

***Silene conica L*.**

Striated catchfly

[Picture: Carmen Van Mechelen]

***Lagurus ovatus L*.**

Hare's tail grass

[Picture: Carmen Van Mechelen]

Linum binene Mill

Pale flax

[Picture: Carmen Van Mechelen]

Petrorhagia prolifera (L.) P.W.Ball and Heywood

Proliferous pink

[Picture: Carmen Van Mechelen]

Plantago afra L.

Black psyllium

[Picture: Carmen Van Mechelen]

Perrenials – Herbs

***Carthamus carduncellus L*.**

Distaff thistle

[Picture: Carmen Van Mechelen]

Dianthus superbus L.

Large pink

[Picture: Carmen Van Mechelen]

***Euphorbia cyparissias L*.**

Cypress spurge

[Picture: Carmen Van Mechelen]

***Helianthemum nummularium (L.) Mill*. Common rockrose**

[Picture: commons.wikimedia.org]

***Lobularia maritima (L.) Desv*.**

Sweet alyssum

[Picture: Carmen Van Mechelen]

Sideritis hyssopifolia L.

Mountain tea

[Picture: Carmen Van Mechelen]

Perrenials – Succulents

***Sedum acre L*.**

Biting stonecrop

[Picture: Carmen Van Mechelen]

Sedum album L.

White stonecrop

[Picture: Carmen Van Mechelen]

Perennials – Geophytes

Allium sphaerocephalon L.

Round-headed leek

[Picture: Carmen Van Mechelen]

Iris lutescens (Lam.)

Crimean iris

[Picture: Carmen Van Mechelen]

Chapter 5. Effects of addition of organic material and arbuscular mycorrhizal fungi on initial green roof plant development

Adapted from Van Mechelen, C., Baert, F., Torrez, V., Dutoit, T., Honnay, O., Hermy, M. Effectsof addition of organic material and arbuscular mycorrhizal fungi on initial green roof plant development. Urban Ecosystems. Under review

1. Introduction

Urban biodiversity is increasingly considered as an important element of sustainability, enhancing urban life quality and human health through the provision of ecosystem services (cf. Cilliers & Siebert, 2011; McDonald & Marcotullio, 2011; Robinson & Lundholm, 2012; Gaston et al., 2013). It should therefore be promoted and managed carefully, an objective achievable through application of urban green infrastructure elements like green roofs (GR). GRs are generally defined as roofs covered with plant species installed on top of specialized layers including substrate, drainage, filter and roof protection. Next to their role in biodiversity conservation (Kowarik, 2011; Braaker et al., 2014; Madre et al., 2014), they mitigate both the urban heat island effect (UHI) and air pollution, reduce stormwater runoff and energy consumption and offer aesthetic, psychological and physical benefits (Oberndorfer et al., 2007). Although intensive green roofs (IGR) may accommodate more species diversity and reduce stormwater runoff more efficiently because of a deeper substrate (> 20 cm), it is the extensive green roof type (EGR) with a substrate depth of 2-20 cm that is particularly interesting as it is low-maintenance and broadly applicable. Plant species for such roofs are generally chosen for their drought tolerance and their ability to be self-sustaining. However, even for typically selected stress tolerant plants, the severe environmental conditions on EGRs remain a challenge for successful establishment, growth and reproduction. As the GR often should be as light as possible (70-170 kg/m² when water-saturated) and the substrate highly water permeable without losing stability and hampering oxygen diffusion, substrates are mainly composed of mineral aggregates with macropores (Oberndorfer et al., 2007; FLL, 2008). This decreases the available water for plants, and because the proportion of organic material (OM) is limited (generally 10-20 % of the weight-volume), the nutrient exchange capacity is low as well (Busch & Lelley, 1997; Oberndorfer et al., 2007; Emilsson, 2008). All this may strongly hamper GR development and may result in reduced overall performance (Nagase & Dunnett, 2011).

Low resource availability could be overcome by (1) increasing species diversity to stimulate more complete resource use (cf. Hooper et al., 2005), (2) use of different substrate materials including water retention additives (e.g. hydro-absorbent polymer gels cf. Sutton 2008) or adding extra irrigation, (3) addition of fertilizers, (4) addition of OM or (5) inoculation with micro-organisms like arbuscular mycorrhizal fungi (AMF; Sutton, 2008; Molineux et al., 2009; Dvorak & Volder, 2010; Oliveira et al., 2011). In this study, the focus will be on adding OM and AMF. For a review on the first two options, we refer to a review of Cook-Patton and Bauerle (2012) and to Farrell et al. (2013). Because fertilization is a non-sustainable solution, this option is not preferred (Sutton, 2008). OM increases nutrient exchange capacity, adds nutrients to the substrate, and improves soil structure and water retention (Friedrich, 2005; Emilsson, 2008; Molineux et al., 2009). Despite the positive effects, there are also some drawbacks of this approach. OM will decay over time, causing shrinkage of the substrate volume, and again decreasing water and nutrient-holding capacity (Friedrich, 2005; Snodgrass & Snodgrass, 2006; Rowe, 2011). Furthermore, weed establishment becomes more likely (Nagase & Dunnett, 2011).

AMF addition could be a valuable alternative for OM enrichment. AMF are symbiotic fungi (Phylum *Glomeromycota*) that form mutualistic associations with plant roots of most plant species (Parniske, 2008; Bonfante & Anca, 2009; Willis et al., 2013). Intracellular structures, or 'arbuscules' are formed where nutrient and carbon exchange takes place (Newsham et al., 1995; Smith & Read, 1997). Host plant benefits of having AMF associations include improved phosphorus and nitrogen uptake, protection against pathogens and insect herbivores, toxic metal resistance and improved water uptake (Newsham et al., 1995; Augé, 2001; Rillig, 2004; Veresoglou & Rillig, 2012). The association between AMF and plant roots could therefore be of major importance to increase the performance of EGRs (cf. Busch & Lelley, 1997; Oberndorfer et al., 2007; Feldmann, 2008; McGuire et al., 2013). The literature also points at some links between AMF and OM. It has been shown that OM is an important source of nitrogen, necessary for AMF growth (Hodge & Fitter, 2010), and that it can lead to increased formation of AMF-root associations (Azcón-Aguilar & Barea, 1997; Feldmann, 2008).

Generally, GR substrates are sterilized before use, in order to eliminate seeds of undesired species, hence also eliminating AMF (Gormsen et al., 2004; Emilsson, 2008; Feldmann, 2008). AMF should therefore be added through inoculation, but only since the nineties, the potential of mycorrhizal inoculation applications in horticulture became evident (Azcón-Aguilar & Barea, 1997; Feldmann, 1998). More recently, also the GR industry started promoting the use of AMF (Streit, 2003; Feldmann, 2008; John, 2013).

Evidence of the beneficial effects of AMF under GR conditions or in other shallow-soil communities remains scarce however (Poot & Lambers, 2008; John, 2013; McGuire et al., 2013; Rumble & Gange, 2013). To our knowledge, only Busch and Lelley (1997) studied AMF applications on GRs, reporting that the effect of AMF can be both positive and negative, depending on the plant species used. Indeed, the interactions between AMF and the host plant are expected to depend on many factors including climate, water and OM availability, plant species and the AMF species present in the inoculum (cf. Van der Heijden et al., 1998; Gange & Brown, 2002; Rillig, 2004; Maherali & Klironomos, 2007; Feldmann, 2008; McGuire et al., 2013). Commercial inocula generally contain only *Glomus spp.* of the phylum *Glomeromycota* as these are known to be generalists (Rillig, 2004; Jansa et al., 2008).

The general aim of this study was to examine the effects of AMF and OM on EGR vegetation development. AMF were added to a mineral EGR substrate and to a substrate with additional OM. Experiments were conducted both under greenhouse and rooftop conditions. To improve plant performance, it is essential to establish the mycorrhizal associations as early as possible during seed germination (Azcón-Aguilar & Barea, 1997). Therefore, this study specifically focused on the initial development stages of the GR vegetation. More specifically, the following research questions were addressed:

(1) How do AMF and OM influence species germination and early development in terms of species diversity, vegetation cover and height?

(2) For the greenhouse study in particular, is there microscopic evidence of formation of AMF-root associations and is there an effect on the vegetation biomass?

(3) To what extent can AMF be recommended as a substitution of OM in EGR substrates, in order to enhance vegetation development on EGRs?

2. Material and methods

2.1. Experimental setup

The rooftop experiment was established on the horizontal roof of a building of the University of Leuven, in Heverlee, Belgium (50°51’47’’N, 4°40’28’’E) in September 2013 (*). Until June 2014, daily temperature and precipitation data were collected from a nearby weather station of Brussels (50°9’N; 4°53’E, elevation 58 m). Monthly data are plotted against the yearly averages derived from New_LocClim v1.10, a ‘Local Climate Estimator’ program and database (FAO, 2005). The experimental plots of 1 m² consisted of four empty high-density polyethylene (HDPE) EGR modules (± 0.25 m²; ECCOsedum; www.eccoproducts.eu) that allow free drainage of rainwater. The trays were filled with 7 cm of FLL-approved substrate, either a mineral EGR substrate (MIN) or one with additional OM (ORG) of Peltracom NV (Table 5.1)

(*) The same roof as the Heverlee experiment in Chapter 4.

Half of the experimental plots received 1 g/m² AMF inoculum (MYCO) consisting of *Glomus spp.* on a vermiculite carrier material (Peltracom n.v., personal communication), which is known to be an adequate substrate for formation of AMF spores (Azcón-Aguilar & Barea, 1997). The four experimental treatments ORG, MIN, ORG+MYCO and MIN+MYCO, were each replicated three times and installed in a randomized block design on a fully exposed bitumen roof covered with a root protection layer (Sopranature WF 50). Seeds from a commercial EGR seed mix (Optigreen Seed mix Type E for Nature roof; Optigrün International AG 2014; Table 5.2), containing 35 herbaceous plant species, were added at a rate of 2 gr/m². Seed quality is in accordance with the FLL quality requirements for the composition of wild plant seeds from reproduction stock, with a minimum seed purity and germination capacity above 75 and 70 %, respectively (Optigrün International AG, 2014). AMF dependency of the species is variable (Table 5.2). As a control, four additional HDPE modules of 0.25 m² (one for each treatment) were installed and left unsown. During two weeks after sowing, the plots were irrigated by hand two times a week to saturation, but afterwards they only received water from natural precipitation events.

Setup of the greenhouse experiment was similar to the rooftop experiment, with the four treatments ORG, MIN, ORG+MYCO and MIN+MYCO replicated three times in a randomized block design. However, experimental plots only consisted of one EGR tray (approximately 0.25 m²) instead of four. The plots were subjected to artificial lighting conditions (16h light – 8h dark) and an average temperature of 22°C (maximum and minimum recorded temperatures were 35 and 10°C, respectively). Two times a week, the plots were watered from below to saturation. Two additional unsown plots (one containing MIN and one ORG substrate, ½ of the surface covered with AMF inoculum) served as control.

2.2. Plant and AMF survey

Plant survey on the rooftop took place in April 2014 (after 8 months) and included calculation of species richness (SR) and number of individual plants (abundance), total percentage cover of the plot, and the average height of the developing vegetation. Also relative frequencies of the species present in every treatment were calculated. The Shannon diversity index (H_s) and associated equitability measure E_H were calculated using following formulas (Begon et al., 2006):

$$H_s = -\sum_{i=1}^{SR} pi \ln pi \qquad \text{(Eq. 1)}$$
$$E_H = H/\ln SR \qquad \text{(Eq. 2)}$$

In Eq. 1, p_i is the relative abundance of the i'th species, so the diversity index H_s accounts for both abundance and evenness of the species in the community. The equitability index E_H in Eq. 2 takes a value between 0 and 1, with 1 representing complete evenness.

Table 5.1 EGR substrate specifications of LP24GREXMIN1 (MIN) and LP24GREXORG1 (ORG) (Peltracom n.v.)

	FLL-norm	MIN	ORG	Unit
Particle size distribution				
d ≤ 0.063mm	≤ 15	6	9	Weight %
d> 4mm	≤ 50	53	44	
Volume weight				
Dry	NA	1.1	1	g/cm³
Maximum water capacity	NA	1.36	1.43	g/cm³
Water/air distribution				
Total pore volume	35-65	59	62	Vol.-%
Maximum water capacity	≥ 10	26	42	Vol.-%
Air capacity at maximum water capacity	≥ 20	33	20	Vol.-%
Water permeability	0.6-70	183	27.9	mm/min
Chemical analysis				
pH ($CaCl_2$)	6.0-8.5	7.9	7.6	
Conductance	≤ 3.5		0.7	g>l
Organic material				
Organic material	≤ 65	7	32	g/l
Nutrients				
N	≤ 80	4	33	mg/l
P	≤ 200	11	180	mg/l
K	≤ 700	154	700	mg/l
M	≤ 200	22	120	mg/l

Vegetation development in the greenhouse started one week after sowing. From October 2013 until February 2014, SR, abundance and percentage cover were recorded weekly (15 observations). After this experimental period, all plants were collected, plant height and root length were measured, and H_s, E_H and dry weight (DW) were calculated. DW was determined by drying the aboveground plant parts for 24 hours at 105°C and weighing on a balance with a precision of 0.1 g. This information allowed the calculation of the mycorrhizal inoculation effect (MIE; Bagyaraj, 1992):

$$\text{MIE} = \frac{[DW\ (MYCO) - DW\ (no\ MYCO) * 100]}{DW\ (MYCO)} \qquad \text{(Eq. 3)}$$

The MIE in Eq. 3 accounts for the difference in DW between a substrate with and without additional mycorrhiza. In essence, MIE is an index for the effectiveness of an AMF inoculum, with high values indicating a positive effect on biomass production of a plant community.

The root parts of four species (*Cota tinctoria, Dianthus deltoides, Leucanthemum vulgare,* and *Prunella vulgaris)* differing in AMF dependency, offered sufficient material to be analyzed microscopically for AMF presence, following Dalpé and Séguin (2013). Plant roots were cut into pieces of 2-4 cm and cleared in multiple successive steps: washing with H_2O, clearing with KOH 2.5%, microwave heating (30 s, 900 W) in a domestic microwave (Primo, model MG7) and washing (three times) with distilled H_2O. After clearing, the roots were immersed in acetic acid 5% to bring the pH below 2.5. In the staining step, the acidified roots were immersed into a staining solution consisting of lactic acid-glycerol-acetic acid 5% water solution (12-1-1) and acid fuchsin (0.01%), followed by microwave heating (30 s, 900 W). Finally, the percentage of roots colonized with AMF was evaluated by the grid-line intersection method described by Habte and Osorio (2011) using a light microscope (Wild M3, Leica Geosystems AG, Switzerland) with a magnification factor of 160.

2.3. Data analysis

For the rooftop experiment, differences between substrate type (SUBSTRATE: MIN or ORG) and AMF inoculation (MYCO: YES or NO) in terms of SR, abundance, cover, vegetation height, H_s and E_H were assessed by means of parametric ANOVA or a non-parametric Mann-Whitney U test (MWU), depending on the normality distribution and variance homogeneity of the variables. In the same way, height, root length, H_s, E_H, and DW of the greenhouse experiment were analyzed. The differences in variable values between both experiments were analyzed as well. These statistical tests were performed in SPSS 22.0 (SPSS Inc, Chicago, IL).

For the greenhouse experiment, the weekly recorded SR and cover were analyzed using Linear Mixed Models with Time, SUBSTRATE and MYCO as fixed effects and the intercept as the only random effect. If significant, two-way interaction terms were added to the final model. The weekly recorded plant abundances are count data and were analyzed using Generalized Linear Mixed Models with a Poisson distribution. The Mixed Models were performed in SAS 9.3 (SAS Institute Inc., Cary, NC).

Two-way parametric Anova or a Kruskal Wallis test (KW), depending on the normality distribution and homogeneity of variance of the data, were used to detect significant differences in the percentage of AMF colonization between the four species that were analyzed microscopically. Finally, for both the rooftop and greenhouse experiment, Spearman rank correlations (r_s) were calculated to test for correlations between a) the relative frequencies for the treatments in both experiments, and b) the measured variables. Significance levels were adjusted with a Bonferroni correction. Both tests were performed in SPSS 22.0.

Table 5.2 Plant species present in the Optigreen Seed mix Type E (Optigrün International AG, 2014), relative species frequency in the four treatments and SR at the end of the study period. Plant nomenclature follows The Plant List (2013). The AMF dependency of the species ranges from 1 (no/rare) to 3 (frequent/obligate). [a: Fitter and Peat, 1994; b: Pánková et al., 2014; c: Gucwa-Przepióra and Blaszkwoski, 2004;d Piotrowski et al., 2004; e: Sawilska and Jendrzejczak, 2013].

a) ROOFTOP	AMF dependency	MIN	MIN+MYCO	ORG	ORG+MYCO
Optigreen Seed Mix					
Achillea millefolium L.	3 a	1.25	1.82	1.32	2.7
Allium schoenoprasum L.	3 a	1.25	0.61	1.32	-
Aster amellus L.	3 a	-	-	-	-
Campanula rotundifolia L.	3 a	0.63	-	2.63	-
Centaurea scabiosa L.	3 a	-	-	-	-
*Clinopodium vulgare L. **	3 a	-	-	-	-
Cota tinctoria (L.) J.Gay	unknown	23.75	20	14.47	10.81
*Dianthus armeria L. **	unknown	-	-	-	-
Dianthus carthusianorum L.	2 c	26.88	36.36	25	15.32
Dianthus deltoides L.	1 a	3.13	1.21	3.95	6.31
*Erodium cicutarium (L.) L'Hér. **	2 a	-	-	-	-
*Euphorbia cyparissias L. **	3 a	-	-	-	-
Galium verum L.	3 a	1.25	-	2.63	-
Geranium robertianum L.	2 a	-	-	-	-
*Helianthemum nummularium (L.) Mill. **	2 a	-	-	-	-
*Helichrysum arenarium (L.) Moench **	3 c	-	-	-	-
Leucanthemum vulgare (Vaill.) Lam.	2 d	8.13	6.67	7.89	7.21
Linaria vulgaris Mill.	2 a	1.88	0.61	-	1.8
*Linum perenne L. **	1 a	-	-	-	-
Origanum vulgare L.	3 a	-	-	-	-
Petrorhagia saxifraga (L.) Link	unknown	1.88	0.61	1.32	1.8
Pilosella aurantiaca (L.) F.W.Schultz & Sch.Bip.	unknwon	-	-	-	-
*Pilosella officinarum Vaill. **	3 a	-	-	-	-
Potentilla argentea L.	3 a	8.75	7.88	18.42	23.42
Prunella grandiflora (L.) Scholler	unknown	3.75	1.21	-	1.8
Prunella vulgaris L.	3 a	-	-	-	-
Sanguisorba minor Scop.	3 a	1.88	3.03	3.95	6.31
Saponaria ocymoides L.	unknown	-	-	-	-
Saponaria officinalis L.	1 a	9.38	15.76	11.84	14.41
Sedum album L.	1 a	-	-	-	-
Sedum rupestre L.	1 a	-	-	-	-
Silene nutans L.	2 a	-	-	-	-
*Silene otites (L.) Wibel **	2 a	-	-	-	-
Thymus pulegioides L.	2 c	3.75	1.21	3.95	3.6
Thymus serpyllum L.	3 a	-	-	-	-
Unexpected species					
Alyssum alyssoides (L.) L.		0.63	0.61	-	2.7
Arenaria serpyllifolia (L.)	1 a	1.25	2.42	-	1.8
Capsella bursa-pastoris (L.) Medik.	1 a	-	-	-	-
Poa annua L.	2 a	0.63	-	1.32	-
Sonchus oleraceus (L.) L.	3 a	-	-	-	-
Total species richness		**18**	**15**	**14**	**14**
Germinated from Seed mix		**15**	**13**	**13**	**12**
Unexpected species		**3**	**2**	**1**	**2**

Table 5.2 Continued

b) GREENHOUSE	MIN	MIN+MYCO	ORG	ORG+MYCO
Optigreen Seed Mix				
Achillea millefolium L.	2.29	2.01	2.26	1.94
Allium schoenoprasum L.	0.76	4.02	1.51	1.29
Aster amellus L.	-	-	-	-
Campanula rotundifolia L.	3.05	7.63	4.15	4.52
Centaurea scabiosa L.	-	1.61	0.38	0.32
*Clinopodium vulgare L. **	-	-	0.38	0.65
Cota tinctoria (L.) J.Gay	18.32	11.65	10.19	9.35
*Dianthus armeria L. **	-	-	-	-
Dianthus carthusianorum L.	9.92	6.83	4.15	7.42
Dianthus deltoides L.	6.87	4.02	10.94	6.13
*Erodium cicutarium (L.) L'Hér. **	-	-	-	-
*Euphorbia cyparissias L. **	-	-	-	-
Galium verum L.	3.82	7.23	6.79	3.55
Geranium robertianum L.	0.76	0.4	-	-
*Helianthemum nummularium (L.) Mill. **	-	-	-	-
*Helichrysum arenarium (L.) Moench **	-	-	-	-
Leucanthemum vulgare (Vaill.) Lam.	3.82	16.06	11.7	10.65
Linaria vulgaris Mill.	0.76	0.4	0.75	2.26
*Linum perenne L. **	0.76	1.2	0.38	1.29
Origanum vulgare L.	4.58	8.03	6.04	8.06
Petrorhagia saxifraga (L.) Link	-	-	-	-
Pilosella aurantiaca (L.) F.W.Schultz & Sch.Bip.	-	-	0.38	0.65
*Pilosella officinarum Vaill. **	-	-	-	-
Potentilla argentea L.	5.34	4.42	15.47	14.19
Prunella grandiflora (L.) Scholler	-	-	0.75	0.32
Prunella vulgaris L.	1.53	3.61	1.51	1.94
Sanguisorba minor Scop.	3.82	4.02	4.15	4.19
Saponaria ocymoides L.	5.34	0.8	2.64	2.9
Saponaria officinalis L.	17.56	6.83	9.06	11.29
Sedum album L.	-	-	-	-
Sedum rupestre L.	-	-	-	-
Silene nutans L.	8.4	4.82	3.02	3.23
*Silene otites (L.) Wibel **	-	-	-	-
Thymus pulegioides L.	0.76	4.42	3.4	3.87
Thymus serpyllum L.	-	-	-	-
Unexpected species				
Alyssum alyssoides (L.) L.	-	-	-	-
Arenaria serpyllifolia (L.)	-	-	-	-
Capsella bursa-pastoris (L.) Medik.	0.76	-	-	-
Poa annua L.	-	-	-	-
Sonchus oleraceus (L.) L.	0.76	-	-	-
Total species richness	**21**	**20**	**22**	**22**
Germinated from Seed mix	**19**	**20**	**22**	**22**
Unexpected species	**2**	**0**	**0**	**0**

* Species that can be present in the seed mix as a result of regional differences in seed mix composition

3. Results

3.1. Rooftop experiment

Monthly precipitation was lower than average from December to April and was higher than average during October, November, and especially May (Fig. 5.1a). The average temperature was normal during the first three months of the experimental period, but from December until May, the temperature was between 1.6 and 3.3°C higher than the average yearly temperature (Fig. 5.1b).

On the rooftop experiment, the highest SR was found in the MIN treatment (18 species), followed by MIN+MYCO (15 species), ORG and ORG+MYCO (both 14 species; Table 5.2). Between 12 and 15 species of the sown species established and 3 unexpected species were observed. Most frequently occurring species (relative frequency > 10%) were *Dianthus carthusianorum* and *Cota tinctoria* in the MIN treatment (26.88 and 23.75% respectively), and *D. carthusianorum, C. tinctoria* and *Saponaria officinalis* in the MIN+MYCO plots (36.36, 20 and 15.76% respectively). In the ORG plots, *D. carthusianorum, Potentilla argentea, C. tinctoria* and *S. officinalis* showed the highest frequencies (25, 18.42, 14.47 and 11.84% respectively) and *P. argentea, D. carthusianorum, S. officinalis* and *C. tinctoria* had the highest frequencies in the ORG+MYCO plots (23.42, 15.32, 14.41 and 10.81% respectively). The relative frequencies of the different treatments were highly correlated (r_s between 0.72 and 0.95; Table 5.5a). Of the unexpected species, *Alyssum alyssoides* and *Arenaria serpyllifolia* were recorded in three treatments (MIN, MIN+MYCO and ORG+MYCO) and *Poa annua* occurred in MIN and ORG. *Alyssum alyssoides* probably originated from the neighboring experimental GR (Chapter 4) and the other two species are rather common weedy species that could have reached the roof as seeds or were unintentionally present in the substrate or seed mix. No germination was noticed in the control plots.

Both rooftop and greenhouse experiments differed greatly in their variable values, as indicated by the significant MWU values (Table 5.3b). For the rooftop experiment, the cover of the plots was low (between 0.25 and 3.5%) and treatments did not significantly affect SR, abundance, vegetation height, H_s, E_H (Table 3a), or cover (Table 5.3b). Although average values of plant abundance and SR in MIN plots (54.17 plants and 10 species, respectively) were higher compared to ORG plots (31.17 plants and 6.33 species, respectively), these differences were not significant. Plants were very small (1 cm on average) but H_s and E_H were rather high (approximately 1.5 and 0.8, respectively).

Diversity indices H_s and E_H were rather high (1.5 and 0.8), indicating that no distinct dominance patterns occur in the plots (Table 5.3). SR, abundance, cover, height and H_s were all strongly and positively correlated (p-value ≤ 0.001; r_s between 0.84 and 0.96) but no significant correlations were found with E_H (Table 5.5b1).

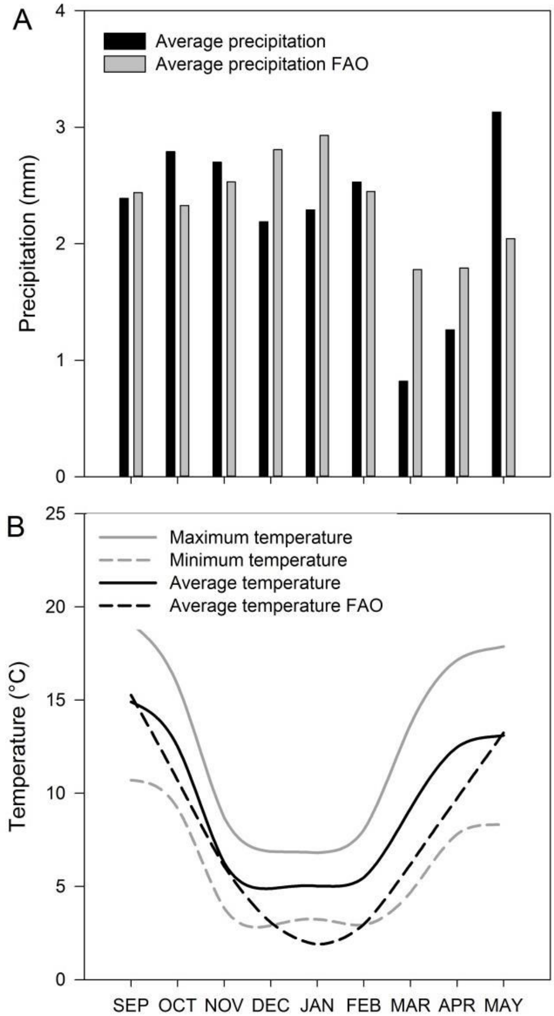

Fig. 5.1 Average monthly data for A: precipitation and B: temperature. Next to the weather data recorded during the rooftop experiment, normal averages for the study site derived from New_LocClim v1.10 (FAO 2005) are plotted.

3.2. Greenhouse experiment

A total of 25 different species germinated in the experimental greenhouse plots, of which 19 to 21 species, depending on the treatment, were present in the seed mix (Table 5.2). The ORG and ORG+MYCO treatments had the highest SR (22 species), followed by MIN (21 species) and MIN+MYCO (20 species). Two unexpected species, *Capsella bursa-pastoris* and *Sonchus oleraceus* were recorded in the MIN treatment and probably reached the roof as seeds or could have been unintentionally present in the substrate or seed mix. *C. tinctoria* and *S. officinalis* were the most frequent species in the MIN plots (18.32 and 17.56 % respectively), and *Leucanthemum vulgare* and *C. tinctoria* in the MINMYC plots (16.06 and 11.65 % respectively). In the ORG treatment, *P. argentea, L. vulgare, D. deltoides* and *C. tinctoria* were most frequent (15.47, 11.7, 10.94 and 10.19 % respectively) and in the ORG+MYCO plots, this was the case for *P. argentea, S. officinalis* and *L. vulgare* (14.19, 11.29 and 10.65 % respectively). The control plots remained unvegetated during the experiment. Like the rooftop experiment, the relative frequencies of the species in the different treatments in the greenhouse were highly correlated (r_s from 0.81 to 0.97; Table 5.5a). Comparing the relative frequencies between the rooftop and the greenhouse experiment, the average Spearman rank correlation was much lower (r_s between 0.34 and 0.71) and only half of the correlation coefficients were significant. Both experiments hence differed in species composition and abundance.

For vegetation height (Table 5.3a) and DW (Table 5.3b), a significant difference was found between the substrate types, with MIN plots having lower average values (7.12 cm and 8.73 g, respectively) compared to the ORG plots (11.8 cm and 29.87 g, respectively). No significant differences between the plots with or without AMF were detected. Root length was around 7 cm for all plants in all treatments. Average values for H_s and E_H were higher than for the rooftop experiment (approximately 2.5 and 0.9, respectively).

For the dependent variables SR, cover and abundance, Time was a strongly significant fixed effect (p-value ≤ 0.001) and the parameter estimates were positive; so SR, cover and abundance increased during the 15 monitoring weeks (Table 5.4). Substrate type and AMF inoculation did not significantly affect SR (Fig. 5.2a), although SR appeared slightly higher in plots with AMF inoculation. A significant effect was found for cover, which was lower in MIN plots compared to ORG plots (Fig. 5.2b). The plots with AMF had a slightly higher cover, but this effect was not significant. For cover, the interaction term Time*SUBSTRATE was significant as well, indicating that the cover in the MIN plots increased slower than in the ORG plots (Fig. 5.2b). Considering abundance, plots with ORG substrate and with AMF inoculum had a higher number of plants, although not significant. However, both interaction terms (Time*SUBSTRATE and Time*MYCO) were significant, so ORG plots and plots with AMF inoculum show a quicker increase in number of plants over time (Fig. 5.2c).

As for the rooftop experiment, the diversity indices H_s and E_H were high (2.5 and 0.9), so there were no dominant species in the plot. Only three significant correlations with p-values ≤ 0.001 were found (Table 5.5b2), between cover and abundance (r_s = 0.83), cover and DW (r_s = 0.84) and SR and H_s (r_s = 0.91).

The overall mycorrhizal inoculation effect, between plots with or without AMF inoculation, was positive (MIE 1.71). When the substrate types were compared separately, a positive effect of AMF inoculation was found in the MIN plots (MIE = 8.76), but the effect in the ORG plots was slightly negative (MIE = -0.45).

The microscopic analysis of plant roots indicated the presence of AMF infected roots in the ORG+MYCO and MIN+MYCO plots except for the roots of *D. deltoides* in the MIN+MYCO plots (Fig. 5.3). In the ORG and MIN plots, no AMF infected roots were found. Arbuscules were only registered occasionally within the root cells and the observed mycorrhizal structures were mostly intercellular hyphae. Differences in AMF colonization between the four species seem to reflect their AMF dependency, with the highest amount of AMF colonization found in *P. vulgaris* (AMF dependency: 3 or frequent), followed by *L. vulgare* (AMF dependency: 2 or occasional) and finally *D. deltoides* (AMF dependency: 1 or rare). The AMF dependency of *C. tinctoria* was unknown, but like *P. vulgaris*, the amount of AMF colonization (on average 13.4 % in ORG+MYCO and 23.7 % in MIN+MYCO) is relatively high. Despite the variability in AMF colonization between the four species, the differences were not significant (ORG+MYCO: Anova F-value = 1.376; MIN+MYCO: Kruskal-Wallis Chi^2 = 5.18). The difference in AMF colonization between ORG+MYCO and MIN+MYCO was not significant either (MWU test statistic = 73).

Table 5.3 Results of the (a) Anova and (b) MWU test statistics of the factors substrate type (SUBSTRATE) and AMF inoculation (MYCO) for the rooftop (R) and greenhouse (GH) experiment. The differences between R and GH experiments were also tested with a MWU test. Results comprise average values together with standard deviations (Av. ± s.d.) and test statistics (F-value for Anova; MWU for the MWU test) followed by the significance level (*: p ≤ 0.05; **: p ≤ 0.001; NS: not significant; NA: not applicable).

a) ANOVA	Treatment			SR	Abundance	Plant height (cm)	H_s	E_H	Root length (cm)	Cover(%)	Dry weight (g)
ROOF	SUBSTRATE										
		MIN	Av. ± s.d.	10 ± 4.0	54.17 ± 42.8	1.21 ± 0.6	See b)	0.82 ± 0.1	NA	See b)	NA
		ORG	Av. ± s.d.	6.33 ± 4.8	31.17 ± 33.6	1.06 ± 0.8		0.82 ± 0.1			
			F-value	2.07 NS	1.07 NS	0.12 NS		0.03 NS			
	MYCO										
		NO	Av. ± s.d.	8 ± 5.7	39.33 ± 44.8	1 ± 0.8	1.5 ± 0.75	0.84 ± 0.1	NA	See b)	NA
		YES	Av. ± s.d.	8.33 ± 3.9	46±35.3	1.27 ± 0.59	1.62 ± 0.52	0.8 ± 0.1			
			F-value	0.01 NS	0.08 NS	0.43 NS	0.1 NS	0.81 NS			
GH	SUBSTRATE										
		MIN	Av. ± s.d.	Table 5.4	Table 5.4	7.12 ± 1.8	See b)	0.9 ± 0.0	See b)	See b)	See b)
		ORG	Av. ± s.d.			11.8 ± 4.0		0.91 ±0.0			
			F-value			6.90*		0.37 NS			
	MYCO										
		NO	Av. ± s.d.	Table 5.4	Table 5.4	9.35 ± 4.1	2.42 ± 0.2	0.9 ± 0.0	7.11 ± 1.3	See b)	See b)
		YES	Av. ± s.d.			9.58 ± 3.9	2.59 ± 0.1	0.91 ± 0.0	7.18 ± 0.7		
			F-value			0.01 NS	2.64 NS	1.76 NS	0.02 NS		

Table 5.3 Continued

b) MWU	Treatment			SR	Abundance	Plant height (cm)	H_s	E_H	Root length (cm)	Cover(%)	Dry weight (g)
ROOF	SUBSTRATE										
		MIN	Av. ± s.d.	See a)	See a)	See a)	1.8 ± 0.3	See a)	NA	1.38 ± 1.2	NA
		ORG	Av. ± s.d.				1.3 ± 0.8			1.27 ± 1.4	
			MWU				13 NS			13.5 NS	
	MYCO										
		NO	Av. ± s.d.	See a)	See a)	See a)	See a)	See a)	NA	1.29 ± 1.4	NA
		YES	Av. ± s.d.							1.35 ± 1.1	
			MWU							14 NS	
GH	SUBSTRATE										
		MIN	Av. ± s.d.	Table 5.4	Table 5.4	See a)	2.45 ± 0.3	See a)	7.26 ± 0.4	Table 5.4	8.73 ± 0.6
		ORG	Av. ± s.d.				2.57 ± 0.1		7.03 ± 1.4		29.87 ± 1.6
			MWU				15 NS		14 NS		0.00*
	MYCO										
		NO	Av. ± s.d.	Table 5.4	Table 5.4	See a)	See a)	See a)	See a)	Table 5.4	19.13 ± 11.8
		YES	Av. ± s.d.								19.47 ± 11.4
			MWU								15 NS
ROOF-GH	ROOF		Av. ± s.d.	8 ± 4.4	43 ± 37.0	1.14 ± 0.7	1.56 ± 0.6	0.82 ± 0.1	NA	1.32 ± 1.2	NA
	GH		Av. ± s.d.	16 ± 2.8	80 ± 28.5	9.46 ± 3.7	2.51 ± 0.2	0.90 ± 0.0		68.02 ± 30.7	
			MWU	0.00**	31.50*	0.00**	4.50**	21.00*		0.00**	

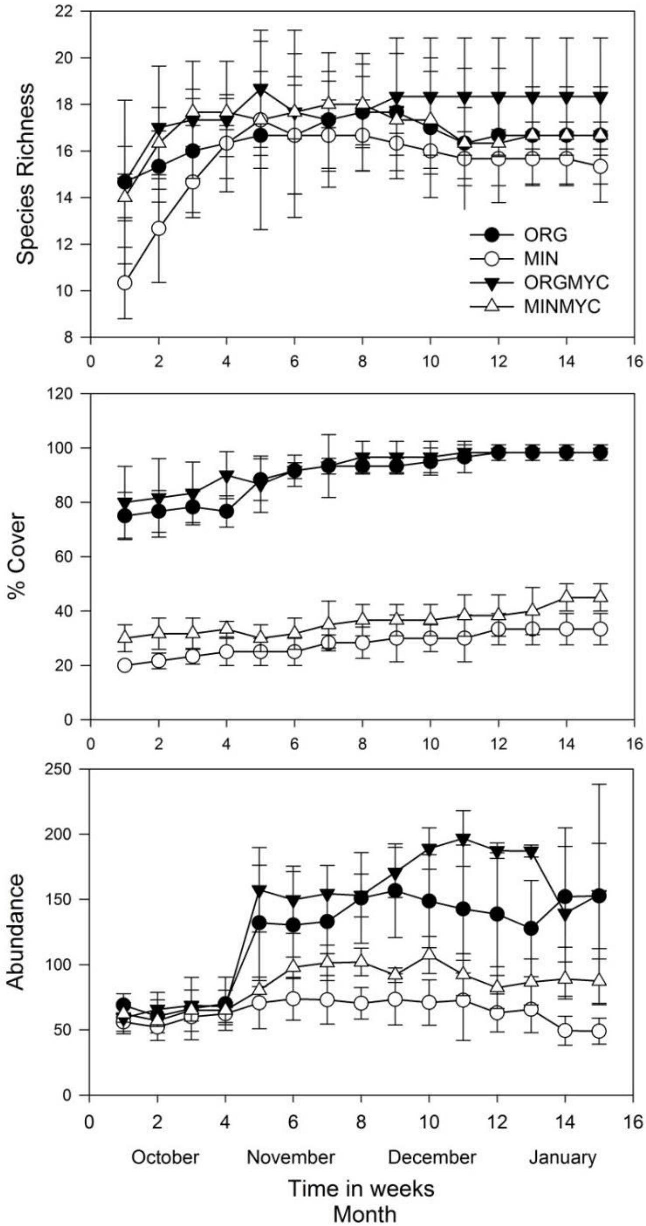

Fig. 5.2 Weekly recorded SR, % cover and abundance of the four treatments in the greenhouse plots, from October 2013 to January 2014. Vertical bars indicate the standard deviation.

