Full Paper

Twenty Years of Extensive Green Roof Research

20 Jahre Versuche zu extensiven Dachbegrünungen

20 anni di ricerca sul verde pensile estensivo

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ABSTRACT

Over a 20-year period, the Laimburg Research Centre in South Tyrol examined the ecological performance, hydrological efficiency, and biodiversity potential of extensive green roofs under sub-Mediterranean climatic conditions. The study evaluated twelve different green roof areas on a facility roof across three experimental phases (2005-2024), focusing on water retention, vegetation development, maintenance costs, and compliance with the Italian green roof standard UNI 11235 (2007, revised in 2015). Results indicated annual water retention rates between 55.6% and 72.4%, with maintenance costs ranging from 0.30 to 85 €/m² per year. None of the systems initially met the UNI 11235 requirements due to challenges related to substrate properties and vegetation coverage. Increasing substrate depth and structural diversity improved both vegetation establishment and ecological functions. Substrates of 14 cm supported higher colonisation of spontaneous species compared to 8 cm, while depths of 20 cm allowed the integration of drought-tolerant shrubs, enhancing evapotranspiration. In later phases of the research, habitat structures such as mounds, deadwood, sandy areas and stone walls were introduced, promoting biodiversity and the typical fauna of dry grasslands such as grasshoppers and butterflies.

KEYWORDS

Green roof, extensive green roofs, sub-mediterranean climate, water retention, evapotranspiration, biodiversity, substrate depth, UNI 11235, maintenance costs, ecological design, Sedum, shrubs, urban ecology, nature based solutions.

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3	1
4	2
7	5
8	6
11	9
12	10
Drainage layer expended shale	Drainage mat FD 25

Fig. 1: Overall view 2024 (© Ivo Corrà 2024) of the 420 m^2 experimental green roof area with 12 sectors and detail with section numbers and type of drainage.

INTRODUCTION

For over two decades, the Laimburg Research Centre in South Tyrol has been investigating the ecological potential of extensive green roofs under local climatic conditions. This long-term research has focused on key aspects such as water retention, plant selection, maintenance costs, and biodiversity. The trials were carried out in collaboration with the Office for Water Protection, Province of Bolzano/Bozen (responsible for measuring rainwater retention), the Laimburg Professional School (maintenance), and Eurac Research Bozen (biodiversity monitoring).

The project aimed to evaluate and adapt commercial green roof systems to local conditions. Three experimental phases (each lasting four-five years), beginning in 2005, examined long-term impacts, especially under warmer weather conditions in the southern area of the Alps. The 12 sectors are each 28.35 m^2 in size and have their own run-off.

Italy has had a national standard UNI 11235 [1] in place for green roofs since 2007 (revised in 2015).

EXPERIMENTAL CONDITIONS

Bolzano experiences a sub-mediterranean climate with hot summers and mild winters. Laimburg and the experimental green roof (Fig. 1), at 222 m a.s.l., recorded 816 mm annual media precipitation and a mean yearly temperature of 13.1 ℃ (Fig. 2) in 2023, with 59 tropical days [2].

The Laimburg meteorological station, together with the storage basins located under each sector, enabled the collection and calculation of run-off coefficients and rainwater retention per sector. The precipitation-free periods (Fig. 3 yellow) lasting more than 14 days in these 20 years indicate a potential stress on local vegetation and water resources.

STUDY SITE

The 420 m^2 roof area with the experimental plots is located on the garage of the Laimburg Professional School and has a 2° incline towards the center. The facility was constructed in 2004 and consists of 12 separate experimental plots, each equipped with its

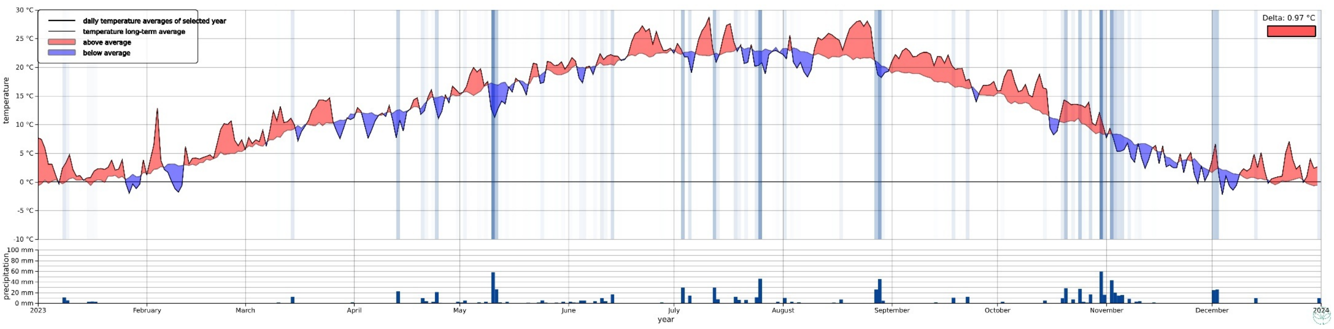


Fig. 2: Temperature daily averages in 2023 and deviations from the 30-year averages and mm precipitation (https://meteo.laimburg.it/).

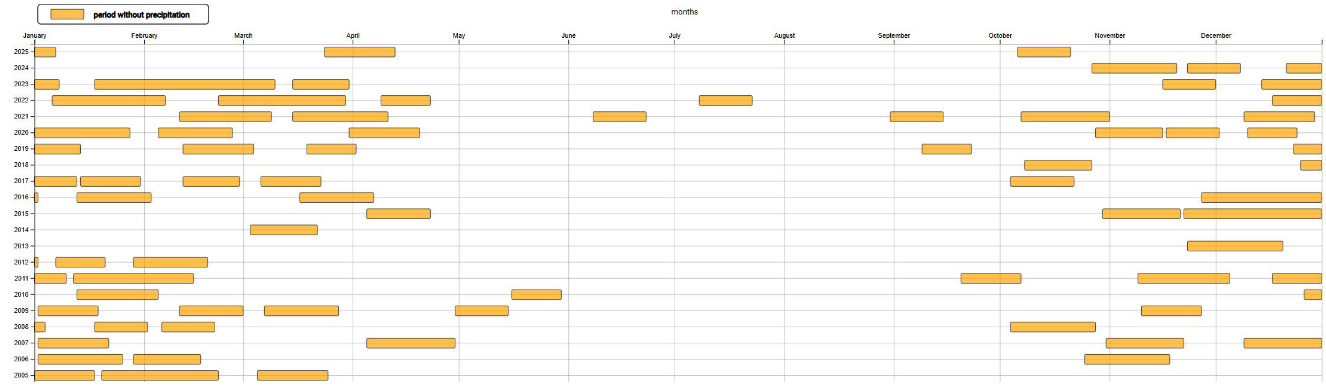


Fig. 3: Precipitation-free periods (yellow) of $\geq$ 14 days between 2005 and 2025 (https://meteo.laimburg.it).

own drainage system. Rainwater from each 6.3 x 4.5 m plot is directed through a drain into a technical room below, where it is collected in storage basins to allow precise measurement of run-off volumes. The Laimburg Research Centre also houses a meteorological station that continuously provides accurate weather data.

