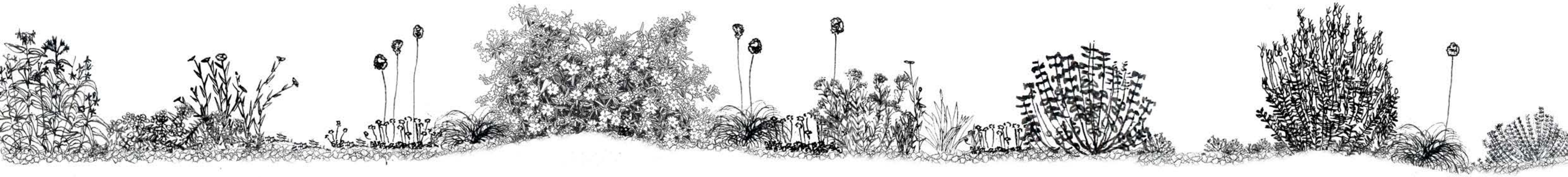
Applying the habitat template

A design framework for translating Mediterranean garrigue vegetation to green roof contexts

Franz Scharnweber



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Abstract

As urbanization and climate change intensify the Urban Heat Island (UHI) effect, extensive green roofs have become crucial nature-based solutions for urban climate adaptation. However, contemporary thin-substrate green roofs predominantly rely on low-diversity succulent monocultures (e.g. *Sedum* spp.). While these systems survive in shallow substrates, their limited structural and functional diversity constrains their ecological potential and long-term resilience under increasingly extreme weather events. This thesis investigates an alternative approach: the integration of Mediterranean garrigue vegetation into thin-substrate green roofs to enhance climatic resilience and ecosystem multifunctionality.

Employing a mixed-methods approach, this research combines a review of climate analogue modelling studies, microclimate aspects, a literature study and qualitative evaluations of both a built case study and natural reference landscapes. This process informs a trait-based plant selection framework grounded in the habitat template approach. The findings demonstrate that both long-term regional climate shifts and the immediate, extreme abiotic stressors of the rooftop microclimate justify the use of drought-adapted Mediterranean xerophytes in temperate urban contexts.

To successfully operationalize the garrigue biome on a roof, the design translates its physical and functional complexity rather than relying on simple taxonomic replication. A conceptual design framework is proposed, e.g. combining variable substrate depths and microtopography. By integrating physical facilitators and maximizing phylogenetic and life-form diversity, the framework supports a resilient, rhythmic matrix of subshrubs, succulents, grasses and forbs.

The plant selection process utilized a systematic, trait-based screening framework to filter a comprehensive pool of ecosystem-associated species against criteria of functional and ecological traits. The design process then translated this curated vegetation palette into a modular green roof prototype that mimics the structural complexity of the natural reference habitat. By grounding these findings in a physical layout, this prototype proves that theoretical ecological concepts can be successfully translated into a functional spatial reality. Ultimately, this research provides landscape architects with an actionable, transferable design methodology, demonstrating how extensive green roofs could evolve into complex, multi-layered ‘rooftop garrigues’ capable of sustaining vital ecosystem services in a changing climate.

Mediterranean vegetation, Source: author

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1. Introduction

1.1. Background and problem description

Heat waves and urban heat island (UHI) effects pose increasing threats to urban populations globally (Cheval et al. 2024), with climate change intensifying the frequency and severity of heat extremes in cities (IPCC 2023). Nature-based solutions are widely recognised as climate adaptation tools for mitigating UHI and climate change impacts (ibid.).

Green roofs represent an effective nature-based approach, especially where ground-based solutions are limited by space constraints (Joshi et al. 2020; Liu et al. 2022; Catalano 2024). They provide multiple ecosystem services, including heat mitigation, stormwater retention, carbon sequestration and habitat provision, though the majority of these effects vary with design and plant composition (Berardi et al. 2014; Balany et al. 2020; Aleksejeva et al. 2024; Chung & Sung 2025). Research indicates that vegetation characteristics such as life-form diversity (Lundholm et al. 2010), phylogenetic diversity (Lundholm 2015; MacIvor et al. 2018) or functional diversity (Van Mechelen et al. 2015) influence the capacity to deliver these services.

Extensive green roofs, characterised by shallow substrates, are widely used for their cost-effectiveness, low-maintenance and low weight, making them suitable for retrofitting in dense urban environments (Shafique et al. 2018a; b). In current practice, extensive green roofs are often dominated by succulents (e.g., *Sedum* spp.) due to their ability to survive in shallow substrates and limited water conditions (Todeschini & Fett-Neto 2025). However, this limited structural and phylogenetic diversity can constrain the range of ecological functions and services compared to more diverse plant communities (Cook-Patton & Bauerle 2012; Van Mechelen et al. 2015). Studies on aesthetic preferences of green roofs show that the public prefers complex green roof designs that move beyond monocultures or low-growing succulents towards more complex vegetation including multiple structural layers and diverse species compositions (Fernandez-Cañero et al. 2013; Thorpert et al. 2024). In natural open-land habitats, shrubs can increase spatial heterogeneity, thereby generating diverse structures and microhabitats that support a variety of other organisms (Pihlgren & Lennartsson 2008; Eldridge et al. 2011; Oksuz et al. 2020; Lopes et al. 2023; Hou et al. 2025; Kettermann et al. 2025).

While plant diversity has been increasingly recognised as a factor that can enhance green roof performance, there is little research investigating the integration of shrubs to create structurally diverse green roofs, particularly with respect to multifunctionality and long-term resilience. A study by Liao et al. 2025 reviewed 87 articles relating to extensive green roofs with 29 of them covering shrub vegetation, either as a single- or in combination with other life forms. Locating these studies, 8 out of 29 studies were referring to trials in the summer dry mediterranean climate zones (Csa and Csb according to Köppen-Geiger classification). Future climate projections for Europe indicate a pronounced southward shift in climate conditions (Rohat et al. 2018) with many central European cities finding the analogue for their predicted end of the century climate in Mediterranean regions or by the western European Atlantic coast (Rohat et al. 2017; 2018; Bastin et al. 2019; Crespi et al. 2023; Bulut et al. 2025). This shift implies changes for urban vegetation strategies and plant species suitability. Climate analogues can function as a decision-support tool for urban planners and enable knowledge transfer between affected cities (Rohat et al. 2018). While regional climate analogues provide a long-term rationale, species selection for extensive green roofs should primarily be guided by functional trait matching to the extreme and highly variable abiotic conditions characteristic of rooftop environments (Du et al. 2018). These systems impose chronic water limitation, high thermal loads and pulsed disturbance regimes that could more closely resemble stress-prone ecosystems such as Mediterranean garrigue than surrounding habitats in temperate climates. Consequently, the use of Mediterranean species can be justified as a trait-based, performance-oriented strategy that enhances survival, ecosystem stability and service provision under both current and future climatic conditions.

In mediterranean-type climates, the selection of native xerophytic shrub species adapted to heat, drought and shallow substrates has been explored and studies demonstrate that native Mediterranean species can provide valuable ecosystem services on green roofs (Raimondo et al. 2015; Bellini et al. 2024; 2025). The southward climate shift in Europe could increase relevance for Mediterranean vegetation even outside of their native range.

This thesis proposes a mixed vegetation concept combining (sub-)shrubs with complementing other life forms from garrigue habitats to provide multifunctional and resilient thin-substrate green roofs in changing climate conditions. Garrigue shrubs could expand structural complexity as well as phylogenetic, life-form and functional diversity, and therefore enhance ecosystem services while keeping the substrate depth relatively low. They exhibit an exceptional drought tolerance and, through evergreen tomentose foliage, provide year-round structure and distinctive aesthetic qualities. This offers potential advantages over vegetation types commonly used in contemporary thin-substrate green roofs.

1.2 Aims and research question

The aim of this thesis is to investigate how Mediterranean garrigue vegetation can be integrated into mixed vegetation systems for thin-substrate green roofs to improve climatic resilience and ecosystem services. The garrigue as a habitat template and reference landscape is examined as an adaptable vegetation model rather than as a fixed typology. Therefore the term does not strictly adhere to the phytosociological definition of this plant community. The research question is:

How can garrigue vegetation be captured with the habitat template approach as a climate resilient and functional option for thin-substrate green roofs?

Questions along the way of the thesis are:

- What are common selection processes in thin substrate green roofs?
- How does vegetation diversity enhance ecosystem services of green roofs?
- What are unique structural and atmospheric characteristics of garrigue vegetation and which framework can be applied to capture these in a built environment?

1.3 Implementation and limitations

The project is characterized by a mixed-method approach combining climate-related considerations, literature review, case study analysis, reference landscape analysis and a design process for an exemplary green roof module. Climate analogue and microclimate analysis were used to assess the long-term suitability of plant communities and to identify a suitable habitat template. A review of plant selection processes for extensive green roofs establishes a theoretical framework and identifies gaps in the use of shrub-dominated vegetation.

Case studies and reference landscapes were analysed with qualitative approaches in an observational process. Findings of literature and case studies were then synthesised into design guidelines that informed a final, conceptual planting design proposal for a green roof. Finally, the design process was reflected upon to gain an understanding of the transferability of the findings.

Limitations include reliance on secondary and predictive data and the absence of long-term empirical testing. The design proposal is speculative and illustrative rather than fully engineered.

1.4 Methods

To assess the long-term suitability of Mediterranean vegetation types in a changing climate, the review uses a twofold approach of different spatial scales. First, an assessment of climate analogue studies demonstrates the long term change of regional climate and how this can influence decision-making for urban vegetation. Secondly, a characterization of green roof microclimate in general demonstrates the functional needs on the vegetation type. This twofold approach provides a qualitative rationale for the selection of Mediterranean shrubs, analyzing their relevance not only as aesthetic references but as climate-adapted vegetation systems for extensive green roofs.

The literature study begins with a comprehensive review on plant selection approaches for extensive green roofs and particularly the habitat templating as a part of plant selection frameworks. It examines current standards and practices with attention to the ecological and functional benefits of diverse plant communities.

Special focus is given to the role of shrub species within extensive green roof systems, addressing their potential contributions in terms of structural complexity, microclimatic modulation, habitat creation and ornamental value. This phase establishes both the scientific foundation and the underutilization of shrub-dominated vegetation types such as the Mediterranean garrigue vegetation in green roof design.

A case study is analysed to investigate how garrigue vegetation has been implemented in a built environment. Furthermore natural garrigue sites are analysed as reference landscapes.

The case study and reference landscape analysis operates on two complementary levels:

- Technical and ecological analysis focusing on vegetation composition, vegetation diversity, substrate depth, maintenance regimes, visuals and performance over time.
- Spatial and atmospheric analysis, examining how garrigue vegetation contributes to spatial structure, species interaction and perceptual experience.

Findings of the literature review, climatic considerations and case studies are synthesized into a selection matrix to inform the plant selection for exemplary green roofs in Malmö and surrounding temperate climate regions. Based on this, design guidelines are created for the integration of mixed plant communities into thin-substrate green roof systems. These guidelines inform the final design proposal, which functions as a spatial and vegetative interpretation of a natural ecosystem adapted to green roof conditions. The proposal demonstrates how ecological resilience, climatic suitability and atmospheric quality can be combined through a design-led approach grounded in scientific research.

2. Climate

To inform resilient plant selection for urban green infrastructure, this chapter evaluates environmental constraints across two distinct spatial scales and methodological frameworks. Section 2.1 utilizes a macroclimatic predictive lens, relying on climate analogue studies to forecast long-term regional shifts under specific greenhouse gas emission scenarios. In contrast, Section 2.2 applies a microclimatic and trait-based lens to address the immediate, acute abiotic stressors of the built environment. While the former method anticipates future climate trajectories through geographic proxies, the latter addresses the current, decoupled reality of rooftop microclimates by identifying plant communities with specific physiological adaptations to extreme, localized stress.

2.1 Climate analogues

Climate analogues have emerged as an effective tool for urban adaptation and climate change mitigation. By identifying locations whose current climate resembles the projected future climate of a given city, land managers and urban planners can immerse themselves in how the future climate conditions might be like, making abstract climate projections tangible and actionable (Bastin et al. 2019; Bulut et al. 2025). This experiential understanding allows decision-makers to anticipate vulnerabilities, evaluate adaptation options and learn from practices already implemented in analogue locations (Rohat et al. 2017; 2018). For urban vegetation specifically, climate analogues can be used to inform species selection, highlighting resilient plant species currently thriving in climates that match a city's projected future conditions, thereby supporting evidence-based urban vegetation management (Esperon-Rodriguez et al. 2022). Collectively, these studies demonstrate that climate analogues serve not only as communication and awareness tools (Fitzpatrick & Dunn 2019) but also as decision-support instruments, enabling urban stakeholders to plan for and adapt their infrastructure and green spaces in the face of climate change.

Climate analogue studies were evaluated for geographical relevance for the project region of Malmö with the closest climate analogue study of Bulut et al. (2025) finding an equivalent for Copenhagen. Bulut et al. (ibid.) identify that the future climate of Copenhagen under a medium to high emission scenario will be analogous to the today climate of:

- Schwerin, Northern Germany in the early future and current climate (2011-2040)
- Lille, Northern France in the mid future (2041-2070) and
- Potenza, Southern Italy in the far future (2071-2100).

Figure 1: climate analogues of copenhagen tied to a medium- to high-emission scenario SSP 3-7.0. based on bulut et al. (2025)
map source: created by author. base by european commission, eurostat (n.d.)

2.2 Microclimatic conditions and functional adaptation

While regional climate analogues offer a long-term rationale for plant selection, the abiotic environment of extensive green roofs already functions as a novel ecosystem. Characterized by extreme thermal loads, rapid desiccation and high temporal variability, these rooftop conditions create a stress regime that is fundamentally disconnected from Malmö's cool-temperate (Cfb, according to Köppen-Geiger (Beck et al. 2023)) macroclimate and far exceeds the intensity of surrounding ground-level habitats. Surface temperatures on conventional bitumen roofs can exceed ambient air temperatures by 30–50 °C under peak summer radiation (Sailor 2008), and even on vegetated roofs, the air temperature at the canopy level remains significantly higher than at the pedestrian level (MacIvor et al. 2016). While green roofs mitigate the most extreme surface temperature peaks, shallow substrates still exhibit intense thermal fluctuations and high substrate temperatures that often prove more decisive for plant survival than solely water deficit (Paço 2026). Consequently, the rooftop microclimate requires a plant selection strategy based on functional stress tolerance rather than regional climate classifications.

Across climatic factors, empirical studies consistently identify water limitation and heat stress as primary constraints on green roof vegetation (Dunnett & Kingsbury 2008). Shallow substrates significantly restrict water storage capacity and lead to frequent drought cycles, with substrate depth directly dictating the stability of the root-zone microclimate (İokhim & Ekşi 2024). Experimental studies demonstrate that plant survival is strongly associated with the ability to withstand repeated desiccation and elevated substrate temperatures, with both above- and belowground heat tolerance dictating overall performance (Butler & Orians 2011; MacIvor & Lundholm 2011). Plant species originating from Mediterranean-type climates are functionally adapted to prolonged seasonal drought, high irradiance and low soil moisture availability (Bellini et al. 2024), conditions that closely match the dominant stress regime observed on extensive green roofs. Incorporating species with functional adaptations that meet these stress factors may enhance the resilience and biodiversity of green roof systems far beyond the plants' native distribution ranges. While the urban heat island effect and projected climate change will likely further intensify rooftop stressors, such extreme conditions are already present in contemporary urban environments, supporting a selection of drought-adapted plant assemblages in design practice. Specifically, the environmental profile of thin substrate green roofs in large parts of central Europe, with the northern boundary reaching as far as southern Scandinavia, closely mirrors the garrigue. The garrigue is a Mediterranean scrubland biome characterized by discontinuous canopy cover and thin, rocky soils (De Dato et al. 2008). In these natural habitats, vegetation must withstand a severe combination of extreme solar radiance, high wind exposure and acute water deficits (Giorgioni & Grandi 2021). By treating the green roof as an urban analogue to the garrigue, practitioners can identify a specialized species pool potentially suitable for the very shallow substrates and high-exposure stressors that define the rooftop environment.

Figure 2: *Sedum ochroleucum* in its scree slope habitat near Marseille, southern France a succulent species potentially adapted to green roof conditions. Source: author

3. Literature study

Extensive green roofs, often defined as systems with a substrate depth below 15 cm and minimal maintenance requirements, represent a highly feasible greening strategy for densely built urban environments due to their relatively low installation costs and minimal structural load (Oberndorfer et al. 2007). However, these systems operate as extreme environments for plant growth. They are characterized by severe abiotic constraints, including high irradiance, intense wind exposure, limited nutrient availability, and shallow substrates that induce rapid heat and water stress (Todeschini & Fett-Neto 2025). Consequently, the long-term viability and reliable provision of ecosystem services on these roofs depend entirely on the targeted selection of stress-tolerant plant species (Oberndorfer et al. 2007; Lundholm et al. 2010; Ksiazek-Mikenas & Köhler 2018).

To contextualize the design proposal of this thesis, this chapter reviews the current literature on green roof vegetation and design methodologies. It begins by examining contemporary plant selection practices (Section 3.1.1) and the role of mixed vegetation in enhancing ecosystem services (3.1.2), followed by an analysis of how structural elements like substrate and spatial heterogeneity influence these systems (Section 3.2). The review then transitions to the experiential aspects of green roofs with an analysis of human aesthetic preferences (Section 3.3). Finally, the Mediterranean 'garrigue' is introduced as a functional ecological template. By analysing ecological mechanisms such as plant facilitation, this chapter evaluates the specific role shrubs could play in resilient, mixed-vegetation systems (Section 3.4).

3.1 Plant selection in extensive green roof systems

3.1.1. Plant selection approaches

Plant selection for extensive green roofs can be conceptualized as a set of distinct but interrelated approaches, as outlined by Liao et al. (2025). These approaches differentiate between environmental filtering, functional performance and structured decision-making, thereby providing a clearer analytical framework for vegetation design. Rather than representing isolated strategies, these approaches address complementary aspects of plant selection, ranging from species suitability under abiotic constraints to the optimization of ecosystem service provision and the integration of decision-support tools. The following chapter examines three key plant selection (cf. ibid.) approaches for extensive green roofs in detail:

- Habitat template method
- Trait-based approach
- Plant selection frameworks

Habitat template

The habitat template approach, proposed by Lundholm (2006), provides a conceptual ecological framework for selecting plant species in urban artificial habitats. The approach aims at identifying plant communities with similar environmental site conditions to artificial ecosystems like green roofs, e.g. rocky and exposed habitats (ibid.). It is predominantly used to find natural sites with analogue stress-prone conditions. Examining the entire ecosystem community is recommended to include various life forms, e.g. to include bryophytes, lichens, algae and the cryptogamic crusts. Mimicking other structural components of the ecosystems like the microtopography with cracks, ledges or varying soil depths reflects this holistic approach as well (ibid.).

Studies have successfully created regional lists of native species that can survive on roofs, thus showing a widely applicable utilization of the concept (Kinder 2009; Caneva et al. 2015; Van Mechelen 2015; Nagase & Tashiro-Ishii 2018; Ksiazek-Mikenas et al. 2021; Schröder & Kiehl 2021). One decade after the initial hypothesis, Lundholm & Walker (2018) reflect on the habitat template approach, its strengths and weaknesses when utilizing it for green roofs. The findings are extracted in the following part:

Lundholm & Walker (2018) validate the concept with the frequent selection of highly functional succulents (like *Sedum*) that originate from analogously extreme nature habitats. The superiority of succulent species is explained by their level of adaptation to an ecological novelty posed by the extreme conditions of green roofs. Limiting the novelty of an environment for a plant species by identifying the analogue habitat is the key idea of the habitat templating. Species less adapted to extreme conditions, such as certain mosses or forbs, may face an ecological novelty too great to thrive. This suggests that habitat templating alone may be insufficient for predicting the full range of species suitable for green roofs, particularly those that rely on complex community interactions. In context of this reflection, they speculate about the most suitable utilization of the concept as a first filter and further combining it with trait-based selection approaches.