Table 5.4 Results of the Mixed Model statistics of the factors substrate type (SUBSTRATE), AMF inoculation (MYCO), TIME and, if significantly contributing to the model, two-way interactions for the greenhouse experiment. Results comprise the test statistics (F-value from the Type III of Fixed Effects) followed by the significance level (: p ≤ 0.001; NS: not significant) and parameter estimates together with standard error (s.e.) of the Solution of the Fixed Effects**

Solution + Type III of Fixed Effects			SR	Cover (%)	Abundance
Intercept		Estimate ± s.e.	16.92 ± 0.9	81.14 ± 2.7	4.41 ± 0.1
SUBSTRATE					
	MIN	Estimate ± s.e.	-0.96 ± 1.0	-54.48 ± 3.2	-0.18 ± 0.1
	ORG	Estimate ± s.e.	0	0	0
		F-Value	0.9 NS	298.74 **	2.9 NS
MYCO					
	NO	Estimate ± s.e.	-1.33 ± 1.0	-5.22 ± 3.0	-0.09 ± 0.1
	YES	Estimate ± s.e.	0	0	0
		F-Value	1.76 NS	3.13 NS	0.71 NS
TIME		Estimate ± s.e.	0.11 ± 0.0	1.6 ± 0.1	0.07 ± 0.0
		F-Value	21.76 **	353.59 **	378.87 **
TIME*SUBSTRATE					
	MIN	Estimate ± s.e.	-	-0.61 ± 0.1	-0.05 ± 0.0
	ORG	Estimate ± s.e.		0	0
		F-Value		19.35 **	159.02 **
TIME*MYCO					
	NO	Estimate ± s.e.	-	-	-0.02 ± 0.0
	YES	Estimate ± s.e.			0
		F-Value			18.85 **

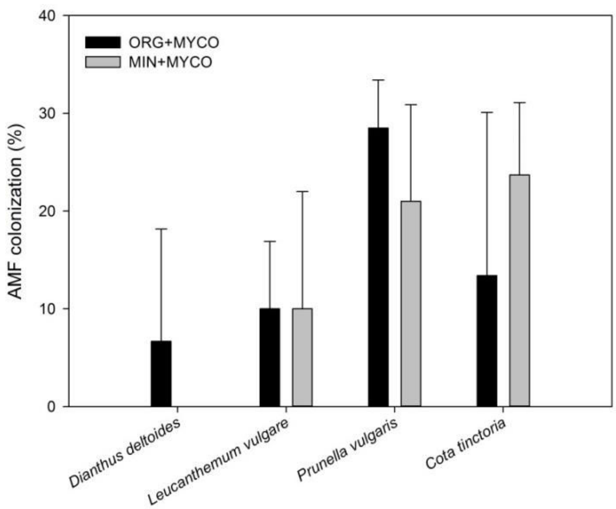

Fig. 5.3 Histogram showing mycorrhizal colonization (%) of roots of four selected species in treatments ORG+MYCO and MIN+MYCO. Error bars represent the standard error. Species differ in their AMF dependency (Table 5.2): *D. deltoides*: 1 or rare; *L. vulgare:* 2 or occasionally; *P. vulgaris*: 3 or frequent; *C. tinctoria:* unknown.

Table 5.5 Spearman rank correlation coefficients (n = 12) and significance level for a) the species relative frequencies in the treatments in both rooftop and greenhouse experiment (n = 29) and b) for the variables measured in the rooftop and greenhouse experiment (n = 12). The significance level was adjusted with a Bonferroni correction. (*: p < 0.006 for a and b1 and 0.008 for b2; **: p ≤ 0.001; NS: not significant).

a) Relative frequencies				**ROOFTOP**				**GREENHOUSE**		
		MIN	MIN+MYCO	ORG	ORG+MYCO		MIN	MIN+MYCO	ORG	ORG+MYCO
ROOFTOP	MIN	1								
	MIN+MYCO	0.91**	1							
	ORG	0.83**	0.72**	1						
	ORG+MYCO	0.89**	0.95**	0.73**	1					
GREENHOUSE	MIN	0.38 NS	0.38 NS	0.58**	0.41 NS		1			
	MIN+MYCO	0.42 NS	0.34 NS	0.65*	0.34 NS		0.81**	1		
	ORG	0.57*	0.49 NS	0.71**	0.52*		0.83**	0.88**	1	
	ORG+MYCO	0.55*	0.49 NS	0.70**	0.54*		0.84**	0.89**	0.97**	1
b) Measured variables										
1) ROOFTOP		SR	Cover	Abundance	Height	H_s	E_H	Root length	Dry weight	
	SR	1								
	Cover	0.96**	1							
	Abundance	0.94**	0.96**	1						
	Height	0.88**	0.94**	0.91**	1					
	H_s	0.95**	0.94**	0.89**	0.84*	1				
	E_H	0.11 NS	0.04 NS	-0.09 NS	0 NS	0.3 NS	1			
2) GREENHOUSE										
	SR	1								
	Cover	0.15 NS	1							
	Abundance	0.48 NS	0.83*	1						
	Height	0.33 NS	0.6 NS	0.57 NS	1					
	H_s	0.91**	0.16 NS	0.45 NS	0.15 NS	1				
	E_H	0.1 NS	0	0.01 NS	-0.3 NS	0.34 NS	1			
	Root length	0.39 NS	-0.15 NS	-0.25 NS	0.17 NS	0.15 NS	0.31 NS	1		
	Dry weight	0.16 NS	0.84*	0.68 NS	0.41 NS	0.11 NS	-0.09 NS	-0.29 NS	1	

4. Discussion

In the greenhouse study, adding OM to the substrate resulted in increased plant height, DW (Table 5.3), and vegetation cover (Table 5.4). These positive effects of OM on initial plant growth are in line with Nagase and Dunnett (2011), who concluded that, together with water availability, the most important factor for plant growth on GRs is the presence of OM. A possible explanation for the positive results of OM could be the differences in substrate composition. The water permeability for example, was 183 mm/min for MIN compared to only 27.9 mm/min for ORG (Table 5.1). The ORG plots hence had higher and longer water availability after rainfall. Moreover, OM and nutrient content were approximately five times higher (0.6 and 3.2% OM for MIN and ORG substrates respectively). In contrast to Nagase and Dunnett (2011) and Molineux et al. (2009) who found that adding respectively 10% and 25% OM was optimal for GR plant growth, the amount of OM used for this study was rather low. Nevertheless, the OM in the ORG substrate together with the higher water retaining capacity proved to be sufficient to obtain positive effects on vegetation cover, plant height and DW. Consequently, plants are competing for light, whereas competition for nutrients is going on in the MIN plots.

The results of the greenhouse study did not show a clear effect of AMF inoculation on species germination and early development. In two other studies (Reidenbach & Pacalaj, 2006; Reidenbach et al., 2010), where the effect of AMF inoculation on plant growth on a mineral IGR substrate was tested, similar results were obtained. However, a positive MIE was found in our greenhouse experiment which suggests that biomass production is positively influenced by adding AMF. This effect appeared highly positive when only the MIN substrate plots were considered but slightly negative in the ORG plots. A possible explanation may be that the effect of OM on plant development in the ORG plots is so pronounced that AMF inoculation does not influence biomass production in this case. In MIN plots, plants have more difficult starting conditions, leading them to make optimal use of the additional AMF to increase their biomass. Next to the MIE, microscopic analysis of root material of four species in the greenhouse experiment confirmed successful AMF-root associations in the ORG+MYCO and MIN+MYCO plots. In the ORG and MIN plots, no AMF infected roots were found, so the AMF inoculum present in nearby plots had not reached and contaminated the plots without AMF. A similar result was found by Sutton (2008), who did not detect any difference in plant growth between control and AMF inoculated plots in the establishment phase, although AMF-root associations were detected. More time is probably needed to fully establish the AMF infection and to obtain positive outcomes on vegetation development. Busch and Lelley (1997) for example, concluded that AMF inoculation resulted in overall better plant survival and drought stress on rooftops. It is hence possible that the effects of AMF inoculation become significant in later stages of vegetation development. In time, it is also possible that AMF are transported to nearby plots, as Reidenbach and Pacalaj (2006) also found AMF-root associations in their control plots and because of the easy colonization onto GR substrates by surrounding AMF (Van der Heijden et al., 1998; McGuire et al., 2013; Rumble & Gange, 2013). Regarding the four species of which root material was used for the microscopy analysis, the AMF dependency of *D.*

deltoides, L. vulgare and *P. vulgaris* was reflected in the rate of AMF colonization. However, the AMF dependency of *C. tinctoria* was unknown, but the relatively high amount of AMF colonization (on average 13.4% in ORG+MYCO and 23.7% in MIN+MYCO), suggest that it is medium to highly capable of forming AMF-root associations.

On the rooftop experiment, the vegetation cover remained low, plants were small, and no significant effects of OM and AMF on early plant development were found (Table 5.3), which could be due to climatic factors. As shown in Fig. 5.1, meteorological values during the experimental period showed some deviations from the yearly average values. Except for the first two weeks after seeding, plots received only water from natural precipitation events. Sufficient water availability is a prerequisite during vegetation establishment (cf. Snodgrass & Snodgrass, 2006), which is why the relatively dry winter and spring months combined with above average temperatures resulted in slow germination and vegetation development. We believe that an additional irrigation system could have mitigated this water shortage problem. Also, as yearly changes occur in weather patterns, vegetation development will likely differ, as well as the monitored measures. Therefore, outdoor experiments should be conducted during several years in order to generalize the obtained results.

5. Conclusion

In conclusion, this study showed that a low amount of OM is sufficient to obtain positive effects on EGR plant growth in terms of vegetation cover, height and DW. The risk of disadvantages like substrate decomposition and decreased water retention capacity is also limited when only low amounts of OM are considered (Friedrich, 2005; Snodgrass and Snodgrass, 2006; Rowe, 2011). However, there is an important trade-off to account for, as bigger plants transpire more, compete for light and have more biomass to maintain, making them less resistant to drought stress, which is a disadvantage when a dry period occurs after establishment (Rowe et al., 2006). Our findings also demonstrate that GR substrates offer a suitable media where associations between AMF and plant roots can take place, but that addition of AMF is not very effective as regards initial plant development. It can hence not yet be considered as a substitution for OM. Next to encouraging studies that test the effect of AMF inoculation on plant productivity in the long term, research should also focus on species-specific inocula, as the effect of AMF inoculation is actually dependent on the used AMF and plant species (Busch & Lelley, 1997; Rillig, 2004). If AMF- and plant choice can be tuned, the GR industry is one step closer to successfully develop productive EGR with high biodiversity value.

Chapter 6. Adapting green roof irrigation practices for a sustainable future

Adapted from Van Mechelen, C., Dutoit, T., Hermy, M. Adapting green roof irrigation practices for a sustainable future: a review. Building and Environment. Under review.

1. Introduction

Next to land use changes and habitat fragmentation, the urbanization process has a pronounced effect on the natural water cycle (Walsh et al., 2005; Schmidt, 2010). As urban green gets more scarce, evapotranspiration (ET) is reduced, thereby reducing precipitation which reduces ET even further and ultimately this leads to dehydration of the urban environment (Schmidt, 2010). In Mediterranean areas, water is amongst the most limiting natural resources (Kotsiris et al., 2013). The problem is becoming increasingly acknowledged and incentives arise to stimulate sustainable water management practices, which aim to balance social, economic and environmental water needs (Schmidt, 2010; Bean & Pitt, 2012; Blanco-Gutiérrez et al., 2013; Islam et al., 2013). Urban green infrastructure elements like urban trees, parks, gardens, green roofs (GRs) and green walls, are a vital part of water management (Gill et al., 2007; Schmidt, 2010). Green infrastructure comprises by definition the entire semi-natural and artificial networks of multifunctional ecological systems in urban areas (Tzoulas et al., 2007; Naumann et al., 2011). GRs provide many ecosystem processes and services, including stormwater management, cooling and insulation of buildings, mitigation of the urban heat island effect, contribution to human health and habitat provisioning (Oberndorfer et al. 2007, Carter & Fowler, 2008; Rozos et al., 2013). They can be classified into two main categories of which extensive GRs (EGRs) represent the most shallow (2-ca.20 cm substrate depth) and light weight (70-170 kg/m²) ones. The vegetation of EGRs generally consists of succulents and other drought tolerant plants (Bousselot et al., 2011). Within the EGR category, semi-extensive GRs (SEGRs) have a slightly deeper substrate (12-ca. 20 cm) and the associated higher water holding capacities allow a more diverse range of plant species (Theodosiou, 2009). Finally, intensive GRs (IGRs) have substrate depths above 20 cm and are also denoted as roof gardens, because a more intensive management is needed (Oberndorfer et al., 2007). Classic IGRs can perform some ecosystem services (i.e. stormwater management and energy efficiency) more efficiently, but both the construction demands (e.g. higher cost, high weight) and additional management such as irrigation, make this type less interesting in terms of sustainability (Theodosiou, 2009).

Traditionally, EGRs are designed so that natural precipitation is sufficient to ensure plant survival (Durhman et al., 2006). However, the harsh environmental conditions on EGRs pose severe constraints on vegetation development and plant diversity, particularly during summer when high temperatures prevail and water is scarce (Oberndorfer et al., 2007; Butler & Orians, 2011; Coutts et al., 2012; MacIvor et al., 2013). Furthermore, climate change will lead to a shift in seasonal precipitation (IPCC, 2014) and it may be expected that irrigation on EGRs even will become a necessity in summer in order to keep the vegetation vital (Gross, 2012; MacIvor et al., 2013; Vanuytrecht et al., 2014). Also for ensuring ecosystem services like urban heat island (UHI) mitigation, a moist substrate and hence irrigation is required in many locations (Ascione et al., 2013; Coutts et al., 2013).

Despite the eventual necessity of irrigation on GRs, there are certain drawbacks in terms of the installation of irrigation systems. The growing consensus on the urban water scarcity problem converted many cities to restrict irrigation rates on GRs (Rowe et al., 2012), especially in regions with frequent droughts like Southern Europe and Australia (Coutts et al., 2012; Ascione et al., 2013). The additional installation and maintenance costs pose another constraint to irrigation installation (Price et al., 2011).

Looking for alternative water sources and water conservation practices are essential to obtain more sustainable GR irrigation practices (Moritani et al., 2013). Sustainable irrigation is a part of the broader sustainable water management and aims at developing policies and practices that ensure functioning and healthy irrigation systems in the long term (Abernethy, 1994; Blanco-Gutiérez et al., 2013). In essence, a sustainable irrigation system should (i) be able to function properly and deliver benefits over its lifetime; (ii) not compromise other water needs; and (iii) be publicly supported (Abernethy, 1994). Knowledge on irrigation practices and specifications for GRs, especially in relation to different climates, is still limited. This chapter hence reviews the available information from scientific publications involving both GRs and irrigation. First, current irrigation techniques will be discussed and an overview of suggestions to make irrigation practices more sustainable will be given. Also public incentives regarding stormwater management will be highlighted. Thereafter, essential irrigation information from studies in which outdoor GR experiments were conducted is related to local climatic conditions in order to propose irrigation specifications for specific climates.

2. Methods

2.1. Publication search and selection

The review is based on scientific studies found through the electronic journal database ISI Web of Knowledge (consulted on 07/07/2014) using the specific search terms ‘green roofs’ and ‘irrigation’. All publication years were considered and papers had to be written in English. Both peer-reviewed scientific publications and conference proceedings were taken into account. The list of studies was further completed with publications, found through Google Scholar using the same search terms. In total 142 publications were found. The content of all documents was screened and not useful or irrelevant documents (not s.s. about GRs or irrigation or information also comprised in another paper) were omitted. After screening, the database for the review comprised 109 publications of which 94 peer-reviewed publications and 15 conference proceedings.

2.2. Data exploration

Essential information (study type, study location, topic, GR type, irrigation method and regime) was extracted to construct a database. The study type categorized the documents into general information, greenhouse experiments, model simulations and outdoor experiments. For outdoor GR experiment studies, the study location was linked to the respective climate using the Köppen climate classification (KCC, Table 6.1; Kottek et al., 2006). Both warm temperate climates (KCC: C) and snow climates (KCC: D) are represented by multiple studies, as well as the arid climate (KCC: B) in Colorado and Spain. Only tropical and polar climates were not covered by the selected publications.

In Table 6.1., the P_{th} is a threshold for dryness (in mm; Eq. 6.1) which has been introduced for the arid climate (KCC: B). It depends on the annual temperature and precipitation cycle (Kottek et al., 2006):

$$P_{th} = \begin{cases} 2 * \{annual\ T\} & if \ \geq \frac{2}{3} of\ annual\ P\ in\ winter \\ 2 * \{annual\ T\} + 28 & if \ \geq \frac{2}{3} annual\ P\ in\ summer \\ 2 * \{annual\ T\} + 14 & if\ otherwise \end{cases} \quad \text{(Eq.6.1)}$$

Irrigation methods and regimes were summarized for the outdoor experiments and greenhouse and model simulation studies (Appendix 6.1). If relevant, the minimum daily summer irrigation requirement (I_{day}) was calculated. When irrigation regimes were given in mm, the minimum value was converted directly to l/m², but when volumetric regimes were provided, the value was first divided by the GR dimensions (length x width) to obtain a value in l/m². Then this value was divided by the irrigation frequency (in days) to obtain the final I_{day}. This allowed comparison of water requirements specified in different studies.

Fig. 6.1 suggests that research regarding GRs and irrigation is growing. Before 1999, no studies were found with the search terms ‘green roofs’ and ‘irrigation’. The first four publications, used in this review (Argue & Pezzaniti, 1999; Velazquez, 2003; Kolb, 2004 and Monterusso et al., 2004), were all conference proceedings, after which many publications emerged.

Table 6.1 Summary of Köppen Climate Classification codes (KCC) covered by the studies collected in this review. (T: temperature in °C; P: precipitation in mm).

KCC	Description	Region examples	# of studies
Bsk	Cold steppe climate / Dry semi-arid Annual T < 18°C; annual P > 5*P_{th}	US (Colorado), Spain	3
Cfa	Warm temperate climate with hot summer, fully humid / Subtropical −3 ◦C < T_{min} < 18 ◦C; T_{max} ≥ 22 ◦C	US (Texas, Alabama, Florida), Japan, China (Shanghai)	6
Cfb	Warm temperate climate with warm summer, fully humid / Marine Annual T < 22°C; −3°C < T_{min} < 18°C; at least 4 months with T ≥ 10°C	UK, Canada (Vancouver)	4
Csa	Warm temperate climate with dry, hot summer / Interior Mediterranean −3°C < T_{min} < 18°C; T_{max} ≥ 22°C; winter P_{max} > 3*summer P_{min}	Greece, Israel	11
Csb	Warm temperate climate with dry, warm summer / Coastal Mediterranean −3°C < T_{min} < 18°C; at least 4 months with T ≥ 10°C; winter P_{max} > 3*summer P_{min}	US (Oregon), Australia (Adelaide)	5
Cwa	Warm temperate climate with wet, hot summer and dry winter −3°C < T_{min} < 18°C; T_{max} ≥ 22°C; summer P_{max} > 10*winter P_{min}	China (Hong Kong)	3
Dfb	Snow climate, warm summer, fully humid / Continental T_{min} ≤ −3°C; T_{max} ≤ 22°C; at least 4 months with T ≥ 10°C	US (Massachusetts; Michigan), Canada (Toronto, Nova Scotia; Kelowna), Germany	17
Dwa	Snow climate with hot summer, dry winter / Moist continental T_{min} ≤ −3°C; T_{max} ≥ 22°C; summer P_{max} > 10*winter P_{min}	China (Beijing), Korea	2

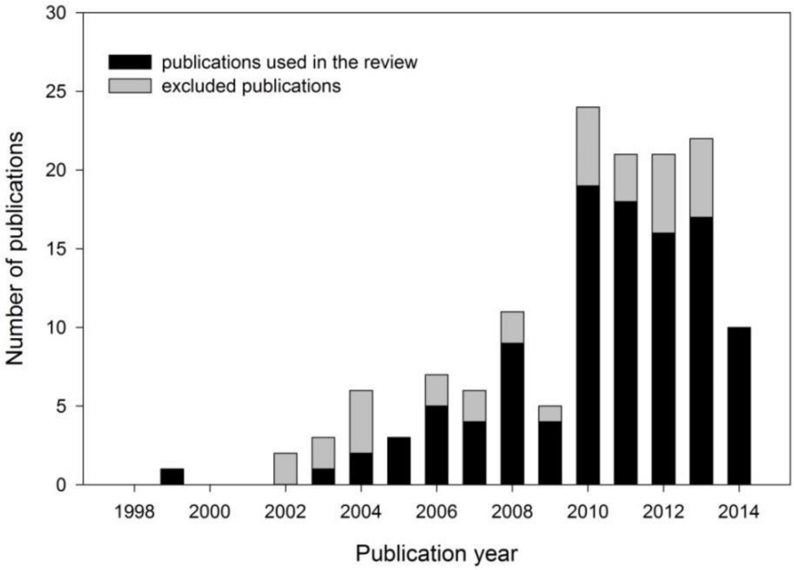

Fig. 6.1 Stacked bar chart showing the evolution in time of the number of publications on GRs and irrigation. Both publications used in the review (n = 109) and excluded publications (n = 33) after screening (because not useful or irrelevant) are shown.

Although the modern GR technology was founded in Northern and Central Europe, only 21.10% of the studies used in this review originate from this continent (Table 6.2). The majority of the studies were conducted in North America (44.04%), especially in the US (40 studies, 15 from the state Michigan). In Asia and Oceania, respectively China and Australia are the countries in which GR research is progressing. In South America, only one study could be found (Vieira et al., 2013) and no studies were found in Africa.

As regards the main topics, only five publications (4.72%) just consider the subject irrigation (Fig. 6.2). The largest part of the publications involved the topics: vegetation performance (35.85%), energy and thermal performance (27.36%) and stormwater management (19.81%). Fig. 6.3 shows that most of the studies were published in scientific journals covering environmental themes like horticulture (HortScience, n = 12), urban ecology and ecosystems (Urban Forestry and Urban Greening, n = 9; Ecological Engineering, n = 8; Urban Ecosystems, n = 6), and building science and energy use (Building and Environment, N=6; Energy and Buildings, n = 5). This suggests that the subjects GRs and irrigation have a wide support base and are of particular interest to ecologists, engineers, designers and policy makers.

Table 6.2 Overview of the continents and countries in which the studies used in the review were conducted. Number of publications and relative frequency indicate where research regarding GRs and irrigation is situated. (NA: not applicable)

Continent	Country	Number of publications	Relative frequency (%)
Oceania		**8**	7.34
	Australia	6	
	New Zealand	2	
Asia		**13**	11.93
	China	7	
	Japan	3	
	Korea	1	
	Israel	2	
Europe		**23**	21.10
	UK	8	
	France	2	
	Germany	2	
	Greece	8	
	Italy	2	
	Spain	1	
South America		**1**	0.92
	Brazil	1	
North America		**48**	44.04
	unknown	3	
	Canada	5	
	US	**40**	
NA		**16**	14.68

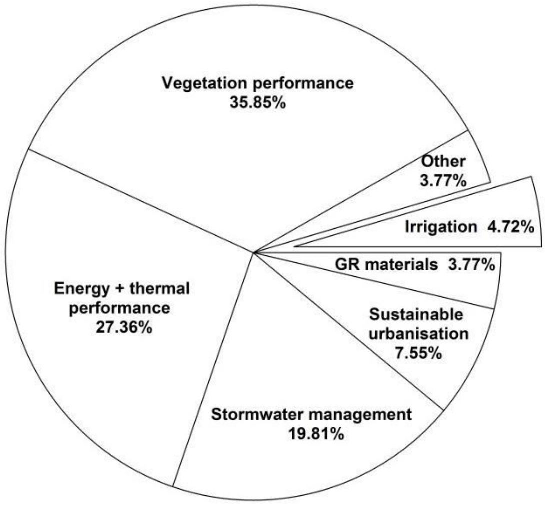

Fig. 6.2 Diagram showing the main topics of the 109 publications used in this review.

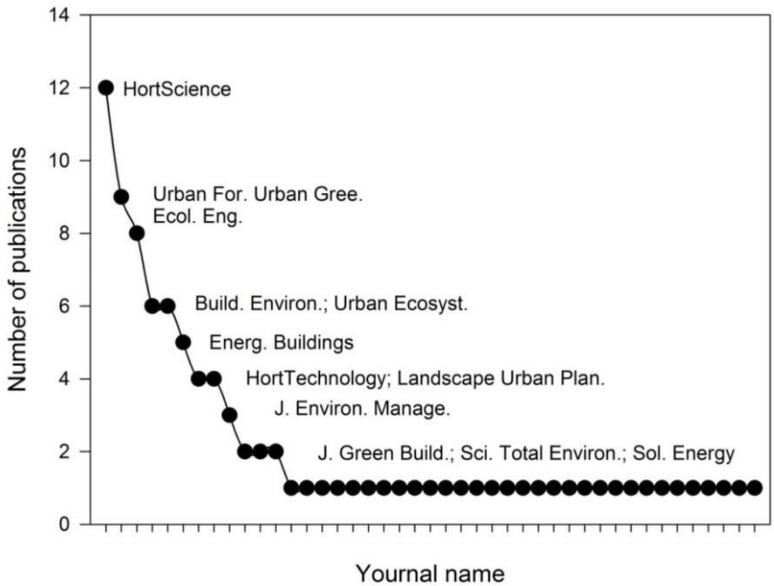

Fig. 6.3 Graph showing the scientific journals in which the publications used in this review (N = 109) were published. Journals are ranked according to the number of publications they represent (in decreasing order).

3. GR irrigation practices and stormwater management regulations

3.1. Current GR irrigation practices

A GR comprises multiple layers that protect the underlying roof and support the vegetation, but the water storage capacity is limited due to physical and economic factors (FLL, 2008). The substrate is the main water storage layer, but water can also be retained in the drainage layer (Theodosiou, 2009) or if present, the water retention layer (WRL), which is a mat from mineral wool or polymeric fibers (1-6.5 cm thick) under or above the drainage layer (Grant, 2007). For EGRs, additional irrigation is often suggested during plant establishment as early drought can be very harmful for further plant establishment, performance and survival (Getter & Rowe, 2006; Nagase & Dunnett, 2010; Thuring et al., 2010). Permanent irrigation would not be necessary after establishment if the EGR is properly designed in terms of plant selection, substrate type and depth, and if sufficient water from precipitation is available (VanWoert et al., 2005a; Getter & Rowe, 2006). Next to improved plant growth and survival under dry conditions (Butler & Orians, 2011; Price et al., 2011), irrigation can be beneficial in other ways as well. Less drought stress implies that more variation in plant species is possible (Köhler, 2006). Irrigation also influences temperature control to a great extent, as moist substrates improve evaporation which mitigates air and building temperatures and hence decreases cooling costs (Theodosiou, 2009; Castleton et al., 2010; Price et al., 2011; Rowe, 2011). The model of Bass et al. (2003) for example, indicated that irrigated GRs can reduce the temperature of a large part of the city of Toronto with 1°C. Furthermore, considering an irrigation system during the GR design phase is less expensive compared to the need of replanting dead plants during the annual maintenance period (Price et al., 2011; MacIvor et al., 2013), an action which should be added to the average maintenance cost (e.g. 1.28 €/m² per year; Porsche & Köhler, 2003; Eastside Sustainability, 2004). It is also less expensive compared to an air conditioning installation. Sun et al. (2014) calculated the costs of different irrigation strategies under the current prizes of water and electricity in Beijing (respectively 0.44 €/m³ and 0.06 €/KwH). An irrigated GR of 100 m² with an irrigation control limit of 0.3 m³/m³ can save 14 € over a 3-month period compared to a non-irrigated but air conditioned building with a moderate performance coefficient (Sun et al., 2014). Notwithstanding these positive effects, less positive effects of irrigation include a decrease in stormwater performance as moist substrates can retain less water during a precipitation event (Spolek, 2008; Schroll et al., 2014b). There is also an increased probability of weed establishment on irrigated GRs, especially when the proportion of bare ground is still high (Schroll et al., 2011a). Furthermore, under saline irrigation (e.g. when secondarily treated municipal wastewater is used) salt accumulation may lead to salinity stress and reduced ET (Moritani et al., 2013). Irrigation is also considered unsustainable in regions with water scarcity or when potable water is used (Moritani et al., 2013; Rowe et al., 2014). In the US for example, almost every region has experienced water shortages over the last five years (EPA, 2008). Globally, water consumption has tripled over the last 50 years, and an increase in water demand has been registered in almost every country (WWAP, 2012). It is expected that by 2030, half of the world's population will be living in water stressed areas (UNEP, 2007). Therefore, the government does not financially support GR installation in many countries with a semi-arid climate, hence opposing the expansion of the GR industry (Ntoulas et al., 2013).

In Northern and Central Europe, the GR technology follows the guidelines of 'The Landscape Development and Landscaping Research Society' (FLL, 2008). These however, provide only little information regarding irrigation specifications. The main irrigation methods suggested in the FLL guidelines are 1) a (spray) hose or sprinkler system; 2) drip lines; 3) overhead irrigation systems and 4) automated irrigation systems with in-built reservoirs (FLL, 2008). In the context of vegetable cultivation on GRs (i.e. lettuce, chicory and endive), Cho et al. (2010) studied the following irrigation methods: water retained in the drainage layer, irrigation through a wick, and drip irrigation. The water holding capacity (WHC) of the substrate was highest when using drip irrigation, but wick irrigation proved to be more efficient for plant growth because the water content in the substrate remained constant for a longer time (Cho et al., 2010). Rowe et al. (2014) suggested that wick irrigation, followed by drip irrigation, are good options for GRs with plug plants, as these types of irrigation mainly provide water at the plant root zone in close proximity to the wick or drippers. However, they might not be the ideal choice for more traditional EGRs where a large vegetated surface consisting of pre-vegetated mats, seeded species or succulents, needs to be irrigated. Combining drip irrigation with an additional WRL could improve irrigation efficiency. Overhead irrigation may be a better choice, as it distributes water more uniformly and leads to higher substrate WHC, less runoff, and better plant growth and health compared to drip irrigation (Rowe et al., 2014).

3.2. Optimizing irrigation practices

Different water conservation strategies have been proposed that enable sustainable irrigation of green areas (Chang et al., 2011). These strategies can be categorized into (1) adaptation of irrigation requirements; (2) alternative irrigation sources and (3) control and monitoring of irrigation regimes (Table 6.3). All strategies can be implemented separately or simultaneously, depending on both design and financial project considerations.

First of all, water can be conserved by targeting the GR vegetation. As indicated before, GRs are mainly designed with drought tolerant vegetation, also called xeriscaping (Carter & Keeler, 2008). Succulent plants are not only drought tolerant, they can also act as nurse plants for other less drought tolerant plants through facilitation, i.e. by reducing the substrate temperature and evaporation rate (Butler & Orians, 2011). Also many mosses can act as facilitators, and they are very well suited to survive harsh environmental conditions, can store a considerable amount of rainwater and only need a thin substrate (Anderson et al., 2010). Alternatively, one could think of GRs with wetland species as these species have an excellent WHC and can effectively decrease surface temperatures (Song et al., 2013). Over an entire growing season, wetland plants only need 20% of the water needed to irrigate traditional EGRs, which makes them more sustainable and less costly. Wetland plants are easy to propagate and they are effective in cooling buildings because of their high transpiration rates. The two macrophyte species tested by Song et al. (2013), *Iris laevigata Fisch.* and *Iris pseudoacorus L.,* proved to be rather stress tolerant, as they could survive both after three weeks of flooding and two weeks of drought. The main problem that withholds wetland GRs from being implemented is their increased weight compared to traditional EGRs, together with a potential pest problem associated with standing water (Song et al., 2013). Another strategy to adapt irrigation requirement is by optimal design of GR materials, by for example developing GR substrates with higher water holding capacities (Table 6.4).

Addition of sandy loam soil and use of amended soil (i.e. mix of red gravel, vermiculite and bark compost), perlite based substrates, foam sheets and fiberglass can all improve the WHC of the GR system (Elstein et al., 2008; Harp et al., 2008; Nektarios et al., 2011; Kotsiris et al., 2013; Papafotiou et al., 2013; Kanechi et al., 2014). Some water holding additives, like hydrophilic gels, are also currently explored (Williams et al., 2010; Sutton et al., 2012). Alternatively, a WRL retains additional runoff and hence available water for GR vegetation (VanWoert et al., 2005a-b; Bianchini & Hewage, 2012; Guo et al., 2014). This layer has been shown to be crucial to plant survival in semi-arid climates (Santamouris et al., 2007; Benvenuti & Bacci, 2010; Guo et al., 2014) but also in other climates, the irrigation requirements can be significantly reduced. In Vancouver (Canada), summer irrigation decreased from 54.4 to 8.6 mm by adding a WRL, and in subtropical Shanghai (China), the WRL suppressed the need of additional irrigation completely (Roehr & Kong, 2010).

