Technique of ultra-extensive urban greening using mosses

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Abstract — The greening of impermeable surfaces, such as rooftops and unused concrete areas, offers multifaceted benefits to urban environments (biodiversity, temperature regulation, water retention, aesthetics). An innovative "ultra-extensive" greening technique, centered on promoting moss growth, provides a lightweight, cost-effective, and low-maintenance solution. The aim of this paper is to describe this technique and offer recommendations for a simple implementation method, providing an alternative to conventional greening practices.

Technique de végétalisation urbaine ultra-extensive avec des mousses

Résumé — La végétalisation de surfaces imperméabilisées, telles que des toitures et des zones bétonnées inutilisées, présente de multiples avantages dans un environnement urbain (biodiversité, régulation de la température, rétention d'eau, esthétique). Une technique innovante de végétalisation "ultra-extensive", axée sur la promotion des mousses, offre une solution légère, peu couteuse et nécessitant peu d'entretien. L'objectif de cet article est de décrire cette technique et de proposer des recommandations pour une mise en œuvre simple, offrant une alternative aux pratiques de végétalisation conventionnelles.

1. Introduction

Adding vegetation to unused impermeable surfaces, such as rooftops or concrete surfaces aims to mitigate some of the negative effects of urbanization (Manso et al., 2021; Oberndorfer et al., 2007; Shafique et al., 2018; Ville de Lausanne, 2018). This has several benefits:

Environmental Benefits - It helps to absorb rainwater, reducing stormwater runoff and preventing flooding. This process also filters pollutants from the water and improves its quality.

Temperature Regulation - Greening impermeable surfaces can help regulate urban temperatures by providing shade and reducing the urban heat island effect. Vegetation absorbs sunlight and release moisture through transpiration, cooling the surrounding air. It also captures CO_2.

Biodiversity and Habitat Creation - Greening impermeable surfaces creates habitat and food sources for urban wildlife, such as birds, insects, and multiple small animals. This contributes to urban biodiversity and ecological balance.

Aesthetic Value - Greened surfaces enhance the visual appeal of urban areas.

Overall, the greening of impermeable surfaces is a strategy that promotes sustainability, resilience, and livability in urban environments.