Tab. 1: Layer setup of the 12 sectors in the first experimental trial.

Sector	Layer	Total height (cm)	Substrate depth (cm)	Vegetation
1	multi-layer	15	8	Meadow, sown
2	multi-layer	16	8	Perennials, potted plants
3	multi-layer	17	10	Perennials potted plants
4	single-layer	5	3	Vegetation mat
5	multi-layer	15	8	Perennials potted plants
6	single-layer	10	9	Perennials potted plants
7	multi-layer	11	9	Perennials potted plants
8	multi-layer	16	8	Sedum sprouts
9	multi-layer	16	12	Perennials potted plants
10	multi-layer	11	8	Sedum sprouts
11	multi-layer	17	14	Sprouts and potted plants
12	multi-layer	9	6	Small bales

Along the edge of the roof, an intensively vegetated area with shrubs and perennials has been planted. This area is regularly irrigated, fertilized, and pruned, but is not part of the scientific experiments.

The 12 experimental plots themselves were irrigated only during the initial establishment phase (four to six weeks), never fertilized, and have been maintained twice a year. A protective mat with thermal fleece (drainage protection mat) was laid in all sectors on top of the waterproofing before they were greened, starting in July 2004.

METHODS

A drainage mat (FD 25) was installed in sectors 1, 2, 5, 6, 9, and 10, on top of the protection layer, while in the remaining sectors a 5 cm thick loose drainage layer made of expanded shale was used.

The maintenance of the extensive green roofs was carried out twice a year, in spring and autumn. During these interventions, pioneer woody species (such as *Populus sp.*, *Paulownia tomentosa*, or *Buddleja davidii*) and herbaceous plants were removed, as their vigorous growth could overtake and suppress the target vegetation.

FIRST EXPERIMENTAL PHASE (2005-2010)

In the first experimental phase, the 12 sectors were built using green roof systems commercially available in South Tyrol, with the total system depth limited to a maximum of 20 cm (Tab. 1). Research topics included evapotranspiration, run-off delay, water quality and vegetation development.

There were monolayers to multilayer sectors, with or without water storage elements or with loose drainage material. The substrate ranged between 3 and 14 cm, and we used pot plants, plants with reduced root balls, seeds, *Sedum*-cuttings or pre-cultivated matting. Measurements included water monitoring, assessment of vegetation cover, and water sampling. Maintenance activities and data from the meteorological station were also recorded.

SECOND EXPERIMENTAL PHASE (2012-2017)

A standardized multi-layer system with one type of substrate and three depths (8 cm, 14 cm, 20 cm) was installed (Tab. 2). Half of the sectors

Tab. 2: Substrate height, drainage layer and used vegetation.

Sector	Substrat	Drainage	Vegetation	Used species
1+2	8 cm	drainage and water storage mat (FD 25)	*Sedum* species thriving on silicate outcrops	*Allium senescens*, *Allium schoenoprasum*, *Antennaria dioica* 'Rotes Wunder', *Dianthus arenarius* 'Froebeli', *Dianthus deltoides* 'Flashing Light', *Dianthus gratianopolitanus* 'Eydangeri', *Gypsophila repens*, *Potentilla aurea*, *Saponaria ocymoides*, *Sedum album* 'Murale', *Sedum album* 'Coral Carpet', *Sedum floriferum* 'Weihenstephaner Gold', *Sedum reflexum*, *Sedum reflexum* 'Angelina', *Sedum sexangulare*, *Sempervivum arachnoideum*, *Thymus serpyllum*, *Koeleria glauca*
3+4	8 cm	5 cm expanded shale	*Sedum* species thriving on silicate outcrops	*Allium senescens*, *Allium schoenoprasum*, *Antennaria dioica* 'Rotes Wunder', *Dianthus arenarius* 'Froebeli', *Dianthus deltoides* 'Flashing Light', *Dianthus gratianopolitanus* 'Eydangeri', *Gypsophila repens*, *Potentilla aurea*, *Saponaria ocymoides*, *Sedum album* 'Murale', *Sedum album* 'Coral Carpet', *Sedum floriferum* 'Weihenstephaner Gold', *Sedum reflexum*, *Sedum reflexum* 'Angelina', *Sedum sexangulare*, *Sempervivum arachnoideum*, *Thymus serpyllum*, *Koeleria glauca*
5+6	14 cm	drainage and water storage mat (FD 25)	compact perennial plants suitable for alkaline soils	*Briza media* 'Limouzi', *Dianthus carthusianorum*, *Euphorbia cyparissias* 'Clarice Howard', *Festuca glauca* 'Blauglut', *Globularia cordifolia*, *Helianthemum nummularium* 'Sterntaler', *Helictotrichon sempervirens*, *Iris pumila*, *Linum perenne* 'Saphir', *Melica ciliata*, *Prunella grandiflora*, *Pulsatilla vulgaris*, *Salvia nemorosa* 'Mainacht', *Sanguisorba minor*, *Sedum album* 'Murale', *Stipa pennata* 'Ponytail', *Thymus praecox* 'Coccineus', *Veronica prostrata*, *Veronica teucrium* 'Königsblau'
7+8	14 cm	5 cm expanded shale	compact perennial plants suitable for alkaline soils	*Briza media* 'Limouzi', *Dianthus carthusianorum*, *Euphorbia cyparissias* 'Clarice Howard', *Festuca glauca* 'Blauglut', *Globularia cordifolia*, *Helianthemum nummularium* 'Sterntaler', *Helictotrichon sempervirens*, *Iris pumila*, *Linum perenne* 'Saphir', *Melica ciliata*, *Prunella grandiflora*, *Pulsatilla vulgaris*, *Salvia nemorosa* 'Mainacht', *Sanguisorba minor*, *Sedum album* 'Murale', *Stipa pennata* 'Ponytail', *Thymus praecox* 'Coccineus', *Veronica prostrata*, *Veronica teucrium* 'Königsblau'
9+10	20 cm	drainage and water storage mat (FD 25)	higher perennial plants and small shrubs	*Berberis vulgaris*, *Chamaecytisus purpureus*, *Colutea arborescens*, *Cotinus coggygria*, *Genista tinctoria*, *Lonicera xylosteum*, *Prunus mahaleb*, *Rosa rubiginosa*, *Salvia nemorosa* 'Mainacht', *Geranium sanguineum*, *Melica ciliata*, *Sedum album* 'Murale', *Sedum album* 'Coral Carpet', *Sedum floriferum* 'Weihenstephaner Gold', *Teucrium chamaedrys*, *Thymus serpyllum* 'Albus', *Veronica prostrata*
11+12	20 cm	5 cm expanded shale	higher perennial plants and small shrubs	*Berberis vulgaris*, *Chamaecytisus purpureus*, *Colutea arborescens*, *Cotinus coggygria*, *Genista tinctoria*, *Lonicera xylosteum*, *Prunus mahaleb*, *Rosa rubiginosa*, *Salvia nemorosa* 'Mainacht', *Geranium sanguineum*, *Melica ciliata*, *Sedum album* 'Murale', *Sedum album* 'Coral Carpet', *Sedum floriferum* 'Weihenstephaner Gold', *Teucrium chamaedrys*, *Thymus serpyllum* 'Albus', *Veronica prostrata*

were still covered with loose drainage material (5 cm expanded shale) and the other six sectors with a drainage and water storage mat (FD 25). The 12 sectors were constructed with different layer combinations to examine the effects of various substrate and drainage systems.