A second way to conserve water is by finding alternative irrigation sources. For example gray water, which is the waste water from in and around the house (except water originating from toilet flushing, dishwashers and kitchen sinks), could be reused for irrigation purposes (Gill et al., 2007; Carter & Keeler, 2008; Williams et al., 2010; Chang et al., 2011; Sutton et al., 2012; Ouldboukhitine et al., 2014). In Sweden for example, gray water, together with black water, currently accounts for 58% of the yearly water discharge into wastewater treatment plants (Semadeni-Davies et al., 2008). By making use of this gray water, potable water consumption of a household can be reduced by 31%, and there is less pressure on the city's sewage system (Chang et al., 2011). However, if the gray water is clean enough to sustain GRs in the long term is still unclear. Ouldboukhitine et al. (2014) showed that the thermal performance of GRs decreased with approximately 30% when irrigated with gray water instead of clean water, as the chemical products in the gray water, like lactic acid, cellulose and glycerol, affected the plant's activity and hence transpiration processes.

Table 6.3 Summary of water conservation strategies, categorized into (1) adaptation of irrigation requirements; (2) alternative irrigation sources and (3) control and monitoring of irrigation regimes. Most important positive and possibly negative aspects are listed per strategy.

1. IRRIGATION REQUIREMENTS	
GR VEGETATION	
Xeriscaping including *Sedum spp*. and moss	Wetland GRs
+ Drought tolerant	+ High WHC
+ Encourage biodiversity through facilitation processes	
	+ Good thermal performance of roof
	+ Stormwater management
	- Increased weight
	- Pest problem
GR MATERIALS	
Substrate with higher WHC	Additional water retention layer (WRL)
+ Many possibilities	+ Stormwater management
- Under study	
2. IRRIGATION SOURCES	
Gray water	Rainwater harvesting (RWH)
+ Reduction potable water consumption	+ Clean enough
+ Less pressure on sewage system	+ Stormwater management
- Clean enough to ensure GR performance in the long term?	- Cost rainwater tanks
3. CONTROL + MONITOR IRRIGATION REGIMES	
Timed irrigation	
+ Based on meteorological factors and/or substrate moisture sensors	
+ Smart controller turns irrigation on when necessary	
- Still under study	

Another possibility is rainwater or stormwater harvesting (RWH), in which runoff is collected and stored (Gill et al., 2007; Coutts et al., 2012). Runoff harvested from GRs themselves has been shown to be sufficiently clean to be reused for urban irrigation (Argue & Pezzaniti, 1999; Razzaghmanesh et al., 2014a). By passing through the substrate, the GR runoff pH increases from approximately 5.5 to 7.5, hence slightly mitigating acid rain (Czemiel Berndtsson, 2010). The GR runoff also has an elevated amount of suspended solids and a higher turbidity, which will decrease over time (Morgan et al., 2011). Besides being an irrigation source, RWH helps to control floods and reduces erosion and stormwater pollution (Chang et al., 2011; Price et al., 2011; Sheng et al., 2011; Wittinghill & Rowe, 2011; Hardin et al., 2012; Islam et al., 2013). There are many ways to harvest rainwater, including rainwater tanks or cisterns, constructed wetlands and treatment trains (Coutts et al., 2012; Hardin et al., 2012). In the latter method, the rainwater passes a bio-filtration system and is stored in a tank. Sometimes, underground aquifers can be recharged with the bio-filtrated rainwater, a process also called Aquifer Storage and Recovery (Argue & Pezzaniti, 1999; Coutts et al., 2012). By installing a rainwater tank on a GR, the total annual stormwater retention increased from 43 to 87% in Florida (Hardin et al., 2012). In Brasil, the potential of RWH has also been acknowledged, although the installation of rainwater tanks still causes some concern as a considerable area is required, which is expensive in urban areas (Vieira et al., 2013). A GR of 100 m^2 for example, would require a reservoir volume of 15.60 to 101.67 m^3, depending on the region (Vieira et al., 2013).

In the third category, irrigation quantity can be minimized through monitoring and controlling of irrigation regimes (Sutton et al., 2012; Guo et al., 2014). Meteorological factors, mainly relative humidity and number of sunshine hours as they affect the water consumption the most, are important to consider for GR irrigation systems (Feng et al., 2012). Water requirements could be calculated by using ET data and precipitation information (Bean & Pitt, 2012; Feng et al., 2012; Stovin et al., 2013), or by studying substrate moisture with sensors (Jim & Peng, 2012a-b; Sutton et al., 2012). Depending on the local climate, it is often possible to use irrigation only during establishment and during prolonged drought (Sutton et al., 2012). Otherwise, irrigation should be turned on when the substrate moisture drops below a specified level, like the stress point (transition between readily available water in the substrate’s larger pores and less available water in the small pores; Jim & Peng, 2012b). Irrigation can be controlled using a smart controller, which turns on when necessary (at night or when soil moisture drops below the stress point) but deactivates when rainfall is registered (Hardin et al., 2012; Ascione et al., 2013; Sun et al., 2014). Ascione et al. (2013) are currently investigating a multivariable controller for irrigation and ET management, which takes both solar radiation and relative air humidity into account. Furthermore, best management practices for monitoring and managing irrigation are examined by Lea-Cox et al. (2010). Their work includes the development of sensor networks and software to control irrigation at the species level.

Table 6.4 Summary of water holding capacity (WHC) values advised by the FLL guidelines (FLL, 2008) and of alternative substrate materials tested in different GR studies. The WHC indicates the ability of a material, in compacted condition, to hold water, and is generally expressed as the water content of a substance after initial water saturation followed by a 2-hour dripping period (FLL, 2008).

Reference	Materials	WHC	Unit
FLL, 2008	General IGR substrate	≥ 45 (max 65)	% vol.
	General EGR substrate	≥ 35 (max 65)	% vol.
Elstein et al., 2008	Potting soil	394[a]	% DW
	Petrochemical-based hydrophilic foam sheets	1994[a]	% DW
	Fiberglass mats	1804[a]	% DW
Harp et al., 2008	Open cell foam	56.5	% vol.
	Polyurethane foam	71.9	% vol.
	Synthetic sponge	65.9	% vol.
	Sand	36.3	% vol.
	Peat moss-bark-sand 3:1:1	51.9	% vol.
	GR substrate	30.3	% vol.
Nektarios et al., 2011	Soilless substrate	37[b]	% vol.
	Substrate with sandy loam soil	38[b]	% vol.
Kotsiris et al., 2013	Pumice-peat-zeolite 65:30:5	25[b]	% vol.
	Pumice-compost-zeolite 65:30:5	30[b]	% vol.
	Sandy loam soil-perlite-zeolite 30:65:5	35[b]	% vol.
Papafotiou et al., 2013	Grape marc compost-soil-perlite 2:3:5	32[b]	% vol.
	Peat:soil:perlite 2:3:5	30[b]	% vol.
Kanechi et al., 2014	Amended soil	58.7	% vol.
	Furnace bottom ash	43.8	% vol.

[a] WHC on a dry weight (DW) basis = [(saturated weight - DW) / DW] *100
[b] WHC at 50 cm tension

Next to water conservation strategies, many cities also aim at saving energy, as the energy required for heating and cooling buildings is expensive (Chang et al., 2011). Solar shading end evaporative cooling are two ways to mitigate urban temperatures and hence the need for heating or air conditioning (Santamouris et al., 2007; Chang et al., 2011). GRs play an important role in improving thermal comfort, especially during the day (Gross, 2012; Kolokotsa et al., 2013) and when the climate is not very hot (KCC: Cfb or Dfb; Sailor, 2008; Sailor et al., 2011; Ascione et al., 2013). But in order to maintain the reduced energy demand during summer, irrigation is needed to keep the substrate moist (Sailor et al., 2011; Kolokotsa et al., 2013; Li et al., 2014). Therefore, other solutions to save energy are investigated in warm to hot climates. Cool roofs (also referred to as reflective or white roofs) for example, are considered a good alternative (Ascione et al., 2013; Kolokotsa et al., 2013; Santamouris, 2014). This roof type can decrease the total daily heat flux by around 80% compared to a traditional (black) bitumen roof, while GRs decrease the daily heat flux by 52% (Scherba et al., 2011). However, the performance of cool roofs is strongly hindered by factors like dirt accumulation, acid rain and UV radiation (Li et al., 2014; Santamouris, 2014), and compared to GRs, cool roofs do not contribute to stormwater management, aesthetics or habitat value.

3.3. Examples of stormwater management regulations

Next to the water conservation and energy saving strategies described above, public authorities can develop regulations involving stormwater management (Carter & Keeler, 2008). For example, in several countries, building owners need to pay a fee for the quantity of runoff that runs into the sewer system. If green infrastructure elements like GRs are installed, the owner can be exempt from paying this fee (Carter & Keeler, 2008). In Portland (OR), building height restrictions are attenuated if a building owner has a floor-area ratio (FAR) bonus. By definition, the FAR is the ratio of the total floor area of the building to the area of its zoning lot, which is the basic unit for zoning regulations (NOAA, 2012). The bonus can only be obtained if a GR is installed and irrigation regulations (≤ 12.7 mm every 10 days during establishment; ≤ 6.35 mm every 10 days after establishment) are met (Schroll et al., 2011a). In the US, it is also possible for building owners to obtain a Leadership in Energy and Environmental Design (LEED) certificate if GRs without irrigation or using gray water or recycled water for irrigation are installed (Grant, 2007; Carter & Keeler, 2008). A University in Atlanta (Georgia, US) for example, obtained a LEED certificate by applying multiple sustainable practices, including controlled irrigation, RWH, and gray water recycling for irrigation, toilet flushing, sinks and showers. This way, the total water consumption was already reduced by 12% from 2007 to 2009 (Lynch & Dietsch, 2010). A last incentive worth mentioning is the Water Sensitive Urban Design (WSUD), which is applied in amongst others Australia to restrict water use and retain water in the urban landscape (Coutts et al., 2012). Technologies that fall within the WSUD include RWH for irrigation, bio-retention systems, treatment wetlands and GRs and green walls (Coutts et al., 2012; Razzaghmanesh et al., 2014a).

4. Irrigation specifications for GRs in different climatic contexts

4.1. Dry semi-arid climates

For GRs in dry semi-arid or steppe climates (KCC: Bsk) it is strongly advised to install an irrigation system. Coutts et al. (2013) conducted a study in Melbourne (Australia) with unirrigated SEGRs and concluded that the ET potential of the succulent vegetation was low and those GRs only slightly offered any thermal benefit. Irrigation is hence necessary in order to mitigate both the UHI effect and surface heating during hot summer days, by stimulating evaporative cooling (Voyde et al., 2010; Coutts et al., 2012; Jim, 2012; Coutts et al., 2013). One condition is that GR vegetation should consist of plant species with elevated transpiration rates, like for example grasses, which constitute together with shrubs, the main vegetation in these steppe climates (Nektarios et al., 2011; Jim, 2012; Coutts et al., 2013). If irrigation is not possible, then only succulent species should be used, as their probability of survival during and recovery after summer drought is more likely compared to herbaceous vegetation (Bousselot et al., 2011). Possible irrigation techniques are drip irrigation or overhead rotator systems, which should be active during growing seasons and especially summer (Bousselot et al., 2010; Pérez et al., 2012; Table 6.5). When vegetation is well-established, an irrigation regime of 6.4 mm per week, or 0.91 l/m² per day for an EGR with substrate depth of 10 cm can be sufficient to support a variety of plant species, including *Antennaria parvifolia* and the grass *Bouteloua gracilis*, two species native to the Rocky Mountains region (Bousselot et al., 2010).

4.2. Warm temperate climates: subtropical and marine regions

In warm temperate regions with hot summers and sufficient annual rainfall (KCC: Cfa), GRs are very beneficial in terms of improving thermal comfort during summer (Dvorak & Volder, 2013). It has been shown by Dvorak and Volder (2013) that this benefit can even be achieved on unirrigated GRs with succulent vegetation. The results of their study, conducted in Texas, were comparable to results of studies on irrigated GRs in the same climate (Sonne, 2006; Simmons et al., 2008). Unirrigated GRs are the most sustainable option but the vegetation is limited to succulents. By providing a minimum irrigation regime, the range of potential plant species can be widened, while decreasing soil temperature and hence the thermal benefit (Provenzano et al., 2010; Price et al., 2011). Subsurface capillary irrigation and drip irrigation are two possible irrigation methods (Price et al., 2011; Kanechi et al., 2014; Table 6.5). During summer and after establishment, daily watering with 500 ml (or 0.62 l/m² for a 10 cm EGR) favored the growth and flowering of *Evolvulus pilosus* (a non-native but common ornamental groundcover plant in Japan) compared to watering every other day (Kanechi et al., 2014). Other ornamental species like *Thymus serphyllum* and *Petunia x hybrid*a can be used as GR plants when irrigated with 5 l of water every two days, or 6.17 l/m² daily (Sendo et al., 2010). To prevent waste of water, irrigation should be turned off on days when more than 5 mm of rain is predicted (Sendo et al., 2010; Aithkenhead-Peterson et al., 2011; Kanechi et al., 2014).

When the climate is rather marine, with warm summers and fully humid (KCC: Cfb), typical for the UK, irrigation is generally unnecessary (Nagase & Dunnett, 2010). Even on unirrigated EGRs, various plant species and vegetation type options exist, like an annual meadow on 7 cm substrate depth (Nagase & Dunnett, 2013b). Also geophytes like *Iris bucharica, Muscari azureum* and *Tulipa humilis,* non-native to the UK but suitable for GR purposes, can survive without irrigation in only 5 cm substrate depth (Nagase & Dunnett, 2013a). However, plant growth can be improved by increasing substrate depth (Fassman & Simcock, 2012), or with a limited amount of irrigation once a week in summer or when substrate moisture drops below 15%. This can be done manually or by means of a drip irrigation system (Dunnett et al., 2008; Nagase et al., 2013; Nagase & Dunnett, 2013b).

4.3. Warm temperate climates: Mediterranean regions

In Mediterranean regions with dry, hot summers (KCC: Csa), GRs could provide great thermal benefits (Jaffal et al., 2012), but irrigation is necessary in these regions for establishment, survival and success of EGR plants especially during dry summers (Benvenuti & Bacci, 2010; Williams et al., 2010; Kotsiris et al., 2013; Ntoulas et al., 2013; Schweitzer & Erell, 2014). Without irrigation, one should think of IGRs with substrate depths over 20 cm, or alternatively select the most drought tolerant plant species (VanWoert et al., 2005a; Benvenuti & Bacci, 2010; Schweitzer & Erell, 2014).

Succulent species are generally considered as the best vegetation option, but even these stress tolerant species have difficulties to survive the hot dry summers in Australia on EGRs if no irrigation system is provided (Williams et al., 2010). Sometimes, increasing substrate depth is sufficient to maintain the plant's growth and physiological status during drought (Ntoulas et al., 2013). Nektarios et al. (2011, 2012) found that the non-native turfgrass *Zoysia matrella 'Zeon'* performed best in SEGRs with 15 cm substrate depth compared to 6 cm deep EGRs. The water requirement of turfgrass was based on the reference ET or pan evaporation (ETo), and ranged from 15% ETo every 10 days (Nektarios et al., 2012) to 80% every 3 days (Nektarios et al., 2011; Table 6.5). Growth and physiological status of turfgrass were only slightly influenced by irrigation (Ntoulas et al., 2013), although irrigation greatly improved the plant's color (Nektarios et al., 2012). Likewise for *Dianthus fruticosus*, native to the Mediterranean region, irrigation during drought did not result in better growth (Nektarios et al., 2011). Other studies point at a considerable water quantity needed to ensure plant survival in these Mediterranean regions. In a study of Schweitzer and Erell (2014) in Israel, the water requirement of the tested species in 5 cm deep EGRs ranged from 3-6 l/m² per day for the South-African Mediterranean succulent species *Aptenia cordifolia* to 7-9 l/m² per day for the tropical East-African drought tolerant grass species *Pennisetum clandestinum*. Although many xerophytic Mediterranean species have potential to be used on GRs in this climate (Benvenuti & Bacci, 2010; Chapter 2 and 3), more research is needed to determine minimal irrigation requirements and optimal substrate depth (Schweitzer & Erell, 2014). Irrigation can be applied manually or by automated drip irrigation (Table 6.5). For EGRs, the best irrigation regime in summer is daily watering until saturation (Pearlmutter & Rosenfeld, 2008; Ntoulas et al., 2012, 2013). Alternatively, irrigation can be applied at a minimum daily quantity of 1.2 l/m² (Santamouris et al., 2007), 1 l/m² (Ntoulas et al., 2012), or 1.96 l/m² (Papafotiou et al., 2013). On IGRs with a substrate depth of 30 cm, a daily quantity of 2.08 l/m² would be required (Kotsiris et al., 2013). Another possibility relevant in Mediterranean climates during summer is to leave the GR unvegetated and only wetting the substrate, which is efficient in terms of evaporative cooling of the roof surface (Pearlmutter & Rosenfeld, 2008). Although plants provide cooling through transpiration and substrate shading, they also prevent soil evaporation and hence reduce the potential of the GR to cool buildings. Without the vegetation layer, the plant-specific irrigation requirement is solved, and their shading function can be replaced by other covering materials (Pearlmutter & Rosenfeld, 2008). However, other beneficial aspects of vegetated roofs, including habitat provision and aesthetic value, are eliminated.

Coastal Mediterranean areas (KCC: Csb) have dry summers but are slightly cooler than interior Mediterranean regions. This is represented in the GR irrigation requirements, as it is possible to install unirrigated GRs in this climate, especially if only succulent species are applied (Nagase & Dunnett, 2010; Razzaghmanesh et al., 2014b). Next to succulents, also geophytes and rhizomatous forbs can be used on unirrigated EGRs in Oregon (Schroll et al., 2011a). In addition, the adapted life cycle dynamics of annual species make them useful for unirrigated GR application in this climate, as they will contribute to GR ecosystem services during periods with sufficient rainfall (cf. Chapter 2 and 3). Also mosses require very little water in summer (Anderson et al., 2010; Table 6.5). In other studies, irrigation is advised throughout the summer to ensure survival of non-succulent species with different life forms (Monterusso et al., 2005; Schroll et al., 2011a-b; Rowe et al., 2012; Razzaghmanesh et al., 2014b). The discussion whether or not to irrigate GRs in coastal Mediterranean climates depends on the main goal for which the GR was designed. A more diverse vegetation is preferred in terms of habitat- and biodiversity value (Nagase & Dunnett, 2010; MacIvor & Lundholm, 2011), but summer irrigation is required, which in turn reduces the GR's stormwater retention potential and also increases weed pressure (Schroll et al., 2011a, 2011b). If irrigation is opted for, it could be done in the early morning (4-5 AM) by use of a sprinkler system, which provides 2.3 l/m² of water per day during the growing season for a 12.5 cm EGR (Table 6.5). For Portland specifically, where the FAR bonus regime is implemented, the maximum summer irrigation is 45.7 l/m² every 5 days (Schroll et al., 2011a-b; Table 6.5). This regime is much higher than the one used by Razzaghmanesh et al. (2014b), which was only 11.1 l/m² every 10 days.

4.4. Warm temperate climates: regions with wet, hot summers and dry winters

Finally, in warm temperate climates characterized by wet, hot summers and dry winters (KCC: Cwa) like Hong Kong (China), irrigation is not essential, but it can mitigate the temperature fluctuations of the building. An EGR can be watered optimally by an automatic sprinkler system with an irrigation regime of 5 l/m² daily (Jim & Tsang, 2011; Jim & Peng, 2012a-b; Table 6.5). The irrigation requirement can be reduced by selecting more drought tolerant species, by a deeper substrate or an additional WRL.

4.5. Snow climates

Multiple studies have been conducted in fully humid snow climates with warm summers (KCC: Dfb). Unirrigated EGRs are possible if succulent species are used, but geophytes (e.g. *Allium cernuum*) and other perennial plants, all native to Michigan, like *Coreopsis lanceolata* and *Tradescantia ohiensis* are useful as well (Monterusso et al., 2005; Rowe et al., 2006; MacIvor & Lundholm, 2011). Like in the climates previously discussed, a more diverse plant community is preferred for several reasons. Furthermore, in this climate, *Sedum spp.* can suffer from freezing injury in winter (Durhman et al., 2006; Benvenuti & Bacci, 2010). Other non-succulent drought tolerant plants can be applied if some irrigation is provided, when substrate depth is increased, organic material (OM) is added to the substrate, or when the GR is situated in the shade (Monterusso et al., 2005; Durhman et al., 2006; Köhler, 2006; Rowe et al., 2006; Getter et al., 2009a; Dvorak & Volder, 2010; Thuring et al., 2010; Getter et al, 2011; Sutton et al., 2012). Every year during the growing season, the vegetation on EGRs will face some drought stress, and it is normal that some plants die. This is one reason more to diversify the GR vegetation, including annual species that can fill in the bare spots in the substrate, and some succulents that help neighboring species survive drought (Köhler, 2006; Butler & Orians, 2011). MacIvor et al. (2013) showed that by irrigating EGRs, plant diversity is maintained, although no effect on cover and biomass was found. So in the case that the irrigation system has to be turned off, an EGR with high plant diversity will not undergo any significant visual changes. Many irrigation methods are possible, from initial hand watering to automated overhead irrigation (Table 6.5). Except for the establishment phase and the first growing season, irrigation is not provided in most studies (VanWoert et al., 2005b; Monterusso et al., 2004, 2005; Rowe et al., 2006, 2012; Getter & Rowe, 2008, 2009; MacIvor & Lundholm, 2011). In other studies, GRs are watered when necessary, eventually controlled with a moisture sensor (Durhman et al., 2007; Lundholm et al., 2010; Carpenter & Kaluvakolanu, 2011; Getter et al., 2011; MacIvor et al., 2013).

Very little information was found from studies conducted in snow climates with hot summers and dry winters (KCC: Dwa). Generally, GRs are very beneficial in this climate in terms of thermal performance (He & Jim, 2010). One study tested the potential of wetland GRs in Korea (Song et al., 2013) and concluded that less irrigation is necessary than on traditional GRs. Feng et al. (2012) investigated the most important meteorological factors to determine GR irrigation regimes in Beijing (China). In this context, relative humidity and number of sunshine hours appear to be more important than rainfall and temperature. Their experimental GRs received a minimum additional water quantity of 0.71 l/m² daily in July for a 10 cm EGR and 1.24 l/m² for a 20 cm IGR.

5. Concluding remarks

Irrigating GRs and other urban landscapes is often considered an unsustainable practice, mainly because of the installation and water cost, but also due to competition with other water needs, e.g. for agriculture or consumption (Abernethy, 1994). Watering urban vegetation however, also provides socio-economic and environmental benefits, by ensuring plant survival and related aesthetic aspects of the GR, as well as by improving ET and hence thermal comfort. To ensure sustainable irrigation in the long term, there should be public awareness of sustainable water consumption, and GRs should be designed carefully, without wasting any water and limiting the use of potable water. Potential solutions are gray water re-use, RWH, controlled irrigation in space and time (using for example a smart controller) and the addition of a WRL (Coutts et al., 2012; Razzaghmanesh et al., 2014a; Sun et al., 2014). Also an appropriate selection of vegetation is needed, with a diverse mix of life forms including succulents, geophytes, mosses, annual species and drought-tolerant herbs (Coutts et al., 2012). Ideally, a deeper substrate should be opted for to increase the plant water availability, but as this is not always possible due to building weight limitations and colonization of undesirable weeds, shrubs and invasive plants, efficient irrigation methods should be considered as an alternative. If irrigation is really impossible due to for example governmental restrictions, then a reflective roof could be opted for to provide thermal cooling, although this type of roof does not have the capacity to reduce stormwater runoff. By considering substrate type, depth, vegetation and irrigation regime during the design process, an adaptive approach is created in which GR establishment and sustainability can be facilitated (Kotsiris et al., 2013; Ntoulas et al., 2012, 2013).

Multiple irrigation methods are possible, of which drip irrigation and overhead sprinkler systems are the most commonly applied on GRs. Hand watering is possible as well, but extremely time consuming and only possible for small surfaces. The best way to irrigate is automated overhead irrigation or drip irrigation if an additional WRL is provided (Rowe et al., 2014).

During the establishment phase and the first growing season throughout summer, it is advised to use irrigation on all GR types and climates. Afterwards, irrigation is only necessary on EGRs in (semi)-arid climates (KCC: Bsk and Csa). Installation of EGRs with a substrate depth below 10 cm is discouraged in these climates, as both a deeper substrate and irrigation are necessary to support plant survival during summer (cf. Chapter 4). In the other climates, a minimum amount of irrigation is advised as well to ensure plant growth and survival, diversify the vegetation and improve thermal comfort during summer (Dunnett et al., 2008).

Future research should further elaborate on GR materials with increased WHC, in order to develop GRs with high biodiversity value and with no or only limited irrigation requirements, also in (semi)-arid climates (Dvorak & Volder, 2010). Also studies selecting appropriate drought tolerant plant species should be supported, as well as studies quantifying the contribution of GRs to urban ecosystem services, weighed against the cost of adaptive GR design (Schroll et al., 2011a; Schweitzer & Erell, 2014). This review pointed at sustainable irrigation possibilities that need to be elaborated further with scientific experiments and examples of local implementations. Different irrigation regimes are needed according to climatic context, and guidelines for irrigation specifications in each climate need to be determined.

Table 6.5 Summary of irrigation methods and regimes from studies in which outdoor GR experiments were conducted in different climatic conditions. GR type: extensive (EGR), semi-extensive (SEGR) or intensive (IGR). GR dimensions (length x width) were used to calculate the minimum daily water requirements (I_{day}) during the growing season and summer.

KCC	GR type	Irrigation method	Irrigation regime	GR dimensions (m)	Substrate depth (m)	I_{day} (l/m²)	Reference
Bsk	EGR	Drip irrigation; Overhead rotator system	Growing season 1: 18.7 mm/week, later 8 mm/week; Growing season 2: 6.4 mm/week	NA	0.10	0.91	Bousselot et al., 2010
	EGR	Drip irrigation	In summer	-		-	Pérez et al., 2012
	SEGR	No irrigation	-	-		-	Coutts et al., 2013
Cfa	EGR	No irrigation	-	-		-	Dvorak & Volder, 2013
	EGR	Hand watering; Subsurface capillary irrigation	After planting: every 2 days. Later: 5 l two times/day for 30 min. Winter: no irrigation	0.61 x 1.22	0.10	13.44	Price et al., 2011
	EGR	Drip irrigation	Month 1: 500 ml daily. Later: daily or every two days (except if > 5 mm precipitation event occurred)	0.9 x 0.9	0.10	0.31	Kanechi et al., 2014
	EGR	unknown	Month 1: daily. Later: 5 l every two days (except if > 5 mm precipitation event occurred)	0.9 x 0.45	0.10	6.17	Sendo et al., 2010
	EGR	unknown	1 time/week with tap water (except if > 5 mm precipitation event occurred or if predicted chance of rain is > 50% next days	-		-	Aithkenhead-Peterson et al. 2011
	SEGR	unknown	2 times/week for 15 min with collected rainwater	-		-	Sonne, 2006
Cfb	EGR	No irrigation	-	-		-	Nagase & Dunnett, 2013a
	EGR + SEGR	Drip irrigation	1 time/week in summer	-		-	Nagase et al., 2013
	EGR	Handheld hose	When substrate moisture < 15%, until saturation	-		-	Nagase & Dunnett, 2013b
	SEGR	Hand watering	1 time/week	-		-	Dunnett et al., 2008

Table 6.5 Continued

KCC	GR type	Irrigation method	Irrigation regime	GR dimensions (m)	Substrate depth (m)	I_{day} (l/m²)	Reference
Csa	EGR	Drip irrigation	Year 1: total of 7 l (summer) or 4 l (winter) 8 times/day for 1 min with tap water. Year 2: when necessary	0.5 x 0.5 x π	0.05	8.92	Schweitzer & Erell, 2014
	EGR	unknown	0.6-0.8 ETo every 3 days	-		-	Nektarios et al. 2012
	EGR + SEGR	Handheld hose	Establishment: daily. Later: no irrigation. Growing season 1: daily until saturation. Drought stress treatment: 3 or 6 mm every 3 days (= 12.5 or 25% of ETo)	NA	0.075	1.00	Ntoulas et al. 2012
	EGR + SEGR	Handheld hose	Water deficit cycles (15 days): 25% of ETo every 3 days. In between: daily until saturation	-		-	Ntoulas et al. 2013
	EGR + SEGR	Handheld hose	15 or 30% of ETo every 10 days	-		-	Nektarios et al. 2011
	EGR + SEGR	Automatic drip irrigation	Month 1: 3.3 l/h daily for 25 min (EGR) or 45 min (SEGR). Month 2-5: Every 3, 5 or 7 days	0.6 x 0.4	0.075	1.96	Papafotiou et al., 2013
	SEGR	No irrigation	-	-		-	Benvenuti & Bacci, 2010
	SEGR	unknown	0.4-0.6 ETo every 6 days	-		-	Nektarios et al. 2012
	SEGR	Drip irrigation	Daily until saturation	-		-	Pearlmutter & Rosenfeld, 2008
	IGR	Automatic drip irrigation	9 l per plot every 3 days for 30 min (except if > 3 mm precipitation event occurred	1.2 x 1.2	0.30	2.08	Kotsiris et al., 2013
	unknown	unknown	1.2 kg/m² daily	NA	NA	1.2	Santamouris et al., 2007
Csb	EGR + IGR	No irrigation	-	-		-	Razzaghmanesh et al., 2014a
	EGR + IGR	unknown	20 l every 10 days	1.5 x 1.2	0.10	1.11	Razzaghmanesh et al., 2014b
	EGR	Sprinkler system	Growing season 1: 2.3 mm daily. Growing season 2: no irrigation; Portland FAR bonus regime, 45.7 mm every 5 days; or horticultural regime, irrigation when necessary + 0.3 cm every 2 days	NA	0.127	2.3	Schroll et al., 2011a, 2011b
	SEGR	unknown	0.64 cm in 6 min	NA	0.127	6.4	Anderson et al., 2010
Cwa	EGR + IGR	Automatic sprinkler system	Daily 5 l /m². Regulated by a rainfall detector to stop the pump when antecedent rainfall > 10 mm	NA	0.05	5	Jim & Peng, 2012a, 2012b; Jim & Tsang, 2011

Table 6.5 Continued

KCC	GR type	Irrigation method	Irrigation regime	GR dimensions (m)	Substrate depth (m)	I_{day} (l/m²)	Reference
Dfb	EGR	No irrigation	-	-		-	MacIvor & Lundholm, 2011
	EGR	Overhead irrigation	Day 1-20: 30 ml 5 times/day for 5 min, until saturation. Day 21-41: 2 min. Later: irrigation when necessary. Growing season 2: no irrigation	-		-	Durhman et al., 2007
	EGR	Hand watering	Only during planting. No further irrigation	-		-	Getter & Rowe, 2008, 2009
	EGR	unknown	Month1: 3 times/day for 20 min; Month 2: daily. Later: no irrigation	-		-	Getter et al., 2009a
	EGR	Automated overhead irrigation	Month 1: 0.38 cm 3 times/day for 15 min. Month 2: 2 times/day. Month 3: daily. Later: no irrigation. Year 2 June: daily. Later: no irrigation	NA	0.10	3.8	Monterusso et al., 2004, 2005; Rowe et al., 2006
	EGR	Overhead irrigation	Year 1: when necessary. Year 2-7: no irrigation	-		-	Rowe et al., 2012
	EGR	Handheld hose + sprinkler; Drip irrigation	Establishment: 7.12l 3 times/day for 1 min. Later: no irrigation; daily for 5 min or when moisture is low	2.4 x 1.2	0.10	2.47	MacIvor et al., 2013
	EGR	unknown	Year 1-7: irrigation. Later: no irrigation	-		-	Köhler, 2006
	EGR	Hand watering	when necessary	-		-	Getter et al., 2011
	EGR	unknown	Month 1: 3-6 times/week. Later: only when necessary in summer (3 times 750 ml in 1 week)	0.36 x 0.36	0.12	2.48	Lundholm et al., 2010
	EGR	unknown	Year 1-2: irrigation. Later: no irrigation	-		-	Carpenter & Kaluvakolanu, 2011
	EGR	Automated overhead irrigation	Establishment: 6 times/day for 10 min. July: 4 times/day. August: no irrigation	-		-	VanWoert et al., 2005b
	EGR	unknown	Months 1-3: 2.8 mm 3 times/day for 20 min. Growing season 2: No irrigation	-		-	Getter et al., 2009b
	SEGR	unknown	Week 1: every 2 days. Week 2-4: decrease. Later: once every 5 days (if two weeks without rain)	-		-	Butler & Orians, 2011
Dwa	EGR	unknown	0.71 l/m² daily in July	NA	0.10	0.71	Feng et al., 2012
	IGR	unknwon	2.48 l/m² daily in July	NA	0.20	1.24	Feng et al., 2012

Chapter 7. Functional and phylogenetic diversity as a framework for novel ecosystem design, the example of extensive green roofs

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1. Introduction

Biodiversity is believed to be the major driver of ecosystem services through ecosystem processes and functions (Tzoulas et al., 2007; Cardinale et al., 2012; Quijas et al., 2012; Gamfeldt et al., 2013; Pinto et al., 2014). Overall there is a positive relation between ecosystem properties (e.g. resilience, resistance) and biodiversity and there is increasing evidence that biodiversity improves the stability of ecosystems through time (for a review, see Cardinale et al., 2012). There is also sufficient evidence that biodiversity either directly influences or is strongly correlated with provisioning and regulating services (cf. Isbell et al., 2011; Cardinale et al., 2012). Furthermore, consensus is growing that functional traits, and especially the range and value of those traits, rather than species richness and evenness are important for the provision of ecosystem properties (e.g., Hooper et al., 2005; Lavorel et al., 2011). Functional trait composition amongst plant communities can be compared through a series of functional diversity (FD) indices (Petchey et al., 2004; Mouchet et al., 2010). Next to FD, phylogenetic diversity (PD) is considered a holistic diversity measure, because genetically related species commonly show similar traits due to their shared evolutionary history (Cadotte et al., 2009; Devictor et al., 2010; Flynn et al., 2011; Srivastava et al., 2012).

Recently, as a result of advancing habitat loss, land use changes and urbanization, the concept of novel ecosystems has gained momentum. These are, by definition, self-organizing systems originating from human interference and with actual altered biotic, abiotic and social components as compared to the prevailing historical ecosystems (Hobbs et al., 2013). Urban ecosystems, like green roofs, parks and gardens, fall within this definition due to their novel elements but differ from novel ecosystems in cultivated or degraded landscapes because continued management is necessary (Hobbs et al., 2006; Lundholm & Richardson, 2010; Kowarik, 2011; Perring et al., 2013). Based on evidence of previous studies, we assume that designing functional diverse urban ecosystems will improve ecosystem services (cf. Isbell et al., 2011; Pinto et al., 2014; Witthinghill et al., 2014) and the quality of life of urban residents (Chiesura, 2004; Tzoulas et al., 2007; Wolch et al., 2014). We analyze novel ecosystems by use of FD and PD techniques and propose two generic methods for improved design in terms of species composition. The methodology is inspired by the Noah's Ark Problem (cf. Billionnet, 2013), because the goal is to achieve optimal allocation of a limited amount of resources by maximizing the species FD. We use extensive green roofs (EGRs), which offer many benefits in urban areas such as stormwater management and mitigation of the urban heat island effect (Carter & Jackson, 2007; Oberndorfer et al., 2007; Tzoulas et al., 2007; Gaston et al., 2013), as a case study to explore and illustrate the methods. EGRs are semi-artificial ecosystems with vegetation on substrate (2-20 cm in depth) and specialized materials placed on a building's roof (Oberndorfer et al., 2007). Species selection in these novel urban ecosystems is often determined by opportunistic criteria such as commercial availability, aesthetic qualities, adaptation to the environmental conditions and substrate depth (Getter & Rowe, 2008). A practical approach that directs to plant species with improved ecosystem properties value is a meaningful addition to this criteria list, and because the approach is generic in nature, the methods will be useful for the design of other novel ecosystems as well.