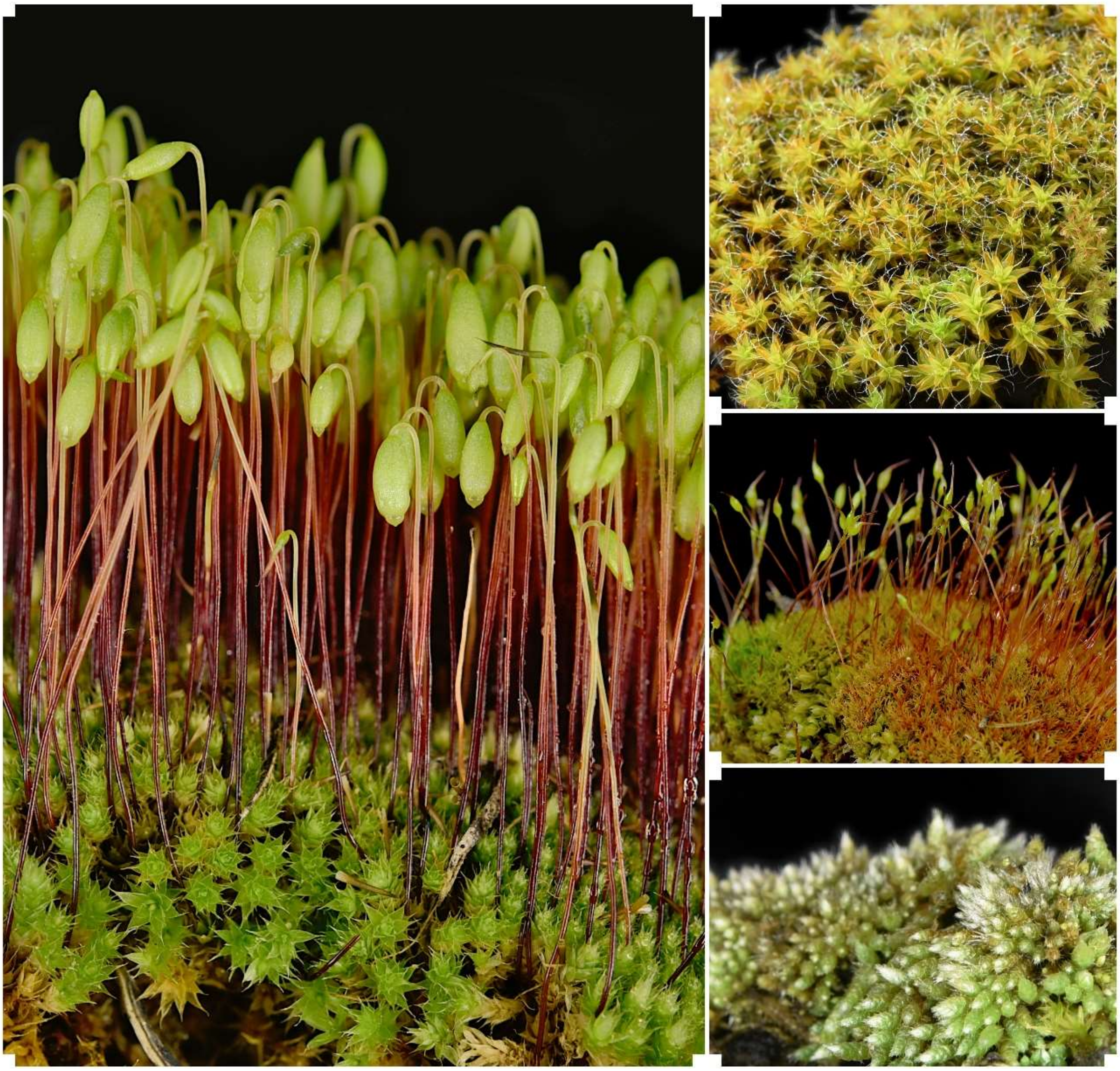

Fig. 1 Some species generally well adapted to this greening technique: *Bryum capillare* (left), *Syntrichia ruralis* (top right), *Ceratodon purpureus* (middle right) and *Bryum argenteum* (bottom right).

2. Greening using mosses

Green roofs are normally categorized as either intensive (depth ≥ 300 mm) or extensive (depth = 100 mm to 250 mm) (FLL, 2002; Razzaghmanesh & Beecham, 2014). The main aim is generally to promote vascular plants, although mosses are often found in empty spaces.

Here, we introduce an “ultra-extensive” greening technique (depth = 10 mm to 50 mm) that primarily promotes moss growth. The terms "moss roof" or "ultra-thin moss roof" seems to be occasionally used as well. This technique offers several advantages:

- The substrate is thin, minimizing weight: this can be beneficial for green roofs that were not originally planned and have limited load-bearing capacity.
- The technique is simple and requires few materials.
- Costs are low.
- Mosses provide numerous benefits.

3. Benefits of mosses

Mosses are often misunderstood and underappreciated in urban environments, where they are commonly seen as weeds or nuisances. However, mosses are deliberately encouraged to grow under aesthetic principles