A limitation of habitat templating is its tendency to favour generalist species (Lundholm & Walker 2018). Generalists have a higher tolerance for a wide range of abiotic conditions and thus experience a lower ecological novelty (Simmons 2015). As a result, more specialized species, which may be crucial for ecosystem diversity, could be overlooked. Lundholm and Walker (2018) question the focus on abiotic factors when examining key limiting factors of the survival of a species. They demonstrate that biotic factors also constitute a major influence on the survival of plant species (e.g. by competition, facilitation, herbivory or root-microbe relationships). General conclusions from Lundholm & Walker's (ibid.) reflection of the habitat template approach are following recommendations:

- Combining the habitat template approach with a functional-trait analysis and protocol to provide a more detailed resolution for species selection (see chapter 2.2.3),
- Selecting entire ecological communities including companion species like bryophytes (e.g. mosses) and lichens rather than isolated species,
- Incorporating structural features like woody debris, gravel piles or varied soil depths to imitate the microtopography of natural templates.

If a weed grows on a sidewalk, is it because it thinks it's on a scree slope, or just because it can grow anywhere?

thought about the reasoning behind the approach by lundholm (2006) taken the reflection by lundholm & walker (2018) into account. is the the cause of a plant's presence in a harsh urban environment due to evolutionary specialization or a broad adaptability?

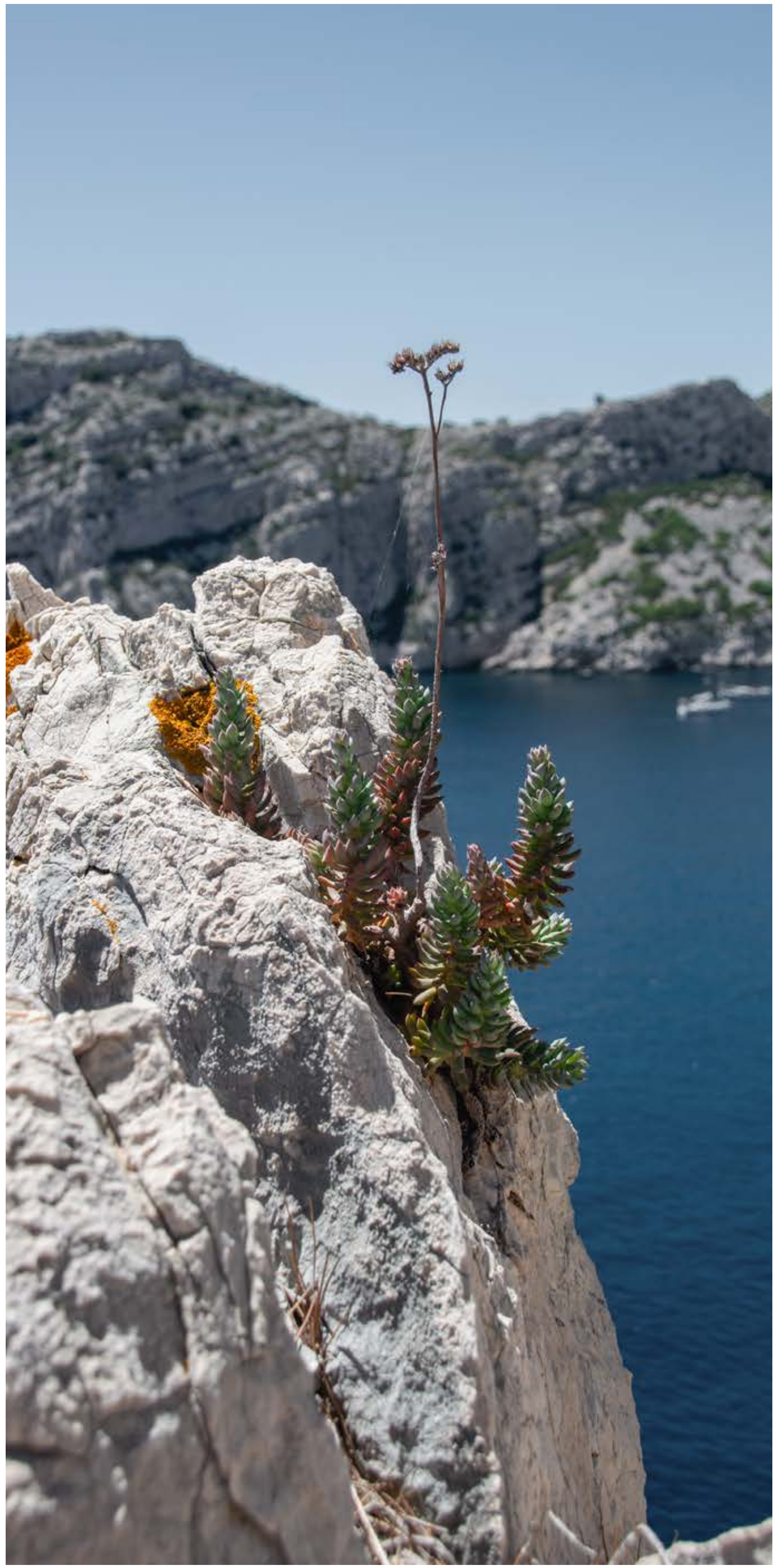


Figure 3: a species that would be suspected to perform well in green roof conditions based on the habitat template approach: *sedum sediforme* growing together with lichen on a rocky outcrop in the calanques national park, marseille. Source: author

Trait-based approach

The selection of plant functional traits for green roofs must be highly site-specific, requiring careful customization to local conditions and broader design objectives (Paço et al. 2026). To maximize the provision of ecosystem services, plant trait selection should explicitly align with targeted performance goals (Kemp 2017; Thuring & Dunnett 2019) such as thermal regulation, biodiversity enhancement or stormwater retention. For instance, a green roof designed primarily for cooling benefits from vegetation with high specific leaf area and dense canopy cover, which maximize evapotranspiration (Kemp 2017; Lundholm et al. 2014). Conversely, if the primary objective is low maintenance and survival in harsh, shallow-substrate microclimates, the implementation of drought-tolerant succulents, which utilize water-saving strategies like CAM photosynthesis, is heavily favored (Paço et al. 2026; Thuring & Dunnett 2019; Todeschini & Fett-Neto 2025).

Ultimately, the long-term resilience and functionality of urban greening systems depend on moving beyond generalized recommendations and rigorously adapting plant traits, such as frost tolerance, to the specific climatic realities of the local environment (Vranayová et al., 2025).

The trait-based approach provides a quantitative framework for assessing plant traits to predict how well species tolerate environmental stress (Liao et al. 2025). Pérez-Harguindeguy et al. (2013:169) define functional traits as any observable attribute of an individual plant that impacts its fitness. These attributes, which can be measured at any scale from the cellular level up to the whole organism, fall into three main categories:

- Morphological traits, such as succulence, leaf shape, or tomentosity;
- Physiological traits, including photosynthetic pathway adaptations like Crassulacean Acid Metabolism (CAM); and
- Phenological traits, such as flowering time (ibid.).

By systematically assessing these traits, designers can select plant species most likely to thrive under site-specific stressors such as drought, heat or shallow substrate depth. This ensures ecological function and long-term resilience of the green roof.

Plant selection frameworks

Plant selection frameworks serve as holistic decision-support tools that integrate multiple ecological filters to guide species choice for green roofs (Liao et al. 2025:4). These frameworks combine the habitat template approach, functional trait analysis, and ecosystem service assessments into structured, multi-criteria selection processes (Lundholm 2006; MacIvor & Lundholm 2011; Van Mechelen et al. 2014b). By synthesizing experimental performance data with site-specific design objectives, these methodologies provide a transparent and reproducible approach for identifying species that can withstand the physiological stressors of urban environments while delivering targeted ecological benefits.

For example, Van Mechelen et al. (2015:17-34) formulated a plant selection tool that utilizes the habitat template approach to identify natural analogues, such as rocky outcrops and Mediterranean dry grasslands, as sources for candidate species. This framework filters potential plants through a hierarchy of functional traits to select those best suited for extensive green roofs, balancing survival resilience with hydrological and thermal performance.

Similarly, Calviño et al. (2023) utilized a multicriteria decision framework to rank species identified through literature reviews and local nursery availability. Their selection process involved two distinct evaluation rounds: the first prioritized a species' tolerance to abiotic green roof conditions (the 'survival filter'), while the second weighted its ecological potential to support beneficial arthropods and enhance urban biodiversity. Ultimately, these frameworks operationalize the integration of diverse criteria, allowing designers to move beyond aesthetic preference toward evidence-based choices that optimize ecological function and long-term resilience.

3.1.2 Biodiversity, mixed vegetation and ecosystem services

Strategic selection of vegetation is crucial to optimize the provision of ecosystem services. Increasing plant biodiversity on green roofs provides significant benefits to urban ecosystem services. While traditional green roofs often rely on a few *Sedum* species, diverse communities, including variations of species, functional traits and phylogeny, have shown to provide several advantages. The following overview summarizes key ecosystem service benefits associated with increased plant diversity on green roofs. It serves as a conceptual foundation for the subsequent sections, where these benefits are linked to specific biodiversity dimensions, and is based on the synthesis by Cook-Patton & Bauerle (2012) and Cook-Patton (2015).

- Enhanced insulation: Diverse plant communities often exhibit greater structural complexity and height variation, creating air pockets that improve the thermal insulation of the roof.
- Evapotranspirative cooling: Higher biomass and productivity in diverse mixtures increase rates of evapotranspiration, which cools the surrounding air and reduces energy demands more effectively than monocultures.
- Reflectance: Diverse plantings can maintain more consistent cover, increasing the reflectance of sunlight (albedo) compared to conventional rooftops.
- Increased retention: The structural complexity and higher biomass of diverse vegetation help slow and absorb rainwater, reducing urban runoff and the demand on drainage networks.
- Complementary water use: Certain plant combinations, such as mixing dryland grasses with other species, can maximize water capture even if those individual species perform poorly in isolation.

- Air and water quality: Diverse communities utilize nutrients like nitrogen and phosphorus more efficiently through complementary resource use, which improves water filtration and reduces the need for fertilizers.
- Pollutant removal: Certain structural plant types, like tall herbaceous plants in mixtures are particularly effective at removing air pollutants such as ozone and small particulates.
- Carbon sequestration: Increased biomass production in diverse systems leads to higher potential for capturing and storing carbon.
- Supporting animal communities: Diverse plant communities provide a wider range of food (nectar, pollen) and nesting sites, supporting more abundant and diverse populations of bees, beetles, spiders, and birds.
- Resource specialization: Adding specific plant families can attract specialist animal species that are often absent in urban areas.
- Stable food sources: A variety of species with different flowering times ensures that pollinators have stable and continuous resources throughout the growing season.
- The insurance Effect: Diverse roofs are more resilient to environmental fluctuations; if one species fails during a dry or wet period, others can compensate to maintain functional coverage.
- Resistance to pests and disease: Diversity can reduce the transmission of plant diseases (the dilution effect) and limit outbreaks of specialist herbivores by diluting their preferred food sources.
- Invasion resistance: By more completely filling available niche space and maintaining constant cover, diverse plant communities are better at preventing the colonization of undesirable weed species.
- Psychological benefits: Increasing plant diversity on green roofs enhances their aesthetic value, which contributes to overall human well-being in urban environments.

Although plant diversity is clearly linked to multiple ecosystem services, understanding the mechanisms behind these relationships requires a nuanced approach. Recent literature on green infrastructure, notably the reviews by Ndayambaje et al. (2024) and Liao et al. (2025), frames biodiversity as a multidimensional construct rather than a simple count of species. By distinguishing between structural, trait-based and evolutionary drivers, this multidimensional system clarifies the actual mechanics underlying the ecosystem performance. Unlike approaches based solely on species richness, this framework improves causal inference by mapping specific biodiversity components directly onto ecological functions. In the following sections, these components are examined through three lenses:

- Structural classifications that categorize plant communities based on life forms (e.g., succulents, forbs and grasses) to understand how physical architecture influences environmental adaptation (Liao et al. 2025).
- Trait-based measures that utilize functional diversity to quantify differences in species' morphological and physiological characteristics, which provides a more precise prediction of stress resilience (Ndayambaje et al. 2024).
- Phylogenetic approaches that use evolutionary relationships as a proxy for biological variation, offering a high-resolution perspective on how relatedness influences ecosystem service delivery and resilience (Ndayambaje et al. 2024).

Together, these lenses offer distinct perspectives on how plant communities influence service provision, thereby providing increasing levels of ecological resolution and predictive capacity for sustainable green roof design.

Life form diversity

Among the biodiversity dimensions, life-form diversity represents a commonly used and practically applicable entry point, as it captures broad structural and functional differences between plant groups. The term life form has been shaped by Raunkiær (1934) as a classification of plants based on the location of their perennating buds during unfavourable seasons. Raunkiær's original definition is not commonly used today; however, the term life form remains one of the most frequently applied criteria to classify plants based on structural and morphological characteristics (Liao et al. 2025). In contemporary green roof research, life forms are typically grouped into broad functional categories such as succulents, grasses and forbs, which reflect differences in growth form, resource use and stress tolerance rather than strictly following Raunkiær's original classification (ibid.).

The hypothesis that life-form diversity enhances the provision of ecosystem services is strongly supported by the work of Lundholm et al. (2010). In an experimental study conducted in Halifax, Canada, different vegetation assemblages (monocultures, three life-form mixtures and five life-form mixtures) were compared regarding their ecosystem service performance. The results demonstrated that green roof ecosystem services can be significantly improved by combining diverse structural groups. While individual monocultures may maximize a single ecosystem function, mixtures of multiple life forms consistently performed better across several functions simultaneously. This supports the concept of ecosystem multifunctionality, where the goal is not to optimize a single process but to achieve balanced performance across multiple services.

The study identifies two primary mechanisms explaining the improved performance of mixtures:

- Sampling effect: The increased probability that a community includes a highly productive species which drives overall system performance.
- Transgressive overyielding: Certain mixtures outperform even the best-performing monocultures, indicating that species interactions enhance system-level functioning.

The latter mechanism is commonly attributed to niche complementarity, where species differ in their resource acquisition strategies (e.g., rooting depth, growth timing), allowing more efficient overall resource use without direct competition. However, higher species diversity does not automatically result in improved functionality. Including many species (e.g., all species across five life forms) did not always outperform simpler mixtures. This suggests functional redundancy or dilution effects, where less effective species occupy space without contributing substantially to ecosystem processes (Lundholm et al. 2010). A follow-up study by Lundholm (2015) confirmed the persistence of this 'mixture advantage' over a four-year period.

The longer observation period revealed important temporal dynamics:

- Increasing performance over time, particularly in canopy density and substrate cooling
- Strengthening relationships between species richness and ecosystem services
- Dominance and trait-dependent complementarity became more significant
- A time lag before competitive species became dominant within mixtures

These findings indicate that diversity effects are not static but develop over time as plant communities establish, interact and respond to environmental conditions.

Further evidence for the stability of mixed communities emerges from research comparing monocultures and mixed life forms in a subtropical climate (Chell et al. 2022). Mixed communities showed more stable performance through a 'gap-filling' effect; for instance, grasses provided rapid initial cover while slower-establishing forbs ensured long-term persistence. This temporal complementarity resulted in more consistent vegetation cover and system stability.

High vegetation cover is facilitating essential ecosystem services such as habitat provision and stormwater management (Lönnqvist et al. 2021). Furthermore, a dense canopy protects the roof by shielding it from solar radiation, though its cooling benefits via evapotranspiration are limited if the substrate lacks adequate moisture (Bevilacqua et al. 2015). A study by Butler & Orians (2011) investigated how *Sedum* species can act as nurse plants for other plants. By lowering soil temperatures and facilitating neighbor survival during water deficits, *Sedum* species help maintain the high vegetation cover essential for green roofs. But they can act as a competitor during favorable wet conditions, actually reducing the maximum growth that neighboring species might achieve if grown alone. Thus, while the mixture may slightly lower peak growth, it results in a more stable and persistent cover across varying seasonal conditions

Another key finding of Chell et al. (2022) was that vegetation cover correlated strongly with functional group composition, whereas survival depended more on specific species traits than on group membership. This reveals a key limitation of life-form-based approaches: while they capture broad functional differences, they may overlook critical variation at the species level.

Consequently, while life-form diversity provides a practical and intuitive framework for vegetation design, a more detailed understanding of ecosystem mechanisms requires consideration of plant traits at a finer scale. This is addressed through the concept of functional diversity.

Functional diversity

Rather than grouping plants into broad categories, functional diversity quantifies the range and distribution of functional traits within a community that directly affect ecological processes. Trait-based variety has been identified as a strong predictor of ecosystem service capacity in green roofs. Systems dominated by a single functional strategy, such as succulent *Sedum* species, typically exhibit lower trait richness and support a narrower range of outcomes compared to more diverse plant assemblages (Van Mechelen et al. 2015; Lundholm 2015; Xie et al. 2018). Higher functional diversity is consistently associated with improved ecosystem multifunctionality. This occurs because varying plant traits, such as differences in the timing and depth of resource acquisition, contribute to distinct system dynamics. By enabling communities to utilize available resources more completely, these diverse assemblages can simultaneously enhance stormwater retention, thermal regulation and nutrient uptake while reducing system losses (Lundholm 2015). These dynamics are mediated by variation in plant traits such as rooting depth, leaf morphology or growth rate which determine how plants acquire resources, tolerate stress, and interact with their environment.

However, ecosystem functioning is not solely determined by diversity. The mass-ratio hypothesis states that ecosystem processes are largely governed by the traits of dominant species (Grime 1998). Empirical evidence from green roof systems supports this, showing that these key constituents disproportionately influence functions such as water retention and biomass production (Xie et al. 2018). This aligns with observations from life-form studies, where individual species performance often dictates survival and long-term system dynamics.

In this context, life-form diversity can be understood as a simplified entry point for achieving functional diversity, while trait-based variety allows for more precise optimization of ecosystem services. Overall, functional diversity refines and extends the life-form concept by providing a quantitative and mechanistic basis for plant selection, forming an important component of a trait-based framework for green roof design.

Phylogenetic diversity

Trait information can be difficult to obtain, functional differences may be complex to quantify, and selected traits may not adequately capture ecologically relevant variation. In such cases, phylogenetic diversity serves as a comprehensive proxy (Ndayambaje et al. 2024). By incorporating evolutionary relationships, this metric reflects the range of ecological strategies present within a community without requiring detailed trait data. Rather than measuring biodiversity solely via species number, phylogenetic diversity quantifies the total evolutionary history represented in a community by summing the branch lengths connecting species in a phylogenetic tree (Faith 1992). Consequently, it provides a synthetic way to represent the trait differences that underpin the processes described in previous chapters.

Higher phylogenetic diversity is generally associated with enhanced service provision. Greater evolutionary divergence increases the likelihood of differences in resource-use strategies; as distantly related species are less likely to occupy identical niches, communities often exhibit increased complementarity and more efficient partitioning of water, nutrients, and space (MacIvor et al. 2018; Xie et al. 2018). These interactions can increase productivity and system stability. For example, phylogenetically diverse communities have been shown to produce greater biomass (Cadotte 2013), which can enhance evapotranspiration as a key mechanism for thermal regulation (MacIvor et al. 2018).

In summary, phylogenetic diversity captures functional differences through an evolutionary lens. While dominant species traits remain influential, as highlighted by the mass-ratio hypothesis, this perspective offers a vital alternative to trait-based models, particularly when data are incomplete or difficult to apply.

3.2 Structural layout of green roofs

3.2.1 Substrate

Substrate characteristics are fundamental drivers of biodiversity on extensive green roofs, directly influencing plant community structure and long-term ecosystem outcomes (Thuring & Grant 2016). The physical and chemical properties of the media act as the primary abiotic filter, governing which species can establish and persist in the harsh rooftop environment.