The specific goals of this study were to:

(i) Analyze the initial plant species composition, as provided by commercial EGR systems, in terms of FD and PD;
(ii) Offer a methodology to optimize species choice for incorporation into EGR design, making use of the FD approach.

2. Material and methods

2.1. System and trait selection

The European Federation of Green Roof Associations was used to select EGR systems (www.efb-greenroof.eu, consulted on 24/02/2013). The webpages of all the companies associated with this Federation were screened for EGR systems and their corresponding plant species (i.e. species that are or can be part of the original planted GR vegetation). When information was not published online, we requested the species lists from the company. In total, 57 systems originating from 19 GR companies spread over six European countries were used in the analysis (Appendix 7.1). Some companies are active in multiple countries, so the systems provided by them are assumed useful for Northern, Western and Central Europe. All systems together accounted for 199 vascular plant species (Appendix 7.2); nomenclature follows The Plant List (2013). Varieties and subspecies were not taken into account. In order to link essential variation in GR systems with FD and PD, we collected and partly derived information on percentage of succulent species, substrate depth, installation method (cuttings, mat, seeds or plugs) and species richness (SR).

Trait selection (29 in total; Table 7.1) was determined by important GR ecosystem properties as explicitly mentioned in specific literature on GRs: Getter and Rowe (2006), Oberndorfer et al. (2007), Wolf and Lundholm (2008), Lundholm et al. (2010), Cook-Patton and Bauerle (2012), Robinson and Lundholm (2012), Dakin et al. (2013), and Oudolf and Kingsbury (2013). These properties were related to supporting, provisioning, regulating and cultural services based on the literature and on best professional judgment. Trait values for the plant species were obtained from multiple sources (Table 7.1).

2.2. Data analysis

2.2.1. Exploring the EGR systems

The 57 EGR systems were clustered based on their plant species composition using hierarchical clustering with Sørensen distance measure and flexible beta (β = -0.25) as group linkage method (McCune & Mefford, 1999). We used Indicator Species Analysis (Dufrêne & Legendre, 1997) to obtain the optimal number of system types in the cluster analysis and to define species that significantly differentiate these types. Clustering and Indicator Species Analysis were performed in PCord 6.0 (MjM Software, USA). Non-parametric tests (Kruskal Wallis and Pearson Chi²) were used to explore significant differences between the system types in terms of system characteristics. Statistical tests were performed with SPSS 22.0 (SPSS Inc, Chicago, IL).

Table 7.1 List of 29 traits used for the FD approach, selected after screening of the literature on ecosystem services of GRs. Every trait is supplemented with the following information: ecosystem properties explaining the importance of the trait for the ecosystem service; ecosystem service category (C: cultural; R: regulating; S: supporting; P: provisioning); brief description, variable type (N: nominal; S: scale; O: ordinal) and missing values which indicate the % of species for which no trait information could be found. [Source references: Fitter and Peat, 1994; Shipley, 1995; Cornelissen, 1996; Kühn et al., 2004; Couplan, 2008; Kleyer et al., 2008; Oudolf and Kingsbury, 2013].

Plant trait	Ecosystem properties	Ecosystem service category	Brief description	Variable type	% Missing values
Design type	Structural complexity (SC)	C, S	Ranking order of planting. 1. Base plants; 2. Matrix plants; 3. Scatter plants	N	0
Drought tolerance	Drought tolerance (DT)	C	0. None, very low; 1. Medium; 2. High	O	0
Flower colour	Aesthetic (A); attract pollinators (Pol); habitat (H)	C, S	1. Yellow, red, orange; 2. White; 3. Blue, violet, purple, pink; 4. Brownish; 5. Green, discreet	N	0
Flowering time	A; Pol	C, S	Season when flowering starts. 1. Spring; 2. Early summer; 3. Midsummer; 4. Late summer/autumn; 5. Winter	N	1
Lateral spread	SC	C	0. None; 1. Moderate; 2. Extensive	O	2
Leaf area	Evapotranspiration (ET)	R	Mean leaf size (mm^2)	S	31
Leaf colour	A	C	1. Green (including dark- and light green); 2. Blue-green; 3. Grey-green	N	0
Leaf dry mass	Biomass (BM)	S, R	Whole leaf dry mass (mg)	S	55
Leaf phenology	ET; SC; A	C, S, R	Timing of leaf expansion. 1. Spring green; 2. Summer green; 3. Overwintering green; 4. Persistent green	N	4
Leaf type	SC	C	1. Simple; 2. Compound	B	21
Persistency	Self-sustainability (SS)	C	Capacity of the plant to remain at the same place for multiple years. 1. Low; 2. Medium; 3. High	O	2
Photosynthetic pathway	ET; DT	C, R	1. C3; 2. CAM	B	17
Plant architecture	ET; SC	C, S, R	Relationship between stem and leaf. 1. Basal leaves; 2. Stem leaves; 3. Multiple stem; 4. Branched; 5. Grasses	N	0
Plant height	BM; SC	C, S, R	Mean individual height (m)	S	2
Plant life form	ET; BM; SC	C, S, R	Life form categories according to Raunkiaer. 1. Phanerophyte; 2. Chamaephyte; 3. Hemicryptophyte; 4. Geophyte; 5.Therophyte	N	0

Plant longevity	BM; SC; SS	C, S, R	Longevity of the plant. 1. Annual; 2. Biennial; 3. Short living perennial, <10 years; 4. Real perennial, >10 years	O	1
Plant strategy type	DT	C	Survival strategies according to CSR-model of Grime. 1=c (competitor); 2=s (stress tolerant); 3=r (ruderal); 4=cs; 5=cr; 6=sr; 7=crs	N	20
Pollinator reward	Pol; H	S	0. None; 1. Nectar; 2. Pollen; 3. Nectar + pollen	N	24
Provisioning value	Provisioning	P	Direct value for humans. 0. None; 1. Medicine; 2. Herb; 3. Edible plant parts	N	0
Relative growth rate	BM	R	1. Slow; 2. Medium; 3. Fast	O	71
Rooting depth	ET; SC; DT	R	Average depth of the roots (m)	S	71
Seed bank index	SS	C	Proportion of short and long term persistent seed records on total number of records per species	S	39
Self-seeding	SS	C	Capacity of the plant to multiply itself through seeds. 1. Low; 2. Medium; 3. High	O	1
Shoot growth form	SC	C, S, R	Orientation of stem: 1. Erect; 2. Ascending to prostrate; 3. Prostrate	N	25
Structural design interest	A	C	Duration of the plant's design interest. 1. Short, <3 months; 2. Medium, 3-9 months, flowers and seed heads; 3. Long, ≥9 months, good seed heads	O	1
Succulence	ET; DT	C, R	Capacity of the plant to store water in the leaves. 0. None; 1. Yes	B	0
Ultraviolet feature	Pol; H	S	UV-visibility of the flower. 0: No; 1: Yes	B	34
Vegetative dispersion	SS	C	Capacity to disperse through vegetative growth. 0. None; 1. Low; 2. Medium; 3. High	O	0
Woodiness	BM; DT; SC	C, S, R	0. Non woody; 1. Semi-woody; 2. Woody	O	0

2.2.2. Diversity analysis

FD and PD were quantified by two independent diversity indices (Mason et al., 2005). The richness index is the amount of trait or phylogenetic space filled by the community and the evenness index is a measure of the uniformity of distribution of species in trait or phylogenetic space. Functional richness was quantified in this study with FDpg (referring to the FD measure as proposed by Petchey and Gaston, 2002). FDpg is the total branch length of the functional dendrogram constructed using a dissimilarity matrix (Gower distance) based on the species functional traits. Functional evenness was quantified with FEve as proposed by Villéger et al. (2008). The FD indices were calculated using the FD (Laliberté & Shipley, 2013), Ape (Paradis et al., 2013) and Picante package (Kembel et al., 2010) in R2.15.3 (R Development Core Team, 2012).

The phylogenetic tree was constructed from Daphne, a dated phylogeny of a large European flora (Durka & Michalski, 2012) in Phylocom 4.2 (Webb et al., 2008). The few unresolved relationships were treated as polytomies and remained unresolved. We quantified PD with two different indices: Faith's index of PD (PDf; Faith, 1992) and mean phylogenetic distance (MPD; Webb et al., 2002). PDf is an index for phylogenetic richness and is defined as the minimum total length of the phylogenetic branches connecting the species together on the phylogenetic tree and corresponds to FDpg (Cadotte et al., 2009). MPD is a phylogenetic evenness index and is the average distance between two random species (Webb et al., 2008). The branch lengths on the phylogram were used as distance measure. The indices of PD were calculated in R with the Picante package (Kembel et al., 2010).

FDpg, FEve, PDf and MPD were calculated for every EGR system and related to SR using Spearman rank correlation (r_s). Differences in diversity indices between the system types were tested using Kruskal Wallis tests at a significance level of 0.05.

2.3. Species selection for optimization of EGR ecosystem functioning

Each species has its own habitat requirements and not all species can be applied on every GR type. In order to optimize ecosystem properties and services of EGR systems, we compiled a species list per EGR type of which species FD is maximized (FDMax1). Because the debate about which component of biodiversity influences ecosystem properties the most is still going on (Hooper et al., 2005; Flynn et al., 2011; Gasc et al., 2013), the compilation of the species lists may be based on both FD and PD. However, because the resolution of the phylogenetic tree was not fine enough (many species occurring together at the same branch), evolutionary information could not be used in this analysis (Swenson, 2009). Richness and evenness are both important factors that influence ecosystem properties, but as the calculation of FEve is very complex, we chose to maximize FDpg. We started with a species list and accompanying functional trait matrix per EGR type with the species that were present in the systems of that type. A separate species dissimilarity matrix for each of the EGR types was calculated with the Gower index as distance measure (in R2.15.3). The selection process started with the two species with the highest dissimilarity value. Next, a new species was added that maximized the average dissimilarity to the species that were already in the list. This step was repeated until the average SR of that EGR type was reached. The final result was a species list per EGR type - equal to the average SR of that EGR type - that maximized FDpg. In order to calculate the gain in FDpg of the optimized species lists, we wanted to compare the FDpg of the optimized species lists with the FDpg values of the initial EGR systems. However, values of FDpg depend on the number of species in the functional dendrogram and FDpg values that are calculated from different dendrograms can therefore not be compared. In order to be able to compare the FDpg of the optimized species lists with the FDpg values of the initial EGR system, we also calculated the FDpg of the optimized species lists based on the functional dendrogram constructed with all species.

Because not all species in the optimized species lists are readily available in every commercial assortment, the optimized species lists are not very practical. Therefore, we also provided a method to optimize the FD of EGRs that is practically applicable by GR companies (FDMax2). Per EGR type the species present in that GR type were classified in functionally similar groups based on the functional dendrogram. The number of groups corresponded again to the average SR of the EGR type. By choosing one species of each group, the maximum FDpg is approached.

The proposed methods FDMax1 and FDMax2 offer a solution to the Noah's Ark Problem (Billionnet, 2013), in which FD of the respective species is maximized. Billionnet (2013) also addressed this problem by using nonlinear mixed-integer programming, a complex and elaborate method because transformations and logarithmic function techniques are necessary to account for the nonlinearity. Here we tackled the problem in a more simple way by using a dissimilarity matrix (FDMax1) and hierarchical clustering techniques (FDMax2).

3. Results

3.1. EGR type description

Clustering the sample of 57 EGR systems resulted into three types, each characterized by a number of significant indicator species (Appendix 7.2) and attributes (Table 7.2). The 22 EGR systems belonging to type 1, hereafter called '*Sedum* type', contained mainly succulent species, had the shallowest substrate depth (5 cm on average) and species were mainly installed by cuttings or mats. SR was significantly lower than those of type 2 and 3 (8.2 ± 2.32, Table 7.2) and eight *Sedum spp*. were significantly associated with this type. Type 2, or '*Dianthus-Thymus* type' (after two highly significantly associated species, see Appendix 7.2), contained 27 systems with more diversified vegetation, although *Sedum spp*. were still present in most systems. The vegetation was mainly installed by seeding on a substrate of around 9 cm thick. The SR was high (22.3 ± 8.43), with 17 species that were significantly associated with this type. The eight systems belonging to type 3, the '*Linaria-Galium* type', contained 30 indicator species and were characterized by the almost absence of succulent species. Installation of plants was mainly achieved by application of plug plants. Substrate depth and SR were not significantly different from the *Dianthus-Thymus* type.

Table 7.2 Summary of the three green roof types in terms of key variables. Significance of differences between the types was tested using: a) Kruskal Wallis tests for quantitative variables. Average values and standard deviation are listed for every type, followed by a letter indicating the significant differences (Kruskal Wallis post hoc test). b) Pearson Chi² tests for nominal variables, with indication of number of green roof systems per category for every type. (*: p ≤ 0.001).**

a) Quantitative variables	**Kruskal Wallis**	***Sedum* type**	***Dianthus-Thymus* type**	***Linaria-Galium* type**
# Green roof systems		22	27	8
Species richness	33.10 (***)	8.18 ± 2.3 a	22.33 ± 8.4 b	19.50 ± 7.8 b
Substrate depth	34.50 (***)	4.91 ± 1.5 a	9.22 ± 2.6 b	9.63 ± 2.3b
Percentage of succulent species	42.96 (***)	97.73 ± 9.2 b	18.87 ± 16.3 a	6.88 ± 9.7a
b) Nominal variables	**Pearson Chi²**	***Sedum* type**	***Dianthus-Thymus* type**	***Linaria-Galium* type**
Installation method	54.50 (***)			
Cuttings		9	0	0
Mat		12	2	1
Seeds		0	18	1
Plugs		1	7	6

3.2. Diversity analysis

Kruskal Wallis test results showed significant differences between the three EGR types for all functional and phylogenetic diversity measures (Fig. 7.1). The largest differences were observed for FDpg, PDf and MPD (p-values < 0.001), where values of the *Sedum* type were significantly lower compared to the *Dianthus-Thymus* and *Linaria-Galium* type. Differences between EGR types were also significant for FEve (p-value < 0.05), with the *Sedum* type showing significant higher values than the *Dianthus-Thymus* type. Despite the significant differences, values for FEve ranged from 0.96 to 1, suggesting a rather uniform distribution of species in trait space. The boxplots also show considerable variation in the value range of FDpg and PDf for the *Dianthus-Thymus* and the *Linaria-Galium* type.

FDpg and PDf were strongly positively correlated with SR (r_s = 0.96 and 0.91 respectively; p-values < 0.001) (Fig. 7.2). So the higher the number of species in the EGR system the higher the FD and PD and the supposed positive impact on ecosystem services. Next to the correlation with SR, the correlation between FDpg and PDf appeared highly significant too (r_s = 0.95; p-value < 0.001). Although systems from the *Sedum* type were situated at low SR, the systems of the *Dianthus-Thymus* and *Linaria-Galium* types showed variation on the X-axis, meaning that the observed variation in Fig. 7.1 can be explained by the systems variety in SR. MPD is also correlated with SR (r_s = 0.76; p-value < 0.001), but FEve and SR showed no correlation. For a given SR, the values of FDpg and PDf showed some variation, indicating that a better design in terms of species selection is possible.

3.3. Maximizing functional diversity

Table 7.3 shows the combined results of FDMax1 and FDMax2. A complete table with the results of FDMax2 is included in Appendix 7.3. Species with the highest functional dissimilarity are for the *Sedum* type *Phedimus selskianus* and *Prunella grandiflora*, for the *Dianthus-Thymus* type *Sedum montanum* and *Tripleurospermum maritimum* and for the *Linaria-Galium* type *Papaver rhoeas* and *Sedum album* (Table 7.3a). *Phedimus selskianus* could for example be replaces by *Sedum album*, which belongs to the same group according to FDMax2 (Table 7.3b). In the same way, *Tripleurospermum maritimum* could be replaced by *Calendula arvensis* or *Arenaria serpyllifolia*. These species substitutions illustrate the practical aspects of FDMax2. For all the EGR types, the attained value of FDpg by using FDMax1 was higher than the initial FDpg value of the EGR type. For a *Sedum* type system containing eight species FDpg increased with 22%, for a *Dianthus-Thymus* type system containing 22 species FDpg improved 10% and for a *Linaria-Galium* type system with 20 species FDpg increased with 7%.

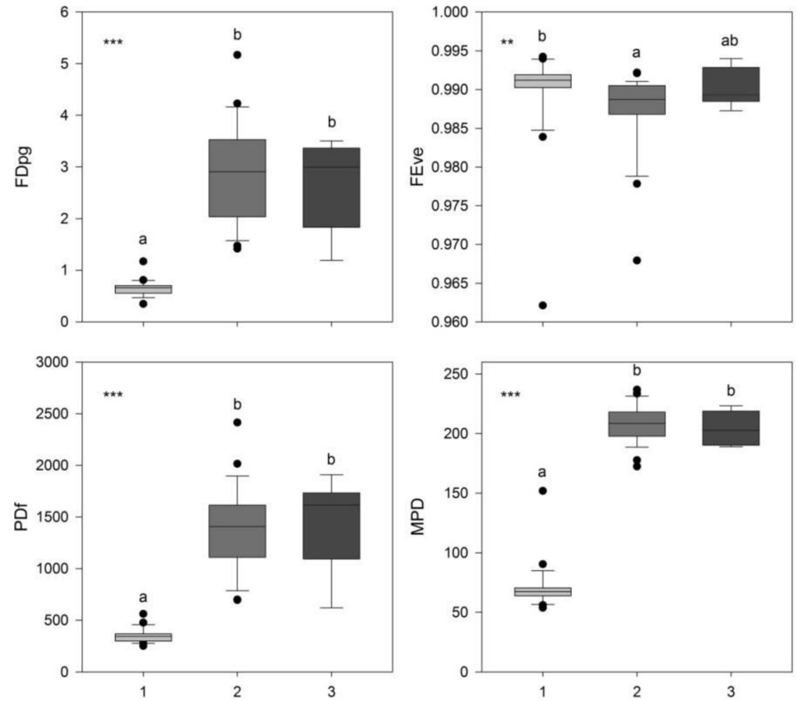

Fig. 7.1 Boxplots of the FD indices FDpg and FEve and the PD indices PDf and MPD EGR types 1-3 (*Sedum, Dianthus-Thymus* and *Linaria-Galium* type respectively). Significance of the Kruskal Wallis test is indicated, with post hoc test results for every type expressed by letters above the boxes. (: p ≤ 0.05; ***: p ≤ 0.001).**

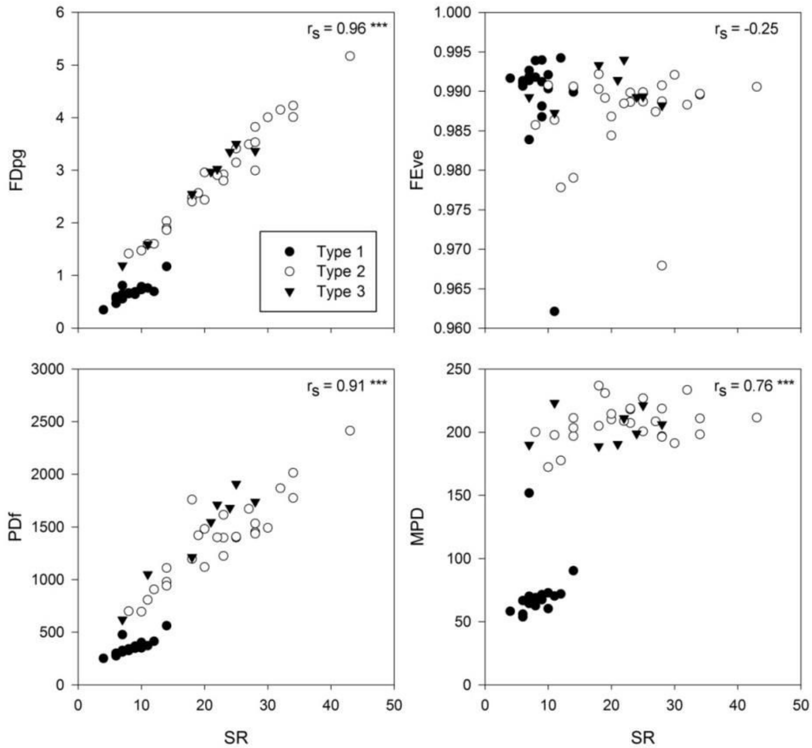

Fig. 7.2 Scatterplot of the relation between species richness (SR) for every EGR system and the functional (FDpg and FEve) and phylogenetic (PDf and MPD) diversity values. EGR systems are grouped into types 1-3 (*Sedum*, *Dianthus-Thymus* and *Linaria-Galium* type respectively). Spearman Rank Correlation coefficients (r_s) and significance are indicated (*: $p \leq 0.001$).**

Table 7.3 Combined results of the FD maximization methods FDMax1 and FDMax2, offering an exact and practical species list, respectively. Number of groups corresponds to the average SR of every type. Species of FDMax1 are underlined and the subsequent numbers rank these species according to decreasing functional dissimilarity. The other species (up to 6, for the complete list we refer to Appendix 7.3) can be used as alternatives. For comparison, both the system FD and the maximized FD of FDMax1 for a system with the average SR are shown.

System type	*Sedum* type		*Dianthus-Thymus* type		*Linaria-Galium* type	
Average SR	8		22		20	
System FDpg	0.9		2.9		2.8	
Maximized FDpg	1.1		3.2		3.3	
Group						
1	*Phedimus selskianus* 1 *Sedum album* *Sedum hybridum*	*Sedum lydium* *Sedum rupestre* *Sedum sexangulare …*	*Achillea millefolium* *Anthemis tinctoria* *Daucus carotus*	*Leucanthemum vulgare* *Pimpinella saxifraga* *Trifolium arvense*	*Achillea millefolium* *Daucus carota* *Echium vulgare*	*Leucanthemum vulgare* *Reseda lutea*
2	*Campanula portenschlagiana* 6	*Campanula poscharskyana*	*Aurinia saxatilis* 11	*Achillea tomentosa*	*Agrimonia eupatoria* 17	*Hypericum perforatum*
3	*Sedum spathulifolium* 8		*Dianthus carthusianorum* *Dianthus deltoides* *Linum perenne*	*Potentilla argentea* *Potentilla verna* *Prunella grandiflora …*	*Saxifraga granulata* 16 *Armeria maritima* *Bellis perennis*	*Geranium sanguineum* *Leontodon hispidus* *Primula veris …*
4	*Hylotelephium spectabile*		*Allium roseum* 14 *Iris pumila* 4 *Allium schoenoprasum*	*Allium sphaerocephalon* *Iris tectorum* *Leopolida comosa*	*Anthemis tinctoria*	
5	*Prunella grandiflora* 2		*Anemone pulsatilla*		*Anthyllis vulneraria*	*Lotus corniculatus*
6	*Saxifraga cotyledon* 3	*Sedum hispanicum*	*Armeria maritima* *Briza media* *Dianthus anatolicus*	*Primula veris* *Saxifraga granulata* *Saxifraga paniculata …*	*Carex flacca* 3	
7	*Sedum cauticola* 4 *Sedum cyaneum* 7	*Sedum ewersii* *Sedum telephium*	*Anthoxanthum odoratum* *Carex sylvatica* *Euphorbia cyparissias*	*Festuca glauca* *Festuca ovina* *Koeleria glauca …*	*Centaurea cyaneus* 6	*Papaver rhoeas* 1
8	*Sempervivum tectorum*5	*Sempervivum*	*Anthyllis vulneraria*	*Petrorhagia saxifraga*	*Cichorium intybus* 15	*Linaria vulgaris*

	Sempervivum arachnoideum	*globiferum* *Sempervivum montanum*	*Lotus corniculatus*		*Knautia arvensis* 4 *Pseudolysimachion spicatum* 18	*Scabiosa columbaria* *Silene vulgaris …*
9			*Aquilegia vulgaris*		*Centaurium erythraea* 14	*Viola tricolor* 10
10			*Papaver rhoeas* 7 *Tripleurospermum maritimum* 2 *Arenaria serpyllifolia*	*Calendula arvensis* *Viola arvensis*	*Dianthus arenarius* *Plantago media*	*Silene uniflora*
11			*Bromus tectorum* 5		*Thymus serpyllum* 19 *Dianthus deltoides* *Glechoma hederacea*	*Jasione montana* *Thymus praecox* *Veronica officinalis*
12			*Erodium cicutarium* 12	*Centaurea cyanus* 19	*Festuca ovina* 12 *Festuca rubra*	*Pilosella officinarum*
13			*Cerastium arvense* *Cerastium tomentosum*	*Sagina subulata*	*Filipendula vulgaris* 7	
14			*Teucrium chamaedrys* 17 *Clinopodium alpinum* *Helianthemum nummularium*	*Thymus pulegioides* *Thymus serpyllum* *Thymus vulgaris …*	*Geum rivale* 13 *Galium verum* *Potentilla neumanniana*	*Potentilla reptans* *Ranunculus acris*
15			*Clinopodium vulgare*		*Helianthemum nummularium* 5	
16			*Draba aizoides* *Hieracium aurantiacum* *Hieracium pilosella*	*Pilosella rubra* *Silene otites*	*Plantago coronopus* 9	
17			*Echium vulgare* *Iberis sempervirens*	*Satureja subspicata*	*Ranunculus bulbosus* 11	
18			*Euphorbia myrsinites* 13 *Sedum album* 15	*Sedum stenopetalum*20 *Sempervivum arachnoideum* 8	*Rhinanthus minor* 20	

		Sedum cauticola 6 *Sempervivum tectorum 22* *Sedum montanum 1* …	
19		*Verbascum nigrum 9* *Malva moschata* *Verbascum phlomoides 16* *Inula conyza* *Verbascum lychnitis 21* *Verbascum phoeniceum …*	*Sanguisorba minor*
20		*Lavandula angustifolia 3*	*Sedum acre 8* *Sedum album 2*
21		*Ranunculus bulbosus 10*	
22		*Sanguisorba minor 18*	

4. Discussion

4.1. The FD approach and EGR systems

The objective of this study was to examine EGR systems, exemplary for novel urban ecosystems, and to offer an applicable approach to achieve better ecosystem services. The role of GRs in offering a variety of ecosystem services becomes increasingly acknowledged in scientific literature (e.g. Carter & Jackson, 2007; Oberndorfer et al., 2007; Lundholm et al., 2010; Cook-Patton & Bauerle, 2012; Gaston et al., 2013; Perring et al., 2013). The specific ecosystem properties on which the trait selection was based (Table 7.1) are essential to provide those services. Plant evapotranspiration and biomass are properties influencing the regulating services climate regulation and water management. Traits like flower color, flowering time and pollinator reward help to attract pollinators or provide habitat for local flora and fauna, hence contributing to the supporting ecosystem services. The provisioning component of ecosystem services is determined by the trait provisioning value, which indicates if a species is of potential value for humans in terms of medicinal use or edibility. The cultural service is determined by the GR's esthetic and amenity value (Dakin et al., 2013). Drought tolerance and self-sustainability are properties necessary to cope with extreme conditions typical for GR environments, and hence ensure the resilience of the system. This is essential for the amenity value, and thus the cultural service, of the GR (Getter & Rowe, 2006; Oberndorfer et al., 2007). Finally, structural diversity, determined by variation in multiple plant traits such as height, architecture and longevity, is an important aesthetic determinant, but contributes also highly to the other services (Cook-Patton & Bauerle, 2012; Oudolf & Kingsbury, 2013). Table 7.1 clearly indicates that the selected plant traits relate to different and often multiple ecosystem services. Therefore, we assumed that the ecosystem services are adequately represented by the selected traits.

Similar to Madre et al. (2014), who proposed an ecological oriented GR typology, the EGR systems could be classified both on technical system properties (Table 2) and diversity values (Fig.1). Succulent species, characteristic for the systems in the *Sedum* type, are the most commonly applied species on EGRs. Their specific photosynthesis pathway (CAM) makes them better suited to withstand extreme conditions on roofs (Oberndorfer et al., 2007), and they have the greatest potential in terms of applicability on existing roofs, as they are easy to install and relatively light weight due to shallow substrate depth requirements. However, the FD of *Sedum* systems was significant lower compared to the other two EGR types, but we showed that FD could be improved with 22% by using FDMax1. These species-poor systems can thus become ecologically more interesting by considering alternative species. Although the FD analysis demonstrated that species-rich systems (the *Dianthus-Thymus* and the *Linaria-Galium* type) have higher FD values and hence potentially provide 'better' ecosystem properties (cf. Gamfeldt et al., 2013), we showed that even in these systems the FD could be increased up to 10%. The higher biomass and leaf area index of plants in these EGR types result in a higher evaporative capacity which improves stormwater management and temperature regulation (Lundholm et al., 2010). The structural diversity of these systems also supports the cultural, supporting and regulating ecosystem services (Cook-Patton & Bauerle, 2012). However, more diverse systems do impose constraints like a higher weight and cost, and more complexity and maintenance (cf. Snodgrass & McIntyre, 2010). As less succulent species are present in the species-rich GR systems, the ability of these systems to tolerate drought could be questioned. In a GR context, drought tolerance is often equated to only succulence. However, drought tolerance is actually achieved by a combination of different traits, of which succulence comprises only one. For example, traits related to leaf and root morphology, and photosynthetic pathway, all contribute to a plant's tolerance to drought (see e.g. Markesteijn & Poorter, 2009; Chapter 3). We only considered plant traits related to GR ecosystem services, but still multiple traits related to drought tolerance were included in the FD analysis (e.g. leaf area, leaf phenology, photosynthetic pathway). So next to opting for succulents and hence drought tolerant species (trait convergence strategy), selecting plants that differ in their traits can also contribute to a drought tolerant vegetation. The trade-off between systems with succulents and the more species-rich and diverse systems should be considered carefully and placed in the context of the main purpose and construction limitations of the respective design project.

4.2. Considerations for further research

Advantages of the FD and PD approach are that they account for trait value or evolutionary complementarity between species, that diversity is measured at all hierarchical scales and that the resulting values are continuous (Petchey & Gaston, 2002). Although being valuable diversity measures (Petchey et al., 2004; Hooper et al., 2005; Devictor et al., 2010; Mouchet et al., 2010; Petchey et al., 2004), there might also be some limitations when applied to specific examples. The used EGR systems for instance only provided information on the initial species presence/absence, but not their relative abundance and vegetation dynamics once installed on a roof. This information would have resulted in more detailed clustering results and it would have affected the calculated FD and PD, and the FD maximization procedures (FDMax1 and FDMax2). However, this limitation does not fundamentally alter the approach adopted here, as for species selection for designing urban green elements, one often starts from simple species lists. Adding species that establish spontaneously and that have potential to increase the FD of the GR system is an interesting option. Nevertheless, more research is needed in order to ensure that those additional species will be successful on GRs in the long term, as they are not considered 'tried-and-true' as the other species present in the initial EGR systems. Another limitation regards the plant trait values, which were not available for species varieties and cultivars. The species lists of the EGR systems were thus reduced to the species level, therefore possibly causing some information loss as plant traits inevitably show some variability (cf. De Bello et al., 2011). Also, as indicated by the % missing values in Table 7.1, it was impossible to find specific trait information for certain species. Therefore, further trait screening of plant species and their intraspecific taxa is essential (cf. Pakeman, 2014).

The scientific evidence that biodiversity, species functional traits and their phylogenetic relationships are linked with ecosystem properties is increasing (Hooper et al., 2005; Isbell et al., 2011; Lavorel et al., 2011; Cardinale et al., 2012; Quijas et al., 2012; Pinto et al., 2014). Whether this also fully applies for novel urban ecosystems has not yet been proven, as the literature on FD and PD and their effects on ecosystem properties of for example GRs is still very limited. Lundholm et al. (2010) focused on summer roof cooling and water capture and concluded that these services can be improved by combining different life forms. However, for some ecosystem services (e.g. roof cooling), species-poor GR systems outperformed the ones with high diversity, hence stressing the need for further investigation of biodiversity-ecosystem functioning relationships in GR ecosystems (Lundholm et al., 2010). Furthermore, our study showed that EGR systems with high FD are also the ones that require deeper substrates. This result is in line with findings of Madre et al. (2014), who pointed at an important role of substrate depth on GR plant diversity. Next to substrate depth, also substrate type (e.g. the water holding capacity or amount of organic matter) and local GR parameters (e.g. age and height) can also greatly influence the vegetation composition in the long term, hence influencing the FD (Madre et al., 2014). So further research is needed to elucidate the relative contribution of substrate and GR properties to the FD of the GR system and linked to that, the provisioning of ecosystem services.

PD indices are assumed to be a valuable proxy for FD (Flynn et al., 2011; Srivastava et al., 2012; Gasc et al., 2013). PD accounts for species evolution and hence encompasses many additional and often unmeasured traits that may be important to determine ecosystem functioning (Cadotte et al., 2009; Flynn et al., 2011; Srivastava et al., 2012). A possible problem here might be that some species were treated as polytomies because of unresolved relationships. Also, the evolutionary resolution of the phylogenetic tree was not detailed enough, which caused us to rely on FDpg for the diversity maximization procedure. This in contrast to the Noah's Ark Problem on which our approach was inspired and in which the expected PD of the considered species is maximized (Billionnet, 2013). However, we believe that the use of FDpg is justified, as the correlation between FDpg and PDf proved to be highly significant.

4.3. Recommendations for urban ecosystem design

The two proposed methods, delivering an exact species list (FDMax1) and perhaps a more practical one that offers alternative species (FDMax2), illustrate how current GR systems can be adapted to maximize FD and presumably also the overall ecosystem properties and services. The focus of this study was on EGRs, but the methods used are generic and offer a framework for improved design of a broad range of novel ecosystems, particularly in an urban context. For a new project, whether that be for instance, abandoned industrial sites, agricultural remnants, parks or gardens, one could start from an inventory of the species, eventually supplemented with potential interesting species considered for introduction on the site and then follow the approach adopted here. Clustering can yield insight into available or desired vegetation types. Next, databases should be consulted for relevant traits of the plant species, representing the range of desired ecosystem properties, after which FD and PD analyses (eventually per vegetation type) will provide insights on the ecological properties. The application of FDMax1 and FDMax2 will then indicate the most optimal species combination in terms of ecosystem properties. It is also possible to focus the approach on plant traits that relate to a specific ecosystem service and therefore select plant species that maximize this service (cf. Lundholm & Richardson, 2010; Perring et al., 2013).

The approach adopted in this study only focused on FD and PD and how we can use these measures to optimize species selection for GR purposes. We acknowledge that as more empirical research becomes available, other possibilities may arise that also offer ways to improve species selection for GRs, for example by looking at specific plant traits that are related to one or multiple ecosystem services. Also, the FD maximization methods proposed in this study should be interpreted with caution, as GRs with high FD will only offer optimal ecosystem services when the initial high plant trait diversity can be conserved. This however, is not guaranteed, as some scientific studies indicate a decline in SR of the GR over time (e.g. Rowe et al., 2012; Lundholm et al., 2014). Despite the number of current drawbacks of the FD and PD approach, this study offers a way to design GRs with high plant trait diversity. It also highlights that currently used EGR systems differ greatly in their FD and PD.