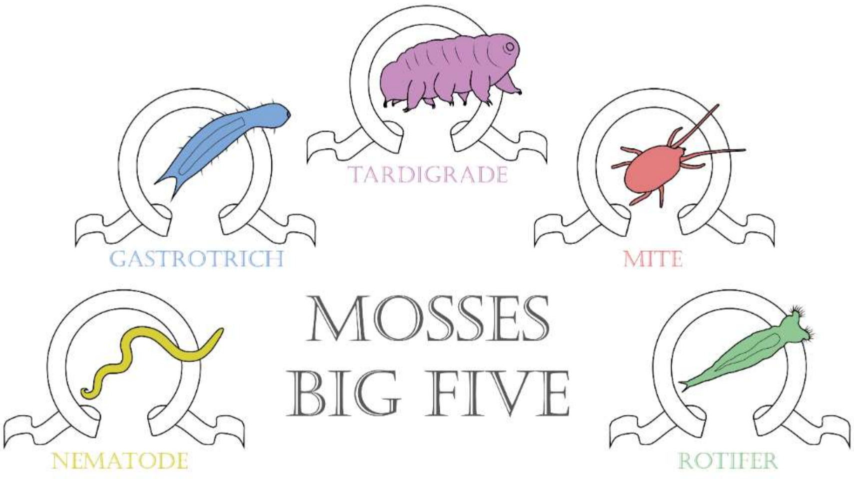

Fig. 2 Mosses are real mini-jungles, rich in biodiversity. Who knows the 'big five' of mosses microfauna?

exemplified by Japanese gardening (Marsaglia et al., 2023). They play several important roles in ecosystems and can actually offer numerous benefits to urban areas.

Mosses are important because with limited needs, they manage to settle in environments where most land plants are unable to survive (Marsaglia et al., 2023). They are easily adaptable organisms in urban habitats, with some species specially adapted to harsh environments such as city rooftops or concrete surfaces (Fig. 1).

Mosses, like miniature jungles, harbor rich biodiversity (Fig. 2). They serve as crucial microhabitats for a wide range of microfauna, contributing significantly to the overall biodiversity and ecological functioning of terrestrial ecosystems (Fantham & Porter, 1945; Šatkauskienė & Vosyliūtė, 2010; Sayre & Brunson, 1971). Additionally, they provide

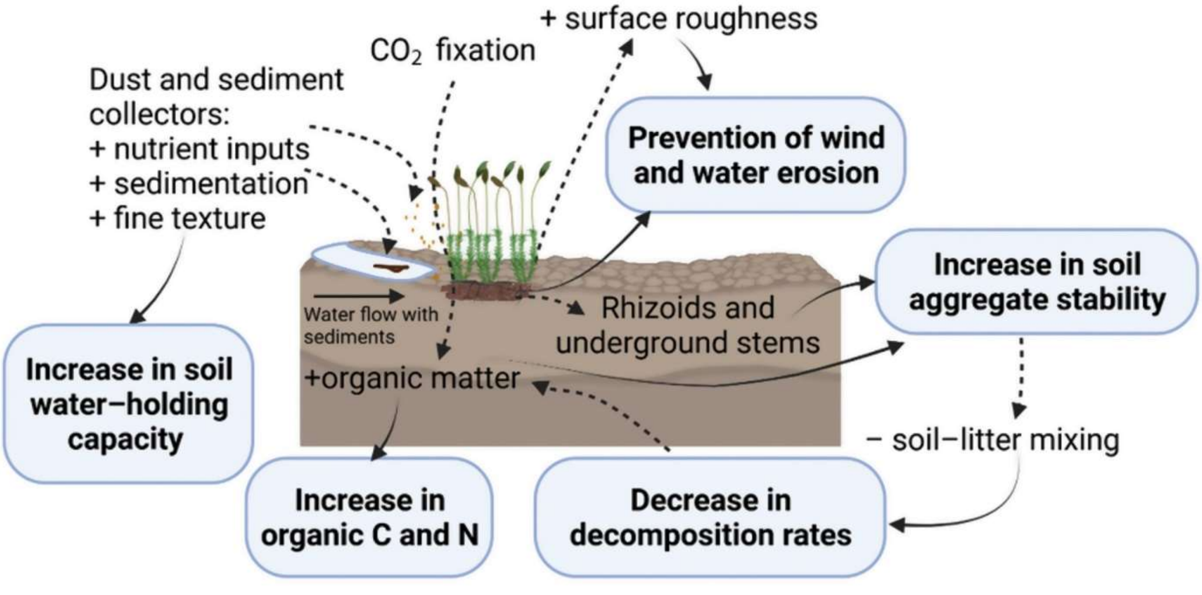

Fig. 3 Effects of mosses on soil properties. Soil variables and processes increased and decreased by the presence of mosses are indicated by + and – signs, respectively. Figure from Ladrón de Guevara & Maestre (2022).