Sectors 1 and 2 were each equipped with a 5 cm layer of expanded shale, a filter fleece, and 8 cm of substrate. Sectors 3 and 4 featured a 2.5 cm drainage and retention mat, topped with a filter fleece and likewise 8 cm of substrate. Sectors 5 and 6 were built with 5 cm of expanded shale, a filter fleece, and a substrate depth of 14 cm. Sectors 7 and 8 followed the same structure, also with 14 cm of substrate. Sectors 9 and 10 included a 5 cm layer of expanded shale, a filter fleece, and a particularly deep substrate layer of 20 cm. Finally, sectors 11 and 12 were constructed with a 2.5 cm drainage and retention mat, a filter fleece, and 20 cm of substrate.

THIRD EXPERIMENTAL PHASE (2019-2024)

In collaboration with Eurac Research biodiversity became the focus. Deadwood, stone piles, dry walls, and water features were added to create new habitats. The green roof became part of the biodiversity monitoring in South Tyrol [3]. Surveys between 2022 and 2023 recorded grasshoppers, butterflies, birds, and bats.

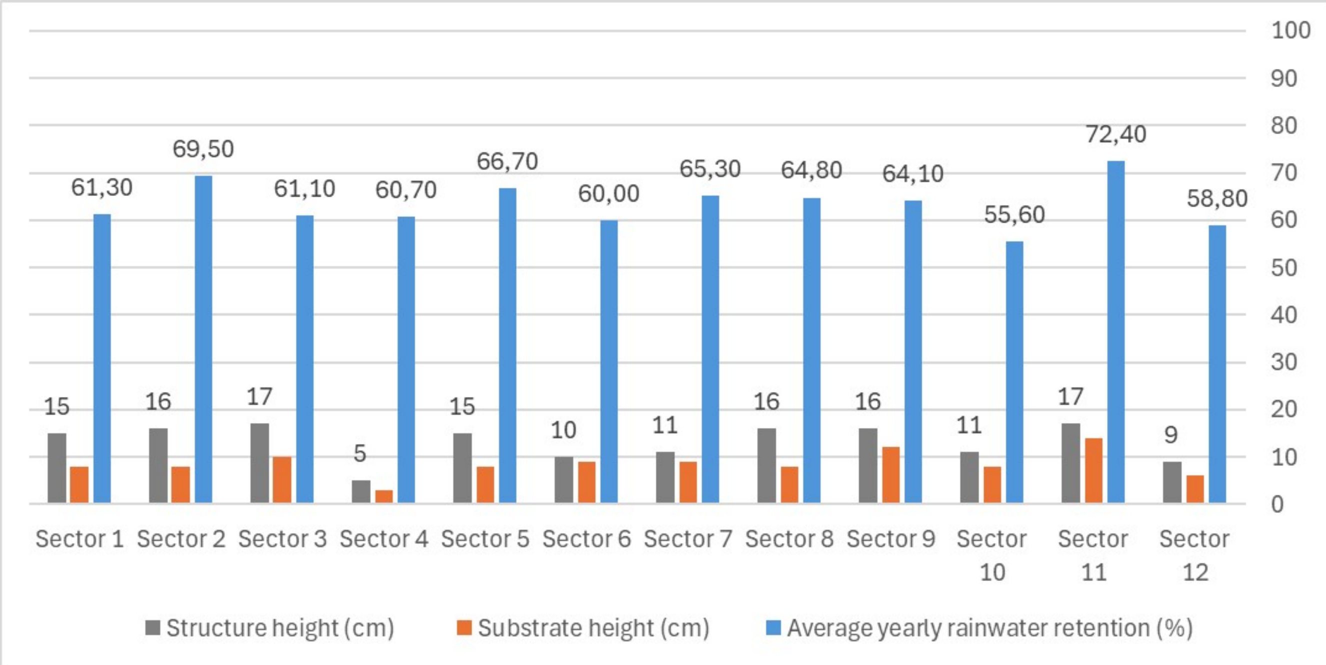


Fig. 4: First experimental phase (2005-2010): Comparison between total structure height (grey), substrate heigh (orange) and average yearly rainwater retention (blue).

The existing extensive green roof with a multi-layer structure could be reused for the new trial without changing the filter, drainage or sealing layers. An existing extensive roof can be retrofitted to increase biodiversity if the static load-bearing capacity allows it.

Modelling (formation of mounds and hollows) over 30 cm in height ensures that soil animals are protected from frost in winter and from drying out in summer. The intensity of sunlight varies on these mounds and hollows, creating shaded areas and a differentiated microclimate. Vegetation-free areas such as sand lenses and gravel areas are needed by small animals as breeding and sunbathing areas or for feather care. The areas lined with pond liner collect water for drinking and bathing after rainfall and dry out again in 2-5 days, depending on the weather. Elevated structures (tree trunks with side branches) are important perches for birds and, at the same time, provide a habitat for wood-decaying insects. The application of organic matter can facilitate the germination of seeds that are carried by the wind onto the roof surface. This increases the possibility of native plant species settling spontaneously.

In addition to diversifying the habitat as a place for animals to live, breed and hibernate, the availability of food is also crucial for colonisation. Insects feed on pollen, nectar or leaves and themselves become food for birds or bats.

In 2018-2019, habitat elements and plants were specifically added to the existing test roof to enrich the habitat and encourage biodiversity:

To enhance the diversity of plant species, a variety of perennials and small shrubs were planted in autumn 2018, including *Allium senescens*, *Geranium sanguineum*, *Hieracium pilosella*, *Iris pumila*, *Prunella grandiflora*, *Sedum acre*, *Sedum album* 'Murale', *Sedum floriferum* 'Weihenstephaner Gold', *Sedum* 'Green Acre', *Sedum reflexum*, *Sedum sexangulare* and *Cytisus praecox* 'Allgold'. Additionally, 100 geophytes were planted in November 2019, consisting of *Tulipa dasystemon tarda* and *Tulipa turkestanica*.

To increase the genetic diversity of vegetation, organic material in the form of composted soil was applied to facilitate the establishment of native species via wind dispersal. In sectors 1-4, compost was applied to approximately 10% of the area in the form of circular rings with a height of roughly 8 cm.

Habitat diversity was expanded by incorporating various materials, such as sand and gravel/crushed stone, thereby creating dry and wet microhabitats. For water retention and slow evaporation, a 1 mm rubber sealing membrane was installed in 4 areas, each measuring 1.5 × 1.5 m. Dry stone walls were constructed from mixed quarry stones, measuring approximately 2 m in length and 50 cm in height, with a total volume of around 2 m³. Behind these walls, stone piles were created to provide refuges for reptiles and insects.