5. Conclusion

EGR systems, as model examples of novel urban ecosystems, offer a variety of ecosystem services. We assume that ecosystem properties and services are positively correlated with FD and PD. The FD and PD analyses highlighted that species-rich EGR systems offer higher FD and PD than the commonly used *Sedum* type, but also that the FD of the other types can be improved. Two methods are proposed that both maximize FD and thus offer a foundation for improved design of these novel ecosystems. These result in optimal species lists, an ‘exact’ one and one that also offers alternatives. The approach is generic and can thus also be used for other novel ecosystems, in particular urban green elements. It also offers the possibility to target specific ecosystem properties or services. By carefully considering species that maximize FD, the design of urban green infrastructure elements can become a more sustainable and vital tool to improve urban life quality.

Chapter 8. General discussion

1. Nature as a source of inspiration for extensive green roof plant species selection

1.1. Green roofs and the habitat template concept

Research question 1: What kind of vegetation can be found in natural (sub) Mediterranean areas selected according to the habitat template concept of extensive green roofs (EGRs)? To what extent do the plants in the resulting Mediterranean plant list offer new possibilities for use on EGRs?

The first part of the thesis was based on the 'habitat template hypothesis'. In essence, a habitat template can be considered as a set of biotic and abiotic conditions that define a particular (semi)-natural habitat and the species that can live in it (Southwood, 1977; Lundholm, 2006). There is a common perception that cities are unnatural and do not have any analog in nature (Larson et al., 2004). However, as indicated by Lundholm and Marlin (2006), urban areas do harbour different habitat templates that mimic natural habitats. For example, urban lawns do contain conditions that allow many grassland species to live in them. Similarly, urban pavements and walls provide niches for many rock outcrop species, and at tree bases, mainly species originating from natural forest and riparian habitats can be found. So engineered urban ecosystems (including GRs) are novel, as they originate from human interference and the ecosystem was not present in that area before, but replicate natural habitats at the same time (Hobbs et al., 2006; Lundholm & Marlin, 2006; Hobbs et al., 2009; Kowarik, 2011).

The GR industry mainly relies on 'tried-and-true' plants with drought tolerant features (mainly succulents), but there is a growing interest to incorporate other native plants in GR design (Lundholm, 2006; Sutton et al., 2012). According to the habitat template hypothesis, potential species for EGRs can be found in natural habitats with similar biotic and abiotic conditions as on EGRs. These natural template habitats comprise mostly rocky environments, free draining dunes, open areas on very shallow substrates, and limestone pavements (Lundholm, 2006). Based on the habitat template concept, Sutton et al. (2012) studied natural prairie and grassland communities and found that there are many species originating from those specific habitats that can survive on GRs (e.g. *Bouteloua gracilis*, *Dalea purpurea, Geum trifolium, Allium cernuum, Huechera richardsonii*).

The goal of Chapter 2 was to look at possibilities of native vegetation on shallow soils and rocky habitats in (sub) Mediterranean France. The Mediterranean region with its exceptional diversity of plant species (Médail & Quézel, 1997; Lavergne et al., 2006) contains a lot of these habitats, so we hypothesized that it should be possible to find drought-adapted, native plant species that could thrive on EGRs. (Semi)-natural open habitats in Southern France were described and variation in species composition in relation to environmental factors was analyzed. In a total of 20 locations, 372 local plant species were found, and together with species lists found in literature describing specific Mediterranean habitats, the list was complemented with 261 species, resulting in a total Mediterranean plant list (MEDPL) of 633 species. Species in the MEDPL could be grouped into four major vegetation types with distinct climatic, geographic and soil-related properties. Next, the MEDPL list was compared with a list of species commonly used on GRs in NW Europe (GRPL). We found that 79% of the Mediterranean species are currently not used on GRs and hence comprise a potential source for urban greening. A first rough screening was performed based on 10 general plant traits associated with survival on EGRs (including life form and Grime strategy). 28 Mediterranean species not yet used on GRs meet at least 6 out of 10 important attributes, indicating good potential.

We pointed at some ecological recommendations that need to be considered during GR design. *Sedum spp.* comprise a good option for EGRs in a Mediterranean climate. Succulents have been found to facilitate growth of herbaceous species under abiotic stress (Butler & Orians, 2011). Besides succulents, different life forms should be incorporated. This recommendation has already been proposed by other GR researchers (e.g. Lundholm et al., 2010; MacIvor et al., 2011; Cook-Patton & Bauerle, 2012). The use of different life forms has been shown to provide better ecosystem functioning and resistance to environmental stress, mainly due to niche complementarity and facilitation (Lundholm et al., 2010). Grasses and herbaceous species are less drought tolerant compared to succulents, but are more effective for evapotranspiration and thus stormwater retention (Wolf & Lundholm, 2008). Furthermore, highly diverse GRs have a higher survival probability and are more aesthetically pleasing even under dry conditions (Nagase & Dunnett, 2010). Other new potential species include *Bromus rubens* (annual grass), *Ceterach officinalis* (drought tolerant fern), *Linum tenuifolium* (drought tolerant perennial) and *Crassula tillaea* (annual succulent). The latter species has only been reported exotic and invasive in some provinces of California, USA; Invasive Plant Atlas of the US, www.invasiveplantatlas.org; consulted on December 1, 2014).

Annual species are currently rarely regarded for GR purposes but in the habitat template context, this life form is an important part of Mediterranean vegetation and should be considered in GR design. They contain properties that can guarantee GR performance in regions with harsh environmental conditions. More specifically, seed production is added to the seed bank, hence forming a buffer against eventual gap formation should other herbaceous plants die off (Madon & Médail, 1997). Studies demonstrating the potential of annual species in a GR context were until recently very limited. Nagase and Dunnett (2013b) studied the establishment of an annual meadow on EGRs and concluded that in the UK, annual seed mixtures provide many benefits (e.g. long flowering, quick establishment, easy installation and little maintenance). Benvenuti (2014) demonstrated that wildflower GRs in a Mediterranean context (Italy) are characterized by periodic senescence of the vegetation, but that they are nevertheless valuable for biodiversity and landscape improvement. Our study specifically pointed at the value of annual species in the context of the GR habitat template and the need for more profound research on this topic. Also in a climate change context, in which more extreme weather events are predicted, annuals comprise a valuable adaptive strategy by bridging the harsh period as seeds.

Bryophytes are also promising, as they are part of the vegetation (sometimes covering > 50% of a plot; Table 2.1). These non-vascular plants have been shown to be valuable in a GR context (e.g. Krupka, 1992; Anderson et al., 2010). First of all, they can colonize the substrate spontaneously through spores (sometimes vegetative propagules) and can survive extreme drought (Anderson et al., 2010; Butler & Orians, 2011). The drought tolerance capacity is a result of both desiccation tolerance and avoidance (Proctor, 2000; Glime, 2007). Desiccation tolerance involves dry tissue survival and restart of photosynthesis upon rehydration through a suit of interacting mechanisms (e.g. cellular protection through ABA and osmotically active substrates; accumulation of dehydrins and osmotically active sugars; Lakatos, 2011). In desiccation avoidance, the plant avoids drying out through structural adaptations and by specialized life cycle stages (e.g. dormancy; dying while leaving spores behind for the next generation; altered phenology; requirement of a dry season to let the operculum burst; Lakatos, 2011). Small size, thick cortices, hydrophobic surfaces, spore formation, dormancy, leaf orientation, hair points, mucilage and dense rhizoids are all properties that contribute to the drought tolerance strategy of bryophytes (Proctor, 2000; Glime, 2007; Lakatos, 2011). They only require a thin substrate, can store a considerable amount of rainwater and facilitate the establishment and survival of vascular plants in extreme conditions (e.g. Krupka, 1992; Anderson et al., 2010). The facilitation property might explain the positive correlation between the bryophyte cover and the species richness (cf. Fig. 2.3). It has been suggested that bryophytes could offer an alternative for an additional water retention layer (Anderson et al., 2010). Furthermore, they play a significant role in ecosystem functioning in terms of carbon and nitrogen sequestration, thermal and hydrological soil regime, and provisioning of microhabitats for small organisms (Glime, 2007; Lakatos, 2011). Moss species present on the experimental EGR in Heverlee after two growing seasons include Silky Forklet-moss (*Dicranella heteromalla (Hedw.) Schimp*.), Redshank (*Ceratodon purpureus (Hedw.) Brid.)* and Umbrella liverwort (*Marchantia polymorpha L*.). Other potential moss species for both exposed and sheltered EGRs include Black Rock-moss (*Andreaea rupestris Hedw.),* Rough-stalked Feather-moss (*Brachythecium rutabulum (Hedw.) Schimp.*), Silky Wall Feather-moss (*Homalothecium sericeum (Hedw.) Schimp*.) and Frizzled Crisp-moss (*Tortella tortuosa (Hedw.) Limpr*.; Krupka, 1992). The positive aspects of bryophytes should be interpreted with caution, as only few studies have assessed this topic in a GR context (Emilsson, 2008; Anderson et al., 2010), and bryophyte cover can have both positive and negative effects on species establishment under natural conditions (Emilsson, 2008). For example, the seedling germination of some short lived forbs in limestone grasslands (e.g. *Carlina vulgaris, Euphrasia officinalis* and *Linum catharticum*) was negatively correlated with the bryophyte cover, although seed mortality decreased when the bryophyte cover was high (Keizer et al., 1985). Also when the environment is dry, seedling emergence, especially of small-seeded species (e.g. *Arenaria serpyllifolia, Veronica spicata*) is rather inhibited by a bryophyte cover (Zamfir, 2000). Furthermore, spontaneous colonization of GR substrates is limited due to the presence of bryophytes (Emilsson, 2008).

In conclusion, the habitat template concept applied in Chapter 2 provided interesting outcomes. A comprehensive list of species in the Mediterranean region of southern France with a potential for use on EGRs was compiled. Evidence is provided that natural habitats can indeed inspire and improve the design of GRs in the (sub) Mediterranean region.

1.2. A plant trait approach for potential EGR species selection

Research question 2: How can the plants in the MEDPL be ranked according to their potential use for EGRs by making use of their plant traits?

In a climate change context, occasional, unpredictable drought and heat waves, heavy rainfall, flooding and cyclones are predicted (Jentsch & Beierkuhnlein, 2008; Mooney et al., 2009). To cope with these perturbations, a GR ecosystem should be stable, which means that it should be both resilient and resistant. There is still discussion on the relationship between biological diversity and ecosystem stability (Diaz & Cabido), but evidence is growing that functional diversity (FD), and more specifically the range and value of the plant's functional traits, can maintain ecosystem stability in the long term (Diaz & Cabido, 2001; Elmqvist et al., 2003; Hooper et al., 2005; Perrings et al., 2010). FD comprises two concepts, namely functional redundancy and functional insurance. According to the functional redundancy concept, the loss of one or several species does not affect an ecosystem process (e.g. primary productivity or nutrient cycling) significantly as there are still other species that guarantee this ecosystem process (Diaz & Cabido, 2001). In the functional insurance concept, a greater functional richness in the community implies that less species are necessary to buffer the respective ecosystem against perturbations (Diaz & Cabido, 2001).

In Chapter 3, we elaborated further on the results of Chapter 2 in which new insights on suitable native species for use on EGRs in the (sub) Mediterranean climate were explored. Both the plant species lists MEDPL and GRPL from Chapter 2 were used. The ultimate purpose of Chapter 3 was to reveal the most important attributes of GR plants by making use of a plant trait analysis, i.e. a correlation analysis of the species in the GRPL and a list of their functional traits and utilitarian aspects. The choice for functional plant traits can be explained from an ecosystem stability viewpoint, as explained in the previous paragraph. As GRs are still engineered ecosystems, more utilitarian aspects (e.g. flower color, flowering period, commercial availability) may be essential too, as these will point out the species with e.g. aesthetic appeal or that meet specific design considerations.

In a preparatory step, relevant traits related to drought adaptation and/or self-regulation (considered as key-factors essential for survival on EGRs under dry conditions) were identified through an extensive literature search. The utilitarian aspects were selected through a similar approach. This way, 67 plant traits (53 functional and 14 utilitarian) were assembled for the 985 unique plant species (MEDPL: 633 species; GRPL: 483 species of which 131 also comprised in the MEDPL). The TRY Initiative (Kattge et al., 2011) was then screened for trait values. The goal was to highlight the most important traits for GR plants in order to use these traits for appropriate species selection, so the correlation analysis was carried out on the GRPL species*trait matrix. Traits related to frequently applied GR species were referred to as ‘primary traits’ (n = 8), and traits related to the primary traits were called ‘derived traits’ (n = 12). The utilitarian traits did not end up in the primary trait list, but 6 out of 7 were correlated to the primary traits and were hence placed in the derived trait list (Table 3.4). As the primary trait list was composed of functional traits only, we conclude that drought tolerance properties are more important for EGR species selection than aesthetic and design considerations expressed by the utilitarian traits.

Together with exclusion criteria (n = 5), both primary and derived traits were incorporated into a screening tool. As an example, this tool was illustrated on a subset of the MEDPL, which identified 34 new potential GR species. 35% of these species were annuals, which are, as was discussed in part 1.1 of the general discussion, a promising life form that has until now rarely been considered on EGRs. Also *Sedum spp.* (*S. album, S. acre*) and Mediterranean species already used on GRs (e.g. *Thymus praecox, Draba aizoides, Hyppocrepis comosa, Helianthemum nummularium*), result in a high screening score (SS ≥ 16/28).

Although the plant trait approach described here has some limitations (mainly due to the high amount of missing trait values), it is useful as it offers both new possibilities for GR design in the Mediterranean and it can help GR companies in the temperate climate to adjust GR design to cope with upcoming climate change. The screening tool is a useful framework for making substantiated decisions for appropriate GR design in terms of species choice.

1.3. Testing potential Mediterranean plants in different climates and under different experimental setup

Research question 3: Next to theoretical evidence, can the potential of some Mediterranean plants for EGRs be confirmed experimentally? Do other factors including climate, substrate depth, water retention layer (WRL) and exposition affect the suitability of these plants?

The screening tool developed in Chapter 3 delivers a potential list and should ensure EGR performance and sustainability, yet the ultimate prove should come from experimental outdoor trials. Indeed, the ultimate purpose of Chapter 3 was to reveal the most important attributes of EGR plants by use of a plant trait analysis. However, next to important attributes, the potential species also have specific habitat requirements (e.g. climate, organic matter, nutrient content, substrate depth) and the GR structure design will need customization to ensure good plant health. Because habitat requirements were not considered, some odd species have been proposed (e.g. *Gymnadenia odoratissima*, *Ophrys insectifera*, *Succisa pratensis,* *Peucedanum oreoselinum*). They have suitable trait values, but their suitability under real EGR conditions in the Mediterranean is questionable. So the traits and niches do not correspond 100%, which is why the screening tool should be interpreted with caution, and potential species need to be tested under EGR conditions. Chapter 4 discusses the results of a two-year experiment on unirrigated EGRs which were constructed in both a Mediterranean (Avignon, France) and a temperate climate (Heverlee, Belgium). In order to gradually increase GR biodiversity, the EGR vegetation should comprise different life forms, and both novel and already applied species. We tried to test as many novel potential species as possible but the supply of these species in nurseries was limited as general nurseries offer mainly horticultural and 'tried-and-true' plants. Therefore, the number of tested species was here limited to 11 novel species and 7 already used GR species. Nevertheless, the selected species belonged to different life forms (annuals, perennial herbs, succulents and geophytes) and varied in their screening score (SS), so the experiment offered possibilities to demonstrate multiple recommendations offered in Chapter 2 and 3.

The experimental plots installed in Avignon and Heverlee differed in exposition (sheltered north-side of the roof or exposed south-side) and structure (substrate depth of 5 or 10 cm and presence/absence of a WRL). Major differences were found between the locations for both cover and abundance data, which could be attributed to the divergent climatic conditions (Fig. 8.1). Cover values in Avignon reflect the summer drought and following rainy autumn periods. Only for some variables and periods, the EGR performance appeared significantly better in the sheltered plots. Placing the EGR in a sheltered location is hence not a major requirement to obtain a successful EGR. The structure type on the other hand appeared of much higher importance. Overall, the deepest substrate of 10 cm with a WRL resulted in the highest cover and abundance values, species richness and Simpson Index values throughout the experiment (Fig. 8.1).

Of the tested species, *Lagurus ovatus* is recommended on EGRs in the Mediterranean. *Euphorbia cyparissias* can be used in temperate climates on EGRs if a WRL is present. *Sedum spp.* should be considered as part of the EGR vegetation as they performed very well in both locations and because of their nursing effect (cf. Butler & Orians, 2011; Boivin et al., 2001; Farrell et al., 2012). We also advise *Alyssum alyssoides, Lobularia maritima* and *Silene conica* for use on EGRs in both locations. In Heverlee, next to *Dianthus superbus, Sideritis hyssopifolia* and *Linum bienne* are good performing species for EGRs with a WRL. The geophytes *Allium sphaerocephalon* and *Iris lutescens* are advised as an accent plant, as they only flower for a short time. Both bryophytes and weeds established spontaneously over the two years, especially in the sheltered plots. If one wants to establish an EGR dominated by a bryophyte layer, a very shallow substrate (± 5 cm) without a WRL should be opted for, and this kind of EGR is more certain to succeed in the temperate climate. Weeds are mostly ruderal species present in the EGRs' environment. They can germinate in these novel urban habitats, especially during the establishment phase as competition with the installed vegetation is not yet going on, but when climatic conditions become too extreme (either high temperature and prolonged drought or very low temperatures), the weeds die off. However, the next growing season or autumn period, new seeds can be recruited on the EGR. The weedy species therefore represent a natural and inevitable part of the EGR vegetation dynamics. Nevertheless, the probability that weedy species will ever become a dominant part of the EGR vegetation is very low or even inexistent.

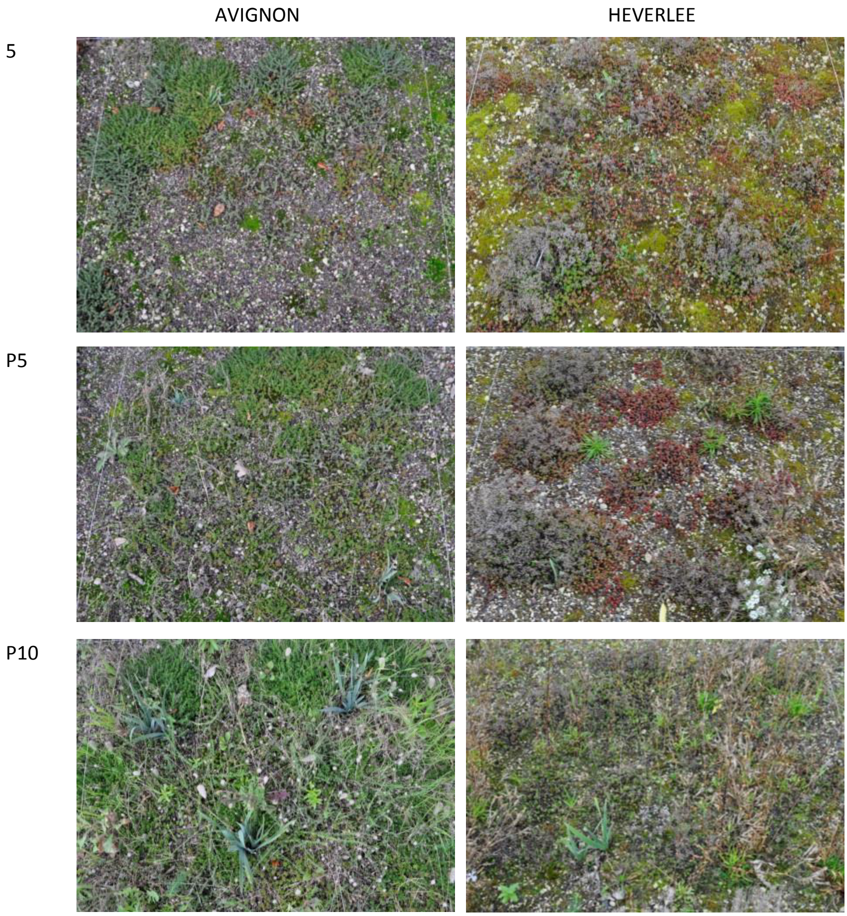

Fig. 8.1 Overhead pictures of a plot with structure type 5, P5 and P10 in both Avignon and Heverlee in autumn 2014 [Pictures: Carmen Van Mechelen, October 2014].

Table 8.1 List of species tested on EGRs in Chapter 4 together with their respective screening score (SS) derived from the screening tool developed in Chapter 3. The species overall performance during the experimental period in Avignon and Heverlee is indicated on an ordinal scale (- : no germination or no reoccurrence after first growing season; +, ++, +++: species performing respectively OK, well and very well).

	Screening Score (SS)	AVIGNON	HEVERLEE
ANNUALS			
Alyssum alyssoides (L.) L.	12	++	++
Clinopodium acinos (L.) Kuntze	2	-	-
Erophila verna (L.) DC.	10	-	+
Lagurus ovatus L.	2	+++	-
Linum bienne Mill.	2	+	+
Petrorhagia prolifera (L.) P. W. Ball & Heywood	14	-	+
Plantago afra L.	3	+	-
Silene conica L.	9	+++	++
PERENNIALS			
Herbs			
Carthamus carduncellus L.	Unknown	-	-
Dianthus superbus L.	10	+	+++
Euphorbia cyparissias L.	10	+	++
Helianthemum nummularium (L.) Mill.	16	-	-
Lobularia maritima (L.) Desv.	8	+++	++
Sideritis hyssopifolia L.	2	-	++
Succulents			
Sedum acre L.	23	+++	++
Sedum album L.	25	+++	+++
Geophytes			
Allium sphaerocephalon L.	12	+	++
Iris lutescens (Lam.)	Unknown	++	++

In order to offer a small scale verification of the reliability of the screening method developed in Chapter 3, we compared the overall species presence in the two locations with the species respective screening score (SS), which is an indication of their potential for success on Mediterranean GRs based on their plant traits (cf. Chapter 3). Although the species used in this study originate from natural Mediterranean habitats with similar characteristics as on EGRs, variability between the species' SS was very high, ranging between 2 and 25 on a maximum of 28 (Table 8.1). Therefore, it was believed that some species would perform much better than others. Indeed, eight species performed in accordance to their screening score and six species performed even better than expected. The SS for *C. carduncellus* and *I. lutescens* was unknown due to lack of trait information, so no statement on these species could be made. *H. nummularium*, performed worse than expected, as both the SS and seed viability were high but germination and survival were low in both locations. Also for *P. prolifera*, better performance was expected, as this species only germinated in Heverlee at the end of the experiment despite its rather high SS of 14. *S. acre* and *S. album* have a very high SS and they both constitute an important part of the total cover. Other species that performed according to their SS were *A. sphaerocephalon*, *A. alyssoides, E. verna* and *E. cyparissias*. Their SS was medium (10-

12) but they germinated and survived in one or even both locations. Two other species also performed as expected, as no germination was recorded for *C. acinos*, and *P. afra* did not reoccur after the first growing season in Avignon, which is in accordance with their very low SS of 2. The species that performed better than expected all had a low SS (2-10), but performed well in one or both locations. *L. ovatus* (SS = 2) performed very well in Avignon, *L. bienne* (SS = 2) germinated and survived in both locations, *S. hyssopifolia* (SS = 2) was recorded in Heverlee. Finally, *S. conica* (SS = 9), *D. superbus* (SS = 10) and *L. maritima* (SS = 8) did even become part of the dominant species in one or both locations. In summary, most species performed according to what was expected from their respective SS, and other species performed even better than expected. So the screening tool is a good method to indicate species potentiality for use on EGRs in climatic regions with frequent summer drought, but we stress that the tool should be used with caution as some species with a relatively high SS can also perform worse than expected. Also, the correlation between the SS and the species performance, as calculated by means of a Spearman correlation, was not significant (Avignon: r_s = 0.126, p-value = 0.642; Heverlee: r_s = 0.396, p-value = 0.129; N = 16).

In Chapter 4 we offered specific design and species recommendations for both the Mediterranean and temperate climate, which can be used as a base for further testing or for immediate application. An irrigation system is commonly provided on GRs in order to keep the vegetation alive and aesthetically pleasing as long as possible throughout summer. Watering the plants on critical moments (after for example 3-5 days without rain) is generally believed to prevent the maintenance time and cost of reseeding the next year. We would like to stress that the EGRs in this experiment were unirrigated and that the experiment was conducted over the course of only two years. GR vegetation development is amongst others dependent on weather conditions, which are instable and uncertain in the Mediterranean, so the GR vegetation is not expected to ever reach a stable and balanced state. Although summer drought is a general attribute of the Mediterranean climate, it was observed that the yearly weather conditions were rather variable (mild, rainy spring and three months of summer drought in 2013; dry spring and extended summer drought in 2014; Fig. 4.2). The annual plant species applied in this study did indeed suffer from high temperatures and drought, but they were expected to wilt when environmental conditions became too harsh, as this is a distinctive feature of this particular life form. Even after the long summer drought of 2014, new seeds were able to germinate after autumn rain, which proves that these annual species are suitable for use on EGRs in the Mediterranean, even under unirrigated conditions. Their presence in the GR vegetation offers an insurance that the GR will revive after a dormant state during summer. Next to the annual species, the *Sedum spp*. and *I. lutescens* resumed their growth upon autumn rain. *A. sphaerocephalon* and the perennial herbs (except *L. maritima*) suffered highly from the elevated temperatures and drought, hence not allowing them to germinate or leading to premature wilting before the plants were able to set seed. Envisaging an irrigation system would be beneficial for these plants during the establishment phase and upon summer drought in order to provide a sufficient amount of water to allow them to germinate and grow and keep them alive until they are ready to set seed for the next year. However, as the EGR should be sustainable in the long term, irrigation practices (especially water source, time and quantity of watering) should be adapted to the local climatic conditions (see Chapter 6).

GRs have been demonstrated to provide a suitable habitat for many organisms whose natural habitats are often endangered (Butler et al., 2012), and they can function as stepping stones for many high-mobility, and eventually also low-mobility arthropod species (Madre et al., 2013; Braaker et al., 2014). Colla et al. (2009) showed that GRs have potential for pollinator conservation, as a variety of bee species use the GR for foraging or nesting. This is important for ecological restoration purposes, as the presence of pollinators makes the GR look more 'natural' and contributes to seed production and hence the GR's sustainability in the long term (Colla et al., 2009; Braaker et al., 2014). A GR with diverse and mainly native vegetation offers a variety of nesting habitats and may further attract pollinators (Tonietto et al., 2010). Our experimental EGRs attracted many animal species (Fig. 8.2). *Bombus spp*. and *Coleoptera spp*. (e.g. *Coccinellidae*) lingered near the flowering *S. album* and *A. sphaerocephalon*. *Lepidoptera* larvae, *Formicidea* and *Caelifera spp*. were also noted on the EGRs. Considering predators, lizards (*Podarcis muralis spp*.) did inhabit the EGRs. Birds (e.g. *Pica pica* and *Corvus monedula*) visited the EGRs regularly, as indicated by the small gaps in the substrate where they foraged. This is often considered a problem as birds can adversely affect GRs, especially during the establishment phase, as they peck at seeds and small plug plants (Fernandez-Canero & Gonzalez-Redondo, 2010). A possible solution consists of covering the newly installed GR temporarily with a specialized bird net that does not entangle the birds or the plants. In addition, this kind of protection can prevent domestic cats from damaging the GR. Although cats have difficulties to reach GRs in most cases, some GRs are accessible (including the experiment in Avignon), and cats like to use the loose GR substrate as a litter tray. Until the vegetation has covered the GR sufficiently, a net is an appropriate solution if the presence of cats is considered a problem.

People should be aware that even when EGRs do not appear very attractive during part of the year when the vegetation is dry, their value as a habitat for local flora and fauna cannot be neglected (cf. Brenneisen, 2006; Colla et al., 2009; Madre et al., 2014). Other GR benefits like stormwater retention and mitigation of the urban heat island effect are also guaranteed during summer, because of the major role that the GR substrate plays in providing those benefits.

Fig. 8.2 Pictures of some animal species that were observed during the monitoring periods on the EGRs. a) *Lepidoptera* larvae; b) *Bombus sp.*; c) *Caelifera sp*.; d) *Coccinellida sp.*; e) *Podarcis muralis sp.* [Pictures: Carmen Van Mechelen, 2013-2014].

2. Factors for improved green roof performance

2.1. Effects of organic matter and mycorrhiza on green roof vegetation development

Research question 4: Plant performance can also be enhanced by adding organic matter (OM) and arbuscular mycorrhizal fungi (AMF) to the growing medium. Is this also the case for plants developing under EGR conditions?

In Chapter 5, the main focus, which was the selection of appropriate GR vegetation in Chapter 2-4, is now shifted to the GR substrate. GR substrates have specific characteristics, as they have to be light weight, shallow, and should only contain a relatively low amount of nutrients (Oberndorfer et al., 2007; FLL, 2008). This is challenging for GR plant growth and survival. It has often been suggested that adding OM or AMF could overcome these limits.

OM adds nutrients to the substrate and is known to increase nutrient exchange capacity and to improve soil structure and water retention (Friedrich, 2005; Emilsson, 2008; Molineux et al., 2009). However, it comes with certain disadvantages as OM decays over time which causes shrinkage of the substrate volume, and decreases water and nutrient-holding capacity (Friedrich, 2005; Snodgrass & Snodgrass, 2006; Rowe, 2011). Instead of adding OM, AMF, which are symbiotic fungi (Phylum *Glomeromycota*) that form mutualistic associations with plant roots of most plant species, could be considered (Parniske, 2008; Bonfante & Anca, 2009; Willis et al., 2013). AMF- root associations are known to provide multiple benefits to plants. Plant physiology is influenced, as expressed by improved mineral nutrition and plant development (cf. Bethlenfalvay, 1992; Azcón-Aguilar & Barea, 1997). Mainly phosphorus (generally only available in low quantities in natural soils) and nitrogen uptake are improved in presence of AMF (Smith & Smith, 2011, 2012). Plant growth and development is indirectly influenced because of a stabilized soil structure (Azcón-Aguilar & Barea, 1997). AMF also protect plants against multiple biotic and abiotic stressors (e.g. nutrient deficiency, drought, salinity, pollution, pathogens; Azcón-Aguilar & Barea, 1997).

Since the nineties, the mycorrhizal technology has developed considerably and many (urban) horticultural practices are now available. For example, vegetables, fruit crops, perennial herbs, shrubs and trees can be inoculated with suitable commercial inoculum (e.g. Azcón-Aguilar & Barea, 1997; Feldmann, 1998). This enhances seedling growth, reduces the phosphate requirement, and increases plant survival and development. Furthermore, plants become better resistant to fungal root pathogens and abiotic stresses. The inoculum also results in earlier flowering and fruiting, better rooting and fruit production (cf. Azcón-Aguilar & Barea, 1997). More recently, also the GR industry started promoting the use of AMF, as it is assumed that nutrient cycling and drought tolerance associated with AMF would be very beneficial for GR vegetation growth and survival (Streit, 2003; Feldmann, 2008; John, 2014; Molineux et al., 2014).

The benefits of AMF on plant growth and development are acknowledged in horticulture, but studies investigating the effects of AMF on vegetation in a GR context have until recently been very limited (but see McGuire et al., 2013; John et al., 2014; Molineux et al., 2014). Generally, GR substrates are sterilized before use in order to eliminate seeds of undesired species (Gormsen et al., 2004; Emilsson, 2008; Feldmann, 2008; John et al., 2014). Succulents are known to form no or very weak mycorrhizal associations, probably as an adaptation to the harsh conditions in their natural habitats (cf. John et al., 2014). This makes these plants a good option for application on sterile GR substrates. However, in order for other AMF-dependent plants to obtain the benefits associated with AMF, the fungi should be added as inoculum, be present in the growing media of the plug plants, or transported by animal vectors like arthropods, birds and small mammals (cf. John et al., 2014).

The effects of addition of OM and AMF on GR vegetation development in a greenhouse and a rooftop experiment were studied in Chapter 5. The study was conducted in Heverlee (Leuven, Belgium) on the same roof as the experiment in Chapter 4. The experimental plots of 1 m² were filled with either a mineral EGR substrate or an EGR substrate with additional OM (Peltracom NV). Half of the plots received 1 g/m² AMF inoculum consisting of *Glomus spp.* As vegetation, we opted for a commercial EGR seed mix (Optigrün International AG) containing 35 herbaceous plant species. In April, eight months after installation, plant surveys on the rooftop were done and included calculation of cover and abundance data, plant height, and diversity measures in terms of species richness and Shannon diversity index and evenness. Vegetation development in the greenhouse was observed weekly from October 2013 until February 2014 and included the same measurements as on the rooftop. However, at the end of the experimental period, the plant material in the greenhouse was used to determine the dry weight and to calculate the mycorrhizal inoculation effect, an index for the effectiveness of an AMF inoculum. Also the roots of four species (*Cota tinctoria, Dianthus deltoides, Leucanthemum vulgare,* and *Prunella vulgaris)* were analyzed microscopically for AMF presence.

In the greenhouse, positive effects were found of OM on plant height, dry weight and cover, and evidence of AMF-root associations was found although no significant effects of AMF on vegetation development could be demonstrated. The plots with mineral EGR substrate resulted in a positive mycorrhizal inoculation effect, indicating a positive effect of AMF on biomass production. In general, we found that AMF lead to better performance in terms of species richness and cover, but this trend was not significant. On the rooftop experiment, no significant effects of OM and AMF on vegetation development were found, which could be due to climatic factors. During two weeks after sowing, the plots were irrigated by hand two times a week to saturation, but afterwards they only received water from natural precipitation events. The EGR vegetation experienced a relatively dry winter and spring. Together with above average temperatures, this resulted in slow germination and vegetation development. Just like the experiment in Chapter 4, we believe that an additional irrigation system during the establishment phase could have mitigated the water shortage problem on the rooftop.

In conclusion, this study showed that a low amount of OM is sufficient to obtain positive effects on plant growth in terms of vegetation cover, height and dry weight. However, an important trade-off should be taken into account, as bigger plants transpire more, compete for light and have more biomass to maintain, making them less resistant to drought stress, which is a disadvantage when a dry period occurs after establishment (Rowe et al. 2006). Our findings also demonstrate that GR substrates offer a suitable media where associations between AMF and plant roots can take place. This finding is in line with a recent study of McGuire et al. (2013) who examined parks and GR substrates in New York and found that a considerable fungal diversity was present, of which most of the genus *Glomus* (*Glomeromycota*). This suggests that if AMF are added or when they reach the roof spontaneously, the GR substrate offers a suitable media where AMF-root associations can take place. However, in our study, addition of AMF was not very effective as regards initial plant development. This in contrast to Busch and Lelley (1997) who demonstrated that by adding AMF on a GR, plant loss could be reduced and plants became more drought tolerant. Also Molineux et al. (2014) very recently offered evidence that adding AMF inocula to GR substrates is sustainable, and that GRs with healthy AMF-root associations may be more resilient to summer drought. GRs would hence be greener and be able to provide ecosystem services (e.g. stormwater management and thermal performance) for a longer time period (Molineux et al., 2014). Although our results suggest that AMF inocula cannot yet be considered as a substitution for OM, other very recent studies (McGuire et al., 2013; Molineux et al., 2014; John et al., 2014) demonstrate positive effects of AMF and other soil microbiota on EGR vegetation. The topic of AMF inoculation in a GR context is hence rather novel but promising, and more research is needed to sort out the knowledge gaps.

2.2. Towards sustainable green roof irrigation methods in different climatic contexts

Research question 5: What kinds of irrigation methods are commonly used on GRs? Can irrigation recommendations be made for different climates (including the Mediterranean) and are there sustainable methods that should be promoted?