Depth is a critical determinant of community composition as it modulates abiotic stress by defining the volume of resources available to the root zone (ibid.). Shallow substrates typically favour drought-tolerant succulents, such as *Sedum* species, but often result in lower total biomass and restricted species richness due to limited moisture and nutrient reserves (ibid.). Conversely, deeper profiles provide expanded rooting volume and greater water-holding capacity, supporting a more diverse array of functional groups and taller vegetation forms (Van Der Kolk et al. 2023). Beyond resource retention, depth provides essential thermal buffering; deeper media reduce temperature extremes at the root level and improve plant water status, which stabilizes community dynamics over time (Brown & Lundholm 2015; Ganthaler et al. 2025).

Finally, plant–microbe interactions are intricately linked to these substrate properties. Extensive green roof media host specialized, stress-tolerant microbial taxa essential for nutrient cycling and plant resilience. These microbial assemblages are closely correlated with the specific plant communities present, suggesting a feedback loop where substrate characteristics shape the microbiome, which in turn influences plant vigour and the successional trajectory (Van Dijck et al. 2024). In conclusion, substrate depth and composition define the physiological baseline for the roof, serving as the foundation upon which more complex community structures are built.

3.2.2 Spatial heterogeneity

While Section 3.2.1 establishes the foundational role of substrate and profile depth, ecological theory predicts that the spatial arrangement of these environmental variables, known as environmental heterogeneity, is what ultimately promotes high species richness by increasing niche availability and reducing competitive exclusion (Stein et al. 2014). The relationship between heterogeneity and richness is moderated by the area-heterogeneity trade off. This principle posits that increasing spatial variance within a fixed, finite area reduces the ‘effective area’ available to any individual species. This fragmentation can lead to smaller population sizes, elevating the risk of stochastic extinction (Allouche et al. 2012; Bar-Massada 2015). Consequently, the heterogeneity-richness relationship on green roofs may be unimodal, with biodiversity peaking at intermediate levels of variability before declining as niches become too small to sustain viable populations.

Spatial heterogeneity arises from a mosaic of interacting abiotic and biotic factors:

- Substrate gradients: Variation in media depth creates microhabitats that support species with contrasting rooting strategies and moisture requirements, facilitating coexistence (Lundholm et al. 2020; Ganthaler et al. 2025).
- Microclimate gradients: Within-roof variation in solar exposure, wind and shading from adjacent structures generates distinct thermal and moisture regimes. For example, shaded patches have been shown to maintain significantly lower temperatures and higher moisture (7–26% volumetric content), improving survival for species that would otherwise perish in fully exposed zones (Buckland-Nicks et al. 2016).
- Vegetation structure: Diversity in plant growth forms (e.g., succulents, grasses and forbs) introduces biotic structural complexity, which further modifies light penetration and local humidity (Cook-Patton & Bauerle 2012).

The ecological outcome of this arrangement is highly dependent on the scale of the species arrangement (Lundholm 2017):

- Fine scale mixtures: Closely intermixed species tend to maximize plant productivity and ecosystem functions through niche complementarity and facilitation.
- Coarse scale mixtures: Arranging species into distinct monospecific patches increases habitat diversity across the roof (ibid.).

While increased heterogeneity often correlates with niche diversity, its benefits are context dependent. In small systems, the trade-offs of habitat fragmentation limit the development of more complex biological communities, suggesting that the success of heterogeneous designs depends heavily on the specific configuration and total area of the roof environment.

3.3 Aesthetic preferences in green roofs

The successful implementation of innovative urban vegetation requires an understanding of public preconceptions and the specific design features that drive visual preference and restorative potential (Fernandez-Cañero et al. 2013; Lee et al. 2014).

A functional trait approach offers a mechanistic framework for understanding how specific plant characteristics generate cultural ecosystem services like recreational values (Goodness et al. 2016). Effect traits, such as plant size, morphology and growth form, directly impact human perception and aesthetic evaluation (ibid.). Research in urban streetscapes suggests that visual preference often increases with structural complexity; for example, multi-layered vegetation is consistently preferred over simpler or more open arrangements (Babington et al. 2023).

The structural composition of green roof vegetation significantly influences public acceptance. Studies indicate a preference for taller, grassy life-forms over low-growing succulents or standard turf lawns (Lee et al. 2014). In fact, on living roofs, vegetation height acts as a critical predictor of preference, persons with a strong emotional connection to nature tend to distinguish more clearly between taller, naturalistic vegetation and lower-growing varieties, often associating the former with higher ecological function (ibid.).

Beyond physical structure, visual aesthetic quality is largely driven by the colour palette and the presence of flowers. Green and white hues consistently score higher for attractiveness and relaxation, whereas high proportions of red or brown foliage correlate with lower preference (Thorpert et al. 2024). Flowering improves preferences across all structural types (Lee et al. 2014). Acting as powerful 'effect traits,' flowers directly enhances the cultural services (Goodness et al. 2016).

The perceived maintenance of green roofs is vital for their acceptance. Using discrete choice experiments, Vanstockem et al. (2018) demonstrated that vegetation gaps (bare substrate) represent the single most significant deterrent to positive public perception, often outweighing cost as a primary concern for stakeholders. Systems that appear 'untidy' or dominated by conspicuous weedy species are often rated poorly. Interestingly, the presence of moss does not appear to negatively impact choice behaviour on extensive green roofs, suggesting a higher tolerance for 'spontaneous' elements when contributing to a full-cover appearance (ibid.).

Green roof vegetation is not static; its visual attributes change dynamically across seasons and successional stages. Public preference varies seasonally, with summer and autumn often receiving higher ratings than winter due to changes in foliage colour and bloom presence (Thorpert et al. 2024). Successional age also influences perception: older, established systems, which may feature a greater variety of spontaneous species and a near-complete moss layer, can generate higher aesthetic values than newly established, uniform plantings (Vanstockem et al. 2018). Effective management must therefore accommodate these temporal dynamics to maintain visual interest year-round.

3.4 (Sub)-shrubs in green roofs

Potential and limitations of shrubs on vegetated roofs

Shrubs are commonly defined as woody, perennial plants characterized by multiple stems arising from or near the base, lacking a single dominant trunk, and typically not exceeding 3 to 5 meters in height (Jansen & Di Gregorio 2000). While this structural definition effectively distinguishes shrubs from single-stemmed trees and non-woody herbaceous vegetation, it only partially captures the ecological nuances of woody growth forms. A more functional approach is found in the life-form classification system developed by Raunkiær (1934), which categorizes plants based on the position of their perennating buds. Under this system, taller shrubs and trees are typically classified as phanerophytes (buds located well above ground), while sub-shrubs are classified as chamaephytes (buds situated close to the ground). In the context of green roof systems, these distinctions are particularly relevant: shrubs and especially subshrubs (also chamaephytes or dwarf shrubs) represent a feasible intermediate growth form between low-growing herbaceous mats and larger woody trees, offering unique contributions to vertical complexity and ecological functionality.

Despite their potential, the inclusion of shrubs in green roof plant selection has been historically limited. According to Savi et al. (2016), species screening has predominantly focused on ecological or morpho-anatomical approaches favouring succulents and herbaceous species. This represents a significant missed opportunity, as for instance specific shrubs possess superior ecophysiological adaptations. E.g., woody plants generally exhibit a higher capacity for stomatal control over transpiration compared to herbaceous plants (Galmés et al. 2007; Farrell et al. 2013 see Savi et al. 2016). Consequently, shifting toward an ecophysiological selection process, one that rigorously quantifies functional traits enabling plants to cope with severe drought and high temperatures, is essential for optimizing species assemblages on Mediterranean green roofs (Savi et al. 2016).

The primary limitation restricting the use of taller vegetation like shrubs and trees is the assumption that their substrate depth requirements are physically incompatible with extensive green roofs. The depth of the growing medium governs both the ecological performance and the engineering feasibility of the system. While increasing substrate depth improves vegetation growth, biodiversity potential and water retention by providing greater nutrient storage and rooting space (Durhman et al. 2007; Getter & Rowe 2009; Eksi & Rowe 2019), it also substantially increases the dead load applied to the building. Deeper, water-saturated substrates require buildings to have higher static load-bearing capacities or costly reinforcement measures (Berardi et al. 2014; Cascone 2019).

To navigate these structural constraints, Papafotiou et al. (2013) evaluated the viability of three Mediterranean shrubs by comparing their performance in shallow 7.5 cm and deeper

15 cm substrates. All three species established successfully and survived in both depths, with the deeper profile generally promoting more robust growth in terms of height, diameter, and dry weight. However, plants in the 7.5 cm profile performed remarkably well when amended with compost, often matching or exceeding the vitality of plants in deeper peat-based substrate.

Studies of this nature are vital for determining whether certain drought-adapted shrubs can be harnessed without exceeding the weight limits of extensive or semi-intensive roof profiles. Ultimately, integrating shrubs into green roofs could offer substantial ecological rewards. Whereas the assumption of higher demands on the profile depth could be misleading as studies as those from Papafotiou et al. (2013) show that some species can also thrive in shallower profiles with the right conditions.

3.4.1 Facilitation effects

This dichotomy, balancing structural load feasibility against the profound ecological benefits of more complex vegetation, remains a central challenge that will be explored further in this chapter through a review of ecological literature.

Drawing from ecological theories of natural open habitats, shrubs frequently act as 'nurse plants' (Pihlgren & Lennartsson 2008; Eldridge et al. 2011; Oksuz et al. 2020; Lopes et al. 2023; Hou et al. 2025; Kettermann et al. 2025). In Mediterranean and semiarid environments they facilitate the establishment and survival of companion species by creating favorable microhabitats, or 'regeneration niches' (Castro et al. 2002; Gómez-Aparicio et al. 2005). This facilitation occurs through several interrelated above-ground and below-ground mechanisms:

- Microclimate amelioration or canopy effect: Shrub canopies provide shade that protects understory species from high irradiance and extreme temperatures. This reduces the atmospheric evapotranspiration demand, improving the water status of seedlings and reducing summer mortality caused by drought (Castro et al. 2002; Gómez-Aparicio et al. 2005).
- Soil property modification: Shrubs improve soil conditions by accumulating litterfall, which increases organic matter and accelerates nutrient cycling (Castro et al. 2002; Gómez-Aparicio et al. 2005). Notably, pioneer shrubs have been shown to significantly increase available potassium in the soil, which can improve the water-use efficiency and drought resistance of associated plants (Gómez-Aparicio et al. 2005).
- Protection: In winter, shrub cover acts as a buffer against frost and desiccating winds (Castro et al. 2002).

The facilitative role of shrubs is applicable to green roof environments, which often show similarities to the harsh, drought-prone and exposed conditions of Mediterranean habitats. On a green roof, incorporating shrubs could create regeneration niches for more sensitive herbaceous or flowering species that might otherwise fail in bare substrate (Castro et al. 2002). Selecting specific shrubs for green roofs could provide micro-climatic benefits to the surrounding vegetation without outcompeting them for moisture.

3.4.2 Garrigue shrubs

Synthesizing the findings of several studies on Mediterranean vegetation, with a particular focus on chamaephytes (subshrubs, this section explores the balance between their significant ecological enhancements and distinct physical limitations.

The use of Mediterranean garrigue species, including low-growing shrubs, aromatic perennials, and therophytes (annuals), represents a resilient and biodiverse alternative to traditional *Sedum* monocultures for extensive green roofs in arid and semi-arid regions (Van Mechelen et al. 2014a; Bellini et al. 2025). Their primary advantages include superior thermal regulation, with denser canopies providing enhanced substrate shading and evaporative cooling that can reduce ceiling temperatures by up to 4.4°C compared to conventional roofing (Giorgioni & Grandi 2021; Bellini et al. 2025). Furthermore, these assemblages enhance ecosystem services such as stormwater retention, often outperforming succulents during rainy seasons, and support urban biodiversity by providing resources for indigenous pollinators (Papafotiou et al. 2013; Van Mechelen et al. 2014a; Bellini et al. 2024).

To manage harsh microclimatic conditions, garrigue species utilize specialized morpho-physiological strategies. Morphological adaptations include silvery pubescent trichomes that reflect solar radiation to reduce leaf temperatures and 'cushion' growth that minimize water loss while capturing air pollutants (Giorgioni & Grandi 2021; Bellini et al. 2025). Physiologically, these species exhibit diverse hydraulic strategies: isohydric species (e.g. *Arbutus unedo*) strictly limit stomatal conductance to maintain stable leaf water potential, whereas anisohydric species (e.g. *Salvia officinalis*) tolerate significant drops in water potential to maximize carbon gain (Raimondo et al. 2014).

Consequently, isohydric plants are ideal for drought-resistant, low-irrigation green roofs (Rowe et al. 2014, cited in Raimondo et al. 2014). Conversely, anisohydric species that upkeep photoynthetic activity while enduring very low water potential values are better suited for maximizing evaporative cooling (Schweitzer and Erell 2014, cited in Raimondo et al. 2014) and stormwater interception during heavy rain (Nardini et al. 2012, cited in Raimondo et al. 2014).

Despite these benefits, several constraints limit their implementation. The most critical factor is substrate depth; shallow systems (<10 cm) significantly increase mortality rates because extreme substrate temperatures (frequently exceeding 42 °C) pose a greater threat to root membrane stability than drought itself (Savi et al. 2016). Many species also exhibit slow initial colonization rates, which may leave the substrate vulnerable to weed invasion or erosion during establishment, often necessitating emergency irrigation during the first two years (Benvenuti & Bacci 2010; Papafotiou et al. 2013; Giorgioni & Grandi 2021).

Beyond the summer extremes that dictate survival within Mediterranean climates, the winter survival of these species outside their native range is a major concern. While various factors affect plant distribution, the northerly limits of plants from Mediterranean origins are primarily determined by low winter temperatures (Larcher 2005). Successful survival outside their native range relies on a complex interaction between achieving sufficient mid-winter cold hardiness and the appropriate timing of cold acclimation (Pagter and Arora 2013). Specifically, survival requires a successful transition to winter dormancy before the onset of extreme cold (Larcher 2005). If plants are caught in sensitive, unhardened phases by episodic frosts, they fail to undergo proper hardening and can suffer severe damage even at moderate sub-zero temperatures (Larcher 2005).

Besides frost considerations, garrigue plants are also traditionally considered intolerant of waterlogging (King et al. 2012). This reputation for waterlogging intolerance stems from their natural development in lithic, inclined environments that facilitate rapid drainage (ibid.). Despite this reputation, empirical research by King et al. (ibid.) demonstrates that species such as *Stachys byzantina, Lavandula angustifolia, Salvia officinalis* and *Cistus × hybridus* are remarkably resilient, achieving 100% survival during 17-day winter flooding events with performance levels comparable to some wetland species. This resilience is supported by adaptive rooting, such as the surface and adventitious 'aerial' roots observed in *Salvia* and physiological cross-adaptation, where xerophytic traits like rapid stomatal closure help plants manage the 'physiological drought' caused by anaerobic soil (ibid.). The researchers suggest that the poor survival rates cited in garden literature for plants in wet soils might not be due to the water itself, but to other factors common in heavy or non-mineral soils, such as:

- Fungal pathogens like *Phytophthora*, or
- Low irradiance and high relative humidity associated with wet winter climates.

The study concludes that before making final recommendations for urban landscapes in north-west Europe, more research is needed on the effects of substrate depth and structure on long-term performance.

While their publication focusses on general urban landscape plantings, green roofs exhibit substantially different conditions than ground-level habitats. The artificial architecture of a green roof presents unique hydraulic challenges, as impermeable waterproofing membranes frequently induce a 'perched water table' (Rowe 2025). When combined with organic-rich media, this prolonged water stagnation suffocates roots and leads to rapid, fatal fungal decay (Zhang et al. 2024; Bodley et al. 2022; Kumar et al. 2025). Furthermore, high organic content is ecologically counterproductive for stress-adapted plants, as it promotes lush vegetative growth that is ultimately less tolerant of drought and pests (Ampim et al. 2010). Therefore, to successfully support mineral-adapted garrigue species, the physical profile must rely on two distinct structural layers. First, the growing medium itself must guarantee rapid vertical percolation by utilizing highly porous inorganic aggregates like pumice (FLL 2018) and strictly limiting organic matter to standard thresholds of 10–20% (Ampim et al. 2010; Bodley et al. 2022). Second, to balance this intense drainage with summer drought resilience, the system must incorporate a dedicated water-retention layer at the very base of the profile. This structural separation ensures that roots do not sit in saturated soil during winter, while safely storing a reserve of moisture below the root zone to sustain the plants during extreme summer heat (Rowe 2025).

Parallel to the flooding tolerance, another constraint on the use of garrigue plants in Central and Northern European contexts is the frost tolerance. While scientific studies outside of the native context regarding the frost tolerance of these plants are lacking, experiences from garden culture might provide some information regarding this. The book 'Bringing the Mediterranean into your garden : how to capture the natural beauty of the garrigue' by Olivier Filippi (2019) connects increased frost tolerance of Garrigue plants in colder climates primarily to a well-drained soil. He mentions extensive plant collections in the United Kingdom or the Netherlands, which all show this crucial soil characteristic for growing typical Garrigue genera like *Cistus, Euphorbia, Lavandula, Oregano, Salvia* or *Thymus*. Filippi (ibid.) exemplifies the frost tolerance strategies by showing the convergence to the morphological drought tolerance adaptations. Sclerophylly, tomentose leaves or reduced leaf sizes help to minimize the hydric deficit caused by drought in summer or frost in winter. Compact ball- or cushion shapes keep the plants close to the slightly less cold ground and enhances facilitation between plants to shelter each other from cold winds. Physiological adaptations include the concentration of essential oils, which protect plant tissues from fungal pathogens that thrive in damp, cold conditions. Furthermore, physiological strategies include similar mechanisms to boreal or alpine plants to withstand the formation of ice crystals within their cells. Beyond morphological traits, these plants employ biochemical defences to survive sub-zero temperatures. To prevent intracellular ice formation, they undergo a comprehensive metabolic reconfiguration. This includes the accumulation of cryoprotectant osmolytes, primarily soluble carbohydrates, which lower the freezing point of cellular fluids. Simultaneously, the plants alter their membrane lipid composition to maintain essential fluidity at low temperatures and produce dehydrin proteins to protect cellular structures from freeze-induced desiccation (ibid.). In specific tissues, these combined mechanisms allow the plant to resist ice formation through deep supercooling, potentially reaching the physical limit of approximately -39°C (Larcher 2003).

Adaptations like this are not represented in every Mediterranean plant. Filippi (2019) as well as a scientific research on *Thymus vulgaris* in natural habitats in France confirm the dependence on local evolutionary adaptation to frost. The study by Thompson et al. (2007) shows that frost tolerance in thyme is not a universal trait of the species but is dependent on the evolutionary history of a population, which dictates whether the local chemotype has developed the physiological adaptations and acclimation timing necessary to survive local winter extremes.

4. Case study and reference landscapes

Designing with Mediterranean garrigue vegetation outside its native range offers a potential strategy for climate-adapted landscape architecture, though it introduces inherent complexities. A primary challenge in these novel environments involves mitigating unfamiliar environmental stressors, particularly frost and winter moisture. Beyond establishing initial survival, the long-term performance of these plantings is highly context-dependent. How these systems develop relies on site-specific variables, including engineered substrate composition, microclimate fluctuations and adaptive management. Furthermore, predicting how multi-species assemblages will interact, compete and evolve as a community over time is difficult to model in theory alone. Therefore, observing a built, operational project offers a direct method to evaluate these intricate dynamics. By utilizing a case study approach, this research aims to capture the real-world performance, ecological interactions and maintenance realities of a Mediterranean plant community.

To address these knowledge gaps, this chapter examines two types of garrigue-like vegetation in one built and several natural environments. Recognizing that authentic Mediterranean ecosystems cannot and should not be directly replicated in temperate climates, this research anticipates the emergence of novel mixed systems compiled of various plant communities. Therefore, the focus shifts toward the use of functional analogues, prioritizing key ecological and structural traits such as drought and heat tolerance or structural diversity. The investigation evaluates these principles in a real-world case study: a semi-extensive, low-tech green roof trial in Erfurt, Germany.

In the following, this chapter operates on two complementary methodological levels to fully capture the properties of the case study site and the reference landscapes.