Additional habitat structures included approximately 1 m³ of washed fine sand (grain size 0.3-1 mm) distributed across four areas, and approximately 1.5 m³ of washed gravel (grain size 2-64 mm) also distributed across four areas. Substrate depth was increased to up to 30 cm to establish windward and leeward sides and create varying light conditions. Deadwood was added through the installation of eight fallen tree trunks, comprised of larch and birch, to provide further structural habitat.

Nesting opportunities for fauna

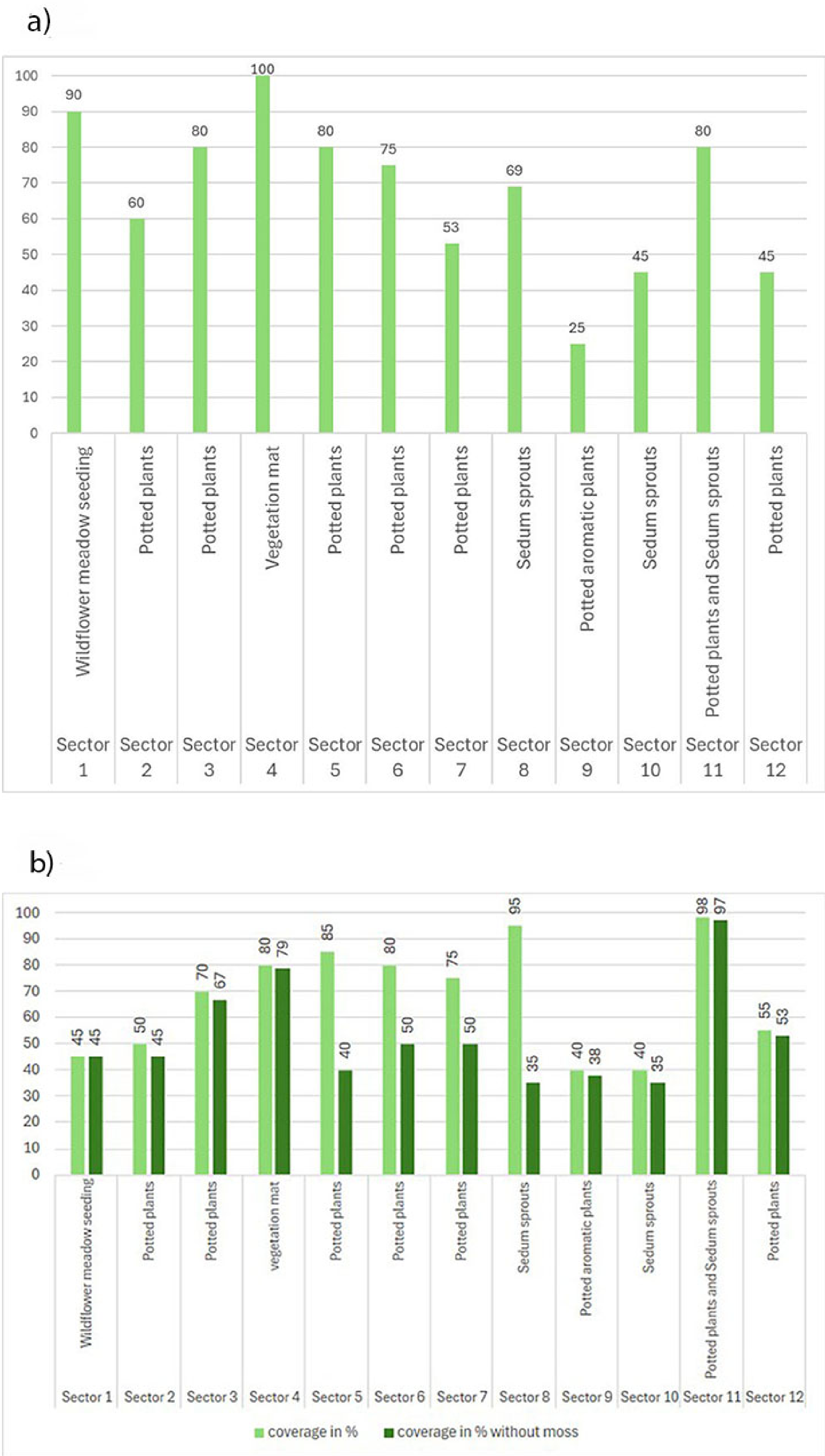
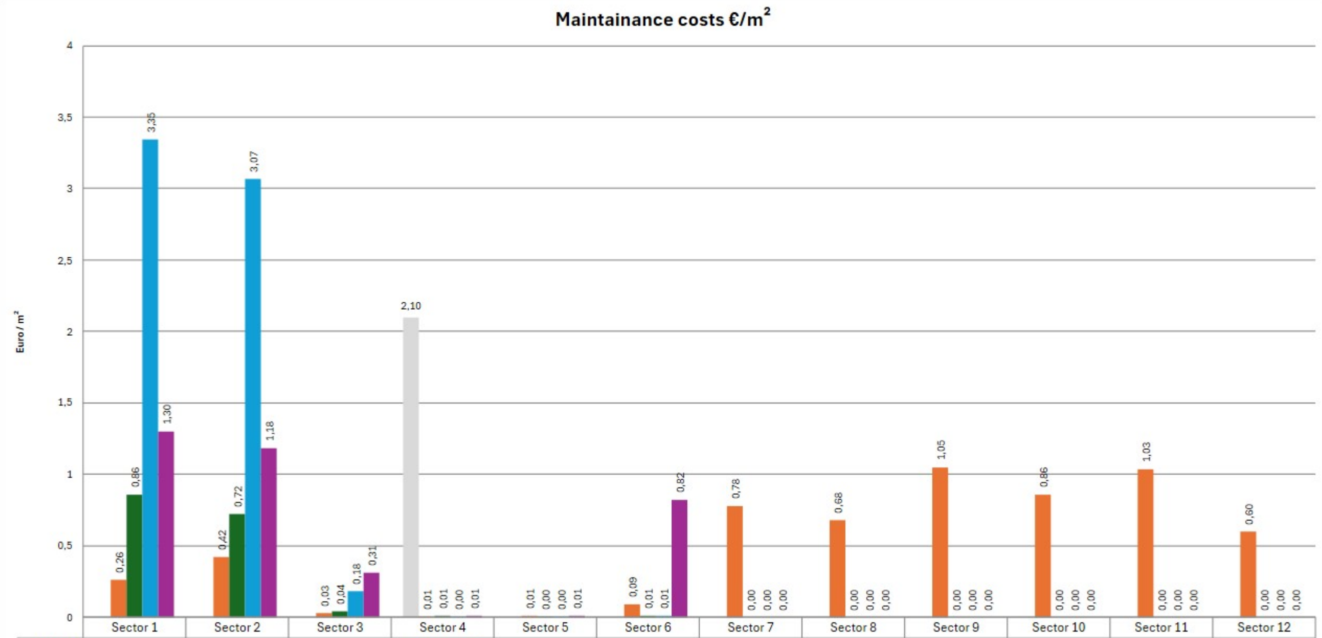


Fig. 5: Coverage (%) after 12 months (a) and at the end of the first experimental phase in the year 2010 (b) with and without moss.



