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Role of substrate properties in the provision of multifunctional green roof ecosystem services

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31 points of modern architecture", published in 1927 by Le Corbusier and Pierre Jeanneret. However, the 1950s and
32 the associate quick succession of urban plans marked a halt to the investment of roofs by vegetation. The current
33 concept of green roof only emerged during the 1970s and 1980s. These years were characterized by the
34 emergence of environmental concerns at an international level. Reports such as "The limits to growth" (1972,
35 commissioned by the Club of Rome), or "Our common future" (1987, Brundtland report of the World
36 Commission on Environment and Development) have led to the notion of sustainable development. In this
37 context, Germany decided to launch an active policy for the development of environmental technologies and
38 public policies (Oberndorfer et al., 2007), which has favoured the emergence of modern green roofs. This has led
39 to the adoption by Germany in 1982 of its first professional rules for green roofing (FLL, 2010).

40

41 **2. What constraints on and caused by green roof substrates?**

42 Vegetated roofs are intended to reintroduce a living component in cities while integrating building structural
43 constraints. Two of these constraints have guided the development of roofing vegetation technologies. The first
44 concerns the need to maintain roof water-tightness despite the presence of roots. Above all, the fundamental role
45 of a roof is the protection it offers to people and objects. The problem has been solved by the development of
46 anti-root membranes associated with conventional roof protections (bituminous layers in particular). The second
47 constraint is that of weight. At a time when the precision of architectural techniques makes it possible to
48 precisely calculate the loads supported floor by floor, little margin is provided for roofs except for the snow load
49 or other technical elements. In the 1970s, while some companies had already developed suitable membranes and
50 lightweight substrates, several German studies have shown that green roofs are likely to bring environmental
51 benefits. This includes limiting rainfall run-off to storm sewer pipes, but also thermal protection of buildings
52 (Dunnett and Kingsburry, 2008).

53 Because the issues of roof overload and water-tightness are so crucial to the integrity of buildings, but also to
54 the comfort and safety of people who live or work there, the vegetation market for roofs has been structured
55 around these constraints. The substrates are not only light but also have to be shallow, leading to the existence of
56 green roofs whose thickness in some case may not exceed 2 cm. However by doing this, this also creates a new
57 constraint in the limited choice of plants species that must be suitable for both shallow substrates and drought
58 conditions. These conditions of restricted root development and poor water reserve, associated with significant
59 sun exposures and potentially high windiness (Cao et al., 2013), create unfavourable growing conditions for
60 many plant species. Species of the genus *Sedum*, from the family Crassulaceae, in other words succulent plants,

61 respond to these expectations: they have restricted root system, their metabolism limit water loss through
62 transpiration (Ting, 1985) and they can store water in their succulent leaves (Sayed, 2001). However, these
63 *Sedum* species are not exempt from high mortality rates (Durhman et al., 2007) and the counterpart of the
64 success of *Sedum* / artificial substrate association is that it constitutes the vast majority of green roofs in the
65 world, leading to poor plant diversity, but also to limited plant and substrate functional diversity.

66

67 **3. What is a green roof substrate?**

68 As the greening of roofs is closely associated with the waterproofing and roofing sectors, the term "layers"
69 refers to the different components of green roofs (Berardi et al., 2014). In fact, several technical layers are
70 necessary before any revegetation (Vijayaraghavan, 2016). Green roof will consist of at least waterproofing and
71 anti-root membranes, to which, according to the manufacturers, may be added various layers of insulation,
72 drainage or water retention. Finally, the terms growth layer and vegetation layer are regularly used, both in the
73 technical and scientific literature, to evoke the soil or substrate and the vegetation used. The composition of the
74 growth layer (or growth substrate) reflects the search for lightness and is characterized by the artificial mixing of
75 mineral and organic compounds (Sutton et al., 2015). There are two types of mineral elements. These are
76 primarily volcanic rocks, such as pumice or pozzolan, or artificial elements, such as expanded clay or expanded
77 shale. Some substrates also mix these different elements. All these natural or artificial materials have the
78 particularity of being highly porous, and therefore light (Massazza, 1998), although in varying degrees. While
79 porosity of perlite is generally close to 30% of its total volume (Vijayaraghavan and Raja, 2014), artificial
80 materials such as expanded clay can exceed 80% (Berretta et al., 2014). The organic part of the substrates aims
81 to provide the nutrients needed for plant development (including through the promotion of soil biodiversity and
82 its associated functions) and is usually peat (Nardini et al., 2011) or compost from recycled organic waste. The
83 use of high organic matter substrates (or even of natural soils) is however subject to controversies (Best et al.,
84 2015). On the one hand, their use enhances the soil micro- and macro-diversity, and nutrient cycling and
85 retention. On the other hand, there are concerns about increased roof loading and fine particle illuviation, and to
86 unpredictable biological activities (in or above the substrate). These last concerns have led so far industry
87 professionals to strongly discourage the use of high organic matter substrates or natural soils, in particular for
88 maintenance reasons (e.g. removal of opportunistic ruderals plant species).