First, a technical and ecological analysis assesses site data, including vegetation composition, substrate depth, maintenance regimes and long-term performance metrics such as plant turnover or failure as well as a qualitative reflection on design goals and a speculation on the perception of the designed plant community focussing on aesthetical parameters.

Second, a spatial and atmospheric analysis examines how garrigue plant communities show structural rhythm, seasonality, a spatial interplay of species and further characteristics. To capture spatial and sensory qualities that elude conventional quantitative metrics, a design-led atmospheric interpretation is conducted within the natural reference habitats. Capturing these traits with on-site photographs acts as a spatial research tool to abstract and interpret essential traits like density or layering.

Ultimately, this comparative framework integrates design intent with actual ecological development, bridging the disciplines of ecology and landscape architecture. By capturing the realities of spatial heterogeneity, characteristic components and long-term maintenance needs, the analysis moves beyond the limitations of short-term experimental plots. Findings synthesized from both designed plant communities and natural habitats are subsequently extracted and translated into actionable design principles in the next chapter.

Green roof trial in Erfurt

A semi-extensive low-tech green roof trial to test out the general suitability of Garrigue vegetation in a temperate, slightly continentally influenced climate. Focus on species selection, maintenance regime, hardiness, substrate, vitality and aesthetics.

Figure 4: location of the case study in erfurt
Map base : european commission, eurostat, n.d.

Figure 5: green roof trial in erfurt, germany
Source: jonas reif (2026)

4.1 A low-tech trial

4.1.1 Site context

An experimental trial roof of ca. 75m² on the campus of the University of Applied Sciences in Erfurt (FHE) consitutes the first case study. This chapter is a characterization of layout, design objectives and approach while establishing the green roof. The location of the case study was chosen as a consequence of the authors previous education, with the experimental plot being established as part of the author's bachelor's thesis (Scharnweber 2024). This chapter is derived from information based on this previous thesis (ibid.) .

Climatic conditions

Erfurt, located in eastern Germany, has a temperate climate with warm summers and no dry season in the Köppen-Geigen zone Cfb (Beck et al. 2023). The climate in Erfurt is slighty continentally influenced with summer temperatures in the short term past reaching up to 37 °C (20/07/2022) and winter down to -22°C (29/12/1996). The trial bed is located on west facing ground-level roof on the campus of the FHE, sequentially the wind exposition is lower than on regular green roofs. But sun exposition and thermal reflection of a facade creates irradiance and therefore climatic extremes similar to regular rooftops.

Substrate

The substrate is a specialized tree substrate characterized by its porous, reddish-brown composition of crushed natural stone, recycled brick fragments, and organic fibers. Optimized for urban vegetation, the substrate features a 0/32 grain size and a rough, edge-rounded mineral structure. Technically, the substrate achieves a critical ecological balance between drainage, moisture retention and aeration, maintaining a vital air capacity of 12.9 Vol.-% even at its maximum water capacity of 29.9 Vol.-%, supported by a permeability coefficient of 1.7×10−4 m/s. These properties, coupled with a neutral pH of 7.0 and a low organic substance content of 2.6%, create a stable mineral environment. Before the planting of the garrigue trial, the roof was vegetated by a *Sedum album* monoculture on a coarse mineral gravel substrate. Displaying the low tech character of the trial, the new substrate was simply accumulated on top of the existing substrate. The idea was to create a two-layered profile with a 'vegetation' substrate on top of a coarse drainage layer (see Figure 6). Profile depth of the substrates vary slightly on the roof. The front part of the vegetation grows in 7cm new substrate on top of 8cm drainage layer. The parts closer to the facade have 15cm tree substrate on 5cm drainage layer. Therefore a minimal variation of substrate depth was created in order to be able to host different plant types.

Planting

Vegetation of the roof was planted in early November 2023 with 62 perennial species, mostly from Mediterranean regions. Acquired from two different plant nurseries in Germany and Austria, they were planted in 0.5l pots. Plants were ordered with at least 2 individuals to allow a substantiated analysis of the management regime.

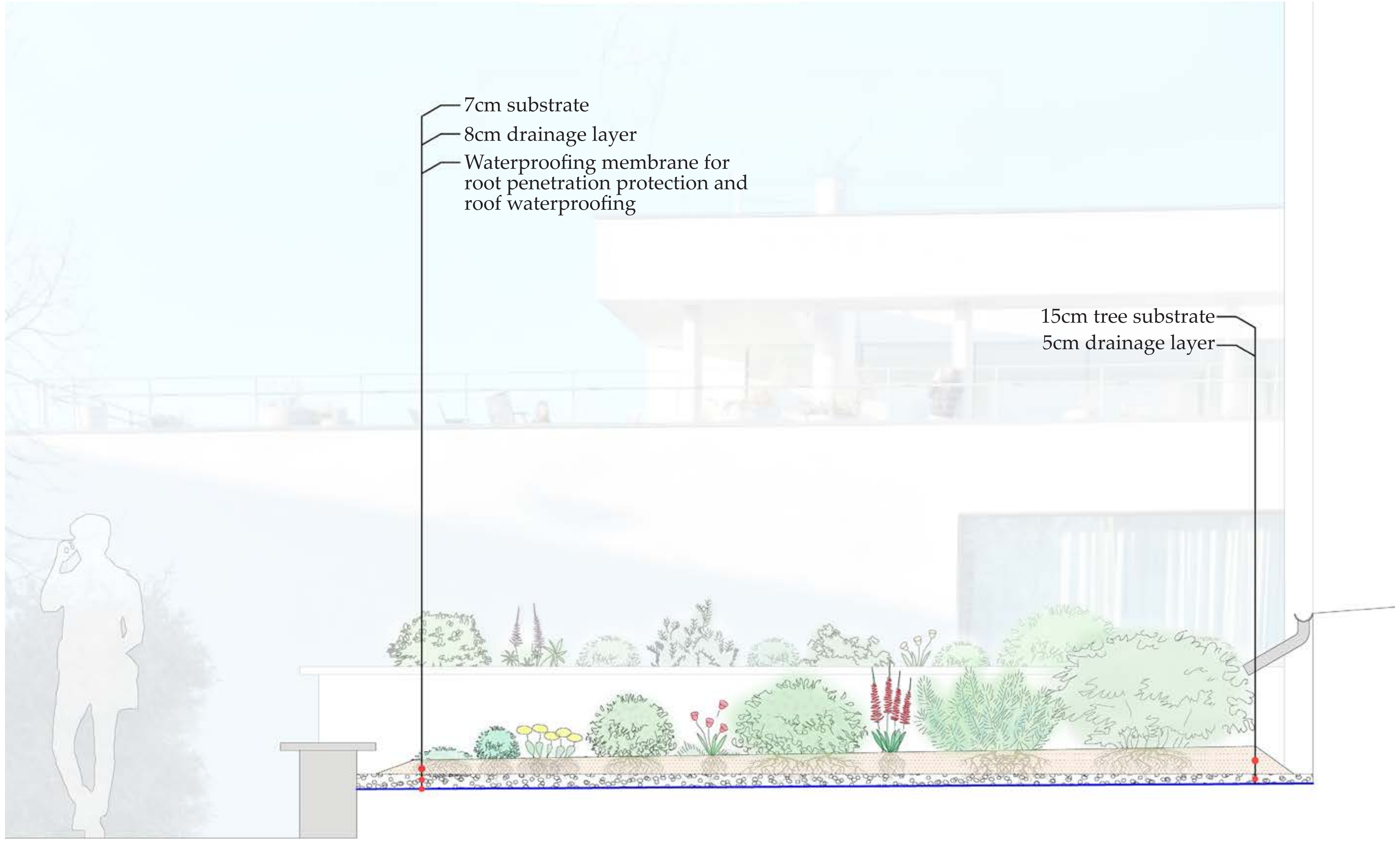


Figure 6: Profile section of the trial bed
Source: edited by author based on scharnweber (2024).

Plant selection

The concept of the plant selection was based on resembling the vegetation of Mediterranean garrigue landscapes. The species pool was expanded with species from other regions and ecosystems that match the visual habitus of the intended vegetation type. Selecting these plants was mostly based on a habitus with grey or blue foliage, tiny or needle-like leaves and most importantly the compact cushion-like architecture. The rationale to expand the species pool to other regions (e.g. *Eriogonum* from North America) was to enhance the phenological attributes of the planting. Plants from Mediterranean shrub ecosystems mostly concentrate their bloom in spring before the drought period starts (Petanidouet al. 1995). A filtering factor was the availability of plants in plant nurseries as the selection of Mediterranean plants could still be limited by constraints regarding their limited frost tolerance (Larcher 2000).

Adjacent ground level beds provided a hardy species pool from garrigue habitats. In the A selection of those plants were dug out to carry out an analysis of their rooting type. Most of the plants had dense fibrous rooting systems. Considerations of the rooting type of the plants also supported excluding of plants with taproots (e.g. *Euphorbia* species). This was due to the assumption that their drought avoiding mechanism of deep rooting may not be suitable for shallow growing media.

Figure 7: compact root system of *santolina chamaecyparissus*
Source: author

Maintenance

One point of interest already in the conception of the trial bed was the division of the roof in varying maintenance regimes. One half is trimmed twice a year in spring and autumn, whereas the other part is only trimmed once a year in spring. Imitating the grazing regimes of many garrigue landscapes this should investigate an optimal maintenance regime to create compact and healthy plants that authentically display a similar aesthetical character to the plants in their nature habitat.

4.1.2 Discussing the development

In the following section the two and a half years of observing the development of the vegetation brings particular aspects to discuss and conclude. Observations reflect reoccurring site visits of the author and analysis of photographs over this time period. Findings are therefore an addition to the findings of the previous publication of the author (Scharnweber 2024) and are based on observation after the completion of this initiative project. The area was not set up as a perfect scientific experiment, rather as a low-tech approach to test boundaries of the vegetation type in a colder climate zone. Consequently the analysis is focussed on a limited number of qualitative aspects and rather with a horticultural lens.

Vitality and habitus

The late planting in November lead to a high mortality in the first winter with a loss of 81 individuals with 69 of the originally 150 plants surviving. Starting with 62 species in total, the plant community was reduced to 27 species in this first cold period. The losses were mostly concentrated on species whose frost tolerance was expected to be at the limit. The next two winters did not lead to an increased loss of plants, which demonstrates the general resilience towards cold temperatures considering temperatures as low as -15° C in these winters (Daily minimum air temperature at ground level in Erfurt, Deutscher Wetterdienst 2026).

In regards of growth structure and visual aesthetics of the individuals the vegetation has developed as expected with a compact and low habitus. The plants show their natural, cushion-like growth (see Figure 8) developed through stress exposition and the repeated trimming as a light disturbance regime. The difference of trimming regimes leads only to minor differences in growth habitus. As a consequence to the limited soil profile the plants grow lower and their development is slower than in comparable ground level plantings. The drought tolerance as the main design rationale for species selection is as good as expected considering the vegetation thrived throughout 2 summers without any signs of drought damage.

Figure 8: *teucrium flavum* in the double-trim cluster, after trim in spring 2026
Source: author

Figure 9: *teucrium flavum* in the single-trim cluster, after trim in spring 2026
slighty more loose habitus. Source: author

Self-seeding and succession

Most of the species thrive in the roof setting, some even self seed into the mineral substrate (see Figure 10). This could lead to a stronger ground covering percentage of the vegetation, potentially benefitting ecosystem services and fitness of the whole population. With splitting up of the area into two separate management regimes, the vegetation also reacts and develops slightly different to varying levels of disturbance. The double-trim side (Figure 12 on the right) shows a large abundance of bare soil with neatly shaped and compact cushions. On the other side the single-trim regime lead to a bit wider canopies, a more loose habitus. Also the self seeding on the single-trim regime seems to be explicitly strong. Suspectedly the outlets of 2 drainage pipes lead to higher soil moisture and a nutrient accumulation in the corner as also fertility indicator plants are found there. Following this observation the effect of the management regime might not be too significant. Nevertheless an absent trimming in late summer to autumn is suspected to enable a stronger self-seeding as seed heads can stay longer on the plants to ripen and the seeds have a longer period to be dispersed into the substrate. The maintenance team also carried out occasional weeding throughout the areas, thereby preventing the establishment of spontaneous vegetation.

Figure 10: self seeding of *hyssopus officinalis* and *teucrium chamaedrys* in the foreground, ysop is listed in the invasive plant list in sweden *(slu artdatabanken 2025)*. Source: author

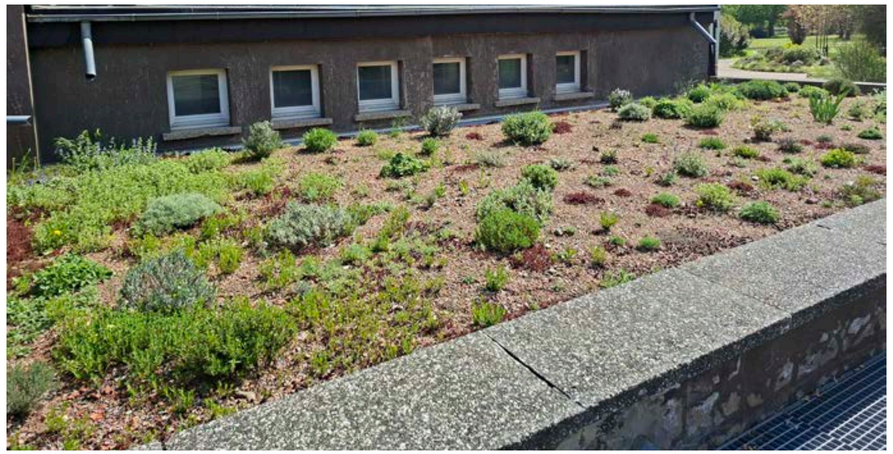


Figure 11: separation of trimming management regimes, on the left twice a year in spring & autumn, right side once a year in spring. Source: author

Aesthetics and vegetation cover

As most of the species are evergreen the vegetation is also providing structure in winter which potentially improves aesthetic values all year round.

Flowering resources of the vegetation are mostly concentrated into spring and early summer. Lacking resources in other periods of the vegetation period could be unfavourable for wildlife, e.g. arthropods. This aspect is mitigated by the addition of species from other regions that extend the flowering period. Actions like this could be an inspiration for other projects to increase resources for wildlife in green roofs.

While a majority of the plants developed well in regards of their individual appearance, for instance do most plants show their natural habitus and show a good drought tolerance as well as other crucial functional traits like flower phenology, the trial still lacks some base characteristics of a functional green roof vegetation. Experimenting with the hardiness of Mediterranean subshrubs plants put a strong emphasis on this life form. Whereas their benefits and functions are an interesting addition to green roofs (see Section 3.4.2), the ground cover or canopy cover of the total vegetation is quite low. As the green roof vegetation is still in an early stage of development and plants show some favourable reproduction tendencies, the cover will presumably increase in the future. But a ground cover as low as seen in the current stage could result in heat induced mortality as studies have shown that a higher ground cover e.g. by *Sedum* species can reduce peak soil temperatures (Butler & Orians 2011). Additionally could the low ground cover potentially lead to increased soil erosion, invasion by unwanted plants (Cascone 2019:11) or worse perceived aesthetic by the public (Vanstockem et al. 2018:9). Therefore the weeding as a management action could be reflected and adjusted in the future. It also illustrates the dilemma of balancing tidy aesthetics with naturalistic visuals in representational areas.

Figure 12: a lot of flowering throughout spring and early summer, here in may 2025. Source: jonas reif (2025)

Futhermore could a wider variety of vegetation lead to a higher degree of canopy cover, especially the *Sedum album* that previously covered the managed to push through the newly applied substrate and started to colonize the area from the edges. This shows how other life forms could lead to a more coherent greening as most subshrubs do not spread vegetatively.

Species

A list of species from this trial is later used in this thesis as a part of the species pool for plant selection. The extracted species are primarily the ones that actually grow in garrigue habitats or in similar habitats around southern Europe and show the typical characteristics with narrow leaves, silvery tomentose foliage or aromatic properties with the containing of essential oils.

4.2 Reference landscapes

Various natural sites serve as references for analyzing the atmospheric qualities of garrigue vegetation. Rather than serving as exact models to be copied identically, these sites highlight unique atmospheric and structural qualities. Aspects like this are These qualities are then simplified and translated into a design language to adapt specific characteristics. In the following paragraphs base definitions and general features will be outlined to grasp an understanding of formation processes, geographical distribution and common environmental influences of this vegetation type.

4.2.1 What is the garrigue?

Following universal features of garrigue habitats are derived from factsheets of the European Environment Agency (EEA 2021) Garrigue habitats are primarily characterized as open, low scrub vegetation. They are typically dominated by xerophytic (drought adapted) sub-shrubs and low trees.

Location

The garrigue as a Mediterranean ecosystem is largely influenced by harsh climate conditions, primarily the hot and dry summers. Drought periods in these clinate zone often last throughout the whole summer. Their length ranges from 3 months in the western to rather 6 months in the eastern Mediterranean basin caused by a gradient of continentally influenced climate.

Soil characteristics

Garrigues typically occur on shallow, thin, or eroded soils that have limited water-holding capacity. While they share shallow soils, the specific bedrock varies by type:

- Basiphilous and Supramediterranean garrigues occur on base-rich/alkaline rocks like limestone or dolomite
- Acidophilous garrigues are found on acidic, silicate-derived soils or dune sands

Vegetation characteristics

Shrubs from the *Lamiaceae, Fabaceae* and *Cistaceae* families are frequent dominants across different types. The vegetation often includes cushion-shaped plants, mats, tufted perennial grasses, and various herbs. Many of these plants are R-strategists (pioneer species) and pyrophytes (fire-prone), adapted to thrive in disturbed environments. Garrigue habitats also exhibit a significant floristic diversity across their ranges.

Succession

In most instances, garrigue is a seral or secondary vegetation stage. These plant communities typically replace degraded evergreen forests or woodlands (with e.g. *Quercus* or *Juniperus*) following human-induced disturbances like fire, grazing, or the clearing of land for agriculture. They are maintained by ongoing low-intensity disturbances, including traditional sheepherding, periodic burning, and long fallow periods in agricultural cycles. Without these disturbances, most garrigue habitats naturally undergo ecological succession, eventually progressing toward pre-forest and forest communities. They may only form stable, permanent climax vegetation on specific sites like rocky outcrops, crests, or in semi-arid regions where soil conditions are too poor to support taller trees.

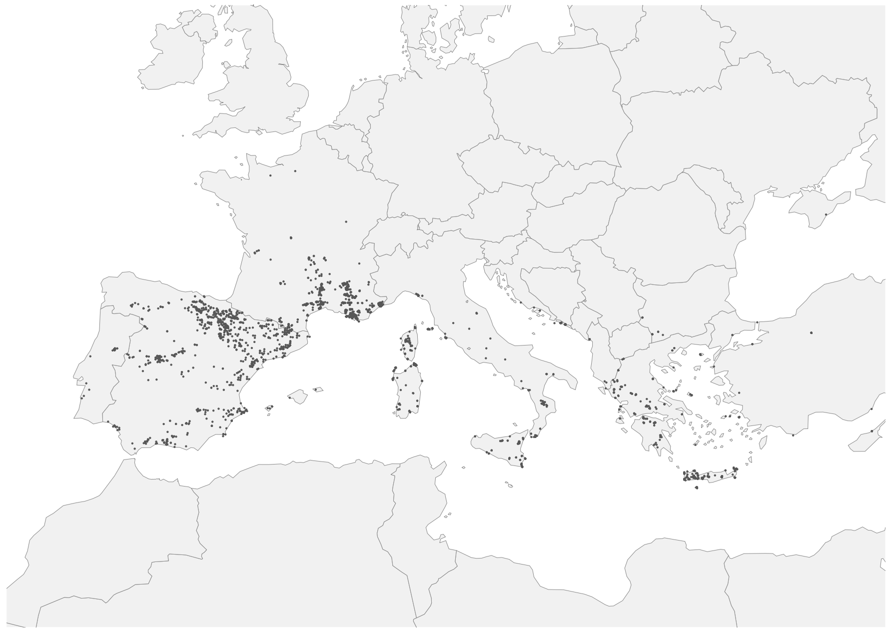


Figure 13: Location of garrigue habitats throughout the mediterranean basin
Source: author, data base: european environment agency (EEA 2021)

Common pressures and threats

The different garrigue habitats face similar conservation challenges:

- Abandonment of land Use: A decline of traditional grazing and sheepherding leads to natural succession, which eventually causes the garrigue to be replaced by taller woody vegetation.
- Agricultural intensification: Shortening fallow periods or using modern machinery can destroy these pioneer communities.
- Afforestation: Planting forests, particularly with non-native species, directly replaces the open scrub habitat.
- Other actors: Urbanization, touristic expansion, and a lack of natural fires (which halts the rejuvenation of fire-prone pioneer species) are also significant pressures.