	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Sector 7	Sector 8	Sector 9	Sector 10	Sector 11	Sector 12
07/2004				2,096534392								
10/2005	0,264648442	0,419787184	0,025936508	0,005283363	0,007684891	0,089817166	0,77569371	0,680112875	1,046586126	0,855424456	1,033137566	0,5979806
09/2006	0,856865373	0,723820694	0,03794415	0,008165197	0,003842446	0,012487948	0	0	0	0	0	0
09/2007	3,345809524	3,066271605	0,179634333	0,000960611	0,000960611	0,008645503	0	0	0	0	0	0
10/2009	1,30210876	1,182992945	0,309797178	0,012968254	0,012968254	0,817960611	0	0	0	0	0	0

Fig. 6: Maintenance costs during four/five years (04/2005-06/2010) in €/m².

were enhanced through the installation of six bird nesting boxes, four dormouse boxes, sixteen insect nesting boxes, four earwig sleeping tubes, two ant observation stones, five nesting elements for dry stone walls, four niche boxes for small mammals, four surface bumblebee boxes, and two watering stations suitable for birds or insects.

Biodiversity surveys

In 2023, the roof was included as a special site in the sampling campaign of the Biodiversity Monitoring South Tyrol (BMS). The BMS experts surveyed five different BMS focus groups at this location: butterflies, grasshoppers, vascular plants, birds, and bats. The methodology of the surveys follows, the one used by the BMS [3] with minor adaptations.

Vascular plants

For the survey of the vascular plants the BMS methodology was adapted. On every part of the roof, i.e. on the 8 cm, 14 cm and 30 cm areas respectively, on a surface of 10 m^2 (3.16 x 3.16 m) every single vascular plant was recorded, and a cover value was estimated. A full species list was subsequently recorded for a total of 100 m^2 (10 x 10 m). Once the survey had been carried out, the list was divided into species that had been deliberately introduced and those that had settled spontaneously.

Grasshoppers

The chosen method combines acoustic and visual identification. The survey is conducted on a 10 x 10 m plot, starting with a net sweep across the diagonal and including a thorough search. Specimens are only collected in case of doubt, and the survey is conducted once in late summer. The entire survey takes 30 minutes.

Butterflies

For the butterfly survey, the Austrian "Viel-Falter" methodology was applied. It involves three to four annual surveys between May and September. Usually, a 50 m-long transect is traversed, recording all butterflies within a radius of 2.5 m; followed by a time recording over an extended area of 1000 m^2. In the case of the roof surveys the entire surface of the roof was considered. The initial transect survey was omitted.

Birds

The survey method is based on the MITO2000 protocol, which uses acoustic point counts. Each survey lasts 10 min./site and takes place from the beginning of the breeding season until mid-July, to largely exclude migratory birds. Observations start at dawn and continue until late morning. Bird species are recorded within a 100 m radius around each monitoring point, with three repetitions per point; at higher-altitude sites, at least two repetitions are conducted. The survey also included species that were only found outside the roof area.

Bats

The methodology used to record bats is based on the use of ultrasonic recording devices known as bat loggers. Acoustic recordings from deployed bat loggers, collected over three consecutive nights, were used to identify species or species groups. These acoustic signals not only enable differentiation between individuals searching for food, but also between migrating individuals, thus enabling precise recording and study of the bat population. With the chosen

Tab. 3: Used plant species and their development.

Plant species	Development	Observation
Sector 1,2,3 and 4: *Sedum* species thriving on silicate outcrops		
Allium senescens	+	The vegetation consists almost exclusively of *Sedum* species and *Thymus serpyllum*. *Koeleria glauca*, *Dianthus* sp. and *Potentilla aurea* died completely. New arrivals have been *Euphorbia cyparissias*, *Prunella grandiflora* and *Hieracium aurantiacum*.
Allium schoenoprasum	+	
Antennaria dioica 'Rotes Wunder'	-	
Dianthus arenarius 'Froebeli'	-	
Dianthus deltoides 'Flashing Light'	x	
Dianthus gratianopolitanus 'Eydangeri'	x	
Gypsophila repens	–	
Potentilla aurea	x	
Saponaria ocymoides	-	
Sedum album 'Murale'	++	
Sedum album 'Coral Carpet'	++	
Sedum floriferum 'Weihenstephaner Gold'	++	
Sedum reflexum	++	
Sedum reflexum 'Angelina'	+	
Sedum sexangulare	+	
Sempervivum arachnoideum	-	
Thymus serpyllum	++	
Koeleria glauca	x	
Sector 5,6,7 and 8: compact perennial plants suitable for alkaline soils		
Dianthus carthusianorum	x	The vegetation is dominated by *Sanguisorba minor* (seedlings), *Prunella grandiflora*, *Sedum album* and *Euphorbia cyparissias*.
Euphorbia cyparissias 'Clarice Howard'	+	
Festuca cinerea 'Blauglut'	++	
Globularia cordifolia	-	
Helianthemum nummularium 'Sterntaler'	x	
Helictotrichon sempervirens	x	
Iris pumila	+	
Linum perenne 'Saphir'	x	
Melica ciliata	–	
Prunella grandiflora	++	
Pulsatilla vulgaris	+	
Salvia nemorosa 'Mainacht'	-	
Sanguisorba minor	++	
Sedum album 'Murale'	++	
Stipa pennata 'Ponytail'	x	
Thymus praecox 'Coccineus'	–	
Veronica prostrata	x	
Veronica teucrium 'Königsblau'	x	

Tab. 3: Used plant species and their development.

Plant species	Development	Observation
Sector 9,10,11 and 12: higher perennial plants and small shrubs		
Berberis vulgaris	x	
Chamaecytisus purpureus	x	*Prunus mahaleb*, *Teucrium chamaedrys* and *Lonicera xylosteum* dominate among the shrubs. The perennials *Geranium sanguineum*, *Salvia nemorosa* and *Melica ciliata* are particularly impressive. *Dianthus carthusianorum* has become widespread.
Colutea arborescens	–	
Cotinus coggygria	-	
Lonicera xylosteum	+	
Prunus mahaleb	++	
Prunus spinosa	+	
Rosa rubiginosa	+	
Salvia nemorosa 'Mainacht'	+	
Geranium sanguineum	++	
Melica ciliata	+	
Sedum album 'Murale'	+	
Sedum album 'Coral Carpet'	+	
Sedum floriferum 'Weihenstephaner Gold'	+	
Teucrium chamaedrys	++	
Thymus serpyllum 'Albus'	–	
Veronica prostrata	x	
++ very strongly developed, + well developed, - declining, - - greatly reduced, × dead		

methodology, it is not possible to accurately locate individual persons.

RESULTS

FIRST EXPERIMENTAL PHASE

Average yearly water retention ranged from 55.6% to 72.4% (Fig. 4). No sector fully met the UNI 11235 standard with challenges in pH levels and substrate properties (air content). Maintenance costs varied from 0.3 to 85 eurocents/m^2 per year (time value 1.9 sec per plant, hourly wage € 26).