As indicated in Chapter 4 and 5, vegetation development on the experimental unirrigated EGRs could have been improved if an irrigation system were available. By definition, the goal of irrigation is to maximize the net profit in the long term, by keeping soil water content between the stress point and field capacity (Fereres et al., 2003). On GRs, which are usually non-productive systems, irrigation is generally believed to be beneficial as it improves both plant survival and temperature control. On the other hand, irrigation of GRs and other urban green infrastructures often has a negative connotation in a water management context. Globally, the main proportion of the total available freshwater is used for irrigation of agricultural fields, reaching up to 80% in (semi)-arid regions (Fereres & Soriano, 2007; Bjornlund & Wheeler, 2014). Extraction of water for agricultural irrigation and the excessive water use can lead to environmental problems, including water scarcity, soil salinity, soil erosion and pesticide pollution (Fereres et al., 2003; Newley & Treverrow, 2006; Bjornlund & Wheeler, 2014). Together with competition with other water needs (e.g. town water supplies, environmental flows, recreation), the pressure to limit irrigation in agri- and horticulture grows (Fereres et al., 2003; Newley & Treverrow, 2006).

Sustainable water management is an important global action to alleviate the growing pressure on our water resources and a way to balance both socio-economic and environmental water needs (Pereira et al., 2002; Bjornlund & Wheeler, 2014). To ensure sustainable irrigation in the long term, there should be public awareness of sustainable water consumption, and similar to agro- and horticulture, GRs should be designed carefully, without wasting any water and limiting the use of potable water (Newley & Treverrow, 2006).

Information on GR irrigation is still very scarce, and the review in Chapter 6 attempted to draw attention to alternative water sources and water conservation strategies in order to make GR irrigation practices more sustainable. Just like in horticulture, there are three main questions to consider for more efficient irrigation: How, when and how much (Fereres et al., 2003).

Agricultural irrigation systems include surface or flood irrigation, sprinkler systems and micro-irrigation like drip-irrigation, micro-sprinkling and sub-irrigation (Pereira et al., 2002). In horticulture, similar irrigation technologies are available, but surface irrigation and sprinkler systems on big scale are considered not very efficient as they do not specifically target the root zone of the plants (Newley & Treverrow, 2006). Drip irrigation and micro-sprinklers are better suited for horticultural purposes as they are better controllable (Fereres et al., 2003). Drippers deliver water at the right locations and are less subject to wind, and micro-sprinklers do not waste water due to overlapping irrigation areas (Fereres et al., 2003; Bjornlund & Wheeler, 2014). Also for GRs, multiple irrigation methods are possible (cf. FLL, 2008), of which drip irrigation and overhead sprinkler systems are the most commonly applied. Hand watering is possible as well, but extremely time consuming and only possible for small surfaces. The best way to irrigate is automated overhead irrigation or drip irrigation if an additional WRL is provided (Rowe et al., 2014).

Alternative irrigation sources are also part of more sustainable water use. In agriculture, reuse of wastewater will definitely be developed further (Fereres et al., 2003). Suggestions for more sustainable GR irrigation showed that water can be conserved by using gray water (i.e. all untreated household effluents except those originating from toilet use) and by rainwater harvesting. Gray water is a nutrient-rich irrigation supplement with broad applicability in the urban environment (e.g. domestic gardens, small-scale food production, green infrastructure elements; Rodda et al., 2011). The main problem that should be investigated further is the high amount of micro-organisms which could be harmful for human health, plant growth and yield (Rodda et al., 2011). Next to its usefulness in an urban context, rainwater harvesting, i.e. the process of concentrating and storing rainwater runoff, can also be applied in agriculture (Oweis & Hachum, 2006).

Based on outdoor GR experiments, irrigation specifications for different climates were proposed. It became clear that irrigation is essential during establishment and the first growing season on all types of GR and in all climates here considered. Afterwards, irrigation is necessary on GRs in (semi)-arid climates, and advised in small amounts in the other climates. One could assume that irrigation should be applied when the soil water content reaches the stress point, because below this point, evapotranspiration (ET) will be restricted and water uptake from the roots will be difficult (Jim & Peng, 2012; Bjornlund & Wheeler, 2014). However, irrigation is more efficient if applied when soil water content is slightly above the stress point, and irrigation should stop before the field capacity is reached (Bjornlund & Wheeler, 2014). Therefore, soil water content and ET should be monitored carefully (Fereres et al., 2003; Newley & Treverrow, 2006; Bjornlund & Wheeler, 2014).

Water can also be conserved by adapting irrigation requirements, more specifically by targeting the GR vegetation or materials. An appropriate selection of vegetation is needed, with a diverse mix of life forms including succulents, geophytes, mosses, annual species and drought-tolerant herbs (Coutts et al., 2012). Ideally, a deeper substrate should be opted for to increase the plant water availability, but as this is not always possible due to building weight limitations and colonization of undesirable weeds, shrubs and invasive plants, efficient irrigation methods should be considered as an alternative. By considering substrate type, depth, vegetation and irrigation regime during the design process, an adaptive approach is created in which GR establishment and sustainability can be facilitated (Kotsiris et al., 2013; Ntoulas et al., 2012, 2013).

Another adaptive approach could be found in the concept of deficit agriculture irrigation. In (semi)-arid regions, precipitation is usually unpredictable and sporadic, and as it is quickly lost to evaporation and runoff, the contribution of rainwater to crop yield is rather low (Oweis & Hachum, 2006). Irrigation is used to supplement rainfall in order to achieve maximum and more stable crop yields (Zhang & Oweis, 1999; Fereres & Soriano, 2007; Oweis & Hachum, 2006). Due to water scarcity, this supplemental irrigation is often extracted from groundwater aquifers, leading to a decline of the groundwater table and further encouraging the water scarcity problem (Zhang & Oweis, 1999). A better strategy would be to maximize the production per unit of water consumed (the water productivity) instead of maximizing production per unit area (Fereres et al., 2003; Oweis & Hachum, 2006; Fereres & Soriano, 2007). In the deficit irrigation strategy, which is often applied in regions where water is scarce, irrigation is applied at quantities below the full ET requirement of the crop, thereby increasing the water potential while only marginally decreasing the crop yield (Pereira et al., 2002; Oweis & Hachum, 2006; Costa et al., 2007; Fereres & Soriano, 2007). It has been shown that the maximum water potential can be reached when only 1/3 to 2/3 of the full irrigation requirements are applied to the crop (Pereira et al., 2002). This optimization strategy could be useful in a GR context as well, as by limiting irrigation to drought-sensitive growth periods (i.e. establishment phase and growing seasons), the water productivity can be maximized, while also stabilizing yield (in the case of GRs, plant growth and survival and hence the contribution to urban ecosystem services). However, in order for the deficit irrigation strategy to be successful, the exact response of the GR vegetation to drought stress in different development stages should be known, as well as the impact of reduced GR vegetation performance caused by drought stress on ecosystem functioning.

This review pointed at sustainable irrigation possibilities that need to be elaborated further with scientific experiments and examples of local implementations. Different irrigation regimes are needed according to climatic context, and guidelines for irrigation specifications in each climate need to be determined. If public awareness of sustainable water consumption is promoted and if GRs are designed carefully, then irrigation practices can be sustainable in the long term and contribute to better urban life quality.

2.3. Ways to improve green roof functional diversity and the ecosystem services they provide

Research question 6: Assuming that functional diversity (FD) and phylogenetic diversity (PD) of plant communities have a positive effect on ecosystem functioning, to what extend do different GR systems available on the market contribute to GR ecosystem functioning? Can FD and hence the ecosystem services of GRs be improved?

Improving ecosystem services is important for a more sustainable urban planning and a way to ensure good life quality. Therefore, examining urban ecosystems (in this case EGRs) and constructing an applicable framework to achieve better ecosystem services is essential. The role of GRs in offering multiple ecosystem services is becoming increasingly acknowledged (Carter & Jackson, 2007; Cook-Patton & Bauerle, 2012; Gaston et al., 2013; Lundholm et al., 2010), but there are still many questions about the link between biodiversity and the delivery of ecosystem services in a GR context. Lundholm et al. (2010) for example, demonstrated that combining different life forms on GRs can improve ecosystem services (e.g. stormwater management) but that for the case of roof cooling, species-poor GR systems were a better option than those with high diversity. There is hence a need for further studies on the relationship between biodiversity and ecosystem functioning. The work in Chapter 7 was based on the assumption that FD and PD are linked to ecosystem services. The goal was to analyze the initial plant species composition, as provided by commercial EGR systems, in terms of FD and PD, and to offer a methodology to optimize species choice for incorporation into EGR design, making use of the FD approach.

The EGR systems (n = 57) and their corresponding plant species (n = 199) were selected by screening the webpages of all the companies associated with the European Federation of Green Roof Associations. Information on percentage of succulent species, substrate depth, installation method and species richness (SR) were derived from the EGR systems. 29 plant traits were selected based on important GR ecosystem properties as explicitly mentioned in specific literature on GRs. Differences in FD, PD and SR between the EGR systems were considerable. Also correlations between FD, PD and SR were strongly positive, suggesting that species-rich systems offer better ecosystem properties and services. Based on species composition, the EGR systems could be grouped in three general types that differ in SR, percentage of succulent species, substrate depth and installation method. GR systems that comprise only succulent species have significant lower FD and PD values compared to systems containing more diverse vegetation. However, results also show that the FD within the GR types could be improved. Although the species-poor GR systems have lower FD and PD values, they contain many succulent species that are considered to be highly drought tolerant, so in these systems, species have been selected to optimize the drought tolerance capacity (trait convergence strategy). In the species-rich GR systems with higher FD and PD, fewer succulent species are present and it is questionable if these systems are sufficiently drought tolerant. In a GR context, succulence is often considered as the only way to address the drought tolerance issue. However, drought tolerance is actually achieved by a combination of multiple traits, including leaf area, size, presence of hairs or waxes, root length and biomass, and photosynthetic pathway (Markesteijn & Poorter, 2009; Cook-Patton & Bauerle, 2012). So next to the trait convergence strategy, the diversity approach can also contribute to drought tolerant vegetation, while (assumingly) enhancing ecosystem services.

Based on a species trait dissimilarity matrix, two methods were then proposed to define species combinations (one exact and one applicable species list) that maximize the FD for every GR type, and thus the assumed overall ecosystem properties and services value.

The used species lists are the ones proposed by the GR companies, so they only provided information on the initial species presence. Vegetation dynamics and abundance data once installed on the GR were not considered. As GRs are dynamic systems, the vegetation composition will change over time, hence also the FD and PD of the system. Some scientific studies for example, have noted a decline in GR species richness over time (Rowe et al., 2012; Lundholm et al., 2014). However, the FD and PD approach remains valid, as for GR design one often starts from simple species lists.

Despite the number of current drawbacks of the FD and PD approach, this study offers a way to design GRs with high plant trait diversity. It also highlights that currently used EGR systems differ greatly in their FD and PD. The described approaches are generic in nature and can be used for a broad range of urban ecosystems. By carefully considering species that maximize FD, the design of urban green infrastructure elements can become a more sustainable and vital tool to improve quality of life in urban areas. We acknowledge that as more empirical research becomes available, other possibilities may arise that also offer ways to improve species selection for GRs, for example by only looking at the plant traits that are highly related to one or multiple ecosystem services. Also, the optimization problem could have been approached from an operations research perspective. Mixed Integer Linear Programming for example has been used for optimal material selection in terms of design, monetary and environmental aspects of green buildings (Castro-Lacouture et al., 2009). The technique uses mathematical models to optimize a certain objective (e.g. optimal material selection) while considering multiple constraints (e.g. budget and design constraints). Tsang and Jim (2013) use a stochastic approach (demand-responsive optimal-inventory model) to model and predict the future GR demand and optimize contractor inventories of GR components under different market scenarios. To our best knowledge, such mathematical models have not yet been used for optimization of GR vegetation selection. The operations research examples mentioned above are rather time-consuming and require mastering of specific mathematical skills. Therefore, we opted for the FD and PD analysis, which is more practical and in line with the plant trait approach of Chapter 3.

3. Research gaps and directions for future research

Overall, the chapters of this thesis present multiple opportunities for future studies, emerging from encountered problems, research gaps or just making use of the methodologies elaborated in this work. First, we summarize some general perspectives:

- A general problem we encountered upon working with plant traits (Chapter 2, 3 and 7) was that there were many missing values for Mediterranean species and particular traits. In Chapter 2 and 3, the most extended and complete data source currently available was consulted (Try Initiative, Kattge et al., 2011), but still a large amount of missing values was encountered. Therefore, some interesting species could possibly have been omitted. Furthermore, substantial information was available for more general and common species but lacking for not well known local Mediterranean species, which resulted in a high amount of common species in the final potential species lists. The lack of detailed information has been shown to be a common bottleneck in ecological research (e.g. Diaz & Cabido, 1997; Franzel et al., 1996; Reubens et al., 2011), stressing the necessity to further complete and update available plant trait databases like the TRY Initiative.
- In Chapter 3 the plant trait selection was based on the assumption that drought tolerance and self-sustainability are very important for plant survival on EGRs in the Mediterranean. We expect that drought tolerance and self-sustainability are important on EGRs in other climatic regions as well (cf. Dvorak & Volder, 2010; Getter & Rowe, 2008; Williams et al., 2010), but other factors could also influence species survival on EGRs in those regions. For example, if Scandinavian countries would be the target, the literature study should rather focus on tolerance to low temperatures and humid conditions, which would significantly alter the screening tool (cf. Emilsson, 2005). Therefore, the screening tool developed in Chapter 3 is particularly interesting for EGR plant selection in a Mediterranean context, but is not advised to use on species not native to the Mediterranean. The methodology however, is a useful framework for parallel research in other climates.
- As demonstrated in section 1.3 of the general discussion, most species performed according to what was expected from their respective SS, and other species performed even better than expected. The screening tool is therefore a rather reliable tool to indicate species potentiality for use on EGRs in climatic regions with frequent summer drought. Knowing this, it would be interesting if some species with a high SS, like *Thymus serpyllum, Silene otites, Petrorhagia prolifera and Polygala vulgaris*, could be commercialized by nurseries and seed suppliers, in order to make them the subject of further EGR experiments. Also, after testing of the potential species under GR conditions, nurseries should take the successful species into account in their supply, in order to diversity and improve the GR performance.

- Research should also focus on the development of species-specific AMF inocula, as the effect of AMF inoculation is actually dependent on the used AMF and plant species (Busch & Lelley, 1997; Rillig, 2004). If AMF- and plant choice can be tuned, the GR industry is one step closer to successfully develop productive and biodiverse EGRs.
- In line with the suggestions on sustainable GR irrigation practices described in Chapter 6, future research should further elaborate on GR materials with increased water retention capacity. Such research is necessary in order to develop GRs with high biodiversity value and with no or only limited irrigation requirements, also in (semi)-arid climates (Dvorak & Volder, 2010). Studies selecting appropriate drought tolerant plant species should also be supported, in order to limit irrigation requirements (Schroll et al., 2011a, Schweitzer & Erell, 2014). Furthermore, the potential and effects of gray water reuse and the deficit irrigation strategy should be explored further.

Upon working on the experimental EGRs in Chapter 4, following ideas for further research emerged:

- The exploration of natural Mediterranean habitats as described in Chapter 2 and the subsequent screening in Chapter 3 showed that a high amount of unused, local Mediterranean species with variable life forms comprises a potential source for urban greening. However, the results do not offer scientific evidence that the species will effectively thrive on GRs in the Mediterranean or temperate climate. The research offers the ecological fundamental knowledge necessary for further testing of species and final implementation into a successful GR system. 18 species were tested in Chapter 4, but many other species with high potential could be tested in the future.
- The vegetation development on the EGRs in Chapter 4 was highly affected by climatic conditions. As weather conditions vary from year to year and EGRs are dynamic systems, we expect a similar variation in behavior like in the past two years. A further monitoring could of course add extra detail to the development.
- Not only climatic conditions, but also other ecological assembly rules determine the species that will eventually become part of the actual GR community. Both dispersal and (a)biotic assembly processes (i.e. habitat filtering and biotic interactions) need to be studied to evaluate the potential of species in the regional species pool to colonize and establish on EGRs (cf. Götzenberger et al., 2012). Currently, little information exists on factors (situated both at landscape and local level) that determine spontaneous colonization and GR vegetation performance in the long term. Well established and novel technologies including Geographical Information System technology, and proximal and remote sensing, could be very helpful in this respect.
- The colonization process can manifest in two directions. Next to investigating the potential of regional species to colonize the GR spontaneously, the species applied on the GR intentionally can also spread

to the surrounding environment. It was noticed that *S. album* and *S. acre*, installed on the experimental GRs, were able to colonize and establish on other parts of the roof. This is another topic that needs consideration, for example in the context of invasive species monitoring.

- The positive aspects of bryophytes as drought tolerant GR vegetation and as additional water retention function were discussed in part 1.1 of the general discussion. We also pointed at some negative effects that those species could have on the colonization and establishment of spontaneous and intentionally installed vascular plant species on GRs. Further studies should unravel all the positive and potential negative aspects of the bryophyte layer for other GR vegetation.
- In part 1.3 of the general discussion, some animal species that were observed during the experimental period were briefly mentioned to point at the habitat value that GRs offer. More attention should be paid to both above- and belowground biodiversity on GRs, as biodiversity research comprises only a small portion of the current research efforts on GRs (Blank et al., 2013). Bee species ensure pollination of GR plant species and are hence essential for seed production and the insurance of GR performance in the long-term (Colla et al., 2009). A stable microarthropod community in the GR soil is critical for ecosystem functioning as well (Rumble & Gange, 2013).
- Finally, next to looking at the soil biota, it is also necessary to study the seed bank composition (both transient and persistent seed bank aspects) and dynamics of the EGR. To our best knowledge, the soil seed bank has not been the main focus of any GR investigation yet. However, regarding ecosystem resilience, seed bank ecology is an important concept because soil seed banks represent a stock of regeneration potential after disturbances (cf. Wang et al., 2013). Information on the GR soil seed bank is useful as it can predict new plant recruitment and the sustainability of the GR in the long term. Brenneisen (2006) suggested, in a context of natural habitat replacement, to use top soil of natural habitats (which includes part of the seed bank and soil microbiota) as complement to the sterile GR substrate. Different GRs in Berlin have been observed by Köhler (2006) over 20 years, and several annual plants and weeds were able to germinate and grow from the seed bank, although those species disappeared again after some years. Other plants (e.g. *Anthyllis vulneraria* and *Medicago sativa*), although not native to the study region, did survive over the entire study period due to regular irrigation, and complemented the seed bank for regeneration in the future (Köhler, 2006).

The experiments in Chapter 4 and 5 were designed in order to study the aboveground vegetation and did not allow measurement of several aspects of ecosystem functioning. As already mentioned in point 2.3 of the general discussion, there is a need for more research focusing on the relationship between biodiversity and ecosystem functioning in a GR context. In line with this recommendation, following research opportunities can be considered:

- Experiments should be conducted on a bigger scale, comprising different vegetation and structure compositions, and designed in a way that allows the measurement of different GR ecosystem services including stormwater management, thermal performance, nutrient cycling and mitigation of air pollution.

4. Concluding part

The studies described and discussed in this thesis indicate that the Mediterranean vegetation can definitely inspire us as a source for development and improvement of EGR design, whether this is for the current Mediterranean climate itself or for the temperate climate under prospected climate change. The elaborated concept for EGR design is summarized in Table 8.2. Before the start of an EGR project, one should consider some important questions regarding the vegetation and EGR structure. For example, what is the exact location where the GR shall be installed, and what climatic conditions prevail in that location? What is the maximum accepted weight of the EGR and what is the main goal (e.g. biodiversity, thermal insulation, and aesthetics)? Not only EGRs, but also other applications in urban greenery like green walls, parks and gardens can make use of the habitat template hypothesis as a starting point for finding potentially suitable plant species (Lundholm, 2006; Perring et al., 2013). Natural habitats with similar properties as EGRs should be selected and analyzed, and a species list based on fieldwork and/or literature sources should be created.

In a next step, the species list should be screened for the most potential species. The screening tool developed in Chapter 3, includes some primary traits, like CAM metabolism, stress tolerance and succulence, which already proved to be important for the success on GRs (Oberndorfer et al., 2007; Snodgrass & Snodgrass, 2006). The other leaf-related traits emerging from the plant trait analysis have gained much less attention in the literature. Therefore, the presence of these attributes in the screening tool offers some novel insights that reach beyond the usual considered water storage attributes. It is possible that the screening tool needs to be adapted to suit the local climatic conditions. This is for example the case when the EGR is planned to be installed in a location with very harsh winter conditions, which will cause the factor frost-tolerance to become more significant than the factor drought tolerance.

The habitat template approach and screening tool recommended in the EGR context should ensure GR performance and sustainability, even under difficult climatic conditions, although further testing of the potential species is required. We pointed out that plant species with different FD and/or PD should be considered in the EGR design, as this is also the case in natural conditions in Mediterranean habitats. Plant communities with high diversity are also increasingly believed to result in better vegetation performance and ecosystem functioning, although we pointed out that more research on the link between biodiversity and ecosystem functioning in a GR context is still necessary (cf. Lundholm et al., 2010). Until now, hemicryptophytes constitute the major proportion of currently applied GR plants, and only little attention has gone to the possibilities of annuals (also called therophytes). Many annuals germinate, grow, flower and produce many seeds in a very short time period, whereupon they perish. Although they would not be interesting during summer months, they may be attractive in spring and early summer for pollinators as well as having esthetic value, due to their colorful flowers (cf. Filippi, 2008). Under natural conditions, seed production is added to the seed bank, hence forming a buffer against eventual gap formation should other perennial herbaceous plants die off. This property is a natural survival strategy which may guarantee GR performance in regions where weather conditions are very unpredictable, like the Mediterranean region (Madon & Médail, 1997). As stated earlier, the capacity of annuals and other GR plants to contribute to seed bank replenishment, and hence insurance of the GR performance in the long term, needs more study. The conservation value of annuals may also be important, certainly in Mediterranean areas where many annuals of harsh environments are threatened (Lavergne et al., 2006). Next to a combination of annuals and hemicryptophytes, some geophytes (e.g. *Allium spp.; Iris spp.*) can be incorporated on the EGR as accent plants, as they only flower for a short period. *Sedum spp.* should always be considered in EGR design. Also bryophytes need attention, as they are part of the natural vegetation and they can facilitate the establishment and survival of vascular plants under extreme conditions (e.g. Anderson et al., 2010; Krupka, 1992). More research is needed to unravel both the positive and possibly negative effects of bryophytes on spontaneous and installed GR vegetation. In order to risk failure of the EGR, we advise to gradually increase the biodiversity, by use of both novel or rarely used species and some 'tried-and-true' GR species. If one opts to install the EGR vegetation as seeds, then good seed quality is of very high importance. If this cannot be ensured, then plug plants should be used instead.

The potential species also have specific habitat requirements (e.g. pH, organic matter, nutrient content) and the GR substrate needs customization to ensure good plant health. In Chapter 4, we showed that for the tested species, deeper substrates (≥ 10 cm) together with an additional WRL are preferred for EGRs in any climate. Using substrate depths of 5 cm or less without a WRL or provision of an irrigation system is not advised, at least not for the species tested in this study, if good performance and biodiversity value of EGRs need to be ensured. In Chapter 5, we concluded that the most important factor for plant growth on GRs was the presence of OM. A possible explanation for the positive results of OM could be the differences in substrate composition. EGR substrates with additional OM have higher and longer water availability after rainfall, and their nutrient content is much higher. In this respect, it would be interesting to keep the dead plant material on the EGR instead of removing it, which is often done for aesthetic reasons during the yearly maintenance visit. The decomposition of this dead material allows a natural enrichment of the GR substrate with OM, hence eliminating the need of conventional fertilizers which are often polluting the runoff (Czemiel Berndtsson, 2010). It also adds structure to the GR, allowing many arthropod species to find a suitable habitat (Madre et al., 2013; Rumble & Gange, 2013).

No significant effects of AMF inoculation on plant development were found. More time is probably needed to fully establish the AMF infection and to obtain positive outcomes on vegetation development. AMF inocula have been very useful in many (urban) horticultural applications, but their significance in a GR context has only recently started to be discovered (cf. McGuire et al., 2013; John et al., 2014; Molineux et al., 2014). Busch and Lelley (1997) concluded that AMF inoculation resulted in overall better plant survival and drought stress on rooftops. It is hence possible that the effects of AMF inoculation become significant in later stages of vegetation development.

When the effects of different substrate depths, substrate types, exposition and additional structures (e.g. WRL) on the potential plant species are still unclear, then the best option is to establish a heterogeneous GR, with varying substrate depth (within the building weight restriction boundaries), varying substrate types, expositions and in some areas an additional WRL (see also Lundholm, 2006; Madre et al., 2013; Rumble & Gange, 2013; Heim & Lundholm, 2014). This approach creates habitat variability in which the plant species can each find their preferable ones. This way, high biodiversity is encouraged, and the EGR can be used as a case study to follow the vegetation dynamics in the long term.

At the end of Chapter 6 it was concluded that irrigation is essential during establishment and the first growing season on all types of GR and in all climates that were considered. Afterwards, irrigation is necessary on GRs in (semi)-arid climates, and advised in small amounts in the other climates. To ensure sustainable irrigation in the long term, there should be public awareness of sustainable water consumption, and GRs should be designed carefully, without wasting any water and limiting the use of potable water. Potential solutions are gray water re-use, RWH, controlled irrigation in space and time (using for example a smart controller) and the addition of a WRL. An appropriate selection of vegetation, consisting of a diverse mix of life forms is essential as well. By considering substrate type, depth, vegetation and irrigation regime during the design process, an adaptive approach is created in which GR establishment and sustainability can be facilitated.

Some weedy species will recruit spontaneously on the EGR. In a GR context, weeds are labeled as undesired herbaceous plants that reach the GR spontaneously (Nagase et al., 2013). They are often unattractive, annoying and some woody weeds can pose a threat for the installed GR vegetation and underlying structures (Nagase et al., 2013). Most of the weeds observed in the experiments in Chapter 4 and 5 were ruderal species also present in the EGR environment. Like the annual species installed on the EGRs, the development dynamics of the weeds follows the weather patterns of summer drought, autumn and spring rains. When climatic conditions become too extreme, the weeds die off, but the next growing season or autumn period, new seeds can be recruited on the EGR from the neighboring landscape. The weedy species therefore represent a natural and inevitable part of the EGR vegetation dynamics. As GRs are dynamic systems (mainly due to climatic variations), the vegetation composition will change over time and will most likely fluctuate around a stable vegetative state. The probability that weedy species will become a dominant part of the EGR vegetation is therefore very low. Furthermore, many weeds possess several interesting traits that add to the FD and hence performance of the GR. We suggest GR designers to reconsider the definition of GR weeds and only label them as such if they are harmful to the GR vegetation and structure. If any harmful weeds succeed to install on the EGR (e.g. *Buddleia spp.*) they should be removed during the maintenance period. At the same moment, it is possible to reseed the spots where the vegetation was not able to survive, but if the vegetation and structure advices provided in this EGR concept are followed, there won't probably be any need for reseeding.

Finally, in the research part of the EGR concept, possibilities for further research are proposed, as well as adjustments that should be made in the short or long term, to make testing of potential plant species possible, or to offer adapted GR species mixes. The FD and PD analysis conducted in Chapter 7 for example, indicated that even species poor GR systems can gain ecological interest by considering alternative species. The two proposed methods, delivering an exact species list and perhaps a more practical one that offers alternative species, illustrate how current GR systems can be adapted to maximize FD and presumably also the overall ecosystem properties and services. The focus of this study was on GRs, but the methods used are generic and offer a framework for improved design of a broad range of novel ecosystems, particularly in an urban context. It is also possible to target specific ecosystem services with this approach, meeting the main goal of the respective GR project.

People are still rather skeptical towards dehydrated GRs during summer (Dagenais et al., 2010). Nevertheless, even when the vegetation is not very attractive in summer (except for evergreen succulents), GRs should still be the preferred option over bitumen or gravel roofs, as the substrate and other structure layers are also effective in building cooling and rainwater retention. Outside the summer months, GRs can function optimally and offer a wide array of local drought adapted plant species, thereby increasing floral and faunal biodiversity. If people accept that EGRs in the Mediterranean region will not be green all year round, which is in line with the general life cycles of the natural vegetation in this climate, more design possibilities arise which will greatly improve GR interest in the region.

Table 8.2 The EGR concept

	EGR Concept			
	1	2	3	4
VEGETATION	Exploratoring questions	Habitat template approach	Screening tool	Test potential plant species
	Location?	Select + analyze natural habitats	Score the native species according to important plant traits	Incorporate different native life forms
	Climate?	Compose native species list based on field observations and/or literature	Eventually adapt the tool to local environmental conditions (e.g. focus on frost tolerance instead of drought-tolerance)	Both novel and already used GR native species
	Main goal of GR installation?			
STRUCTURE	Design questions	Install species on heterogenous EGR	Install appropriate irrigation system	Maintenance (limited)
	Building weight restrictions?	Use different substrate depths and types (with/without OM and/or AMF)	Adapt irrigation requirements	Remove harmful weeds that survived the dry summer period
	Plant substrate requirements?	Create spots with a WRL	Use alternative irrigation sources	Reseed only if no seeds have germinated after the dry summer period
		Make use of different expositions if possible (shade, exposed)	Control and monitor irrigation regimes for a sustainable use	
RESEARCH	Stimulate research		Short term	Long term
	Further complete plant trait information	Test effects of bryophyte layer on GR vegetation	Nurseries should adjust their offer so potential plant species can be tested	Offer GR species mix with high FD
	Study specific AMF-species relations	Perform long-term GR studies; with emphasis on spontaneous colonization; seed bank and biodiversity		Offer GR species mixes that improve one or multiple urban ecosystem services
	Test different water retention materials; study effects of gray water on GR vegetation; explore potential of deficit irrigation	Study effect of functional diverse GRs on ecosystem functioning and services		

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Appendices

Appendix 2.1

Research site	Department	Locations	Description	Protection	Reference
La Crau	Bouches-du-Rhône	Deserted quarry on calcareous soil	Steppe, mainly littered with silica rich pebbles; Former delta of the Durance river	Réserve naturelle Coussouls de Crau	Buisson & Dutoit, 2006 Blondel et al., 2010
Massif des Calanques	Bouches-du-Rhône	Massif du Puget, Falaises Soubeyrannes	Coastal limestone massif undermined by karst erosion	Parc National des Calanques (since 2012)	Bournérias et al., 1991
Alpilles	Bouches-du-Rhône; Vaucluse	**Caumont-sur-Durance, Plateau de Caume , Lamanon, Vernègues**	*Garrigue*	Plateau de Caume: Parc naturel régional des Alpilles	Capitanio & Carcaillet, 2008
Drôme Provençal	Drôme	**Col d'Aulan, Col Milmandre, Montagne de la Chamouse, La Roche sur le Buis**	*Garrigue*	Parc naturel régional des Baronnies provençales (planned for 2012)	Syndicat mixte des Baronnies Provençales, 2010
Nearby North of Montpellier	Hérault; Gard	**Mas Dieu, Plateau d'Aumelas, Plateau d'Artamon, Cuvette de Pompignan**	*Garrigue* + dry, calcareous grassland	no	David, 2006
Causses	Lozère; Gard	**St. Pierre des Tripiers, Saubert , Cros Garnon, Nivoliers, Causse Begon, Causse Blandas**	Calcareous or dolomitic plateaus intersected by gorges; dry grasslands	Parc National des Cévennes	Parc National des Cévennes, 2007 Bernard, 2008

Appendix 2.2

Vegetation class	Department	Alliances/ Associations	Description	Reference
Asplenietea rupestris	Vegetation relevées in Provence-Alpes-Côte d'Azur: Vaucluse, Bouches -du-Rhône, Var, Alpes Maritimes	*Potentillion caulescentis; Saxifragion lingulatae; Asplenion glandulosi*	Calcareous rocky soils of Provençal massives, hélio- and thermophilic species	Loisel, 1976
Thero - Brachypodietea		*Brachypodio-Stipetum mediterraneae; Phlomido-Brachypodietum ramosi; Asphodelo-Stipetum retortae; Sedum-Arabidetum vernae*	Limestone pavements, vegetation mozaic of different biological types , thermophilic; high amount of therophytes	Loisel, 1976
Brachypodio-Brometea		*Brachypodietum phoenicoidis; Diantho-Brachypodietum pinnati*	Mesoxerophilous grasslands	Loisel, 1976
Ononido-Rosmarinetea		*Rosmarino-Ericion with Rosmarino-Staehelinetum, Rosmarino-Lithospermetum and Helianthemo-Ericetum multiflorae; Aphyllanthion with Aphyllantho-Genistetum and Staehelino-Dorycnietum; Genistetum lobelii*	Species poor to species rich (meso)xerophilous garrigue and dry grasslands, sometimes in open forest; therophytes relatively rare	Loisel, 1976
Cisto-Lavanduletea		*Cistion medio-mediterraneum*	Vegetation type with high abundance of nanophanerophytes and chamaephytes; thermoxerophilous	Loisel, 1976

Thero-Brachypodietea	Bouches-du-Rhône, Vaucluse, Drôme, Gard	*Asphodeletum fistulosi with Crassuletum tillaeae*	Species rich xerophilous vegetation first described by Molinier and Talon (1949) in La Crau; dominance of lichens and mosses	Rieux et al., 1977
Thero-Brachypodietea	Bouches-du-Rhône	*Asphodeletum fistulosi and Helianthemion guttati*	Very species rich dry basophilic vegetation of La Crau, many therophytes; rich in mosses and lichen	Molinier & Tallon, 1949
Ononido-Rosmarinetea	Lozère, Gard	*Aphyllanthetum septentrionale; Hyssopeto-Arthemisietum albae; Helianthemeto-Seslerietum; Festucetum duriusculae calciense; Armerietum junceae; Arrhenatherum elatioris*	Dry calcareous open grasslands and prairies of the Causse region; thero- and geophytes not abundant; calcareous of dolomitic soils; mesoxerophilous	Van den Berghen, 1963
Cliff and scree vegetation		*Potentilleto-Saxifragetum cebennensis and Kernereto-Arenarietum hispidae*	Species poor, calcareous or dolomitic underground, abundance of mosses	Van den Berghen, 1963

Appendix 3.1

Trait "groups"	Reference
<u>Functional traits</u>	
Leaf adaptation; Nitrogen content	Abrams & Mostoller 1995 Tree Physiol. 15:361-370
Growth rate; Carbon content; Photosynthesis; Transpiration; Leaf adaptation; Nitrogen content; Biomass and allocation; Rooting depth; Seed Mass; Life form; Grime strategy (C-S-R model); Leaf phenology; Regrowth after disturbance; Drought tolerance; Regeneration strategy; Wood density	Ackerly 2004 Ecol. Monogr. 74:25-44
Biomass and allocation; Nitrogen content; Plant longevity; Grime strategy; Leaf phenology; Micorrhizal association	Allen & Allen 1986 New Phytology 204:559-571
Leaf adaptation; Reserves and storage	Bacelar et al. 2004 Tree Physiol. 24:233-239
Growth rate; Biomass and allocation; Photosynthesis; Transpiration; Leaf adaptation; Reserves and storage; Plant longevity	Barnabas et al. 2008 Plant Cell Environ. 31:11-38
Photosynthesis; Transpiration; Leaf adaptation; Rooting depth; Life form	Bell et al. 2006 Plant Soil 290:231-243
Primary productivity; Transpiration; Leaf adaptation	Ciais et al. 2005 Nature 437:529-533
Primary productivity; Photosynthesis; Transpiration; Nitrogen content; Leaf adaptation	Damour et al. 2008 J. Plant Physiol. 165:1370-1378
Biomass and allocation; Reserves and storage	Fazeli et al. 2007 Biol. Plant. 51:98-103
Carbon content and allocation; Photosynthesis; Transpiration; Leaf adaptation; Rooting depth; Life form; Leaf phenology	Galmés et al. 2007 J. Arid Environ. 68:206-222
Growth rate; ,Photosynthesis; Transpiration; Leaf adaptation; Leaf phenology	Gratani & Bombelli 1999 Photosynthetica 37:573-585
Seed mass and density; Life form; Seed bank	Gutiérrez & Meserve 2003 Oecologia 134:511-517
Seed mass and density; Plant longevity; Life form	Jurado & Flores 2005 J. Veg. Sci. 16:559-564
Primary productivity; Photosynthesis; Leaf adaptation; Biomass and allocation; Rooting depth	Kozlowski 2002 Bot. Rev. 68:270-334
Nitrogen content; Biomass and allocation; Seed mass and density	Lloret et al. 1999 Funct. Ecol. 13:210-216
Growth rate; Biomass; Leaf adaptation; Rooting depth; Leaf phenology	Markesteijn & Poorter 2009 J. Ecol. 97:311-325
Carbon content and allocation; Primary productivity; Transpiration; Leaf adaptation; Rooting dept; Drought tolerance; Soil texture	McDowell et al. 2008 New Phytol. 178:719-739.
Carbon content and allocation; Transpiration; Reserves and storage	Nicolas et al. 1985 Ann. Bot. 55:727-742
Plant height; Growth rate; Leaf adaptation; Transpiration; Biomass and allocation; Rooting depth; seed mass; Seed bank; Plant longevity; Leaf phenology; Regrowth after disturbance	Pausas et al. 2004 Ecology 85:1085-1100
Biomass allocation; Rooting depth; Mycorrhizal association; Growth rate	Poot & Lambers 2008 New Phytol. 178:371-381
Growth rate; Leaf adaptation; Rooting depth; Seed mass; Reserves and storage	Quero et al. 2007 Am. J. Bot. 94:1795-1803
Growth rate; Biomass and allocation; Rooting depth; Life form; Grime strategy; Regeneration strategy	Reader et al. 2012 J. Ecol. 81:543-550
Biomass and allocation; Carbon content and allocation; Photosynthesis; Transpiration; Nitrogen content; Life form; Rooting depth	Schulze 1986 Aust. J. Plant Physiol. 13:127-141
Biomass; Photosynthesis; Transpiration; Rooting depth	Suriyagoda et al. 2011 Plant Soil 348:281-297
Photosynthesis; Transpiration; Leaf adaptation; Leaf phenology	Tenhunen et al. 1990 Oecologia 82:381-393

Primary productivity; Leaf adaptation; Seed mass; Grime strategy; Leaf phenology; Reserves and storage; Drought tolerance; Shade tolerance	Valladares & Niinemets 2008 Annu. Rev. Ecol. Evol. Syst. 39:237-257
Biomass; Transpiration; Reserves and storage; Photosynthetis; Drought tolerance	Vanwoert et al. 2005 HortScience 40:659-664
Leaf adaptation	Witkowski & Lamont 1991 Oecologia 88:486-493
Nitrogen fixation capacity	Zahran 1999 Microbio. Mol. Biol. Rev. 63:968-989
Utilitarian aspects	
Aesthetic appeal; Design considerations	Getter & Rowe 2008 Extension Bulletin E-3047. Michigan State University Extension
Ecosystem goods and services	Hooper et al. 2005 Ecol. Monogr. 75:3-35
Aesthetic appeal; Design considerations	Monterusso et al. 2005 HortScience 40:391-396
Aesthetic appeal	Spala et al. 2008 Renew. Energy 33:173-177

Appendix 3.2.