Figure 14: calanque national park with its limestone cliffs close to marseille, France
Source: author, May 2024

Figure 15: coastal dune on granite bedrock
capo testa northern sardinia, Italy. source: author, May 2024

Figure 16: garrigue on the mountain plateau of monte corrasi in central sardinia, Italy
Source: author, May 2024

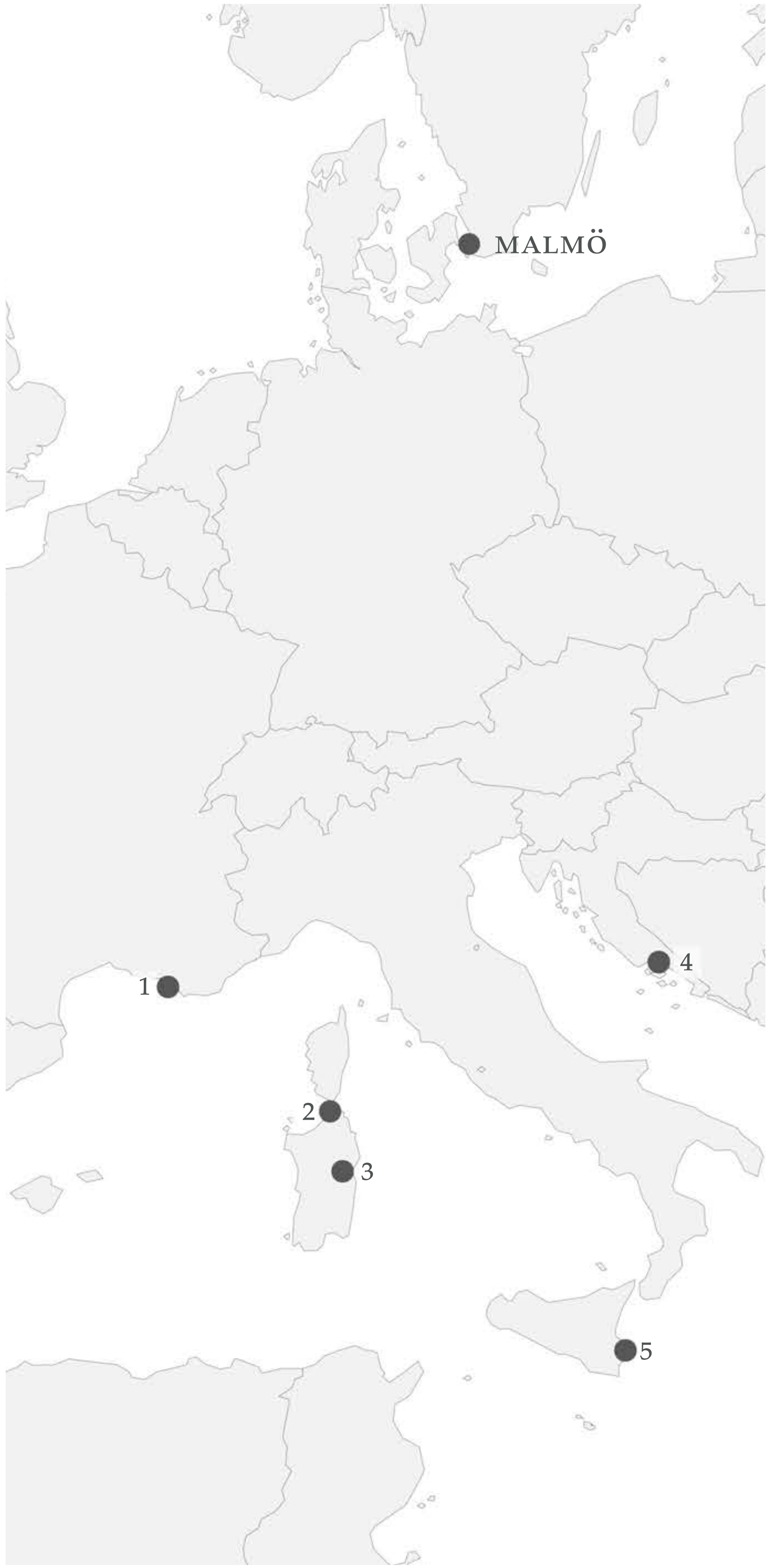


Figure 17: locations of the reference sites
Source: author, map base : european commission, eurostat, n.d.

Selection of garrigue landscapes

Following nature sites are analysed as reference landscapes. The habitats cover a variety of abiotic conditions, e.g. geological or climatic conditions. For instance some sites with soils consisting purely of karstic limestone to one site with rather acidic soil on granite bedrock. Human influence as an often occuring biotic factor in garrigue habitats differs as well throughout these sites in Croatia, France and Italy. The analysis will focus on chosen aspects of garrigue ecosystems in general. The objective is to extract main characteristic aspects to facilitate a design interpretation and translate it into green roof contexts.

Figure 18: karst landscape in the mosor mountains close to split,
adriatic coast, croatia. source: author, July 2023

Figure 19: coastal garrigue by tonnara di santa panagio
outskirts of siracusa, eastern sicily, Italy. source: author, March 2026

Analysis contents

The here featured garrigue habitats were not classified with phytosociological methods, e.g. Braun-Blanquet survey, but rather conclude an ensemble of habitats that share common features, characteristics and plant species with garrigue habitats. These features include similar abiotic conditions (e.g. Mediterranean climate) and visual similarities (rocky landscape, plant cushion shapes, etc.).

The focus of the in depth analysis of the habitats should rather be put on structural and aesthetical aspects of these ecosystems than to compare species composition or ecology to phytosociologically 'true' garrigue habitats. The aspects are selected to inform a design adapting the landscape and putting it into a urban green roof context.

Climate, altitude and aspect

As a common factor the climate in all of the sites is typically Mediterrean, characterized by severe summer drought. The temperate climate with hot summers corresponds to climate zone Csa (Köppen).

Altitude and aspect of the locations differs:

- Monte Corrasi altitude range from 598m to 1463m, steep west-facing slope up to a mountain plateau
- Mosor around 630m, steep southwest-facing slope
- Calanques 150 to 280m, south-facing cliffs and steep slopes
- Capo Testa, coastline with various aspects from west -facing to south-facing rocks, cliffs and dunes
- Siracusa, cliffs along the coastline, variety of aspects

Soil characteristics

Most garrigue landscapes occur predominantly on limestone bedrock with alkaline soils. Four of the here featured landscapes are located in karst landscapes (Bognar et al. 2012; Collina-Girard 2014; Servizio Geologico D'Italia 2019; Audra et al. 2024) with either limestone or dolomite bedrock. Only the landscape of Capo Testa in northern Sardinia is located on granite bedrock (Servizio Geologico D'Italia 2012) which is commonly associated with acidic soils.

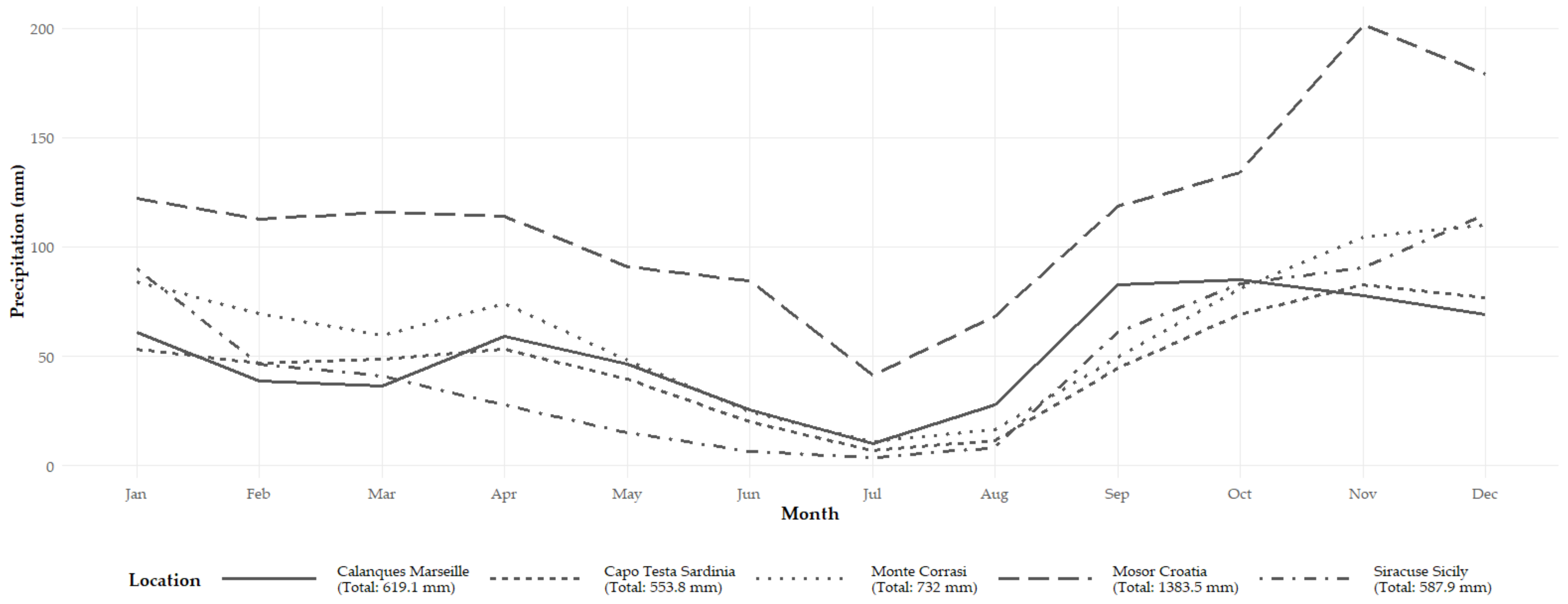


Figure 20: precipitation regimes of the 5 landscapes
Source: compiled by author with r , based on climate data by karger et al. (2021)

Figure 21: karst landscape in the mosor mountains croatia, big proportion of limestone and rocks between the vegetation. Source: author

4.2.2. Atmospheric analysis

Figure 22: garrigue at the foot of monte corrasi .soil and gravel visible between the plants.
Source: author

Bare soil and gravel

When researching literature about garrigue habitats and seeking common ground with the featured nature landscapes, the sparse vegetation with bare soil, gravel and rocks in between is a distinct characteristic. The landscapes, in many cases set on limestone bedrock, often show gravel interspersed with rounded, cushion-like sub-shrubs. (see Figure 22). As decribed on the previous page the soils in garrigue habitats are mostly quite shallow, thereby the amount of moisture and nutrients accessible for plants is very little. Plants adapt with hydraulic strategies to either avoid or tolerate drought.

The gravel offers optimal draining characteristics with its high porosity (see Figure 23 and 24). When combined with a karst bedstone the water availability is massively limited.

Figure 23: *pallenis maritima* growing in limestone gravel of varying fractions
Source: Author

Figure 24: *sedum* species in limestone gravel in sicily
Source: author

Figure 25: limestone rocks on the slopes of monte corrasi, lichen growing on it, plants growing around it. Source: author

Figure 26: *teucrium aureum* growing on a limestone rock wall in the calanques
Source: author

Figure 27: *helichrysum stoechas* growing in a crevice
Source: author

Figure 28: *teucrium marum* growing in typical cushion shape around a rock
Source: author

Rocks as facilitators

Commonly you can see rocks sticking out of the silvery-green and low vegetation (Figure 25), collectively creating the distinct look of this dry landscape. These rocks can serve as nurse objects facilitating plant growth (Shemesh 2025). As plant roots naturally seek out the underside of these rocks where the soil moisture is higher than in the surrounding gravel (ibid.). Plants 'hugging' rocks as seen in Figure 28 with *Teucrium marum* is a common sight.

Where crevices and cracks run through the limestone (Figure 26; 27) some extremely robust plants vegetate the hostile places. They bury their roots in the tiniest accumulations of substrate or root deep into the rocks to access moisture, cooler soil and nutrients.

Cushion shapes

Not only microsites like the rock crevices represent hostile environments. Garrigue landscapes in general represent an interface of generally harsh environmental conditions. Their location in the Mediterranean basin as well as their microclimatic site conditions by the sea, on rocky slopes or on mountain tops. An interplay of abiotic and biotic influences leads to the compact growth of the subshrubs in this biome.

Typical for many mediterranean regions are the unique wind systems like Bora or Mistral that influence the coastal regions heavily from Autumn to Spring. The low cushions offer the least surface area for the wind to catch and are therefore very common in coastal biomes.

Historically garrigue landscapes have been predominantly grazed by sheep and goats which often play a role in keeping the landscapes in an equilibrium of successional stages. This also favors plants that are unpalatable for the grazing animals, e.g. animal with thorns or aromatic foliage.

Foliage and essential oils

Typical for many drought tolerant shrubs as an adaptation to the drought periods is the tomentose, silvery foliage or waxy blueish leaves. To minimize the surface area and evaporation the leaves are often narrow and longitudinal. The foliage of the sub-shrubs often contains essential oils, especially the *Lamiaceae* family with well-known genera like *Helichrysum, Salvia, Satureja or Thymus.* Filippi (2019) mentions that the essential oils in the leaves of garrigue plants serve as a multifaceted defense mechanism to deter herbivores and pathogens, suppress competing plants and mitigate the stresses of intense heat and drought. For an application in horticultural contexts especially the weed-suppressing attributes of the essential oil, known as allelopathy, are interesting. Garrigue shrubs plants release essential oils into the soil, either through rain washing over the leaves, volatilization into the air or the decomposition of fallen leaf litter (ibid.). These compounds act as natural herbicides that inhibit the seed germination and root growth of competing plant species. For example, essential oils from Mediterranean shrubs like rosemary and thyme have been shown to significantly suppress the growth of surrounding weeds, granting the parent shrub exclusive access to limited soil moisture and nutrients (Elghobashy et al. 2023.

Other life forms

Whereas chamaephytes (sub-shrubs) represent the most characteristic life form of the garrigue, this biome shows a wide variety of life forms. Forbs, annuals, succulents, geophytes and phaneropytes grow together in this biome forming the typical landscapes.

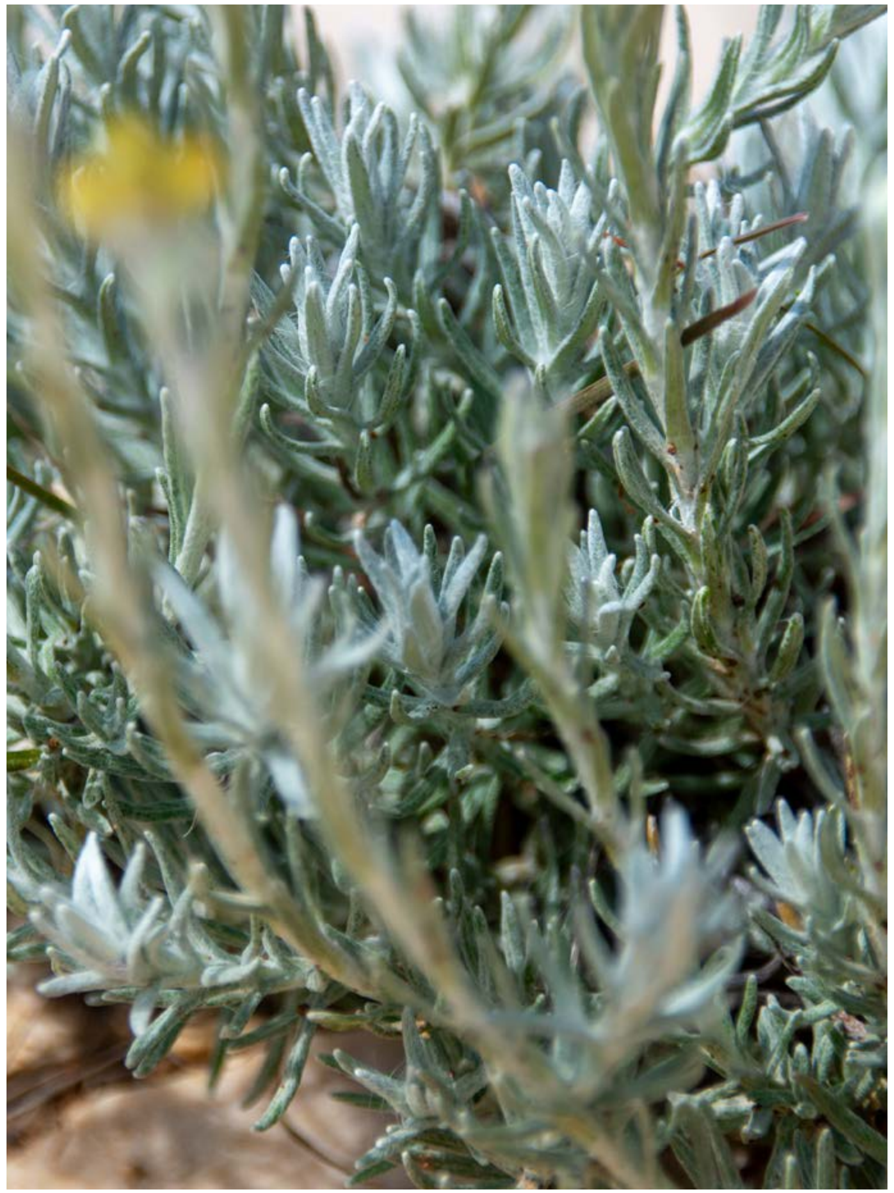


Figure 29: *Helichrysum stoechas* with its tomentose silvery foliage
Source: author

Figure 30: cushion shapes by the coastline in sicily
Source: author

Figure 31: *Nepeta foliosa* on a mountain top, showing the typical round growth
Source: author

Figure 32: rosemary (*Salvia rosmarinus*) aromatic plants that contain essential oils are common in garrigues. Source: author

Figure 33: path leading through the garrigue in sicily
Source: author

Figure 34: cushions by the sea
Source: author

Figure 35: flowering aspect of *calicotome villosa in spring*
Source: author

Rhythm of the landscape

Another typical atmospheric attribute of the garrigue is the unique rhythm of the landscape. Abiotic and biotic factors strongly influence the landscape and create the harsh conditions that rule out a continuous plant canopy cover. Resulting is a mosaic landscape, consisting of bedrock, gravel alternating with the dominant cushion forming sub-shrubs and their companion plants. Mosaics are almost rhytmically arranged

Tonnara di Santa Panagio, Sicily

This garrigue landscape is opposed to the other ones rather grass dominated by *Hyparrhenia hirta* with some dome shapes of *Thymbra capitata*, *Sarcopoterium spinosum* and the yellow flowering *Calicotome villosa* inbetween. *Asphodelus ramosus* just like the dominant grass brings in a vertical visual aspect. An influence of the sea on the growth forms of the plants is visible on the lower image on the left demonstrating the wind impact in the proximity of the shoreline leading to the more compact growth. These plants also have to tolerate the salty sea water spray

Monte Corrasi, Sardinia

The photograph shows a slope on the mountain plateau of Monte Corrasi in the Supramonte Mountain range in central Sardinia. A rhythmic arrangement becomes apparent when focussing on the spherical sub-shrubs and the weathered limestone rocks alternating with low grasses and further ground-covering plants. Character species here are the subshrubs *Teucrium marum* and N*epeta foliosa* as well as the sedge *Carex humilis*. Shallow karst soils, high exposure to wind and irradiance as well as grazing by wild mouflon and local pastoralists with goats and sheep keep the plant community low and prevent a succession. Grazing also influences the plant community in its composition. Unpalatable plants with aromatic contents are favoured by the grazing activity and plants are shaped into characteristic shapes.