During the first maintenance phase, the plants developed more quickly on the drainage layer with expanded shale; after four years, no differences were visible between the two drainage layer types. Only five of twelve sectors reached the required 80% vegetation cover after four years (Fig. 5). The Italian standard for green roofs specifies the coverage ratio until approval. According to this standard, when inspecting green spaces 12 months after completion of the greening, at least 80% of the area must be covered with living plants when viewed from above, 75% of the planted species must be rooted, and weeds must not exceed 7% of the total area. Unfortunately, it has not been defined whether moss coverage can be included in this calculation.

In Sector 1, the sown wildflower meadow failed to establish and died off by the end of 2006, which led to increased maintenance costs in 2007 due to reseeding. In Sector 4, the supplied vegetation mat already contained seeds of *Galinsoga ciliata* (3920 seeds) and *Sonchus asper* (445 seeds). Removing these species during the first year was time-consuming (155 plants removed per m^2 resulted in 4.88 minutes of maintenance per m^2). Sector 6 consisted of a single-layer structure with partly short-lived *Sedum* species (*Sedum hispanicum*, *Sedum sexangulare*) and species that developed only slowly (*Sedum spurium* 'Fuldaglut'). The ground cover decreased annually, and maintenancecosts (Fig. 6) rose accordingly, *Euphorbia maculata* spread rapidly and overgrew carpet-like *Sedum* species.

SECOND EXPERIMENTAL PHASE

Development of vegetation

In 2017, the vegetation was surveyed, the cover percentage was assessed, and the amount of undesirable species was determined (Tab. 3). The vegetation developed better on the loose material, and the coverage was generally slightly higher, but more plants were also

Tab. 4: Coverage and weed growth after 4 years.

Sector	Stratification	Coverage %	Of these, undesirable species %
1	5 cm expanded shale, filter layer, 8 cm substrate	80	5
2		75	5
3	2.5 cm high drainage and storage mat, filter layer, 8 cm substrate	80	3
4		80	3
5	5 cm expanded shale, filter layer, 14 cm substrate	90	10
6		90	15
7	2,5 cm high drainage and storage mat, filter layer, 14 cm substrate	85	5
8		85	5
9	5 cm expanded shale, filter layer, 20cm substrate	75	10
10		80	10
11	2,5 cm high drainage and storage mat, filter layer, 20 cm substrate	75	5
12		80	5

removed during maintenance work. Five of the 12 sectors achieved a coverage ratio of 80% after 12 months.

Results showed that shrubs increased evapotranspiration and biodiversity. Plant selection was adapted to substrate depth, with *Sedum* and low perennials in thin layers, and grasses, geophytes, and shrubs (*Berberis vulgaris*, *Colutea arborescens*, *Prunus spinosa*, *Prunus mahaleb*, *Lonicera xylosteum*) in deeper layers.

When using shrubs for extensive green roofs with a substrate depth of 20 cm (Tab. 3c) was observed that some species are also well suited to a substrate depth of just a few cm and extensive conditions. When using these species, it is advisable to underplant with ground-covering perennials (*Sedum* and other species), as the woody plants grow very slowly, which can reduce maintenance requirements (Tab. 4).

The cover rates improved significantly in the second series of experiments. The number of undesirable species was lowest on the *Sedum* roof with only 8 cm of substrate, while the combination of 14 cm of substrate with perennials showed the highest number of undesirable species. For the combination of shrubs on extensive green roofs, it is advisable to use many ground-cover plants (also underneath the shrubs) to reduce the establishment of unwanted vegetation (Tab. 5).

The year 2015 resulted in very high losses, with sectors 5-8 almost completely collapsing.

For the classic extensive green roof with a substrate depth of 8 cm, the use of perennials from the genera *Sedum* proved to be effective. For the 14 cm substrate depth, it became evident that under such extreme weather conditions as in 2015, many species - although drought-tolerant - were unable to survive.

The shrubs in sectors 9-12 declined significantly, with many dying off. The *Sedum* species on 8 cm of substrate in sectors 1 - 4 showed the best survival rates. Regarding the use of woody plants for extensive green roofs, it can be concluded that some species are indeed suitable for shallow substrate layers and extensive conditions: *Prunus mahaleb*, *Lonicera xylosteum*, *Rosa rubiginosa* and *Teucrium chamaedrys* showed good growth, while *Colutea arborescens* was able to resprout after dying back. When using woody plants, underplanting with ground-cover perennials (*Sedum* and other species) is advisable, as the shrubs grow very slowly, which can help reduce maintenance requirements.

Climatic conditions will continue to be unstable and extreme in the future. Therefore, a high level of species diversity is even more important for extensive green roofs. A relatively stable foundation of succulent plant species, combined with species that spread by seed and thus fill gaps (*Dianthus carthusianorum*, *Sanguisorba minor*, *Euphorbia cyparissias* or *Prunella grandiflora*), appears to be the most successful approach.

Tab. 5: Average number of unwanted plants removed per maintenance cycle over four years.

Sector	1	2	3	4	5	6	7	8	9	10	11	12
Number of removed plants	25	35	27	27	57	71	76	80	188	243	342	554

Tab. 6: Species list of vascular plants (3.5.2023) and cover (%). Species names in bold appeared spontaneously, species names in normal letters were planted/seeded. Species with N: neophytes; *: shrub layer, i.e. woody plants higher than 30 cm; **: ephemeral species, unclear origin.

Species name	Species name German	Species name Italian	Subplot A (8 cm)	Subplot B (14 cm)	Subplot C (20-30 cm)
Agave filifera	Agave	Agave			1.20
Allium schoenoprasum	Schnitt-Lauch	Erba cipollina	1.00		
Allium senescens	Schlangen-Lauch	Aglio romano	0.20		
Anchusa officinalis	Gewöhnliche Ochsenzunge	Buglossa comune			0.30
Anthemis cotula*	Stinkende Hundskamille	Antemide fetida		0.001	
Arenaria serpyllifolia	Quendel-Sandkraut	Arenaria serpyllifolia		5.00	0.01
*Berberis vulgaris**	Gewöhnliche Berberitze	Crespino comune			0.10
Cardamine hirsuta s.lat.	Behaartes Schaumkraut	Cardamine hirsuta			0.002
Colutea arborescens	Blasenstrauch	Colutea		0.01	
*Cotinus coggygria**	Perückenstrauch	Sommacco selvatico			1.00
Dianthus carthusianorum	Kartäuser-Nelke	Garofano dei Certosini	0.05	0.10	1.00
Echium vulgare	Gewöhnlicher Natternkopf	Viperina comune		0.01	
Erigeron annuus N	Einjähriges Berufkraut	Cespica annuale		0.20	
Geranium sanguineum	Blutroter Storchschnabel	Geranio sanguigno		0.002	0.20
Hieracium pilosella	Mausohr-Habichtskraut	Sparviere pelosetto	0.01		
Hieracium sp.	Habichtskraut	Sparviere			0.005
Hypericum perforatum	Echtes Johanniskraut	Iperico perforato		0.10	0.10
Iris pumila	Sumpf-Schwertlilie	Giaggiolo acquatico		5.00	
Oxalis stricta N	Aufrechter Sauerklee	Acetosella minore		0.002	
*Prunus mahaleb**	Felsen-Kirsche, Steinweich-sel	Ciliegio canino			7.00
Pulsatilla vulgaris	Frühlings-Kuhschelle	Pulsatilla primaverile		0.30	0.005
Salvia pratensis	Wiesen-Salbei	Salvia dei prati		0.002	8.00
Sanguisorba minor	Kleiner Wiesenknopf	Salvastrella minore		0.10	
Sedum album	Weißer Mauerpfeffer	Sedo bianco	1.70	0.30	
Sedum kamtschaticum	Dickblätt. Mauerpfeffer	Sedo a foglie spesse	20.00	18.00	47.00
Sedum rupestre agg.	Artengr. Felsen-Mauerpfeffer	Gruppo di Sedo rupestre	0.70	2.50	8.00
Sedum sexangulare	Milder Mauerpfeffer	Borracina insipida	0.45	0.10	
Senecio vulgaris	Gewöhnliches Greiskraut	Senecione comune			0.001
Setaria sp.	Borstenhirse	Setaria, Pabbio		0.01	
Taraxacum sect. Tarax-acum	Artengr. Gewöhn. Löwen-zahn	Gr. Tarassaco comune			0.005
Teucrium chamaedrys	Echter Gamander	Camedrio querciola			1.00
Thymus praecox	Frühblühender Thymian	Timo precoce	1.00		0.10
textbfTrifolium arvense	Hasen-Klee	Trifoglio arvense	3.00	10.00	5.00
Veronica arvensis	Feld-Ehrenpreis	Veronica dei campi		0.01	0.001
Vicia hirsuta	Rauhaarige Wicke	Veccia tentennina	0.20	2.00	0.01
Vulpia myuros	Mäuse-Federschwingel	Vulpia coda di topo	1.00	27.00	5.00