Author	Reference
Atkin, O.	Atkin et al. 1997 Plant Physiology 113: 961-965
Bahn, M.	Bahn et al. 1999 ECOMONT Project Report 247-255
Baldocchi, D.	Xu & Baldocchi 2003 Tree Physiology 23:865-877
Blonder, B.	Unpublished data
Chapin, F.S.	Unpublished data
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Cornwell, W.	Cornwell et al. 2008 Ecology Letters 11:1065-1071
Craine, J.	Craine et al. 2005 Ecology 86:12-19
Diaz, S.	Díaz et al. 2004 Journal of Vegetation Science 15:295-304
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Enquist, B.	Kerkhoff et al. 2006 American Naturalist 168:103-122
Fang, J.	Han et al. 2005 New Phytologist 168:377-385
Flores, O.	Unpublished data
Freschet, G.	Freschet et al. 2010 Journal of Ecology 98:362-373
Garnier, E.	Garnier et al. 2007 Annals of Botany 99:967-985
Gillison, A.	Gillison & Carpenter 1997 Functional Ecology 11:775-783
Green, W.	Green, W. 2009USDA PLANTS Compilation, version 1, 09-02-02
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Higgins, S.	Unpublished data
Kattge, J.	Kattge et al. 2009 Global Change Biology 15:976-991
Kleyer, M.	Kleyer et al. 2008 Journal of Ecology 96:1266-1274
Kühn, I.	Kühn et al. 2004 Diversity and Distribution 10:363-365
Laughlin, D.	Laughlin et al. 2010 Functional Ecology 24:493-501
Leishman, M.	unknown
Louault, F.	Louault et al. 2005 Journal of Vegetation Science 16:151-160
Manning, P.	Unpublished data
Medlyn, B.	Medlyn et al. 1999 Plant, Cell and Environment 22:1475-1495
Moles, A.	Moles et al. 2005 Science 307:576-580
Niinemets, U.	Niinemets 2001 Ecology 82:453-469
Ordonez, J.	Ordonez et al. 2010 American Naturalist 175:225-239
Pausas, J.	Paula et al. 2009 Ecology 90:1420
Penuelas, J.	Ogaya & Penuelas 2003 Environmental and Experimental Botany 50:137-148
Pillar, V.	Muller et al. 2007 Plant Ecology 189:1-14
Poorter, H.	Unpublished data
Reich, P.	Reich et al. 2008 Ecology Letters 11:793-801
Shipley, B.	Shipley 1995 Functional Ecology 9:312-319
Siefert, A.	Unpublished data
Soudzilovskaia, N.	Unpublished data
van Bodegom, P.	van Bodegom et al. 2005 Plant and Soil 271:351-364
White, M.	White et al. 2000 Earth Interactions 4:1-85
Wirth, C.	Wirth & Lichstein 2009 in Old-Growth Forests: Function, Fate and Value
Wright, I.	Wright et al. 2004 Nature 428:821-827

Appendix 3.3.

Species	Source	FREQ	LF	SS
Achillea clypeolata	GRPL	1	H	2
Achillea nobilis	GRPL	1	H	6
Achillea odorata	MEDPL		H	2
Acinos alpinus	GRPL	1	H	7
Adonis aestivalis	GRPL	1	T	5
Adonis vernalis	both	1	H	8
Aegilops neglecta	MEDPL		T	1
Aethionema saxatile	MEDPL		H	6
Aira cupaniana	MEDPL		T	2
Ajuga chamaepytis	MEDPL		T	7
Ajuga genevensis	both	1	H	7
Ajuga iva	MEDPL		H	2
Alchemilla erythropoda	GRPL	1	H	6
Alchemilla hoppeana	GRPL	1	H	4
Allium atropupureum	GRPL	1	G	4
Allium carinatum	GRPL	2	G	10
Allium cernuum	GRPL	4	G	2
Allium cyaneum	GRPL	2	G	3
Allium flavum	both	3	G	7
Allium lusitanicum	GRPL	2	G	10
Allium moly	GRPL	3	G	1
Allium oleraceum	both	2	G	11
Allium roseum	GRPL	1	G	1
Allium rotundum	MEDPL		G	9
Allium schoenoprasum	GRPL	6	G	11
Allium scorodoprasum	GRPL	1	G	12
Allium sphaerocephalon	both	3	G	12
Allium strictum	GRPL	1	G	11
Alyssum alyssoides	MEDPL		T	12
Alyssum montanum	both	4	H	16
Anacamptis pyramidalis	MEDPL		H	8
Anaphalis margaritacea	GRPL	2	H	8
Anchusa officinalis	GRPL	1	H	8
Anemone sylvestris	GRPL	2	H	4
Antennaria dioica	GRPL	5	H	16
Antennaria parvifolia	GRPL	1	H	6
Anthemis tinctoria	GRPL	5	H	9
Anthericum liliago	both	2	H	11
Anthericum ramosum	both	2	H	9
Anthoxanthum odoratum	GRPL	1	H	9
Anthyllis montana	both	1	H	2
Anthyllis vulneraria	both	4	H	8
Arabis alpina	MEDPL		H	9
Arabis collina	MEDPL		H	8
Arabis hirsuta	MEDPL		H	8
Arenaria tenuifolia	MEDPL		T	2
Aristolochia pistolochia	MEDPL		H	1
Armeria arenaria	MEDPL		H	9
Artemisia alba	MEDPL		H	2
Artemisia campestris	MEDPL		H	12
Artemisia pontica	GRPL	1	H	3
Artemisia stelleriana	GRPL	2	H	2

Asphodelus ramosus	MEDPL		H	3
Aster amellus	GRPL	2	H	10
Aster linosyris	both	3	H	15
Aster sedifolius	MEDPL		H	2
Astragalus hamosus	MEDPL		T	1
Astragalus monspessulanus	MEDPL		H	1
Athamanta cretensis	both	2	H	7
Atractylis cancellata	MEDPL		T	1
Aurinia saxatilis	GRPL	3	H	4
Avena barbata	MEDPL		T	5
Bellis sylvestris	MEDPL		H	1
Bergenia crassifolia	GRPL	1	H	1
Biscutella laevigata	MEDPL		H	10
Bituminaria bituminosa	MEDPL		H	5
Blackstonia perfoliata	MEDPL		T	9
Bombycilaena erecta	MEDPL		T	2
Brachypodium distachyon	MEDPL		T	4
Brachypodium phoenicoides	MEDPL		H	7
Brachypodium pinnatum	GRPL	1	H	9
Briza media	both	3	H	12
Bromus diandrus	MEDPL		T	1
Bromus rubens	MEDPL		T	6
Bupleurum baldense	MEDPL		T	3
Bupleurum falcatum	MEDPL		H	13
Bupleurum semicompositum	MEDPL		T	1
Calamagrostis epigejos	GRPL	1	H	4
Campanula alliariifolia	GRPL	1	H	3
Campanula carpatica	GRPL	2	H	2
Campanula cochleariifolia	GRPL	1	H	4
Campanula glomerata	both	1	H	6
Campanula persicifolia	both	2	H	12
Campanula portenschlagiana	GRPL	2	H	2
Campanula poscharskyana	GRPL	2	H	1
Campanula rapunculoides	GRPL	1	H	8
Campanula rotundifolia	both	5	H	10
Campanula sarmatica	GRPL	1	H	2
Campanula trachelium	GRPL	1	H	6
Camphorosma monspeliaca	MEDPL		C	1
Cardamine hirsuta	GRPL	1	T	10
Carduus pycnocephalus	MEDPL		H	1
Carex alba	MEDPL		H	12
Carex buchananii	GRPL	1	H	2
Carex caryophyllea	GRPL	2	H	12
Carex comans	GRPL	2	H	2
Carex digitata	GRPL	2	H	11
Carex firma	GRPL	2	H	9
Carex halleriana	MEDPL		H	10
Carex liparicarpos	both	1	H	2
Carex montana	GRPL	3	H	12
Carex mucronata	MEDPL		H	7
Carex ornithopoda	GRPL	2	H	9
Carex pilulifera	GRPL	1	H	11
Carex sempervirens	GRPL	1	H	11
Carex supina	GRPL	2	H	6
Carex sylvatica	GRPL	1	H	7

Carlina acanthifolia	MEDPL		H	3
Carlina acaulis	GRPL	1	H	8
Carlina corymbosa	MEDPL		H	4
Carlina vulgaris	both	2	H	8
Catananche caerulea	MEDPL		H	5
Catapodium marinum	MEDPL		T	2
Centaurea aspera	MEDPL		H	4
Centaurea paniculata	MEDPL		H	1
Centaurium erythraea	MEDPL		T	13
Centranthus ruber	both	1	H	5
Cephalanthera longifolia	MEDPL		G	7
Cephalanthera rubra	MEDPL		G	8
Cerastium pumilum	MEDPL		T	11
Ceterach officinarum	MEDPL		H	9
Chamaemelum nobile	GRPL	1	H	5
Chondrilla juncea	MEDPL		H	11
Cirsium acaule	both	1	H	8
Cistus albidus	MEDPL		C	6
Cistus salviifolius	MEDPL		C	2
Clinopodium acinos	both	1	T	2
Clypeola jonthlaspi	MEDPL		T	1
Convolvulus lanuginosus	MEDPL		H	3
Conyza sumatrensis	MEDPL		T	2
Coronilla juncea	MEDPL		C	1
Coronilla scorpioides	MEDPL		T	3
Coronilla vaginalis	GRPL	1	H	9
Corynephorus canescens	GRPL	1	H	15
Crassula tillaea	MEDPL		T	9
Crepis capillaris	MEDPL		T	7
Crepis sancta	MEDPL		T	4
Crocus tommasinianus	GRPL	1	G	1
Crucianella angustifolia	MEDPL		T	1
Crupina vulgaris	MEDPL		T	1
Cuscuta epithymum	MEDPL		H	5
Cymbalaria muralis	GRPL	1	H	8
Dactylorhiza fuchsii	MEDPL		G	7
Dactylorhiza maculata	MEDPL		G	6
Dianthus carthusianorum	GRPL	4	H	11
Dianthus deltoides	GRPL	4	H	13
Dianthus gratianopolitanus	GRPL	2	H	18
Dianthus plumarius	GRPL	2	H	6
Dianthus sylvestris	MEDPL		H	10
Diplotaxis erucoides	MEDPL		T	2
Dittrichia viscosa	MEDPL		H	5
Dorotheanthus bellidiformis	GRPL	1	H	2
Dorycnium hirsutum	MEDPL		C	6
Draba aizoides	both	2	H	17
Duchesnea indica	GRPL	1	H	7
Echinaria capitata	MEDPL		T	2
Echinops ritro	MEDPL		H	4
Elymus hispidus	GRPL	1	H	6
Epimedium alpinum	GRPL	1	H	4
Epipactis helleborine	MEDPL		G	4
Erigeron acer	GRPL	1	H	5
Erinus alpinus	both	1	H	2

Eriophyllum lanatum	GRPL	3	H	3
Erophila verna	MEDPL		T	10
Euphorbia amygdaloides	GRPL	1	H	11
Euphorbia cyparissias	both	3	H	10
Euphorbia epithymoides	GRPL	1	H	7
Euphorbia myrsinites	GRPL	3	H	2
Euphorbia nicaeensis	MEDPL		C	0
Euphorbia segetalis	MEDPL		T	10
Euphorbia seguieriana	both	2	H	13
Euphorbia serrata	MEDPL		H	6
Festuca amethystina	GRPL	3	H	5
Festuca cinerea	both	3	H	1
Festuca duvalii	GRPL	1	H	6
Festuca filiformis	GRPL	1	H	6
Festuca glauca	both	2	H	1
Festuca pallens	GRPL	2	H	15
Festuca rupicaprina	GRPL	2	H	8
Festuca rupicola	GRPL	3	H	8
Festuca valesiaca	GRPL	4	H	9
Festuca vivipara	GRPL	2	H	8
Filago pyramidata	MEDPL		T	11
Filipendula vulgaris	GRPL	1	H	8
Fragaria viridis	GRPL	2	H	11
Fumana laevipes	MEDPL		C	6
Galium boreale	MEDPL		H	13
Galium murale	MEDPL		T	2
Galium verum	both	2	H	16
Gastridium ventricosum	MEDPL		T	2
Genista cinerea	MEDPL		C	0
Genista hispanica	MEDPL		C	0
Genista pilosa	MEDPL		C	12
Genista pulchella	MEDPL		C	1
Gentiana cruciata	GRPL	1	H	7
Geranium macrorrhizum	GRPL	1	H	5
Geranium purpureum	MEDPL		T	5
Geranium robertianum	MEDPL		T	5
Geranium rotundifolium	MEDPL		T	7
Geranium sanguineum	both	2	H	5
Geranium sessiliflorum	GRPL	1	H	1
Glechoma hederacea	GRPL	1	H	10
Globularia alypum	MEDPL		C	4
Globularia cordifolia	GRPL	1	H	9
Globularia nudicaulis	GRPL	1	H	7
Globularia punctata	both	2	H	5
Globularia trichosantha	GRPL	1	H	2
Gymnadenia conopsea	MEDPL		G	8
Gymnadenia odoratissima	MEDPL		G	11
Gypsophila repens	GRPL	3	H	17
Hedypnois rhagadioloides	MEDPL		T	1
Helianthemum nummularium	both	3	H	16
Helianthemum oelandicum subsp Incanum	both	2	H	8
Helianthemum salicifolium	MEDPL		T	7
Helictotrichon bromoides	MEDPL		H	5
Helictotrichon pratense	MEDPL		H	12
Helleborus foetidus	MEDPL		H	7

Hieracium aurantiacum	GRPL	2	H	11
Hieracium humile	MEDPL		H	4
Hieracium murorum	both	1	H	7
Hieracium pilosella	both	6	H	12
Himantoglossum hircinum	MEDPL		G	8
Hippocrepis ciliata	MEDPL		T	4
Hippocrepis comosa	both	2	H	17
Horminum pyrenaicum	GRPL	1	H	6
Hornungia petraea	MEDPL		T	10
Hyparrhenia hirta	MEDPL		H	2
Hypericum montanum	MEDPL		H	9
Hypochaeris maculata	MEDPL		H	7
Hypochoeris radicata	MEDPL		H	4
Hyssopus officinalis	GRPL	3	H	10
Inula ensifolia	GRPL	2	H	2
Inula hirta	GRPL	1	H	9
Inula montana	MEDPL		H	2
Inula spiraeifolia	MEDPL		H	2
Iris aphylla	GRPL	2	H	7
Iris graminea	GRPL	2	G	7
Iris pumila	GRPL	4	G	8
Iris ruthenica	GRPL	1	G	1
Iris spuria	GRPL	2	G	7
Iris variegata	GRPL	2	G	8
Jasione montana	GRPL	1	H	13
Jasminum fruticans	MEDPL		C	3
Koeleria glauca	GRPL	4	H	15
Koeleria pyramidata	GRPL	3	H	10
Lactuca perennis	MEDPL		H	7
Lagurus ovatus	both	1	T	2
Lamium maculatum	GRPL	1	H	7
Lathyrus setifolius	MEDPL		T	1
Lathyrus sphaericus	MEDPL		T	1
Lavandula angustifolia	both	3	C	10
Lens nigricans	MEDPL		T	1
Leontodon crispus	MEDPL		H	2
Leontodon hispidus	MEDPL		H	6
Leopoldia comosa (muscari)	both	1	G	1
Lepidium draba	MEDPL		H	2
Limodorum abortivum	MEDPL		H	7
Limonium gmelinii	GRPL	1	H	2
Linaria simplex	MEDPL		T	3
Linum bienne	MEDPL		T	2
Linum catharticum	MEDPL		T	12
Linum flavum	GRPL	2	H	9
Linum perenne	GRPL	3	H	10
Linum strictum	MEDPL		T	6
Linum tenuifolium	MEDPL		H	12
Linum trigynum	MEDPL		T	1
Lobularia maritima	MEDPL		T	8
Logfia gallica	MEDPL		T	3
Lotus edulis	MEDPL		T	2
Luzula nivea	GRPL	1	H	7
Luzula pilosa	GRPL	1	H	8
Lysimachia nummularia	GRPL	1	H	13

Medicago coronata	MEDPL		T	2
Medicago disciformis	MEDPL		T	2
Medicago falcata	MEDPL		H	6
Medicago orbicularis	MEDPL		T	2
Medicago rigidula	MEDPL		T	2
Medicago truncatula	MEDPL		T	2
Melica ciliata	GRPL	4	H	12
Melica minuta	MEDPL		H	3
Melica transsilvanica	GRPL	1	H	7
Minuartia hybrida	MEDPL		T	12
Minuartia laricifolia	GRPL	1	H	2
Minuartia verna	GRPL	2	H	17
Muscari botryoides	GRPL	2	G	9
Muscari neglectum	both	2	G	7
Myosotis ramosissima	MEDPL		T	10
Neatostema apulum	MEDPL		T	1
Onobrychis arenaria	GRPL	1	H	14
Onobrychis caput-galli	MEDPL		T	1
Onobrychis montana	GRPL	2	H	9
Onobrychis supina	MEDPL		H	1
Ononis cristata	MEDPL		H	1
Ononis minutissima	MEDPL		H	1
Ononis natrix	MEDPL		H	4
Ononis pusilla	MEDPL		H	8
Ononis reclinata	MEDPL		T	3
Ononis spinosa subsp procurrens	MEDPL		H	6
Ononis viscosa	MEDPL		T	1
Ophrys bertolonii	MEDPL		G	1
Ophrys fusca	MEDPL		G	1
Ophrys insectifera	MEDPL		G	10
Ophrys lutea	MEDPL		G	1
Ophrys scolopax	MEDPL		G	1
Orchis purpurea	MEDPL		G	6
Origanum vulgare	GRPL	5	H	9
Ornithogalum orthophyllum	GRPL	1	G	2
Ornithogalum umbellatum	both	1	G	10
Orobanche caryophyllacea	MEDPL		G	7
Oryzopsis miliacea	MEDPL		H	2
Parapholis incurva	MEDPL		T	3
Paronychia argentea	GRPL	2	H	2
Paronychia capitata	MEDPL		H	3
Paronychia kapela	GRPL	1	T	4
Penstemom hirsutus	GRPL	1	H	2
Petrorhagia prolifera	MEDPL		T	14
Petrorhagia saxifraga	GRPL	5	H	12
Peucedanum cervaria	MEDPL		H	9
Peucedanum oreoselinum	MEDPL		H	10
Phagnalon sordidum	MEDPL		H	2
Phleum arenarium	MEDPL		T	6
Phleum phleoides	GRPL	1	H	16
Phyteuma orbiculare	MEDPL		H	7
Pimpinella saxifraga	GRPL	1	H	9
Plantago afra	MEDPL		T	3
Plantago argentea	both	1	H	2
Plantago bellardii	MEDPL		T	2

Plantago coronopus	MEDPL		H	14
Plantago lagopus	MEDPL		T	2
Plantago lanceolata	both	1	H	4
Plantago maritima subsp serpentina	MEDPL		H	10
Plantago media	both	1	H	5
Plantago sempervirens	MEDPL		H	6
Poa badensis	both	1	H	7
Polygala monspeliaca	MEDPL		T	2
Polygala nicaeensis	MEDPL		H	2
Polygala vulgaris	MEDPL		H	14
Polygonatum odoratum	MEDPL		H	5
Polypodium vulgare	both	1	H	6
Portulaca grandiflora	GRPL	1	H	5
Potentilla arenaria	MEDPL		H	5
Potentilla argentea	GRPL	4	H	10
Potentilla aurea	GRPL	2	H	8
Potentilla caulescens	MEDPL		H	7
Potentilla erecta	GRPL	1	H	11
Potentilla neumanniana	both	4	H	2
Potentilla pusilla	MEDPL		H	7
Potentilla verna	GRPL	1	H	5
Primula vulgaris	both	1	H	8
Prunella grandiflora	GRPL	5	H	12
Pseudofumaria lutea	GRPL	1	H	7
Psilurus incurvus	MEDPL		T	1
Pulsatilla pratensis	GRPL	1	H	9
Pulsatilla vulgaris	both	4	H	9
Ranunculus bulbosus	both	4	G	6
Ranunculus gramineus	both	1	H	1
Ranunculus paludosus	MEDPL		H	2
Ranunculus repens	MEDPL		H	9
Ranunculus serpens	MEDPL		H	3
Reichardia picroides	MEDPL		T	3
Reseda lutea	MEDPL		H	9
Reseda phyteuma	MEDPL		T	6
Rhinanthus minor	MEDPL		H	9
Rostraria cristata	MEDPL		T	2
Rubia peregrina	MEDPL		H	7
Rumex intermedius	MEDPL		H	1
Rumex scutatus	MEDPL		H	4
Ruscus aculeatus	MEDPL		H	4
Ruta angustifolia	MEDPL		C	1
Ruta montana	MEDPL		H	3
Salvia pratensis	both	3	H	6
Salvia verbenaca	MEDPL		H	5
Saponaria ocymoides	both	4	H	10
Saxifraga caespitosa	GRPL	1	H	3
Saxifraga cuneifolia	GRPL	1	H	1
Saxifraga paniculata	GRPL	3	H	17
Saxifraga tridactylites	both	3	T	10
Scabiosa canescens	GRPL	3	H	10
Scabiosa columbaria	both	2	H	7
Scabiosa lucida	GRPL	1	H	7
Scandix australis	MEDPL		T	1
Scolymus hispanicus	MEDPL		H	3

Scorpiurus muricatus	MEDPL		T	2
Scorzonera austriaca	MEDPL		H	4
Scorzonera laciniata	MEDPL		H	5
Scrophularia canina	MEDPL		H	11
Sedum acre	both	5	H	23
Sedum aizoon	GRPL	3	H	3
Sedum album	both	7	H	25
Sedum anacampseros	GRPL	2	H	2
Sedum dasyphyllum	both	3	H	19
Sedum forsterianum	GRPL	3	H	16
Sedum hispanicum	GRPL	4	H	14
Sedum hybridum	GRPL	4	H	2
Sedum ochroleucum	both	2	H	16
Sedum rupestre	GRPL	7	H	23
Sedum sexangulare	GRPL	7	H	23
Sedum spurium	GRPL	6	H	18
Sedum telephium	GRPL	3	H	11
Sempervivum arachnoideum	GRPL	4	H	15
Sempervivum montanum	GRPL	3	H	3
Sempervivum tectorum	GRPL	3	H	17
Senecio cineraria	MEDPL		H	1
Sesleria albicans	GRPL	1	H	10
Sesleria caerulea	both	2	H	4
Sideritis hyssopifolia	MEDPL		H	2
Sideritis romana	MEDPL		T	2
Silene conica	MEDPL		T	9
Silene italica	MEDPL		H	5
Silene nocturna	MEDPL		T	2
Silene nutans	GRPL	1	H	9
Silene otites	MEDPL		H	17
Silene rupestris	GRPL	1	H	12
Silene saxifraga	MEDPL		H	2
Silene viscaria	GRPL	2	H	4
Silene vulgaris	both	4	H	8
Sisyrinchium angustifolium	GRPL	2	H	4
Sonchus maritimus	MEDPL		H	2
Stachys recta	MEDPL		H	8
Stipa capensis	MEDPL		T	3
Stipa capillata	GRPL	2	H	10
Stipa pennata	both	2	H	8
Succisa pratensis	MEDPL		H	11
Tanacetum corymbosum	MEDPL		H	7
Tanacetum parthenium	GRPL	1	H	6
Taraxacum officinale	both	2	H	4
Teucrium botrys	both	1	T	9
Teucrium flavum	MEDPL		H	3
Teucrium montanum	both	2	H	15
Thalictrum minus	both	1	H	7
Thymus praecox	both	1	H	18
Thymus pulegioides	GRPL	3	H	12
Thymus serpyllum	both	5	H	18
Torilis nodosa	MEDPL		T	11
Tragopogon dubius	MEDPL		H	7
Tragopogon pratensis	MEDPL		H	6
Tribulus terrestris	MEDPL		T	4

Trifolium angustifolium	MEDPL		T	3
Trifolium arvense	both	1	T	11
Trifolium glomeratum	MEDPL		T	4
Trifolium scabrum	MEDPL		T	5
Trifolium stellatum	MEDPL		T	2
Trifolium suffocatum	MEDPL		T	4
Trifolium tomentosum	MEDPL		T	2
Trigonella gladiata	MEDPL		T	1
Trinia glauca	MEDPL		H	8
Tripodion tetraphyllum	MEDPL		T	1
Tulipa sylvestris	MEDPL		G	8
Umbilicus rupestris	MEDPL		H	6
Urospermum dalechampii	MEDPL		H	2
Valantia muralis	MEDPL		T	1
Valeriana tripteris	MEDPL		H	5
Valeriana tuberosa	MEDPL		H	1
Valerianella discoidea	MEDPL		T	1
Velezia rigida	MEDPL		T	2
Verbascum chaixii	GRPL	1	H	2
Verbascum phoeniceum	GRPL	3	H	5
Verbascum sinuatum	MEDPL		H	6
Veronica chamaedrys	MEDPL		H	13
Veronica cymbalaria	MEDPL		T	2
Veronica prostrata	GRPL	2	H	15
Veronica spicata	GRPL	2	H	1
Vicia lathyroides	MEDPL		T	8
Vicia parviflora	MEDPL		T	2
Vincetoxicum hirundinaria	both	2	H	5
Viola odorata	GRPL	2	H	10
Viola reichenbachiana	MEDPL		H	10
Vulpia ciliata	MEDPL		T	6
Vulpia unilateralis	MEDPL		T	4
Waldsteinia ternata	GRPL	1	H	1
Xeranthemum inapertum	MEDPL		T	4

Appendix 3.4.

(i) Functional trait	Var. type	Unit	Categories/Codes	Trait group
Aboveground biomass per plant (AboveBM)	S	g		biomass
Aboveground carbon content (AboveC)	S	%		carbon content and allocation
Adapted to Coarse/Fine/Medium Textured Soils (SoilAdap)	N		Course/medium; medium; medium/fine; all textures	soil texture
Belowground biomass per plant (BelowBM)	S	g		biomass
Fire Tolerance (TolFire)	N/B		No; yes	regrowth after disturbance
Leaf carbon content per dry mass (LeafC)	S	mg/g		biomass and allocation
Leaf density (LeafDens)	S	g/m^3		leaf adaptation
Leaf respiration per dry mass (LeafResp)	S	µmol/g/s		transpiration
Leaf thickness (LeafThick)	S	mm		leaf adaptation
Leaf water content per water-saturated mass (LWC)	S	g/g		moisture use
Leaf weight ratio (LWR)	S	g/g		leaf adaptation
Moisture Use (Moist)	O		1=low; 2=medium; 3=high	moisture use
Mycorrhizal type (Myc)	N		Arbuscular; ectomycorrhiza/arbuscular	mycorrhizal association
Net assimilation rate (NAR)	S	g/m^2/day		primary productivity
Net primary productivity of the site (NPP)	S	g/m^2/year		primary productivity
Nitrogen-fixation capacity (NFC)	N/B		No; yes	nitrogen fixation capacity
Photosynthesis per leaf dry mass (PS)	S	µmol/g/s		photosynthesis
Post fire seedling emergence (PFSE)	N/B		No; yes	regrowth after disturbance
Protein Potential (ProtPot)	O		1=low; 2=medium; 3=high	reserves and storage
Relative growth rate (RGR)	S	g/g/day		growth rate
Resprouting capacity after disturbance (ResprDis)	N/B		No; yes	regrowth after disturbance
Resprouting capacity after fire (ResprF)	N/B		No; yes	regrowth after disturbance
Root carbon content per dry mass (RootC)	S	mg/g		biomass and allocation
Root nitrogen content per dry mass (RootN)	S	mg/g		nitrogen content
Root weight fraction (RWF)	S	g/g		biomass
Root/shoot ratio (RS)	S	g		biomass and allocation
Rooting depth (RootDept)	S	m		rooting depth
Salinity Tolerance (TolSal)	N/B		No; yes	salinity tolerance
Seed bank longevity (SBL)	O		1=transient; 2=short persistent; 3=persistent; 4=long persistent	seed bank
Seed protein content per mass at	S			reserves and

given moisture status (SeedProt)				storage
Shoot biomass nitrogen content per dry mass (ShootN)	S	mg/g		nitrogen content
Stem nitrogen content per dry mass (StemN)	S	mg/g		nitrogen content
Stomatal conductance per leaf area (StomCond)	S	mmol/m²/s		transpiration
Tolerance to drought (TolDrou)	O		1=low; 2=medium; 3=high	drought tolerance
Tolerance to shade (TolShade)	O		0=intolerant; 1=intermediate; 2=tolerant	shade tolerance
Transpiration per leaf area (Trans)	S	mmol/m²/s		transpiration
(ii) Utilitarian aspect				
Active Growth Period (AGP)	N		Spring/summer; spring/fall; spring/fall/winter	aesthetic appeal
Commercial Availability (Comm)	N/B		No; yes	design consideration
Fruit/Seed period (FrSeedP)	O		1=spring; 2=summer	ecosystem goods/service
Lateral spread (LatSpr)	O		0=none; 1=moderate (<10cm); 2=extensive (>10cm)	aesthetic appeal
Plant palatability (Pal)	N/B		No; yes	ecosystem goods/service
Propagation by (Prop)	N		Seed; seed/bulb	design consideration
Toxicity (Tox)	N/B		No; yes	ecosystem goods/service

Appendix 4.1

a) Tetrazolium test	Scientific name	% viable seeds
	Alyssum alyssoides (L.) L.	95.00
	Carthamus carduncellus L.	88.00
	Clinopodium acinos (L.) Kuntze	10.00
	Dianthus sylvestris Wulfen	95.00
	Erophila verna (L.) DC.	25.00
	Euphorbia cyparissias L.	22.00
	Helianthemum nummularium (L.) Mill.	100.00
	Lagurus ovatus L.	23.00
	Linum bienne Mill.	40.00
	Lobularia maritima (L.) Desv.	95.00
	Plantago afra L.	20.00
	Sideritis hyssopifolia L.	90.00
	Silene conica L.	100.00
b) Spearman correlation	Location	s_r
	Avignon	0.623 (NS)
	Heverlee	0.638 (NS)

Appendix 4.2 a

Scientific name	Habitat of preference	Life form	Flowering time (month)	Region of origin
Acer pseudoplatanus L.	Scree slopes, forests with rather mild humus	P	4-5	Eastern and central Europe
Arenaria serpyllifolia subsp. leptoclados (Rchb.) Nyman	Sandy and rocky areas	T	5-8	Temperate regions of the northern hemisphere
Celtis australis L.	Dry slopes, hedges,	P	4-5	Mediterranean
Cerastium fontanum subsp. Vulgare (Hartm.) Greuter & Burdet	Grassland, fallow land, roadsides	C	4-11	Cosmopolitan
Chenopodium album L.	Fallow land, roadsides, farmland	T	7-10	Subcosmopolitan
Crepis foetida L.	Wasteland, pastures, roadsides	T	5-8	Eurasia
Crepis sancta (L.) Bornm.	Farmland, wasteland	T	3-6	East-mediterranean
Crepis vesicaria L.	Wastelant, roadsides, prairie	H	5-6	Submediterranean-subatlantic
Epilobium hirsutum L.	Water edge, ditches	H	6-9	Temperate regions
Erigeron canadensis L.	Gardens, ruderal places, fallow land, railway roads	T	6-10	Cosmopolitan
Euphorbia serpens Kunth	Roadsides, graveyards	T	6-10	South-America but introduced worldwide
Geranium molle L.	Farmland, roadsides, ruderal areas	T	5-9	Subcosmopolitan
Holcus lanatus L.	Grassland, roadsides	H	6-9	Subcosmopolitan
Hordeum murinum L.	Roadsides, wall bases	T	6-10	Subcosmopolitan
Medicago lupulina L.	Roadsides, fields, dry calcareous soils	T / H	4-10	Europe and temperate Asia
Medicago sativa L.	Fields, slopes	H	5-10	Subcosmopolitan
Minuartia hybrida (Vill.) Schischk.	Walls, rocks, fields	T	5-9	Submediterranean
Papaver argemone L.	Fields, dry roads	T	5-7	Europe
Papaver rhoeas L.	Roadsides, fields, fallow land	T	6-7	Europe
Picris hieracioides Sibth & Sm.	Roads, wasteland, scree slopes	H	7-10	Europe
Poa annua L.	Ruderal areas, roads, gardens	T	1-12	Cosmopolitan
Rumex crispus L.	Fields, wasteland	H	6-8	Cosmopolitan
Salix alba	Shores, damp locations	P	4-5	Europe and temperate Asia
Senecio jacobaea	Roadsides, ruderalized dunes, grasslands	H	7-10	Eurasia
Senecio vulgaris L.	Ruderal areas, gardens, farmland	T	1-12	Subcosmopolitan (temperate regions)

Solanum americanum Mill.	Ruderal areas, close to homes	T	7-10	Cosmopolitan
Sonchus arvensis L.	Fields, farmland, ruderal areas, dunes	H	7-11	Subcosmopolitan
Sonchus asper (L.) Hill	Gardens, wasteland, ruderal areas	T	6-10	Subcosmopolitan
Sonchus oleraceus (L.) L.	Gardens, wasteland, ruderal areas	T / H	6-10	Subcosmopolitan
Taraxacum sp.	Fields, roadsides, ruderal areas	H	4-10	Subcosmopolitan
Trifolium campestre Schreb.	Fields, dry slopes, grasslands	T	5-9	Europe
Veronica arvensis L.	Farmland, slopes, roadsides, open grassland	T	3-10	Subcosmopolitan
Viola arvensis Murray	Fields, wasteland	T	5-10	Subcosmopolitan
Additional species that occurred spontaneously in the 20 cm wide border of the plot				
Acer platanoides L.	Scree slopes, forests with rather mild humus	P	4-5	South and central Europe
Agrostis spp.	Grassland, roadsides, meadowes, open forest	H	6-7	Subcosmopolitan (temperate regions)
Avena barbata Pott ex Link	Slopes, roadsides	T	5-7	Subcosmopolitan
Eupatorium cannabinum L.	Shores, ditches	H	7-10	Eurasia
Humulus lupulus L.	Shores, hedges, aluvial forests	H	7-9	Eurasia (temperate regions)
Hypochaeris radicata L.	Grasslands, dunes, ruderal ares	H	7-9	Europe
Pennissetum villosum Fresen.	Cultivated grass species	H	8-10	North and East Afraica
Poa trivialis L.	Moist grasslands, roadsides	H	5-7	Northern hemisphere (temperate regions)
Silene latifolia subsp. Alba (Mill.) Greuter & Burdet	Roadsides, fileds, ruderal areas	H	5-10	Europe
Solanum nigrum L.	Ruderal areas	T	7-10	Cosmopolitan

Appendix 4.2. b

Scientific name	AVIGNON							HEVERLEE						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Acer pseudoplatanus										4.5		37.5	46.2	4.6
Arenaria serpyllifolia subsp. leptoclados	6.9	6.6	6.5											
Celtis australis	12.3	25.9	19.4		18.2	25								
Cerastium fontanum subsp. Vulgare									4.8	1.1		37.5	38.5	
Chenopodium album										1.1				13.6
Crepis foetida		0.5	1.1		13.6	50								
Crepis sancta	6.9	2.5		33.3	36.4		1.72							
Crepis vesicaria		0.5												
Epilobium hirsutum		0.5	1.1							12.4				9.1
Erigeron canadensis	30	39.6	63.4				15.5		85.7	69.7				
Euphorbia serpens							19					18.8		
Geranium molle	1.5	0.5		5.6		25			4.8	1.1	33.3			
Holcus lanatus										1.1				22.7
Hordeum murinum	2.3	2	4.3								16.7	6.3	7.7	
Medicago lupulina											16.7	12.5	7.7	9.1
Medicago sativa	0.8	2.5	2.2											
Minuartia hybrida	1.5	2												
Papaver argemone		0.5												
Papaver rhoeas										1.1				
Picris hieracioides				11.1										
Poa annua	2.3	2	1.1	5.6			34.5			2.3	16.7	6.3		
Rumex crispus	1.54	0.51												
Salix alba														13.6
Senecio jacobaea														9.1
Senecio vulgaris	0.8									1.1				
Solanum americanum										1.1				
Sonchus arvensis							6.9			2.3				
Sonchus asper							3.5							13.6
Sonchus oleraceus.	2.3	2.5		5.6	4.6		17.2							
Taraxacum sp.														4.6
Trifolium campestre	2.3	3.1		38.9	27.3		1.7							
Veronica arvensis	28.5	7.6							4.8	1.1	16.7			
Viola arvensis		0.5	1.1											
Additional species that occurred spontaneously in the 20 cm wide border of the plot														
Acer platanoides										x				
Agrostis spp.														x
Avena barbata					x	x								
Eupatorium cannabinum														x
Humulus lupulus										x				
Hypochaeris radicata							x							x
Pennissetum villosum							x							
Poa trivialis														x
Silene latifolia subsp. alba											x	x	x	x
Solanum nigrum										x				

Appendix 4.3.