FIGURE 36.
SOURCE: AUTHOR

FIGURE 37.
SOURCE: AUTHOR

Capo Testa, Sardinia

This sand dune in the coastal landscape of Capo Testa demonstrates the adaptations harsh conditions as well. Domes and cushions grow close to the ground, minimizing the effect of the wind while they establish favourable microclimates within their sheltered interior of the dome. Dome shapes of the likes of *Lotus cytisoides* and *Helichrysum stoechas* get contrasted by *Euphorbia pithyusa* with its rather upright stems and *Allium ampeloprasum* with its long upright stalks standing out of the domes.

Slopes of Monte Corrasi, Sardinia

On the foot of Monte Corrasi, slopes with deeper soils enable a mosaic of open woodlands and slope plant communites. Blueish foliage and domes of *Helichrysum stoechas* are contrasted by the flowering *Euphorbia characias* and *Cistus creticus.*

Figure 38.
Source: author

5. Synthesis & design parameters

In this chapter conclusions from literature study, case study and reference landscapes are compiled. This creates the basis for a selection of design principles that constitute the final design proposal.

Conclusions of the literature study mainly focus on the process and important criteria of the plant selection. Furthermore, implications of how biodiversity influences ecosystem services are evaluated to find strategies informing a planting design to maximise provision of services. This is also the objective for the conclusions of spatial layout in green roofs.

Conclusions of the case study analysis focus on the real-world performance of functional analogues and the impact of maintenance realities.

Because the analysis of the nature sites predominantly focused on the subjective perception of atmospheric attributes, these do not adhere to scientific methods. Furthermore are they a simplification of complex ecosystems and are directly translated into actionable principles.

All of the conclusions aim to achieve the design goals of implementing the garrigue into mixed green roof modules with a minimal required substrate depth. These modules are the final result of the design process and are tailored for following design objectives that regulate the criteria of the plant selection methods. The vegetation design should achieve following objectives:

- drought tolerance and low maintenance
- structural heterogeneity
- biodiversity
- thermal regulation and cooling
- stormwater retention and interception
- cultural and aesthetic services

These premising traits and climate analysis define the unique characteristis that lead to the selection of the garrigue ecosystem as the habitat template. Furthermore, they provide transparency and demonstrate the conditions for a transferability of the design outcome to differing objectives.

For instance, a pure focus on evapotranspiration and cooling services of a green roof would lead to entirely opposing traits required for the species selection, to a different habitat template and therefore to a totally different design outcome than the focus that led to the garrigue habitat.

Along with the design objectives the spatial context of a design location is crucial. The design is adjusted to urban sites in the mildest hardiness zone in southern Sweden with minimum temperatures as low as -12.2°C (Wulff & Bouillon 2024), which aligns with the USDA zone 8a. Microclimatically it is adapted to the most exposed situations in urban areas of this zone without shading buildings or trees and high exposure to wind.

5.1 Spatial and structural parameters

Substrate composition and drainage

To successfully balance extreme winter precipitation with severe summer drought, the physical roof profile must implement a strictly segregated, two-layer hydraulic system (Rowe 2025; Kumar et al. 2025). First, the growing medium must be engineered for rapid vertical percolation, mandating the use of highly porous inorganic aggregates with organic content strictly capped at a maximum of 10–20% (Ampim et al. 2010; Bodley et al. 2022). Second, a dedicated water-retention layer should be installed at the absolute base of the profile. This structural separation is required to keep dormant roots elevated above winter water tables, while maintaining a secure moisture reserve below the primary root zone for drought resilience (see Section 3.4.2).

Holistic microtopography, physical modifiers and facilitation niches

To fully operationalize the habitat template approach, the structural layout must mimic the physical complexity of the garrigue. A uniform substrate profile limits biodiversity by favoring generalist species (Lundholm & Walker 2018). Therefore, the design will employ a continuously undulating, variable-depth substrate model (Lundholm et al. 2020; Ganthaler et al. 2025):

- Shallow zones: Reserved for highly drought-tolerant succulents and baseline coverage to minimize overall structural load
- Deep nodes and physical modifiers: As derived from the analysis of the reference landscapes and Section 3.4, strategically placed mounds, trenches and characteristic microtopographic elements of the garrigue (such as rocks and crevices) are required to create micro-shading and varied moisture retention zones (Lundholm 2006; Lundholm & Walker 2018; see Section 3.1.1).

Furthermore, to leverage the ‘nurse plant’ effect, these deeper substrate nodes will be planted with higher shrubs to create microspatial environmental heterogeneity. The combination of these physical structures and shrub canopies provides the expanded rooting volume, thermal buffering, and water-holding capacity required to sustain taller shrubs and subshrubs, while providing shading in summer and acting as buffers against desiccating winds and ‘frost heave’ in winter, thereby creating regeneration niches for sensitive specialized companion species alongside dominant vegetation (Papafotiou et al. 2013; Van Der Kolk et al. 2023; Castro et al. 2002; Gómez-Aparicio et al. 2005; see Section 3.4.1).

Rhythmic mosaic layout and continuous cover

Rather than striving for a continuous, monolithic vegetation canopy, the spatial arrangement must mimic the natural ‘rhythm’ of garrigue landscapes. As derived from the reference landscapes, the design will utilize a mosaic approach, intentionally alternating clusters of dome-shaped vegetation with lower patches of vegetation to reflect natural spatial distributions. However, because visible bare substrate is a primary deterrent to public acceptance, the spatial layout in these lower patches should prioritize rapid and continuous vegetation coverage to ensure aesthetic cohesion during the establishment phase. The design will utilize temporary gap-filling species (e.g. fast-establishing grasses and groundcovering forbs) alongside slower-growing specialists (Chell et al. 2022; Vanstockem et al. 2018; see Section 3.3). While this continuous cover opposes pure garrigue characteristics, it is an important reconciliation for the ecosystem service provision and aesthetics.

5.2 Plant selection criteria

Multi-criteria and functional trait filtering framework

Species selection will move beyond simple aesthetic preference by utilizing a structured, hierarchical filter. Plants must first pass a strict abiotic survival filter proving adaptation to garrigue environment conditions, before being selected for specific functional traits and ecological potential (Liao et al. 2025; Calviño et al. 2023; Van Mechelen 2015). The selection must target specific functional traits. These functional traits will follow the work of Van Mechelen (2015) as this framework utilized the habitat templating in connection with an evidence-based scoring matrix.

Life-form diversity and structural contrast

To maximize ecosystem multifunctionality (e.g. thermal regulation, stormwater retention and resilience) and to holistically portray garrigue habitats (Lundholm 2006; Lundholm & Walker 2018), the vascular planting palette will avoid monocultures by mixing structural life forms. While low-growing chamaephytes (subshrubs) will form the foundational matrix of the roof, the plant palette must incorporate contrasting life forms, including succulents, grasses and forbs, to mimic natural structural diversity (Lundholm et al. 2010). The design must integrate vertical architectural elements, such as upright grasses, tall forbs and geophytes, to break up the visual uniformity of the dome shapes and create multi-layered habitat structures.

Trait complementarity and niche partitioning

To achieve true ecosystem multifunctionality and move beyond the limitations of single-strategy *Sedum* mats, the planting design must actively engineer trait complementarity. This requires selecting plant pairings based on divergent traits (e.g. mixing shallow-rooted succulents with deep-rooted subshrubs to prevent competition for the same water layer) while simultaneously utilizing convergent traits (Lundholm 2015; Heim et al. 2023).

Dominant species prioritization

Because ecosystem processes are disproportionately governed by the traits of the most abundant plants (Grime 1998; Xie et al. 2018), the plant palette cannot treat all species equally. The design should identify ‘dominant’ structural or groundcover species based strictly on their ability to perform the site’s primary targeted ecosystem service (e.g. extreme drought survival or evapotranspirative cooling). These dominant species will form the structural matrix, while more specialized, subordinate species will be interspersed to add diversity.

Functional redundancy for system resilience

To protect the green roof against extreme climatic fluctuations, the plant selection should guarantee functional redundancy. The design must ensure that critical ecological roles are fulfilled by at least two distinct species. This ensures that if one species fails due to disease or anomalous weather, the overarching ecosystem service is not lost (Lundholm 2015; Heim et al. 2023).

Allelopathic weed suppression and foliage traits

Plant selection must prioritize functional traits adapted to intense radiation and drought, specifically targeting species with narrow, waxy or silvery-tomentose leaves. Furthermore, the selection must intentionally incorporate species from the *Lamiaceae* family (e.g., *Thymus, Salvia, Helichrysum*) that contain high levels of essential oils. These oils function as natural allelopathic herbicides; as they wash into the substrate or volatilize, they will actively suppress the germination and root growth of competing, unwanted weeds, thereby naturally reducing maintenance requirements.

Phylogenetic diversity as a trait proxy

In instances where precise, quantifiable functional trait data is unavailable for selected garrigue cultivars, the selection framework will default to phylogenetic diversity as a substitute metric. By deliberately selecting species from evolutionarily distant plant families, the design will inherently enforce different resource-use strategies and niche partitioning, thereby guaranteeing a more stable and productive vegetative cover (MacIvor et al. 2018; Ndayambaje et al. 2024).

Garrigue shrub integration and frost tolerance

When selecting Mediterranean garrigue shrubs, selection should prioritize local evolutionary adaptation to winter extremes. Because frost tolerance is not universal within these species, the selected plant material should be derived from chemotypes proven to utilize frost adaptations capable of withstanding prolonged saturation and sub-zero temperatures (Thompson et al. 2007; King et al. 2012; Filippi 2019; see Section 3.4.2).

Aesthetic and cultural effect traits

To optimize the cultural ecosystem services and public perception of the green roof, the final plant palette will prioritize specific visual 'effect traits'. The selection should include multi-layered vegetation, a dominant foliage palette of green and white tones and species with varied phenological flowering times to maintain year-round visual interest and signal ecological health to observers (Lee et al. 2014; Goodness et al. 2016; Thorpert et al. 2024; see Section 3.3).

5.3 Adaptive management parameters

Adaptive trimming and simulated disturbance

In natural reference landscapes, the compact, dome-like habitus of the vegetation is maintained not only by abiotic stress but by the biotic disturbance of grazing (e.g. by sheep or mouflon). To prevent unwanted successional overgrowth and maintain the intended structural shapes on the green roof, the management regime must employ mechanical trimming as a proxy for grazing. This intentional disturbance will keep the plant community low, compact and visually consistent with the garrigue template. However, the maintenance regime must simultaneously be treated as an active driver of ecological succession rather than purely an aesthetic control. To maximize self-seeding and spontaneous gap-filling in the mineral substrate, this trimming should be restricted to a single-trim regime, specifically avoiding late-summer and autumn cuts. This delay ensures seed heads can fully ripen and disperse, promoting a denser, more naturalistic habitus and higher ground cover compared to heavily managed plots (see Section 4.1.2).

Selective weeding and aesthetic balance

While spontaneous vegetation is encouraged for ecological cover, selective weeding must be carefully calibrated to balance naturalistic succession with cultural acceptance. Because extensive bare soil negatively impacts public perception and increases vulnerability to heat and erosion, weeding should only target highly disruptive, competitive invasive species, allowing benign spontaneous colonizers to remain and cover bare substrate (Vanstockem et al. 2018; see Section 4.1.2).

6. Design proposal

6.1 Site strategy and layout

Based on the previous conclusions of literature study, case studies and reference landscapes this chapter should conclude the ideas underlying the design process. These should establish a pragmatic approach of translating the previous findings into design guidelines that steer the potential implementation of the final design product. Considering the limited scope of this work the design product will consist of potential suitable species, a final proposal selection and some spatial recommendations for a green roof module. This prototype could be replicated, adapted to local contexts and then applied to thin profile green roofs in the mildest frost hardiness zone (USDA zone 8a).

Substrate and profile

To mimic the abiotic characteristics of garrigue habitats as best as possible the substrate will predominantly consist of mineral material as following:

- Primary mineral base (60-70% by volume): Pumice 2/12 mm. Provides the lightweight structure and internal moisture retention.
- Secondary mineral base (15-25% by volume): Crushed natural stone or crushed brick (Fraction: 0/8 mm). Adds physical weight for root anchoring and introduces necessary fine particles for capillary action.
- Organic component (strictly 2,5-3,0% by mass / ca. 10-15% by volume): High-quality, fully composted green waste or stable organic fibers.

The substrate will be topped off with 2-3 cm of locally sourced limestone gravel mulch 8/16 mm to imitate the visuals of garrigue habitats of limestone gravel interspersed with cushions of plants.The substrate and limestone mulch will be accumulated in the following profile:

- Shallow zones (< 10 cm) for groundcovering species and low cushions, minimum depth of 5cm for *Sedum* species
- Deep nodes (15 cm-20cm) for larger garrigue shrubs

Smaller rocks could be applied to mimic the habitat in a more complete way, depending on the structural conditions of the building this could be adjusted for particular local context. It could create the rock crevices and nurse rocks that are so typical for garrigue habitats.

In some areas the gravel mulch could be applied in a higher depth to mimic gravel piles and to diversify the habitat.

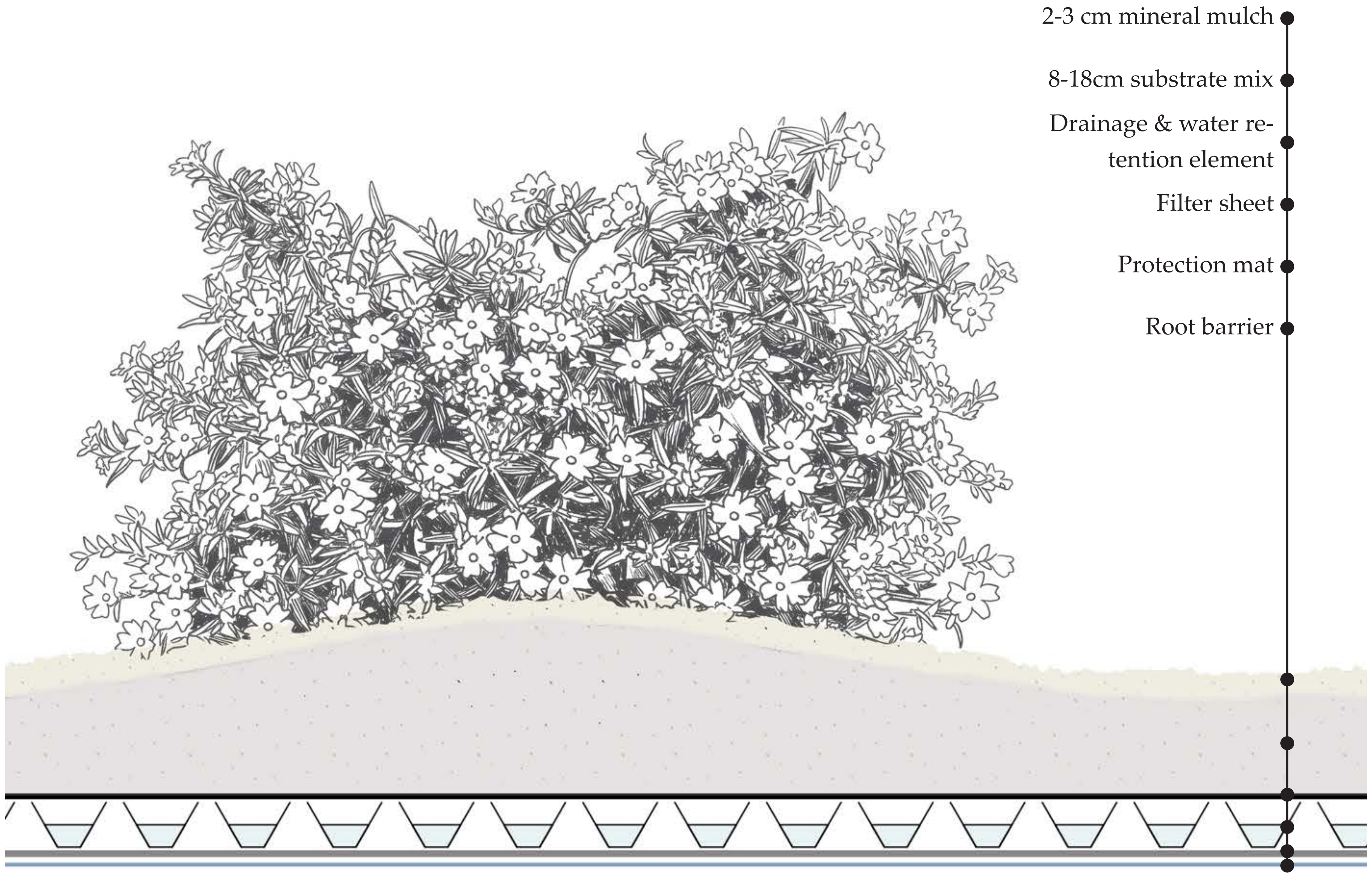


Figure 39: profile section scale 1:5
Source: author

6.2 Plant selection

Following the proposed methodology of the habitat template included in a plant selection framework, a base species pool was established. This species pool consists of different sources, in total giving a detailed representation of the garrigue biome. Plant lists from following sources were compiled in a final species pool that build the base of the selection framework:

1. Surviving plants of the Erfurt case study

These plants are proven to be functional in a temperate climate outside of the species natural occurence. The plants of the total roof community was filtered and only species related to garrigue and similar habitats within the Mediterranean basin were used.

2. Phytosociological study by master students of the FH Erfurt conducted in the Calanques national park close to Marseille

Plots of several square meters on the south facing limestone slopes were studied according to methods by Braun-Blanquet (1964).

3. to 6. reference landscape observations

Following clusters were observations by the author in the case study locations. Species were identified with the Flora Incognita app (Mäder et al. 2021) and a plant field guide for the western Mediterranean Thorogood (2021). Clusters are as following:

- 3. Coastal dune vegetation of Capo Testa, Sardinia, Italy
- 4. Slope and mountain plateau vegetation of Monte Corrasi, Sardinia, Italy
- 5. Slope vegetation of the Mosor mountains close to Split, Croatia
- 6. Coastal garrigue vegetation close to Siracusa, Sicily, Italy

7. Phytosociological study

Based on a phytosociological study of Di Pietro & Misano (2010) this cluster was selected due to the study location in a network of valleys with garrigue vegetation in Apuglia. This location is ca. 80 km away from Potenza, which is expected to have a current climate comparable to the future climate of Copenhagen by the end of the century (Bulut et al. 2025). Furthermore is the implementation of a phytosociological study important to display the whole variety of a plant community. The study features several different garrigue communites from higher shrub dominated vegetation to very low vegetation on extremely shallow soils, only the lower communites were selected as they are expected to be more suitable for green roof conditions. Following plant communites were included in the total species pool:

- *Centaureo subtilis-Thymetum capitati*
- *Trifolio scabri-Sedetum albi*
- *Sedo ochroleuci-Saturejetum cuneifoliae*

8. Typical species of basiphilous garrigues

A list of constant and diagnostic taxa of the habitat classification by the European Environment Agency (Chytrý et al. 2025) was used as well. This list shows typical species of Western basiphilous garrigue communites. To cover most characteristic species of garrigue ecosystems this list is intended to fill gaps and cover a more comprehensive list of species.

Resulting list

Compilation of these individual lists led to a base species pool of 284 species (see Appendix A). These were then filtered with traits from the TRY database (Kattge et al. 2020) to ensure a selection process with evidence based and functional traits.