Tab. 7: Bird species found on the extensive roof.

Bird species	Maximum of individuals within 3 visits
Aegithalos caudatus	1
Carduelis carduelis	1
Chloris chloris	2
Columba palumbus	1
Corvus corax	1
Cyanistes caeruleus	2
Delichon urbicum	1
Falco tinnunculus	1
Fringilla coelebs	3
Garrulus glandarius	1
Motacilla alba	1
Parus major	2
Passer italiae	3
Phoenicurus ochruros	1
Ptyonoprogne rupestris	2
Serinus serinus	3
Streptopelia decaocto	1
Sylvia atricapilla	1
Turdus merula	3
Turdus philomelos	1

THIRD EXPERIMENTAL PHASE

Maintenance of the experimental roof was carried out only once per year (in 2020, maintenance was skipped due to COVID-19). Nevertheless, the cover rate remained sufficiently high, and no damage to the waterproofing or primary vegetation occurred due to newly established plant species. The fewer maintenance interventions required, the better it is for the establishment of fauna and flora. Only spontaneously emerging woody plants (*Ulmus*, *Buddleja*, *Ailanthus*, *Betula*) were removed, as their aggressive roots could damage the waterproofing.

Results of biodiversity surveys

Vascular plants

A total of 49 vascular plants (Tab. 6) were registered, 16 of which were neither planted nor seeded, i.e. they dispersed spontaneously to the area. 6 species grew within the 100 m^2 plot but outside the 3 subplots: *Lonicera xylosteum*, *Tulipa sp.*, *Sempervivum arachnoideum*, *Rosa rubiginosa*, *Euphorbia cyparissias*, *Knautia arvensis* and *Lactuca serriola*. The latter 2 dispersed spontaneously.

Grasshoppers and butterflies

Within one grasshopper survey the recorded grasshopper species were *Anacridium aegyptium* (2 ind.), *Chorthippus brunneus* (13), *Oedipoda caerulescens* (6) and *Omocestus rufipes* (3). Observed butterfly species were *Colias crocea* (1 ind. within 3 surveys), *Pieris napi* (1), *Pieris rapae* (3) and *Polyommatus icarus* (2). Additionally, the moth species *Macroglossum stellatarum* (1) was recorded during the surveys.

Birds and bats

The following bird species (Tab. 7) foraged or rested on the roof surface. The undisturbed nature of extensive green roofs makes these areas particularly attractive as part of a biotope network.

These bat species could be identified (Fig. 7): *Myotis myotis/Myotis blythii*, *Nyctalus noctula*, *Nyctalus leisleri*, *Nyctalus Vespertilio/Eptesicus*, *Pipistrellus pipistrellus*, *Pipistrellus kuhlii/nathusii* and *Hypsugo savii*.

The conversion of a roof area into a dry habitat with high diversity is feasible. The creation of mounds or the installation of structures adds diversification, which is utilized by insects, birds, and bats, partly because these areas are relatively undisturbed. Deadwood and dry stonewalls were used as nesting opportunities by wasps, hornets, and other thermophilic insects. In total, 4 butterfly species and 4 grasshopper species were recorded. Rare or endangered species were not observed; however, it can be stated with confidence that the roof areas are more attractive to light-loving species than intensive orchards or sealed urban surfaces. The diversity and species composition of grasshoppers roughly resemble those found in vineyards.

The planning and construction of a so-called biodiversity roof involve additional effort, as it must be precisely defined which structures are to be installed, where, and at what height. Increasing the substrate in the mounds and behind the dry stonewalls to over 30 cm allowed plant species to establish and survive. At lower substrate depths of 8-10 cm, carpet-like *Sedum* species predominate.

Meadow-like vegetation did not develop; instead, there is a mix of sand, gravel, and chippings with patchy ruderal vegetation, and dry woody areas with shrubs. The number of vascular plant species varies depending on substrate depth. At the lowest substrate depth of 8 cm, 12 plant species were found in 10 m^2, of which 9 had been originally planted or sown and 3 appeared spontaneously. At medium substrate depth of 14 cm, 22 species were recorded in 10 m^2, with half spontaneous and half planted. In the area with the greatest substrate depth (20 cm), 24 species were found in 10 m^2 (11 spontaneous, 13 planted).