Fig. 4 Greening by moss naturally occurs on urbanized surfaces that are no longer in use (here, for example, old railroad tracks and asphalt surfaces). The aim of this greening technique is to replicate this natural succession.

habitats for other organisms: seedbeds for vascular plants, shelter and food for small invertebrates, nesting material for birds, etc. (Marsaglia et al., 2023).

Mosses are common members of biological soil crust communities (biocrusts) and provide key ecosystem services (Antoninka et al., 2016). They are efficient colonizers and stabilizers of bare substrates (Fig. 3) and they can serve as hosts for Cyanobacteria, which have an important role in nitrogen (N) fixation (Antoninka et al., 2016; Ladrón de Guevara & Maestre, 2022; Marsaglia et al., 2023).

Water is clearly needed by mosses, but rather than maintaining hydration, they are able to become metabolically inactive (Marsaglia et al., 2023). Mosses are poikilohydric, which means that they are able to survive drought by drying out and can last an extended time in a drought state without damage. They are capable of rehydration in a short time and able to start photosynthesis immediately after rehydration. They store water in an external way, in capillaries among branches (Burszta-Adamiak et al., 2019). Mosses act, to some extent, as sponges, rapidly absorbing water, holding it, and releasing it only slowly. The runoff from the green roof is much reduced compared to runoff from hard roofs because of evapotranspiration. For example, runoff was studied on a thin, extensive green roof approximately 3 cm deep (Bengtsson et al., 2005). The runoff was initiated when the soil was at field capacity, which for the studied roof corresponded to 9 mm of storage.

Many rooftops can present a dark color that absorbs solar radiation, increasing the temperature inside buildings. This could be attenuated by this green infrastructure. Some bryophytes turn its color from green to brown, which changes its albedo to absorb more solar radiation so the temperature under the moss will increase. However, the minimum daily and range of humidity is always lower under the moss, meaning that the small amount of water that reaches the moss is well absorbed and can be released in the form of humidity during drier periods (Cruz de Carvalho et al., 2019). Mosses are also recommended for a green roof application in terms of CO_2 capture (Seo et al., 2023).