6.2.1 Exclusion and scoring process

The resulting species pool was filtered with 4 functional traits according adapted from Van Mechelen (2015) and the invasion status for Sweden to avoid an introduction of invasive species. Exclusion criteria are shown in Table 1 with the according source of used databases. Data analysis was conducted with R Version 4.6.0 (R Core Team 2026). The R script was written with the help of Google's Gemini artificial intelligence (Google 2026) and afterwards checked manually for logic and correctness. The R script for exclusion criteria and scoring matrix was build up according to the criteria in Table 1. The criteria are based on a PhD-thesis by van Mechelen (2015) that screened Mediterranean vegetation from several nature habitats to find suitable vegetation for green roof conditions. The proposed broad characteristics linked to survival on green roofs from van Mechelen (ibid.) were then reviewed for utilization in the contexts of this thesis. 2 traits were omitted due to incomplete databases and frost tolerance was added to ensure a resilience of the species when planting in southern Scandinavian contexts. The frost hardiness zone 8a (-12.22°C to -9.45°C) was identified for Malmö with the paper of Wulff & Bouillon (2024).

Exclusion process

The initial species pool consists of 284 species from the previously named sources. Frost hardiness as the most critical factor for survival excluded 221. This was also due to a scarce data availability of reliable sources. In addition were 11 species excluded with the further exclusion criteria (see Table 1). 52 species remained for the following scoring process.

Scoring process

According to the scoring criteria shown in Table 1 the remaining species were rewarded a scoring point each trait where it meets the preferrable condition (see Table 2). The total score was calculated through division of the score by available traits in used databases to account for missing entries.

6.2.1 Exclusion and scoring process

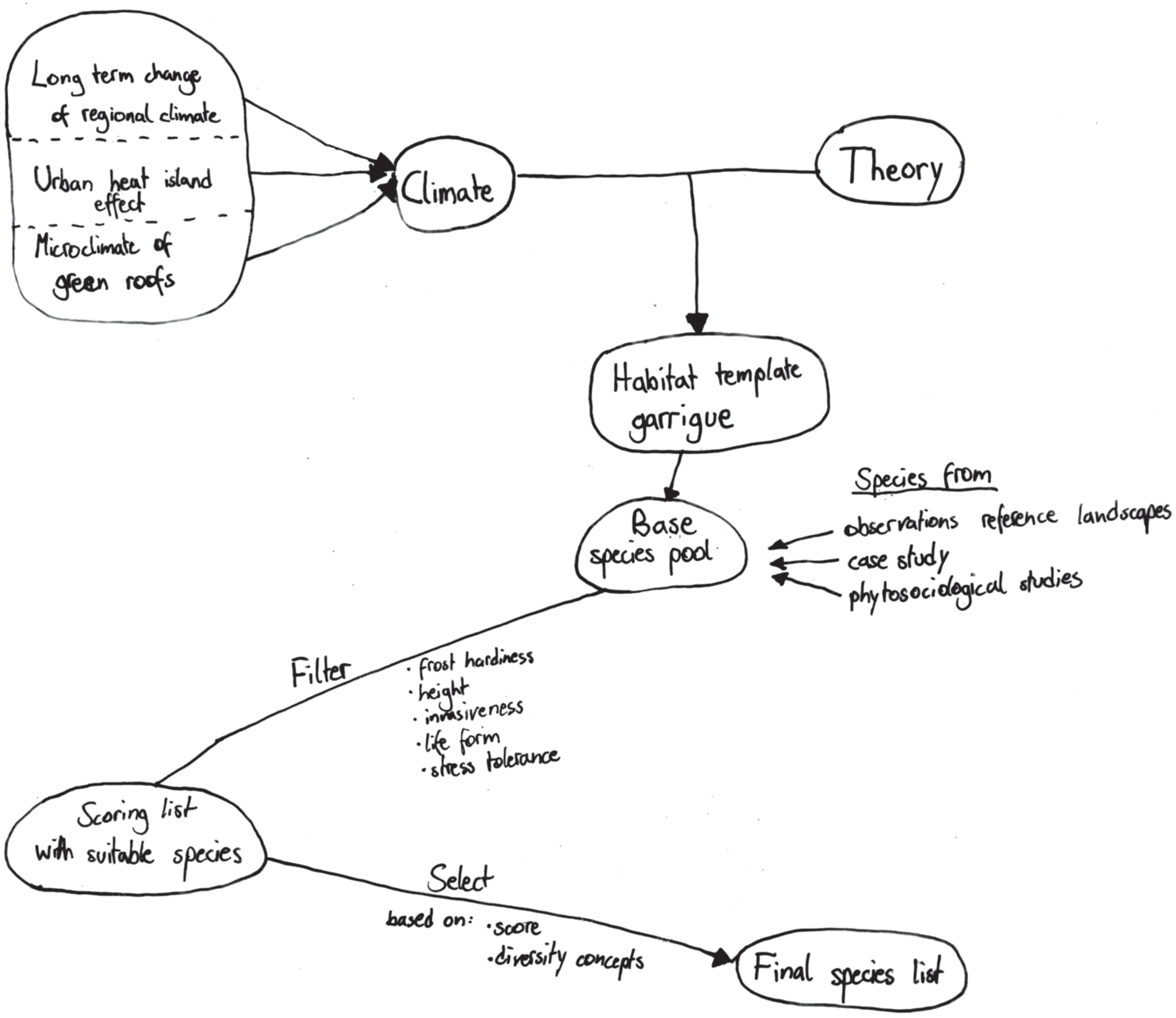


Figure 40: diagram of the selection process leading to the final species selection
Source: author

6.2.2 Selection criteria

Plant traits for species exclusion	**Exclusion criteria**	**Data reference**
Frost tolerance	not tolerant to -12 °C or lower	Pépinière Filippi (n.d.); Petr Hanzelka, Prague Botanical Garden see Filippi (2019); Royal Horticultural Society (n.d.); Tucker & Maciarello (1986); Missouri Botanical Garden (n.d.); POWO (2026); Denver Botanic Gardens (n.d.)
Grime plant strategy	No stress tolerance	Gachet et al. (2005); Kühn et al. (2004); Moretti & Legg (2009)
Invasiveness	Listed in invasive plants list Sweden 'Risklista för främmande arter'	SLU Artdatabanken (2025)
Plant height	Tall plants exceeding 1m height	Kaplan et al. (2019)
Raunkiaer life form	Phanerophyte (nanophanerophytes stay)	Bragazza (2009); Choat et al. (2012); Ciccarelli (2015); Ciocarlan (2009); Dressler et al. (2014); Fitter & Peat (1994); Gachet et al. (2005); Hill et al. (2004); Kaplan et al. (2019); Kleyer et al. (2008); Kühn et al. (2004); Moretti & Legg (2009); Poschlod et al. (2003); Raevel et al. (2012); Raevel et al. (2013); Soudzilovskaia et al. (2013)

Plant traits for scoring steps	**Preferable condition**	**Data reference**
Frost tolerance	tolerant to -15 °C or lower	Pépinière Filippi (n.d.); Petr Hanzelka, Prague Botanical Garden see Filippi (2019); Royal Horticultural Society (n.d.); Tucker & Maciarello (1986); Missouri Botanical Garden (n.d.); POWO (2026); Denver Botanic Gardens (n.d.)
Grime strategy	Ruderal and/or stress tolerant	Gachet et al. (2005); Kühn et al. (2004); Moretti & Legg (2009)
Leaf phenology	Evergreen	Choat et al. (2012); Fan et al. (2017); Fitter & Peat (1994); Gachet et al. (2005); Han et al. (2012); Iversen et al. (2017); Kattenborn et al. (2018); Kattge et al. (2009); Kühn et al. (2004); Lin et al. (2015); Maire et al. (2015); Manzoni et al. (2013); Moretti & Legg (2009); Niinemets (2001); Onoda et al. (2011); Onoda et al. (2017); Poschlod et al. (2003); Reich et al. (2009); Tavsanoglu & Pausas (2018); Wirth & Lichstein (2009); Wright et al. (2004); Wright et al. (2017); Zanne et al. (2013)
Leaf shape	“long” or “grass-like” or “tubular” or “acicular” or “>3 times as long as wide” or “linear”	Dressler et al. (2014); Fitter & Peat (1994); Kühn et al. (2004); Wirth & Lichstein (2009)
Metamorphosis for storage	Succulence	Klimešová & de Bello (2009); Kühn et al. (2004)
Plant lifespan	perennial or annual	Bragazza (2009); Ciocarlan (2009); De Frutos et al. (2015); Díaz et al. (2004); Fan et al. (2017); Gachet et al. (2005); Hill et al. (2004); Kleyer et al. (2008); Klimešová & de Bello (2009); Kühn et al. (2004); Moles et al. (2004); Moretti & Legg (2009); Poschlod et al. (2003); Raevel et al. (2012); Raevel et al. (2013); Schweingruber & Landolt (2005); Silva et al. (2019); Tavsanoglu & Pausas (2018); The Tree of Sex Consortium (2014); Valverde-Barrantes et al. (2020)
Raunkiaer life form	Chamephyte, Geophyte or Therophyte	Bragazza (2009); Choat et al. (2012); Ciccarelli (2015); Ciocarlan (2009); Dressler et al. (2014); Fitter & Peat (1994); Gachet et al. (2005); Hill et al. (2004); Kaplan et al. (2019); Kleyer et al. (2008); Kühn et al. (2004); Moretti & Legg (2009); Poschlod et al. (2003); Raevel et al. (2012); Raevel et al. (2013); Soudzilovskaia et al. (2013)
Root depth	less than 0.2 m	Fan et al. (2017); Fitter & Peat (1994); Iversen et al. (2017); Tavsanoglu & Pausas (2018)

Table 1. Plant traits related to drought tolerance and resilience. First traits and criteria used to exclude unsuitable species. Second are scoring plant traits.

All traits were derived from the TRY initiative (Kattge et al. 2020).

6.2.3 Scoring list

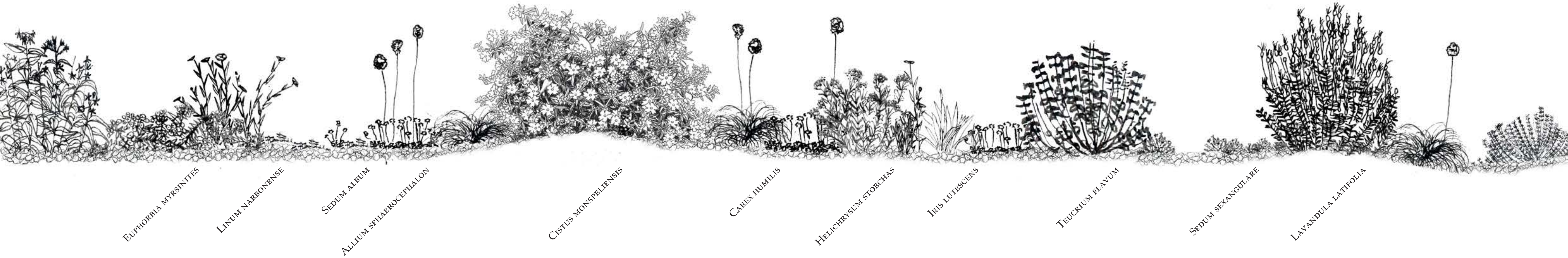
Species name	**Score (%)**	**Score fraction (score/data existent)**	**Cluster**	**Life form**
Aethionema saxatile	71.4	5/7	7	Chamaephyte
Allium ampeloprasum	85.7	6/7	3	Geophyte
Allium paniculatum	75	3/4	5	Geophyte
Allium sphaerocephalon	75	6/8	5, 7	Geophyte
Anthyllis vulneraria	87.5	7/8	4, 6, 8	Hemicryptophyte
Artemisia alba	75	3/4	1	Chamaephyte
Brachypodium retusum	50	3/6	2, 8	Hemicryptophyte
Carex halleriana	62.5	5/8	8	Hemicryptophyte
Carex humilis	62.5	5/8	4, 8	Hemicryptophyte
Centaurea cineraria	0	0/1	2	Hemicryptophyte
Cistus monspeliensis	83.3	5/6	7	Chamaephyte
Coronilla minima	66.7	4/6	8	Chamaephyte
Dorycnium hirsutum	100	1/1	3	Chamaephyte, Hemicryptophyte
Dorycnium pentaphyllum	0	0/1	8	Chamaephyte, Hemicryptophyte
Eryngium amethystinum	66.7	2/3	5	Hemicryptophyte
Euphorbia characias	80	4/5	4, 5	Chamaephyte
Euphorbia myrsinites	75	3/4	5	Chamaephyte
Euphorbia spinosa	75	3/4	4	Chamaephyte
Frankenia laevis	62.5	5/8	3	Chamaephyte
Globularia alypum	71.4	5/7	2, 8	Chamaephyte, Nanophanerophyte
Helianthemum apenninum	100	1/1	8	Chamaephyte
Helichrysum italicum	75	3/4	3, 4	Chamaephyte
Helichrysum stoechas	83.3	5/6	5, 8	Chamaephyte
Hyparrhenia hirta	60	3/5	6	Hemicryptophyte
Iris lutescens	75	3/4	2	Geophyte
Lavandula latifolia	66.7	4/6	8	Chamaephyte
Linum narbonense	100	6/6	8	Hemicryptophyte
Marrubium incanum	50	1/2	1	Chamaephyte, Hemicryptophyte
Marrubium supinum	100	2/2	1	Chamaephyte, Hemicryptophyte
Marrubium vulgare	71.4	5/7	1	Chamaephyte, Hemicryptophyte
Melica ciliata	57.1	4/7	5, 7	Hemicryptophyte
Petrorhagia saxifraga	71.4	5/7	7	Chamaephyte
Phillyrea angustifolia	80	4/5	2	Nanophanerophyte
Phlomis lychnitis	83.3	5/6	8	Chamaephyte
Pistacia lentiscus	42.9	3/7	6, 7	Nanophanerophyte
Prasium majus	33.3	1/3	6	Phanerophyte, Chamaephyte
Pseudodictamnus mediterraneus	0	0/1	1	Chamaephyte
Salvia officinalis	85.7	6/7	1, 5, 8	Chamaephyte
Salvia rosmarinus	57.1	4/7	1, 2, 4	Nanophanerophyte
Salvia verbenaca	66.7	4/6	6	Hemicryptophyte
Santolina chamaecyparissus	83.3	5/6	4	Chamaephyte
Satureja montana	83.3	5/6	1, 5	Chamaephyte
Satureja subspicata	100	1/1	1	Chamaephyte
Sedum album	100	7/7	7	Chamaephyte
Sedum ochroleucum	100	1/1	7	Chamaephyte
Sedum sediforme	100	1/1	8	Chamaephyte
Sedum sexangulare	100	7/7	7	Chamaephyte
Sideritis syriaca	0	0/1	1	Chamaephyte, Hemicryptophyte
Teucrium chamaedrys	75	6/8	1, 8	Chamaephyte
Teucrium flavum	100	6/6	1, 2, 4, 6	Chamaephyte
Teucrium polium	80	4/5	3, 6	Chamaephyte
Vincetoxicum hirundinaria	57.1	4/7	4	Hemicryptophyte

Table 2. Scoring list of garrigue species. Only if data was existing for the specific selection trait, this trait was also considered scoring relevant. Then a percentage of scoring points of these relevant traits was calculated. Bold marked are species with EGR potential (score above 50% and minimum presence in 4 out of 8 trait databases). Calculations are based on 8 key criteria for survival on green roofs (cf. Table 1). Source of each species is indicated with the cluster that it was occuring in (cf. Appendix A). The Raunkiaer life form is shown as well as derived from the TRY database (Kattge et al. (2020); source cf. Table 1 previous page). Missing entries in this database were complemented with information from the FloraVeg.EU database (Dřevojanet al. 2023).

6.3 Planting design and visualization

Ensuring an incorporation of the biodiversity concepts from the literature study, the final scoring list was reviewed with a focus on a diversity of life forms and phylogenic diversity. As the life form definition is adhering to the definition by Raunkiaer, other structural differences (e.g. the succulent *Sedum* species and the shrub forming *Cistus* are both Chamaephytes) are not well demonstrated by the species list. These differences become clearer when looking at the sectional drawing. Taller species like *Cistus monspeliensis* grow on the small substrate mounds and provide facilitation and shelter for other species. Small succulents like *Sedum album* and *Sedum sexangulare* grasses like *Carex humilis* cover the ground inbetween the domes of *Lavandula* or *Helichrysum.* Companion species like *Linum narbonense, Iris lutescens* or *Allium sphaerocephalon* provide flowering resources and add verticality. Opposing to natural garrigue habitats is the substrate mostly covered with vegetation to provide ecosystem services and to cool the shallow soil. Considering the low height of the groundcovering *Sedum* species or structurally similar species like *Aethionema saxatile* it is assumed that this counteracting does not impair the distinct visual character of the 'roof garrigue'.

Figure 41: section scale 1:10 with a selection of proposed plant species
Source: author



Species name	Plant family	Score (%)	Life form
Aethionema saxatile	Brassicaceae	71.4	Chamaephyte
Allium ampeloprasum	Amaryllidaceae	85.7	Geophyte
Allium sphaerocephalon	Amaryllidaceae	75	Geophyte
Anthyllis vulneraria	Fabaceae	87.5	Hemicryptophyte
Artemisia alba	Asteraceae	75	Chamaephyte
Carex humilis	Cyperaceae	62.5	Hemicryptophyte
Cistus monspeliensis	Cistaceae	83.3	Chamaephyte
Eryngium amethystinum	Apiaceae	66.7	Hemicryptophyte
Euphorbia myrsinites	Euphorbiaceae	75	Chamaephyte
Frankenia laevis	Frankeniaceae	62.5	Chamaephyte
Globularia alypum	Plantaginaceae	71.4	Chamaephyte, Nanophanerophyte
Helichrysum stoechas	Asteraceae	83.3	Chamaephyte
Iris lutescens	Iridaceae	75	Geophyte
Lavandula latifolia	Lamiaceae	66.7	Chamaephyte
Linum narbonense	Linaceae	100	Hemicryptophyte
Melica ciliata	Poaceae	57.1	Hemicryptophyte
Petrorhagia saxifraga	Caryophyllaceae	71.4	Chamaephyte
Phillyrea angustifolia	Oleaceae	80	Nanophanerophyte
Phlomis lychnitis	Lamiaceae	83.3	Chamaephyte
Salvia officinalis	Lamiaceae	85.7	Chamaephyte
Santolina chamaecyparis	Asteraceae	83.3	Chamaephyte
Satureja montana	Lamiaceae	83.3	Chamaephyte
Sedum album	Crassulaceae	100	Chamaephyte
Sedum sexangulare	Crassulaceae	100	Chamaephyte
Teucrium flavum	Lamiaceae	100	Chamaephyte
Vincetoxicum hirundinar	Apocynaceae	57.1	Hemicryptophyte

Table 3: species selection based on phylogeny, scoring and life form
Source: author

7. Discussion

7.1 Integration of garrigue into mixed vegetation systems

When working with the habitat templating approach shaped by Lundholm (2006), the aim is to holistically represent an ecosystem in a designed environment (Lundholm & Walker 2018). The proposal reduced the complexity of the garrigue, as the central habitat template in this work, to a simplified design version. This simplification leaves out on various central details that cannot be reproduced in green roof contexts, such as the often deep karst limestone bedrock or often occuring boulders in the natural habitat. However, because the approach itself aims at finding the most similar habitat, a green roof with its shallow soil and extreme climatic regimes acts as an educated proposed analogue for garrigue species. Specifically, the implementation of microtopography with varying soil depths could create the necessary environmental heterogeneity to accommodate diverse vegetation structures, including sheltering subshrubs alongside shallow-rooting succulents.

Based on this structural diversity, the design demonstrates a method to implement the vegetation diversity dimensions introduced in the literature study (Liao et al. 2025; Ndayambaje et al. 2024). Adding to the life-form diversity achieved by sampling the vegetation of an entire ecosystem, phylogenetic diversity was utilized as a practically applicable proxy. During the final selection process, phylogenetic relationships were broken down by deliberately choosing a wide variety of plant families to ensure niche partitioning. In future processes for similar designs, either in green roof or also in ground-level contexts, the metric of mean pairwise phylogenetic distance could be applied. Xie et al. (2018) highlight this as an indicator of evolutionary divergence that operates independently of raw species count. While phylogenetic relationships are relatively simple to obtain, the calculation of specific functional diversity is highly complex and may occasionally be inappropriate or overly burdensome for rapid, simplified design processes. Reflecting on this complexity it is uncertain if the whole process can be transferred to landscape architectural practice. However, partial taking over of methodological elements of this thesis could represent a way to further implement functional parameters to refine evidence based design processes.