				Alyssum alyssoides	*Clinopodium acinos*	*Erophila verna*	*Lagurus ovatus*	*Linum bienne*	*Petrorhagia prolifera*	*Plantago afra*	*Silene conica*	*Carthamus carduncellus*	*Dianthus sylvestris*	*Euphorbia cyparissias*	*Helianthemum nummularium*	*Lobularia maritima*	*Sideritis hyssopifolia*	*Sedum acre*	*Sedum album*	*Allium sphaerocephalon*	*Iris lutescens*
AVIGNON	EXPOSED	5	1	**18**	0	0	7	0	0	0	**25**	0	3	0	0	**13**	0	15	20	2	**3**
			2	12	0	0	**7**	0	0	1	23	0	10	0	0	**16**	0	**12**	18	2	3
			3	12	0	0	6	0	0	0	22	0	8	0	0	13	0	**16**	24	**2**	2
			4	11	0	0	13	0	0	0	0	0	0	0	0	34	0	16	25	3	3
			5	0	0	0	11	0	0	0	0	0	0	0	0	0	0	6	12	1	3
			6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	26	42	0	3
			7	4	0	0	3	0	0	0	44	0	0	0	0	18	0	24	7	0	0
		P5	1	**19**	0	0	4	0	0	1	**24**	0	2	0	0	**24**	0	14	13	3	**3**
			2	15	0	0	**4**	0	0	1	30	0	8	0	0	**23**	0	**8**	10	3	3
			3	13	0	0	5	0	0	1	32	0	7	0	0	**20**	0	**10**	12	**3**	3
			4	13	0	0	8	0	0	0	0	0	0	0	0	68	0	6	6	2	2
			5	0	0	0	25	0	0	0	20	0	0	0	0	0	0	25	30	1	**2**
			6	0	0	0	**4**	0	0	0	4	0	0	0	0	0	0	58	33	0	2
			7	4	0	0	2	0	0	0	63	0	0	0	0	27	0	5	0	1	0
		P10	1	**18**	0	0	4	0	0	0	**30**	0	2	0	0	**29**	0	7	10	3	**3**
			2	16	0	0	**3**	0	0	0	34	0	8	0	0	**27**	0	**4**	7	3	3
			3	15	0	0	3	0	0	0	37	0	7	0	0	**25**	0	**5**	9	**3**	3
			4	8	0	0	5	0	0	0	0	0	0	0	0	**80**	0	4	3	3	2
			5	4	0	0	13	2	0	1	**61**	0	0	0	0	**7**	0	5	8	1	2
			6	0	0	0	**7**	0	0	2	**15**	0	0	0	0	**7**	0	39	29	1	**2**
			7	2	0	0	2	0	0	0	59	0	0	0	0	33	0	3	0	2	1
	SHELTERED	5	1	**17**	0	0	5	0	0	0	**20**	0	4	0	0	**20**	0	17	18	2	3
			2	19	0	0	**8**	0	0	1	20	0	11	0	0	**24**	1	**7**	9	2	3
			3	10	0	0	9	0	0	**1**	14	0	12	0	0	**12**	0	**19**	22	2	2
			4	3	0	0	16	0	0	0	0	0	0	0	0	35	0	14	33	3	3
			5	0	0	0	52	0	0	0	13	0	0	0	0	0	0	8	27	1	**1**
			6	0	0	0	1	0	0	0	2	0	0	0	0	0	0	33	64	0	1
			7	0	0	0	4	0	0	0	8	0	0	0	0	3	0	37	48	0	1
		P5	1	**20**	0	0	5	0	0	0	**17**	0	4	0	0	**31**	0	10	**12**	3	3
			2	15	0	0	**9**	0	0	1	21	0	8	0	0	**28**	0	8	10	3	3
			3	12	0	0	10	0	0	**1**	20	0	12	0	0	**24**	0	**9**	11	3	2
			4	2	0	0	5	0	0	0	0	0	0	0	0	**61**	0	11	21	2	2
			5	0	0	0	30	0	0	0	17	0	0	0	0	0	0	13	**40**	0	0
			6	0	0	0	**5**	0	0	0	2	0	0	0	0	1	0	23	69	0	0
			7	1	0	0	2	0	0	0	16	0	0	0	0	7	0	30	45	1	2
		P10	1	**13**	0	0	3	0	0	0	**23**	0	2	0	0	**43**	0	7	9	3	**3**
			2	9	0	0	**6**	0	0	1	33	0	7	0	0	**29**	1	**8**	8	3	3
			3	7	0	0	**6**	0	0	1	36	0	10	0	0	**24**	0	**8**	8	**3**	3
			4	6	0	0	10	0	0	**0**	0	0	3	0	0	**46**	0	14	22	3	2
			5	2	0	0	18	**1**	0	**0**	**41**	0	0	0	0	**6**	0	8	24	2	**1**
			6	0	0	0	**17**	**1**	0	0	**19**	0	0	0	0	**8**	0	15	41	0	1

			7	1	0	0	13	2	0	0	12	0	0	1	0	6	0	22	43	1	3
HEVERLEE	EXPOSED	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			2	**2**	0	0	0	0	0	0	0	0	0	0	0	0	5	11	82	3	3
			3	2	0	0	0	0	0	0	0	0	0	0	0	2	4	**16**	76	**2**	3
			4	2	0	0	0	0	0	0	0	0	0	0	0	4	0	15	79	1	2
			5	0	0	0	0	0	0	0	2	0	0	0	0	0	0	10	87	2	2
			6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	90	1	2
			7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	95	0	2
		P5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			2	**40**	0	0	0	0	0	0	**4**	0	2	2	0	0	0	9	45	3	3
			3	31	0	0	0	1	0	0	4	0	3	1	0	0	1	11	46	3	**2**
			4	8	0	0	0	2	0	0	0	1	2	0	0	9	0	**17**	59	**2**	1
			5	15	0	0	0	0	0	0	10	1	2	0	0	0	1	14	57	3	1
			6	0	0	0	0	0	0	0	**8**	0	3	1	0	0	1	14	74	1	**1**
			7	0	0	0	0	0	0	0	0	0	**3**	0	0	0	0	10	87	0	1
		P10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			2	**19**	0	0	0	0	0	0	**13**	0	5	3	0	0	3	8	48	3	**3**
			3	18	0	3	0	3	0	0	10	0	7	3	2	**4**	3	**8**	38	**3**	3
			4	6	0	0	0	0	0	0	0	0	6	0	0	**14**	1	8	**65**	3	2
			5	2	0	0	0	1	0	0	33	0	5	0	0	0	0	5	55	3	**2**
			6	0	0	0	0	0	0	0	**20**	0	7	0	0	0	0	6	67	3	2
			7	0	0	0	0	1	**0**	0	0	0	**7**	1	0	0	1	4	85	1	2
	SHELTERED	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			2	**4**	0	0	0	0	0	0	**4**	0	4	4	0	0	2	14	70	3	**3**
			3	3	0	1	0	0	0	0	3	0	1	1	0	**4**	0	**15**	72	2	3
			4	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	16	**83**	3	3
			5	2	0	0	0	0	0	0	2	0	0	0	0	0	0	10	86	2	**3**
			6	0	0	0	0	0	0	0	2	0	0	0	0	0	0	10	87	3	3
			7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	96	0	3
		P5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			2	**13**	0	0	0	0	0	0	**2**	0	3	3	0	0	2	8	69	3	3
			3	9	0	2	0	1	0	0	3	0	5	3	1	**8**	1	**11**	55	**3**	3
			4	3	0	0	0	0	0	0	0	0	4	1	0	**8**	0	6	**76**	3	3
			5	3	0	0	0	0	0	0	2	0	5	0	0	2	0	5	82	3	**3**
			6	0	0	0	0	0	0	0	**4**	0	6	1	0	2	0	5	83	3	3
			7	0	0	0	0	1	1	0	0	0	**6**	1	0	**1**	0	3	88	0	2
		P10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
			2	**5**	0	0	0	0	0	0	**17**	0	3	5	0	0	2	9	61	3	**3**
			3	5	0	5	0	1	0	0	15	1	7	4	2	**11**	3	**11**	36	**3**	3
			4	1	0	1	0	0	0	0	0	0	8	0	0	**10**	0	**8**	**70**	3	3
			5	2	0	1	0	1	0	0	11	0	11	0	0	1	0	6	67	3	**3**
			6	0	0	1	0	1	0	0	**6**	0	13	0	0	1	1	**6**	70	3	3
			7	0	0	0	0	1	**1**	0	**0**	0	**16**	1	0	**1**	1	2	76	0	3

Appendix 6.1

Topic	GR type	Irrigation method	Irrigation regime	Reference
a) Greenhouse experiments				
Irrigation	EGR	Reservoir-drainage, wick irrigation, drip irrigation	unknown	Cho et al., 2010
	EGR	unknown	Frequent (1–3 days) and intermittent irrigation (5–17 days); Quantity: 1.2*ET	Moritani et al., 2013
	EGR + SEGR	unknown	3 or 6 mm every 3 days	Ntoulas et al., 2013
Vegetation performance	EGR	unknown	Every 2 days until saturation; Later: every 3 days, 4 days, then no irrigation	Bousselot et al., 2011
	EGR	unknown	13 mm every 2, 7, 14, 28, or 88 days	Durhman et al., 2006; VanWoert et al., 2005a
	EGR	unknown	1 time/week or every 2 or 3 weeks, until saturation	Nagase and Dunnett, 2010
	EGR	Drip irrigation	when substrate moisture ≤ 90 or 45%	Provenzano et al., 2010
	EGR	Hand watering	No drought: 2 times/week until saturation. Drought treatments: no water for the first 2 weeks after planting, or from week 9 to 11	Thuring et al., 2010
	EGR	Overhead, drip, and sub-irrigation	4.2, 9.6, and 8.5 l for overhead, drip, and sub-irrigation, respectively, for 30 min	Rowe et al., 2014
Energy and temperature performance	SEGR	unknown	Establishment: potable water, 2 times/week. Later: gray or clean water, weekly to saturation	Ouldboukhitine et al., 2014
Stormwater management	EGR	Handheld sprinkler	1 l every 2 weeks for 2 min with distilled water	Morgan et al., 2011
	EGR	Sub-irrigation	Daily for 40 min. Test day: 2h to saturation	Voyde et al., 2010
	EGR + SEGR	unknown	Establishment: regular irrigation. Later: when summer dry periods ≥ 3 weeks	Fassman and Simcock, 2012
	EGR	unknown	When necessary	Harp et al., 2008
GR materials	EGR	Gravity-fed drip irrigation (water tank 6 m above plot)	When necessary	Elstein et al., 2008
	EGR	Automatic sprinkler system	unknown	He and Jim, 2010
	SEGR	unknown	When soil moisture < threshold value	Scherba et al., 2011
b) Model simulation studies				
Energy and temperature performance	EGR	Automatic sprinkler system, timer controlled	10 mm 2 times/day	Jim, 2012
	EGR + IGR	unknown	0, 0.1 and 0.3 W/m²	Kolokotsa et al.,

				2013
	EGR + SEGR + IGR	unknown	When soil moisture < threshold value. 0, 1, 2 cm/week	Sailor, 2008; Sailor et al., 2011
	SEGR	unknown	Nighttime irrigation 2 mm/h	Sun et al., 2014
	IGR	unknown	When soil moisture content < threshold value (0.35 and 0.45 m^3/m^3)	Li et al., 2014
Stormwater management	EGR	No irrigation	-	Stovin et al., 2013
	EGR	Rainwater harvesting	unknown	Vieira et al., 2013
	SEGR	unknown	When soil moisture < wilting point	Roehr and Kong, 2010
	SEGR	Rainwater harvesting, cistern of 127 mm	unknown	Hardin et al., 2012

Appendix 7.1

System	Type	Description	Succulence (%)	Installation method	Substrate depth	Species richness
1.1	1	Sedum-Sortiment	92.86	cuttings	?	14
2.1	2	Samenmisching KS	25.93	seeds	?	27
2.2	2	Sedumsprossen+saatgut	16.28	seeds	?	43
2.3	3	UK Native plugplants: chalk	12	plugs	8	25
2.4	3	UK Native plugplants: alpine	28.57	plugs	8	7
2.5	3	UK Native plugplants: wildflower	0	plugs	8	28
2.6	3	UK Native plugplants: grassland	0	plugs	8	11
2.7	1	Sedumblanket	100	mat	3	11
2.8	3	Wildflower Mix	4.17	mat	13	24
3.1	1	Sedumsprossen	100	cuttings	?	6
3.2	1	Vegetatiemat Typ SM/KG	100	mat	5	6
3.3	2	"Spardach" Saatgut TypA	10	seeds	8	20
3.4	1	"Leichtdach"	100	cuttings	3	10
3.5	2	Saatgutmischung E	0	seeds	10	30
3.6	2	"Naturdach SGK	14.29	seeds	10	28
3.7	2	"Naturdach GK	18.75	seeds	15	32
4.1	2	Saatmischung1	22.22	seeds	7	18
4.2	2	Saatmischung2	16	seeds	7	25
4.3	2	Saatmischung3	0	seeds	7	14
4.4	2	Saatmischung4	0	seeds	7	23
4.5	2	Saatmischung5	26.47	seeds	7	34
5.1	1	Sedumteppich	100	mat	6	7
5.2	1	Sedumteppich (halbschatten)	100	mat	6	4
5.3	2	Steinrosenflur	30.43	plugs	7	23
5.4	1	Steinrosenflur (halbschatten)	57.14	plugs	7	7
5.5	2	Kräuterflur	0	seeds	8	25
6.1	2	Sedumsprossen+saad	46.43	seeds	?	28
7.1	1	Sedumteppich	100	mat	8	10
7.2	2	Krauterwiese	27.27	seeds	8	22
7.3	2	Steinrosenflora	26.32	seeds	9	19
7.4	2	Blütenflora	30	plugs	12	20
7.5	2	ext schatten	16.67	seeds	10	18
8.1	1	Sedummat	100	mat	3	9
8.2	1	sedum plugplants	100	cuttings	3	7
8.3	2	plugplants	9.09	plugs	8	11
9.1	1	Sedummat	100	mat	3	7
9.2	1	sedumpluggen	100	cuttings	5	8
9.3	2	Sedumkruidenmat	58.33	mat	7	12
9.4	2	Gras- en kruidenpluggen	0	plugs	17	8
9.5	2	Sedum-gras-kruidenmat	50	mat	?	14
10.1	1	Sedumplugs	100	cuttings	?	9
10.2	2	Kruiden/gras plugs	0	plugs	?	14
10.3	1	Sedumspruiten	100	cuttings	?	6
11.1	1	Sedumteppich	100	mat	6	6
11.2	2	Steinrosenflur	0	plugs	7	10
12.1	2	extensivkräuter	28.57	seeds	?	28
13.1	2	Saatgutmischung	5.88	seeds	?	34
13.2	1	Sedummischung	100	cuttings	?	9
14.1	2	Extensive begrünung	30.43	plugs	12	23
15.1	1	Sedummat	100	mat	6	6
16.1	3	Wildflower seed	0	seeds	8	22

16.2	1	Sedum plugs	100	cuttings	7	9
17.1	1	Sedummat	100	mat	6	9
18.1	3	Dry Calcareous plants	4.76	plugs	12	21
18.2	3	Biotopdak	5.56	plugs	12	18
18.3	1	Mos-sedumroof	100	mat	3	8
19.1	1	Sedummat	100	mat	3	12

Appendix 7.2

	N°	*Sedum* type	*Dianthus-Thymus* type	*Linaria-Galium* type
# EGR systems per type		22	28	8
Achillea millefolium	16	0	44	50
Achillea tomentosa	3	0	11	0
Agrimonia eupatoria	1	0	0	13
Ajuga reptans	1	0	4	0
Alchemilla vulgaris	1	0	4	0
Allium roseum	1	0	4	0
Allium schoenoprasum	18	0	67**	0
Allium sphaerocephalon	1	0	4	0
Amerosedum divergens	1	5	0	0
Anemone pulsatilla	3	0	11	0
Antennaria dioica	7	0	19	25
Anthemis tinctoria	8	0	22	25
Anthoxanthum odoratum	2	0	7	0
Anthyllis vulneraria	3	0	4	25*
Aquilegia vulgaris	1	0	4	0
Arenaria serpyllifolia	1	0	4	0
Armeria maritima	13	0	30	63**
Aster amellus	4	0	15	0
Aster linosyris	1	0	4	0
Aurinia saxatilis	1	0	4	0
Bellis perennis	2	0	0	25*
Briza media	5	0	11	25
Bromus erectus	2	0	7	0
Bromus tectorum	3	0	11	0
Calendula arvensis	1	0	4	0
Campanula carpatica	1	0	4	0
Campanula glomerata	5	0	7	38*
Campanula persicifolia	2	0	4	13
Campanula portenschlagiana	1	5	0	0
Campanula poscharskyana	1	5	0	0
Campanula rapunculoides	2	0	7	0
Campanula rotundifolia	15	0	33	75**
Carex flacca	4	0	7	25*
Carex humilis	1	0	4	0
Carex montana	1	0	4	0
Carex sylvatica	1	0	4	0
Centaurea cyanus	3	0	7	13
Centaurea jacea	1	0	0	13
Centaurea nigra	1	0	0	13
Centaurea scabiosa	4	0	15	0
Centaurium erythraea	1	0	0	13
Cerastium arvense	1	0	4	0
Cerastium tomentosum	3	0	11	0
Cichorium intybus	1	0	0	13
Clinopodium alpinum	2	0	7	0
Clinopodium vulgare	2	0	4	13
Cymbalaria muralis	1	0	4	0
Cynosurus cristatus	2	0	7	0
Daucus carota	1	0	4	0

Daucus carota subsp. maritimus	1	0	0	13
Dianthus anatolicus	1	0	4	0
Dianthus arenarius	2	0	0	25*
Dianthus armeria	1	0	4	0
Dianthus carthusianorum	21	0	78**	0
Dianthus deltoides	23	0	78**	25
Dianthus giganteiformis subsp. pontederae	1	0	4	0
Dianthus plumarius	3	0	11	0
Dianthus sylvestris	1	0	4	0
Draba aizoides	1	0	4	0
Echium vulgare	4	0	4	38*
Erodium cicutarium	2	0	7	0
Euphorbia cyparissias	10	0	37*	0
Euphorbia myrsinites	2	0	7	0
Festuca amethystina	3	0	11	0
Festuca glauca	5	0	19*	0
Festuca ovina	11	0	33	25
Festuca rubra	4	0	7	25*
Festuca rupicaprina	1	0	4	0
Festuca valesiaca	1	0	4	0
Filipendula vulgaris	1	0	0	13
Fragaria vesca	4	0	11	13
Galium verum	8	0	7	75**
Geranium pyrenaicum	1	0	4	0
Geranium robertianum	3	0	11	0
Geranium sanguineum	4	0	7	25*
Geranium x magnificum	1	0	4	0
Geum rivale	1	0	0	13
Glechoma hederacea	2	0	0	25*
Globularia cordifolia	1	0	4	0
Gormania spathulifolia	1	5	0	0
Gypsophila repens	3	0	11	0
Helianthemum nummularium	6	0	15	25
Helichrysum arenarium	1	0	4	0
Hieracium aurantiacum	12	0	41*	13
Hieracium pilosella	19	0	70**	0
Hylotelephium spectabile	1	5	0	0
Hypericum perforatum	7	0	15	38*
Hypochoeris radicata	1	0	0	13
Iberis sempervirens	1	0	4	0
Inula conyza	1	0	4	0
Iris pumila	1	0	4	0
Iris tectorum	1	0	4	0
Jasione montana	3	0	7	13
Knautia arvensis	2	0	0	25*
Koeleria glauca	7	0	26*	0
Lavandula angustifolia	2	0	7	0
Leontodon autumnalis	1	0	0	13
Leontodon hispidus	4	0	0	50**
Leopoldia comosum	1	0	4	0
Leucanthemum vulgare	11	0	26	50*
Linaria alpina	1	0	4	0
Linaria vulgaris	12	0	19	88**
Linum perenne	13	0	48**	0
Lotus corniculatus	6	0	7	50**

Malva moschata	2	0	4	13
Melica ciliata	3	0	11	0
Origanum vulgare	20	0	63*	38
Papaver rhoeas	5	0	15	13
Petrorhagia saxifraga	21	0	78**	0
Phedimus selskianus	1	5	0	0
Phlox douglasii	1	0	4	0
Pilosella officinarum	1	0	0	13
Pilosella rubra	2	0	7	0
Pimpinella saxifraga	1	0	4	0
Plantago coronopus	1	0	0	13
Plantago media	1	0	0	13
Poa compressa	2	0	7	0
Poa glauca	1	0	4	0
Potentilla argentea	6	0	22*	0
Potentilla aurea	1	0	4	0
Potentilla neumanniana	3	0	7	13
Potentilla reptans	2	0	0	25*
Potentilla verna	11	0	41*	0
Primula veris	4	0	4	38*
Primula vulgaris	2	0	0	25*
Prunella grandiflora	11	5	37*	0
Prunella vulgaris	9	0	19	50*
Prunella webbiana	1	0	4	0
Pseudofumaria lutea	1	0	4	0
Pseudolysimachion spicatum	4	0	7	25*
Ranunculus acris	1	0	0	13
Ranunculus bulbosus	6	0	11	38*
Reseda lutea	1	0	0	13
Rhinanthus minor	1	0	0	13
Sagina subulata	1	0	4	0
Salvia pratensis	2	0	7	0
Sanguisorba minor	7	0	15	38*
Saponaria ocymoides	9	0	33*	0
Saponaria officinalis	5	0	15	13
Satureja subspicata	1	0	4	0
Saxifraga cotyledon	1	5	0	0
Saxifraga granulata	3	0	4	25*
Saxifraga paniculata	3	0	11	0
Scabiosa canescens	1	0	4	0
Scabiosa columbaria	4	0	4	38*
Sedum acre	23	55	30	38
Sedum aizoon	1	5	0	0
Sedum album	39	91**	63	25
Sedum anacampseros	1	0	4	0
Sedum cauticola	4	9	7	0
Sedum cyaneum	2	9	0	0
Sedum ewersii	6	18	7	0
Sedum forsterianum	2	9	0	0
Sedum hispanicum	14	41*	19	0
Sedum hybridum	28	82**	37	0
Sedum kamtschaticum	32	86**	48	0
Sedum lydium	13	45*	11	0
Sedum montanum	3	9	4	0
Sedum montanum subsp. orientale	2	9	0	0

Sedum pulchellum	4	14	4	0
Sedum rupestre	31	77*	52	0
Sedum sarmentosum	1	5	0	0
Sedum sexangulare	29	86**	37	0
Sedum spurium	37	95**	59	0
Sedum stenopetalum	1	0	4	0
Sedum stoloniferum	1	5	0	0
Sedum telephium	5	5	15	0
Sedum triactina	1	5	0	0
Sempervivum arachnoideum	3	9	4	0
Sempervivum globiferum subsp. hirtum	1	5	0	0
Sempervivum montanum	1	5	0	0
Sempervivum tectorum	3	5	7	0
Silene dioica	1	0	4	0
Silene flos-cuculi	1	0	0	13
Silene latifolia subsp. alba	1	0	0	13
Silene nutans	3	0	11	0
Silene otites	1	0	4	0
Silene uniflora	3	0	0	38*
Silene viscaria	9	0	30	13
Silene vulgaris	4	0	4	38*
Stachys officinalis	1	0	0	13
Teucrium chamaedrys	3	0	11	0
Thymus doerfleri	1	0	4	0
Thymus praecox subsp. polytrichus	5	0	0	63**
Thymus pulegioides	12	0	44**	0
Thymus serpyllum	24	0	81**	25
Thymus vulgaris	1	0	4	0
Trifolium arvense	2	0	7	0
Tripleurospermum maritimum subsp. inodorum	1	0	4	0
Verbascum lychnitis	1	0	4	0
Verbascum nigrum	3	0	11	0
Verbascum phlomoides	1	0	4	0
Verbascum phoeniceum	1	0	4	0
Veronica officinalis	1	0	0	13
Veronica teucrium	4	0	15	0
Viola arvensis	2	0	7	0
Viola odorata	1	0	0	13
Viola riviniana	1	0	0	13
Viola tricolor	1	0	0	13

Appendix 7.3

Group	*Sedum* type	*Dianthus-Thymus* type	*Linaria-Galium* type
1	*Amerosedum divergens, Phedimus selskianus, Sedum acre, Sedum aizoon, Sedum album, Sedum forsterianum, Sedum hybridum, Sedum kamtschaticum, Sedum lydium, Sedum montanum, Sedum montanum subsp. orientale, Sedum pulchellum, Sedum rupestre, Sedum sarmentosum, Sedum sexangulare, Sedum spurium, Sedum stoloniferum, Sedum triactina*	*Achillea millefolium, Anthemis tinctoria, Daucus carotus, Leucanthemum vulgare, Pimpinella saxifraga, Trifolium arvense*	*Achillea millefolium, Daucus carota, Echium vulgare, Leucanthemum vulgare, Reseda lutea*
2	*Campanula portenschlagiana, Campanula poscharskyana*	*Achillea tomentosa, Aurinia saxatilis*	*Agrimonia eupatoria, Hypericum perforatum*
3	*Sedum spathulifolium*	*Ajuga reptans, Alchemilla vulgaris, Aster amellus, Aster linosyris, Campanula carpatica, Campanula glomerata, Campanula persicifolia, Campanula rapunculoides, Campanula rotundifolia, Centaurea scabiosa, Cymbalaria muralis, Dianthus armeria, Dianthus carthusianorum, Dianthus deltoides, Dianthus giganteiformis, Dianthus plumarius, Dianthus sylvestris, Galium verum, Geranium pyrenaicum, Geranium robertianum, Geranium sanguineum, Geranium magnificum, Globularia cordifolia, Jasione montana, Linaria alpina, Linaria vulgaris, Linum perenne, Origanum vulgare, Phlox douglasii, Potentilla argentea, Potentilla aurea, Potentilla neumanniana, Potentilla verna, Prunella grandiflora, Prunella vulgaris, Prunella webbiana, Pseudofumaria lutea, Pseudolysimachion spicatum, Salvia pratensis, Saponaria ocymoides, Saponaria officinalis, Scabiosa canescens, Scabiosa columbaria, Silene dioica, Silene nutans, Silene viscaria, Silene vulgaris, Thymus doerfleri, Veronica teucrium*	*Antennaria dioica, Armeria maritima, Bellis perennis, Campanula glomerata, Campanula rotundifolia, Geranium sanguineum, Hieracium aurantiacum, Leontodon hispidus, Origano vulgare, Primula veris, Primula vulgaris, Prunella vulgaris, Saxifraga granulata*
4	*Hylotelephium spectabile*	*Allium roseum, Allium schoenoprasum, Allium sphaerocephalon, Iris pumila, Iris tectorum, Leopoldia comosa*	*Anthemis tinctoria*

5	*Prunella grandiflora*	*Anemone pulsatilla*	*Anthyllis vulneraria, Lotus corniculatus*
6	*Saxifraga cotyledon, Sedum hispanicum*	*Antennaria dioica, Armeria maritima, Briza media, Dianthus anatolicus, Fragaria vecas, Gypsophila repens, Primula veris, Saxifraga granulata, Saxifraga paniculata*	*Carex flacca*
7	*Sedum cauticola, Sedum cyaneum, Sedum ewersii, Sedum telephium*	*Anthoxanthum odoratum, Bromus erectus, Carex flacca, Carex humilis, Carex montana, Carex sylvatica, Cynosurus cristatus, Euphorbia cyparissias, Festuca amellus, Festuca glauca, Festuca ovina, Festuca rubra, Festuca rupicaprina, Festuca valesiaca, Koeleria glauca, Melica ciliata, Poa compressa, Poa glauca*	*Centaurea cyaneus, Papaver rhoeas*
8	*Sempervivum arachnoideum, Sempervivum globiferum, Sempervivum montanum, Sempervivum tectorum*	*Anthyllis vulneraria, Lotus corniculatus, Petrorhagia saxifraga*	*Centaurea jacea , Centaurea nigra, Cichorium intybus, Clinopodium vulgare, Knautia arvensis, Linaria vulgaris, Malva moschata, Pseudolysimachion spicatum, Saponaria officinalis, Scabiosa columbaria, Silene flos-cuculi, Silene latifolia, Silene viscaria, Silene vulgaris, Stachys officinalis*
9		*Aquilegia vulgaris*	*Centaurium erythraea, Viola tricolor*
10		*Arenaria serpyllifolia, Calendula arvensis, Papaver rhoeas, Tripleurospermum maritimum, Viola arvensis*	*Dianthus arenarius, Plantago media, Silene uniflora*
11		*Bromus tectorum*	*Dianthus deltoides, Glechoma hederacea, Jasione montana, Thymus praecox, Thymus serpyllum, Veronica officinalis*
12		*Centaurea cyanus, Erodium cicutarium*	*Festuca ovina, Festuca rubra, Pilosella officinarum*
13		*Cerastium arvense, Cerastium tomentosum, Sagina subulata*	*Filipendula vulgaris*
14		*Clinopodium alpinum, Helianthemum nummularium, Helichrysum arenarium, Teucrium chamaedrys, Thymus pulegioides, Thymus serpyllum, Thymus vulgaris*	*Galium verum, Geum rivale, Potentilla neumanniana, Potentilla reptans, Ranunculus acris*
15		*Clinopodium vulgare*	*Helianthemum nummularium*
16		*Draba aizoides, Hieracium aurantiacum, Hieracium pilosella, Pilosella rubra, Silene otites*	*Plantago coronopus*
17		*Echium vulgare, Iberis sempervirens, Satureja subspicata*	*Ranunculus bulbosus*
18		*Euphorbia myrsinites, Sedum acre, Sedum album, Sedum anacampseros,*	*Rhinanthus minor*

	Sedum cauticola, Sedum ewersii, Sedum hispanica, Sedum hybridum, Sedum kamtschaticum, Sedum lydium, Sedum montanum, Seddum pulchellum, Sedum rupestre, Sedum sexangulare, Sedum spurium, Sedum stenopetalum, Sedum telephium, Sempervivum arachnoideum, Sempervivum tectorum	
19	*Hypericum perforatum, Inula conyza, Malva moschata, Verbascum lychnitis, Verbascum nigrum, Verbascum phlomoides, Verbascum phoeniceum*	*Sanguisorba minor*
20	*Lavandula angustifolia*	*Sedum acre, Sedum album*
21	*Ranunculus bulbosus*	
22	*Sanguisorba minor*	

Publication list

1. Articles in peer-reviewed, international, scientific journals

1.1. Published or in press

Jacquemyn, H., **Van Mechelen, C.**, Brys, R., Honnay, O., 2011. Management effects on the vegetation and soil seed bank of calcareous grasslands: An 11-year experiment. *Biological Conservation,* **144**, 416-422.

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Van Mechelen, C., Dutoit, T., Kattge, J., Hermy, M., 2014. Plant trait analysis delivers an extensive list of potential green roof species for Mediterranean France. *Ecological Engineering,* **67**, 48-59.

Van Mechelen, C., Van Meerbeek, K., Dutoit, T., Hermy, M., 2015. Functional diversity as a framework for novel ecosystem design: The example of extensive green roofs. *Landscape and Urban Planning*, accepted publication.

1.2. Under review

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Van Mechelen, C., Baert, F., Torrez, V., Dutoit, T., Honnay, O., Hermy, M. Effect of addition of organic material and arbuscular mycorrhizal fungi on initial green roof plant development. *Urban Ecosystems.*

Van Mechelen, C., Dutoit, T., Hermy, M. Adapting green roof irrigation practices for a sustainable future: a review. *Building and Environment*.

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