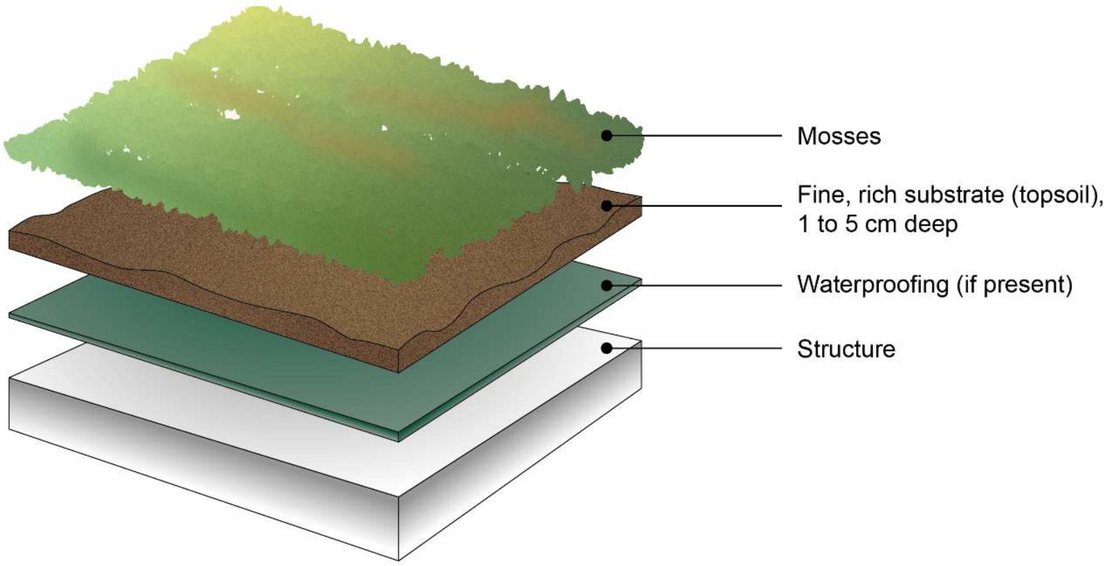

Fig. 5 Diagram illustrating the different layers for an ultra-extensive urban greening with mosses.

Finally, since mosses have no roots, there's no risk of damage to the waterproofing layer beneath the substrate. On the contrary, the thin layer of substrate and the mosses act as mechanical protection, UV protection and the materials are less exposed to large temperature variations.

4. Ultra-extensive greening technique

The aim of this technique is to reproduce the natural colonization of an urban surface by mosses. Worldwide, mosses are present in the earliest stages of primary succession (Condon & Pyke, 2016). In urban environments, mosses settle naturally after some time (it can be long) on most flat surfaces, such as roofs and concrete surfaces (Fig. 4). The primary focus here is on flat surfaces (up to a slope of around 10°). Studies and tests have been conducted on installing moss on walls, but this requires more complex infrastructure and techniques (Perini et al., 2020).

Mosses settle wherever they can find some moisture, in shadier places, but also in exposed places, in cracks or where a thin substrate has formed, allowing some moisture to remain for longer and the mosses to anchor themselves. The aim is to replicate this situation by installing a thin substrate (Fig. 5).

Substrate

The objective is to apply a thin layer of substrate to minimize weight and cost while maximizing water retention, which is crucial for moss growth (Perini et al., 2020). If the substrate thickness is minimal, it will primarily support moss growth (conditions too harsh for vascular plants); slightly thicker substrates can accommodate more vascular plant species, such as *Sedum* species. Additionally, the substrate must be nutrient-rich to adequately support moss growth, although this requirement is not crucial. Mosses primarily derive most of their nutrients from wet deposition, with only a partial uptake from the substrate surface (Burszta-Adamiak et al., 2019).

Utilizing a 10 to 50 mm layer of topsoil (A horizon) emerges as a good choice (Fig. 5, 6), given its local availability, cost-effectiveness, and adaptability. While specific criteria regarding, for example, clay, silt, sand proportions, organic matter content, and pH are not rigid, extremes (e.g., highly acidic, clay-rich, coarse) should be avoided.

The importance of substrate depth is particularly evident in the responses of individual species. Hardy species (e.g., *Bryum argenteum*, *Ceratodon purpureus*) can survive on shallow substrates. Some vascular plant species can also establish on thin substrates, such as *Sedum acre*. Grasses and forbs

Fig. 6 Example of an ultra-extensive green roof with a 5 cm layer of topsoil substrate, colonized by mosses and some vascular plants *(Sedum)*. Situation 2 years after installation.

increase in cover with increasing substrate depth (Gabrych et al., 2016). However, a thin substrate of less than 50 mm, in exposed areas, generally gives vascular plants little chance to survive in summer, except for a few *Sedum* species, leaving space for mosses. The substrate doesn't need to be sterile; if seeds of other plants are present, they may germinate and grow, but they're likely to be naturally eliminated under harsh conditions. In more shaded areas, more vascular plants can establish, which also contributes positively to biodiversity.