7.2 Ecological and climatic implications

Modelling climate change effects is dependent on emission scenarios and societal pathways, and is therefore reliant on complex political interdependencies. Adapting to these complexities is consequently highly speculative, which demonstrates a limitation of the long-term rationale of this thesis.

As mentioned in the climate analysis chapter, climate analogue modelling can induce a knowledge transfer across the climatic shift gradient (Bulut et al. 2025); for example, southern European cities can serve as models for research on drought or heat adaptation in northern climates. In this context, the literature research on garrigue vegetation in Mediterranean regions was highly valuable, though it also highlighted a need for further research. Specifically, studies regarding the transferability of Mediterranean urban vegetation concepts to regions entirely outside of Mediterranean-like climate zones are currently limited.

The process applied in this thesis, mimicking a Mediterranean vegetation type for a northern European context, contains some limitations regarding the current state of research. Finding resilient species for climate change adaptation is generally better researched regarding the application of larger woody vegetation, such as urban street trees (Esperon-Rodriguez et al. 2022). For trees, the long-term perspective of climate analogue modelling appears more obvious, as they require a comparably long time to establish and provide ecosystem services. For lower vegetation like shrubs and forbs, this anticipating timeframe is much shorter. While this does not eliminate the relevance of climate analogues for green roofs, it does slightly diminish its long-term necessity compared to the field of urban forestry. However, considering compounding challenges like the Urban Heat Island (UHI) effect alters this relevant timeframe, shifting the need for extreme heat and drought tolerance into the immediate present. A future combination of climate change effects, UHI modelling and localized microclimate modelling could bring valuable, quantitative evidence for the specific conditions of a site. It could introduce empirical evidence for the the use of exotic, stress-adapted species. Furthermore could the layering of the climatic dimensions, from regional climate to site microclimate create a more complete image of specific site conditions for practitioners.

7.3 Spatial and experiential outcomes

It remains somewhat speculative whether certain visual qualities of the garrigue can be successfully translated into green roofs. Aspects like the featured arrangement of species in the nature habitat could be simply adjusted on a green roof. Mimicking of aspects like this in combination with the use of species from the nature habitat should lead to an authentic ‘experience’. However other aspects, like applying a wide variety of substrate depths might prove difficult in reality, as deep soil nodes (e.g. 15–20 cm) inherently compromise the overarching and intended lightweight nature of standard extensive roofs. Therefore, this vegetation concept should potentially be categorized as a ‘semi-intensive’ intermediate type between extensive and intensive green roofs.

Extensive bare soil is another characteristic of these reference landscapes that was carefully negotiated, in order to maximize the ecosystem services induced by a higher vegetation cover. The attempt at recreating the flat visual character in garrigue habitats of bare soil areas by utilizing low, gap-filling plant species serves as an ecologically productive compromise.

The seasonality of garrigue vegetation is another aspect that could interfere with the widespread application of this vegetation type. Summer dormancy as a drought-avoiding mechanism is common throughout many Mediterranean plant species (Giorgioni & Grandi 2021). The dry aesthetic of dormant plants could inhibit public acceptance, as brown foliage is frequently linked to lower public preference and perceived untidiness (Thorpert et al. 2024). Brown seed heads and a lack of floral resources during extreme summer heat could be particularly unfavourable aspects that need to be further investigated. The aspect of public aesthetic preferences should always be dependent on the actual visibility of the green roof when designing. As not all green roof, and in particular extensive forms, are accessible or visible, designing for the cultural ecosystem services like aesthetic values could be unnecessary.

7.4 Methodological reflections

Substrate limitations and the simplified design process

This thesis relied on a conceptually and ecologically driven, simplified design process. In doing so, it intentionally bypassed strict engineering metrics, such as precise structural load-bearing calculations or detailed cost analyses. This simplification was a necessary methodological choice, by removing heavy engineering constraints, the research could focus entirely on the biological and spatial interactions required to translate the habitat template and functional traits into a spatial layout. A major limitation within this simplified scope is the abstraction of the soil profile. While this deviates from a pure ecological replication, it is an unavoidable compromise to ensure the structural viability and drainage requirements of an artificial roof system.

Qualitative observations vs. quantitative data

Furthermore, the methodology relied on qualitative observations, particularly regarding the evaluation of the functional analogues at the Erfurt trial site. While these horticultural observations provided spatial and visual insights into how these species establish and perform structurally, this approach inherently lacks the statistical power and quantitative data needed to definitively guarantee long-term survival rates.

Trait data availability

The difficulties of obtaining functional traits for plant selection were predicted by Ndayambaje et al. (2024). The methodology of this thesis was focused on utilizing evidence-based traits to inform plant selection. Reflecting on this process, the complexity and difficulty of finding comprehensive databases of functional traits can be strongly confirmed. Even though databases like the TRY initiative (Kattge et al. 2020) covered some species for the featured traits, they still lack comprehensive data for a large amount of species. This reinstates the need for further research and compilation of functional data.

More work building upon the foundation of the selection framework of this thesis could utilize plant traits that further detail the mechanisms of drought tolerance. Traits like the leaf turgor loss point could give more in-depth insights into how species physically react to drought, deepening the understanding of anisohydric (drought-tolerating) versus isohydric (drought-avoiding) reactions. Rather than focusing solely on broad drought resistance, this would reveal the mechanics of physiological processes. Because upkeeping photosynthetic processes is especially important for cooling services (evapotranspiration) and carbon sequestration, this quantitative detail could vastly improve selection processes for vegetation on green roofs and other Nature-based solutions. A recent study by Guzzon et al. (2026) shows that Mediterranean shrubs, evolved in periodically arid environments, actually do not consistently show superior drought tolerance than temperate species. This challenges common assumptions and showcases the need for individual contemplation of functional parameters.

Process Transferability

The process of plant selection in this project could be applied to other contexts, even taking into account potential differences in site context, design objectives, planning resources or data availability. The process of using the habitat template approach as a primary filter and then combining it with functional traits to compile a selection framework, proved to be an effective method for selecting suitable vegetation. The dominating factor in this process is the formulation of design objectives. As mentioned in the sub-chapter regarding trait-based plant selection, the objectives for a green roof can be adjusted to specific functions and geographical contexts. Based on differences in design objectives, not only will the selection of suitable functional traits differ, but so will the selection of the habitat template itself. In the context of this project, the focus on drought tolerance and structural diversity led to the Mediterranean garrigue biome. However, this framework is transferable to other templates given different primary goals.

7.5 Future directions

Based on the limitations of this conceptual framework, two primary paths for future research emerge. First is the necessity for real-world prototyping. The logical next step for this conceptual design is the construction of a physical, monitored green roof prototype to quantitatively test the microtopography model.

Secondly, there is a critical need for focused frost tolerance investigations. As highlighted in the literature, frost resilience in Mediterranean species is highly variable and dependent on specific evolutionary chemotypes and phenotypes. Future research must conduct multi-year, quantitative winter trials on specific garrigue cultivars in northern, temperate climates to definitively assess their survival rates.

8. Conclusion

The intensifying threats of the Urban Heat Island effect and regional climate shifts require proactive, evidence-based adaptations in urban green infrastructure. While extensive green roofs are widely recognized as critical tools for climate mitigation in dense urban environments, like Malmö, their traditional reliance on low-diversity, shallow-rooting succulent monocultures limits their ecological potential and resilience under increasingly extreme site conditions. This thesis set out to investigate an alternative: the integration of Mediterranean garrigue vegetation into thin-substrate green roofs, utilizing the habitat template approach to bridge the gap between ecological theory and spatial design.

The central question of this research asked: How can garrigue vegetation be captured with the habitat template approach as a climate-resilient and functional option for thin-substrate green roofs?

The findings of this thesis demonstrate that the garrigue cannot be captured through simple taxonomic replication, but must be translated through the abstraction of its functional traits and physical structures. To successfully operationalize the garrigue as a habitat template for green roofs, the design must recreate the environmental heterogeneity of the natural biome. This is demonstrated with a multi-layered design framework that combines a variable-depth microtopography with specific substrate profile. By mimicking the spatial ‘rhythm’ and structural complexity of the natural scrubland, the green roof attempts to provide the necessary physical niches to support stress-adapted Mediterranean subshrubs alongside complementary succulents, grasses, and forbs.

The literature and case study analyses revealed that traditional plant selection for extensive roofs often leads to simple vegetation forms dominated by *Sedum* species that prioritize basic survival. This thesis establishes that maximizing functional and phylogenetic diversity is critical. By combining diverse life forms and functional strategies, the green roof achieves trait complementarity and functional redundancy. This biodiversity directly enhances ecosystem multifunctionality.

The unique atmospheric and structural characteristics of the garrigue, such as its rhythmic mosaic layout, dome-shaped subshrubs and aromatic silvery foliage, were captured through a multi-criteria filtering framework. Rather than viewing the sparse, harsh nature of the garrigue as a limitation, the framework leverages these characteristics (such as the 'nurse plant' facilitation effect) to create a vegetative matrix.

The justification for utilizing Mediterranean species in temperate contexts like southern Sweden operates on two distinct scales. Long-term climate analogue studies confirm a pronounced southward shift, indicating that cities in southern Scandinavia must prepare for conditions more and more resembling current Mediterranean climates. However, more immediately, the abiotic reality of the rooftop microclimate already functions as a localized extreme site. The thermal loads, high wind exposure, and chronic water limitations of thin-substrate roofs require an selection towards stress-adapted xerophytic communities. The garrigue provides a specialized, pre-adapted species pool well suited to these intense urban stressors.

While this thesis relies on a simplified conceptual design process, the proposed framework provides a methodology that could inspire design processes for landscape architects and urban planners.

By utilizing the habitat template approach, this thesis demonstrates how green roofs can move beyond basic *Sedum* mats into complex, multi-layered vegetation. This transition shifts the perception of extensive green roofs from passive infrastructural additions to dynamic, resilient ecosystems capable of sustaining vital ecosystem services in the face of an uncertain climate future.

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Appendix

The following list served as the base species pool to initiate the selection process. Derivation of the species is shown with the cluster number with sources as following:

1. Case study, Erfurt Germany. Source: Scharnweber (2024)

2. Phytosociological study from Calanques, Marseille, France. Source: Gehrke & Weppler (2024), Weber & Girschik (2024), Schlossarek & Boos (2024), Leucht & Scipio (2024), Seifert (2024)

3 to 6. reference landscape observations. Species identified by the author on trips to the reference landscapes within the time period 2024 to 2026. Species identification with the help of the Flora Incognita app (Mäder et al. 2021) and a plant field guide for the western Mediterranean (Thorogood 2021).

7. Phytosociological study. Phytosociological study of Di Pietro & Misano (2010). Extracting the following plant communites from the study:

- Centaureo subtilis-Thymetum capitati
- Trifolio scabri-Sedetum albi
- Sedo ochroleuci-Saturejetum cuneifoliae

8. Typical species of basiphilous garrigues.List of S61 Western basiphilous garrigue from European Environment Agency Chytrý et al. (2025).

Species	Cluster
Acinos suaveolens	7
Aegilops geniculata	2
Aethionema saxatile	7
Allium ampeloprasum	3
Allium paniculatum	5
Allium sphaerocephalon	5, 7
Allium subhirsutum	7
Alyssoides utriculata	5
Ampelodesmos mauritanicus	5
Andropogon distachyos	7
Anthemis arvensis	6
Anthemis cretica	2
Anthemis maritima	3
Anthyllis vulneraria	4, 6, 8
Aphyllanthes monspeliensis	2, 8
Argyrolobium zanonii	8
Aristolochia pistolochia	8
Artemisia alba	1
Asparagus acutifolius	2, 6
Asperula aristata	7, 8
Asphodelus ramosus	6
Asyneuma limonifolium	7
Atractylis humilis	8
Avena barbata	7
Ballota nigra	5
Bartsia trixago	7
Bellardia trixago	3
Brachypodium distachyon	2
Brachypodium pinnatum	2
Brachypodium retusum	2, 8
Briza maxima	7
Bromus madritensis	7
Bupleurum baldense	2, 7
Bupleurum fruticescens	8
Bupleurum rigidum	8
Calicotome villosa	6
Capparis spinosa	6
Carduus pycnocephalus	2
Carex distachya	7
Carex halleriana	8
Carex humilis	4, 8
Carthamus lanatus	5
Catapodium rigidum	7
Centaurea cineraria	2
Centaurea linifolia	8
Centaurea subtilis	7
Centaurium erythraea	7
Centaurium tenuiflorum	7
Centranthus ruber	2
Cephalaria leucantha	5
Cerastium supramontanum	4
Chamaeleon gummifer	6
Charybdis pancration	7
Cheirolophus intybaceus	2
Cistus albidus	2, 8
Cistus clusii	8
Cistus creticus	4
Cistus monspeliensis	7
Clinopodium nepeta	6
Consolida regalis	5
Convolvulus althaeoides	6
Convolvulus lanuginosus	8
Convolvulus lineatus	6
Coris monspeliensis	8
Coronilla juncea	2
Coronilla minima	8
Coronilla scorpioides	7
Crepis sancta subsp. sancta	7
Crupina crupinastrum	7
Cynosurus echinatus	7
Dactylis glomerata	8
Dasypyrum villosum	7
Digitalis obscura	8
Dorycnium hirsutum	3
Dorycnium pentaphyllum	8
Echinospartum boissieri	8
Echinum vulgare	2
Echium italicum	5
Elaeoselinum asclepium subsp. ascl	7
Erica multiflora	2, 6, 8
Erodium chrysanthum	1
Erodium corsicum	3
Eryngium amethystinum	5
Eryngium campestre	8
Euphorbia characias	4, 5
Euphorbia myrsinites	5
Euphorbia nicaeensis	8
Euphorbia pithyusa	3
Euphorbia segetalis	6
Euphorbia spinosa	4
Filago pygmaea	6
Frankenia laevis	3
Fumana ericifolia	8
Fumana ericoides	7, 8
Fumana laevis	8
Fumana procumbens	8
Fumana thymifolia	7, 8
Galium mollugo	4
Gastridium ventricosum	7
Genista acanthoclada	3
Genista scorpius	8
Globularia alypum	2, 8
Globularia bisnagarica	7
Hedysarum spinosissimum	6
Helianthemum apenninum	8
Helianthemum cinereum	8
Helianthemum hirtum	8
Helianthemum jonium	7
Helianthemum marifolium	8
Helianthemum salicifolium	7
Helianthemum syriacum	8
Helianthemum violaceum	8
Helichrysum italicum	3, 4
Helichrysum stoechas	5, 8
Helictochloa bromoides	8
Helictotrichon filifolium	8
Hippocrepis ciliata	7
Hippocrepis glauca	7
Hippocrepis scorpioides	8
Hyparrhenia hirta	6
Hypochaeris achyrophorus	7
Hyssopus officinalis	1
Iris lutescens	2
Iris planifolia	6
Jacobaea maritima	3
Juniperus oxycedrus	8
Juniperus phoenicea	2
Koeleria lobata	7
Koeleria vallesiana	8
Krascheninnikovia ceratoides	5
Lagurus ovatus	7
Laserpitium gallicum	2
Lavandula angustifolia	1
Lavandula lanata	8
Lavandula latifolia	8
Leontodon crispus	7
Leopoldia comosa	5
Limbarda crithmoides	6
Limodorum abortivum	4
Linaria repens	5
Linum narbonense	8
Linum strictum	2
Linum suffruticosum	8
Lithodora fruticosa	8
Lolium perenne	2
Lomelosia argentea	1
Lomelosia crenata	7
Lonicera implexa	2
Lotus cytisoides	3, 6
Lotus edulis	7
Lotus ornitopodioides	7
Macrochloa tenacissima	8
Marrubium incanum	1
Marrubium supinum	1
Marrubium vulgare	1
Matthiola fruticulosa	7
Matthiola tricuspidata	3
Medicago arborea	2
Medicago minima	2, 7
Medicago rigidula	7
Melica ciliata	5, 7
Micromeria graeca	7
Minuartia verna	7
Moraea sisyrinchium	6
Narcissus tazetta	3
Neotinea tridentata	4
Nigella damascena	5
Olea europaea	6
Onobrychis caput-galli	7
Ononis minutissima	2, 8
Ononis natrix	6
Ononis pusilla subsp. pusilla	7
Ononis reclinata	7
Onosma echioides	7
Orlaya grandiflora	7
Orobanche latisquama	8
Paeonia corsica	4
Pallenis maritima	2
Pallenis spinosa	6
Pancratium illyricum	3
Papaver rhoeas	5
Paronychia suffruticosa	8
Pentanema verbascifolium	5
Petrorhagia saxifraga	7
Phagnalon rupestre	7
Phagnalon saxatile	6, 7
Phillyrea angustifolia	2
Phillyrea latifolia	2
Phlomis lychnitis	8
Phlomis purpurea	8
Picris hieracioides	7
Pinus halepensis	2, 6, 7, 8
Pistacia lentiscus	6, 7
Plantago afra	7
Plantago bellardii	7
Plantago serraria	6
Poa bulbosa	7
Poa glauca	2
Polygala rupestris	8
Prasium majus	6
Pseudodictamnus hispanica	1
Pseudodictamnus mediterraneus	1
Ptilostemon hispanicus	8
Quercus coccifera	2, 8
Rapistrum rugosum	2
Reichardia picroides	2
Rhamnus alaternus	2, 4
Rhamnus saxatilis	7
Rhaponticum coniferum	8
Rosmarinus officinalis	7, 8
Rubia peregrina	2
Ruta angustiflora	2
Salix cinerea	4
Salvia blancoana	8
Salvia lavandulifolia	1
Salvia officinalis	1, 5, 8
Salvia rosmarinus	1, 2, 4
Salvia verbenaca	6
Santolina chamaecyparissus	4
Sarcopoterium spinosum	6
Satureja cuneifolia	7
Satureja intricata	8
Satureja montana	1, 5
Satureja obovata	8
Satureja subspicata ssp. subspicata	1
Scabiosa canescens	2
Scabiosa holosericea	4
Scolymus hispanicus	5
Scrophularia auriculata	4
Sedum album	7
Sedum caeruleum	6
Sedum ochroleucum	7
Sedum sediforme	8
Sedum sexangulare	7
Serapias cordigera	3
Sideritis hyssopifolia	1
Sideritis incana	8
Sideritis leucantha	8
Sideritis libanotica	1
Sideritis romana	6
Sideritis scardica	1
Sideritis syriaca	1
Sideritis tragoriganum	8
Silene colorata	6
Silene conica	7
Silene latifolia	5
Smilax aspera	2, 6
Sonchus tenerrimus	2
Spartium junceum	5
Stachys glutinosa	4
Staehelina dubia	2, 8
Stipa austroitalica	7
Stipa capensis	7
Stipa juncea	2
Stipa offneri	2, 8
Teucrium capitatum	7
Teucrium chamaedrys	1, 8
Teucrium flavum	1, 2, 4, 6, 7
Teucrium fruticans	6
Teucrium gnaphalodes	8
Teucrium polium	3, 6
Teucrium pseudochamaepitys	8
Thapsia asclepium	6
Thapsia garganica	6
Thesium humifusum	7, 8
Thymbra capitata	6
Thymelaea tartonraira	4
Thymelaea tinctoria	8
Thymus capitatus	7
Thymus vulgaris	1, 2, 8
Thymus zygis	8
Trachynia distachya	7
Trifolium campestre	7
Trifolium scabrum	7
Trifolium stellatum	2, 6
Trisetaria panicea	7
Ulex europaeus	2
Ulex parviflorus	8
Urospermum dalechampii	2
Urospermum picroides	2, 7
Valantia muralis	7
Verbascum sinuatum	6
Verbascum thapsus	5
Vincetoxicum hirundinaria	4