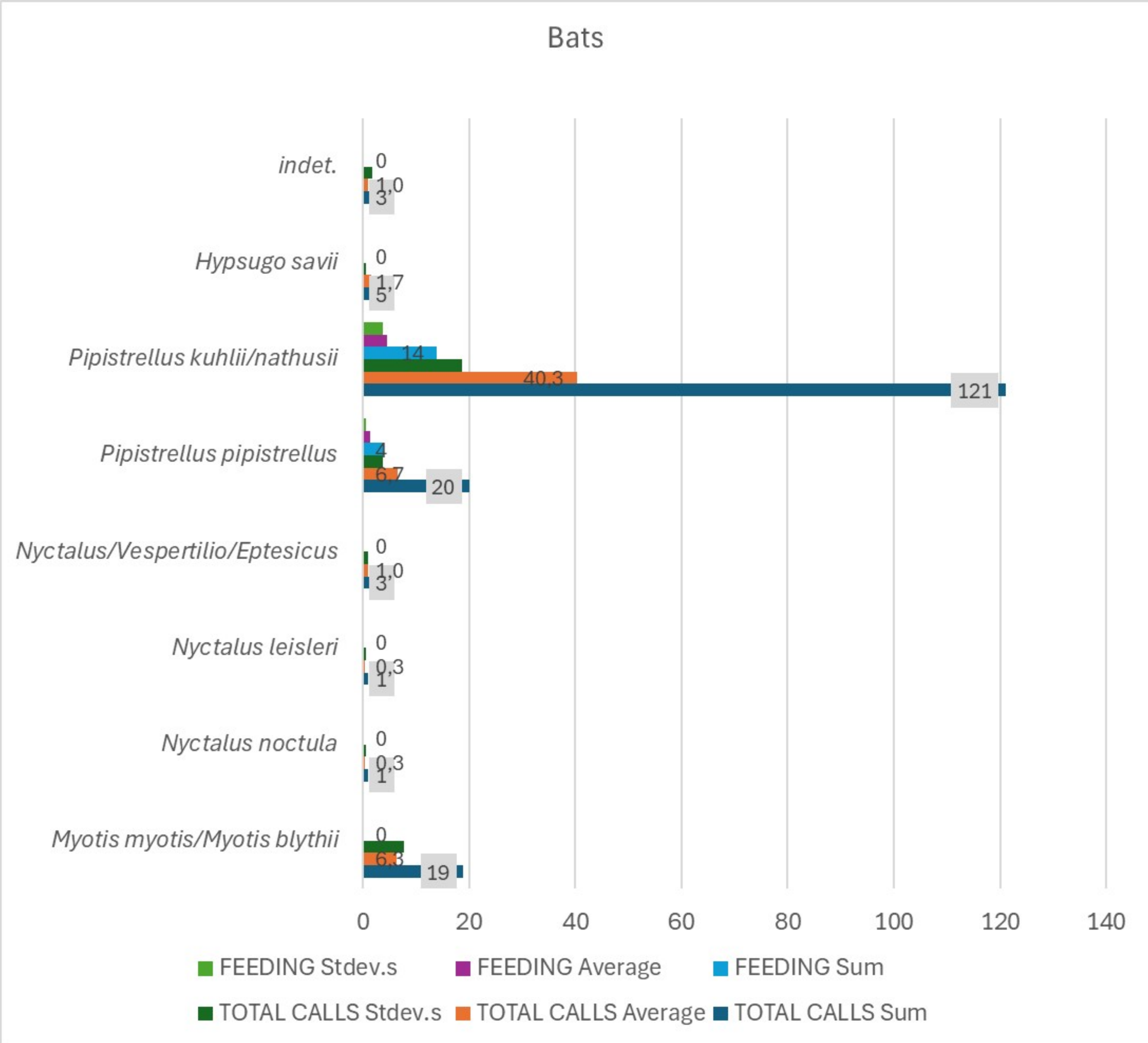


Fig. 7: Number of recorded bat calls (average of three recordings).

Many of the artificial nesting opportunities were colonized by insects, though not always by the intended species; only the ant stones showed no desired colonization. Small mammals were not observed. Particularly notable were the frequent observations of carpenter bees on the flowers of *Colutea arborescens*.

DISCUSSION

The study investigated the performance and ecological characteristics of various green roof system designs under the sub-mediterranean climate conditions of South Tyrol. Adaptations to this regional climate are essential, with a minimum substrate depth of 8 cm required for basic extensive greening. The first research phase demonstrated average annual water retention capacities ranging from 55.6% to 72.4%, indicating substantial but variable hydrological performance among the tested systems. Maintenance costs were found to vary widely, between 0.3- and 85-eurocent/m^2 per year, reflecting differences in system design and vegetation management.

None of the 12 examined green roof structures in the first trial met the criteria outlined in the Italian green roof standard UNI 11235, suggesting a need for design improvements to comply with national guidelines. The introduction of shrub species was shown to be feasible at a substrate depth of 25 cm, which enhanced evapotranspiration rates, although the range of suitable species remains limited.

Ecological assessments revealed that incorporating topographic variation (mounds), heterogeneous grain sizes, deadwood, and sandy areas created microhabitats that supported bird and insect species typical of ruderal, scree, and dry grassland environments. Additionally, roofs with a substrate depth of 14 cm allowed for greater colonization by spontaneous plant species compared to those with only 8 cm of substrate, indicating that substrate thickness plays a key role in promoting biodiversity and ecological resilience in green roof systems.

The results highlight both the potential and the limitations of green roof systems under sub-mediterranean climate conditions [4], such as those in South Tyrol. The considerable range in annual water retention (55.6-72.4%) demonstrates that green roofs can effectively mitigate stormwater runoff, although performance is highly dependent on design parameters such as substrate depth, vegetation type, and structural configuration. The observed variability in maintenance costs - from 0.3 to 85 eurocents/m² per year - further emphasizes that economic feasibility is closely tied to system complexity and the selected vegetation strategy. Simpler extensive systems appear more cost-efficient, whereas designs incorporating shrubs or diverse habitats require more intensive management.

A particularly notable outcome is that none of the studied structures met the UNI 11235 standard. This shortcoming suggests that existing green roof technologies, when applied without sufficient regional adaptation, may not satisfy national performance or safety requirements. The UNI standard was revised in 2015, including a reduction in the required coverage ratio for extensive roofs to 60%.

The experimental inclusion of shrub species at a substrate depth of 20 cm offers promising results in terms of evapotranspiration and ecological function [5]. Yet the limited species palette remains a constraint. Future research should focus on identifying additional drought-tolerant shrubs and subshrubs that can thrive in shallow, nutrient-poor substrates typical of extensive green roofs.

From an ecological perspective, the introduction of habitat diversity through mounds, variable grain sizes, and structural elements like deadwood and sand proved to be a crucial factor in enhancing biodiversity. These design features facilitated the occurrence of species associated with ruderal, scree, and dry grassland environments, thereby extending the ecological value of urban rooftops beyond their hydrological role.

ZUSAMMENFASSUNG

Eine Erhöhung der Substrattiefe und der strukturellen Vielfalt verbesserte sowohl die Vegetationsetablierung als auch die ökologischen Funktionen. Substrate mit einer Tiefe von 14 cm begünstigten eine stärkere spontane Besiedlung durch Arten als Substrate mit einer Tiefe von 8 cm, während eine Tiefe von 20 cm die Integration trockenheitstoleranter Sträucher ermöglichte und die Evapotranspiration verbesserte. In späteren Forschungsphasen wurden Lebensraumstrukturen wie Hügel, Totholz, Sandflächen und Steinmauern eingeführt, die die Biodiversität und die typische Fauna trockener Graslandschaften wie Heuschrecken und Schmetterlinge förderten.

RIASSUNTO

L'aumento dello spessore del substrato e della diversità strutturale ha migliorato sia l'insediamento della vegetazione che le funzioni ecologiche. I substrati di 14 cm hanno favorito una maggiore colonizzazione spontanea delle specie rispetto a quelli di 8 cm, mentre quelli di 20 cm hanno consentito l'integrazione di arbusti resistenti alla siccità, migliorando l'evapotraspirazione. Le fasi successive della ricerca hanno introdotto strutture habitat quali cumuli, legno morto, aree sabbiose e muri di pietra, favorendo la biodiversità e la fauna tipica delle praterie aride, come cavallette e farfalle.

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