Considering an approximate density of 1500 kg/m^3 for topsoil, the substrate layer would therefore weigh around 15 to 75 kg/m^2. The moss layer itself is relatively lightweight, with an average estimated weight of about 2 kg/m^2 in a recent study (ranging from 0.3 to 7 kg/m^2, Burszta-Adamiak et al., 2019).

Propagating mosses

The simplest solution could be to leave the substrate bare, as mosses will naturally colonize the area over time. But this can take years. It's possible to speed up the process by spreading mosses.

An aspect that facilitates the use of mosses as inoculum is that they can grow vegetatively from small fragments from any part of the plant. Since moss naturally propagates by the dispersion of stems and leaves, moss inoculation has often been conducted using fragments as the actual inoculum (Adessi et al., 2021; Liu et al., 2021).

It is suggested to use fragments where apical leaves remain green at the time of desiccation (young leaves), as they have a higher recolonization capability (Condon & Pyke, 2016). Hydrating propagules for 20 minutes before inoculation could also be helpful in order to inoculate actively photosynthesizing moss fragments, which are more tolerant to inoculation stress (Adessi et al., 2021; Condon & Pyke, 2016). Moss fragments can be dispersed by hand. The concentration to use varies depending on the studies (Adessi et al., 2021; Antoninka et al., 2016; Bu et al., 2015; Condon & Pyke, 2016), but it is probably not as important. More moss fragments will simply accelerate moss establishment.

The moss fragments should be secured to prevent them from being blown away, especially if the surface is exposed to wind. It's recommended, for example, to wet the substrate to enhance adhesion and press the fragments firmly against it. Mosses can also be mixed with another material to improve adherence, such as yogurt or a mixture of water and clay soil. Additionally, applying a jute net can be beneficial. The advantages of using a jute net likely extend to reducing soil temperature, providing greater protection and stability for the mosses, and mitigating wind and water erosion (Adessi et al., 2021; Slate et al., 2020).

An important factor for success is selecting the right species of mosses. Specific species of moss can be extremely difficult to maintain away from their natural sites due to their unique requirements, including combinations of light, humidity, substrate, etc. (Marsaglia et al., 2023). Species from similar natural habitats, with similar environmental characteristics, must be selected (see, for example, Swissbryophytes, 2024). For exposed surfaces such as roofs, Acrocarpous mosses, such as members of the families Pottiaceae, Grimmiaceae, and Bryaceae, can be more suitable. Some moss species are sensitive to pollution, but others are indifferent, such as the widespread *Ceratodon purpureus* and *Bryum argenteum* (Rajandu et al., 2021).

Mosses can typically be harvested from nearby surfaces since the quantities needed are usually modest. It's crucial to extract only a portion of the moss mat, opting for small patches to facilitate regeneration. Suitable locations for harvesting include other roofs or abandoned industrial surfaces. Tiled roofs, which are often cleared of moss, provide an opportunity to collect them and give them a second life. A few moss cushions can also be harvested and transferred to the new site, adding aesthetic value.

Due to their poikilohydric nature, dried fragments may be stored for a long time before being inoculated, without a loss of viability. Some fragments of *Syntrichia ruralis* have been able to regenerate after more than 20 years of storage in a herbarium. However, there also seem to be species that lose their regeneration capability after a few weeks or months (Adessi et al., 2021).

Numerous studies demonstrate successful moss propagation through fragment utilization (Anderson et al., 2010; Antoninka et al., 2016; Nagase et al., 2023; Ónody et al., 2016), in a relatively short time under the proper conditions, sometimes as little as three months, but more often after a few years.

Maintenance

An ultra-extensive greened surface requires very little maintenance. At most, periodic checks may be necessary, such as inspecting water drainage exits on roofs. The layer is so thin that woody plants cannot establish themselves, which could otherwise pose problems with roots, thereby reducing the need for monitoring. Mosses do not tolerate disturbances, so surfaces should not be walked on; otherwise, the coverage could decrease (Bu et al., 2015). Overall, very little maintenance is required.

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