89 Depending on the country of origin (e.g. French, German or American policies), the proposed proportions of
90 mineral matter is ca. 70-95%, and thus ca. 5 to 30% of organic matter. The high proportion of mineral material

91 has two explanations. On the one hand, organic matter is generally denser than mineral portions. Chambers et al.
92 (2010) estimated that peat density can reach 2000 kg.m⁻³, when that of expanded clay usually don't exceed 700
93 kg.m⁻³ (Ardakani and Yazdani, 2014). The other explanation is that a too rich substrate would lead to a rapid
94 leaching of nutrients, which would be a source of carbon and nitrogen pollution for runoff water (Rowe et al.,
95 2006). For the same reasons, rapidly decomposing peat is particularly deprecated (Nagase and Dunnett, 2011).

96 The massive incorporation of porous materials into the substrates has the effect of reducing their density, in
97 ranges of ca. 0.6-1 t.m⁻³ when dry and 0.8-1.6 t.m⁻³ when water-saturated. While these substrates have long been
98 the only ones available on the market, the present trend is for diversification. While soils are explicitly excluded
99 from the occupational rules for most systems, recycled materials such as crushed bricks or tiles develop
100 gradually (Ondoño et al., 2015), with the advantage of being both local and potentially mild materials (Graceson
101 et al., 2014). Moreover, the need for more functional diversity led to the definition of different green roof
102 typologies based mainly on their depth, the substrate type used for the growth layer, and therefore the induced
103 load for the building, but also on the type of vegetation and the degree of maintenance required. These different
104 systems are called: extensive (light substrate, no watering, thickness of substrate of 4-15 cm, mainly succulent
105 plants); semi-intensive (light substrate, watering, thickness of substrate of 12-30 cm, grasses or low-development
106 shrubs); and intensive (natural soil, watering, thickness of substrate < 30 cm, unlimited choice of plants). While
107 the majority of the systems sold are extensive, there is a growing rejection of the "all *Sedum*" (*i.e.* very shallow
108 extensive roof, only planted with *Sedum* species) and an increased demand for systems with a greater variety of
109 species, pushing towards the development of "semi-intensive" offers. This evolution, which is still difficult to
110 quantify, echoes the increasing number of environmental approaches taken by local and regional authorities (e.g.
111 in France) to increase the diversity of plant species and the depth of substrate on the roofs, in a context where
112 75% orders are public organisms (CSTB 2008).

113

114 **4. What ecosystem services are provided by green roof substrates?**

115 The reasons for the growing popularity of green roofs are the same as those that prevailed when they were
116 (re)created in the 1980s: the multiplicity of environmental services they provide, highlighted both in terms of
117 supply and demand (Dusza et al., 2015). Because green roofs are a combination of abiotic and biotic components
118 interacting with their environment, and because these benefits are "services people obtain from ecosystems" in
119 the sense of the Millennium Ecosystem Assessment (2005), green roofs provide numerous ecosystem services
120 (Table 1) including important cultural services (Lee et al., 2015).

121 The ecosystem services associated with green roofs are widely put forward, both at the level of prime
122 contractors and owners, and explain to a large extent their popularity worldwide. Green roofs are subject to very
123 wide disciplinary appropriations but are often relatively remote from the biology or ecology fields. The
124 discipline fields most represented are that of energy and physics, followed by hydrology (Blank et al., 2013). *De*
125 *facto* this diversity of disciplinary fields reflects the diversity of services that can be provided by green roofs.
126 The great majority of publications, however, rely on a similar initial objective, namely to determine the
127 effectiveness of green roofs in relation to the ecosystem service studied.

128 In the realization of these services, and the trade-offs between services and disservices, the role of substrate is
129 decisive, and in particular for two of its characteristics: substrate composition and substrate depth. First,
130 substrate composition affect substrate fertility and the availability of nutrients to plants; however rich substrates
131 while benefiting plants also lead to high carbon and nitrogen leaching rates (Beecham and Razzaghamanesh,
132 2015). Beyond nutrients, the risk of heavy metals release from substrates is increased in the presence of recycled
133 materials such as broken tiles or bricks (Alsup et al., 2009). Substrate porosity affect substrate capacity to retain
134 water as green roof manufactured substrates as pozzolan tend to be globally highly porous to gain lightness,
135 while in natural soils the water retention is driven by the pore size distribution (Graceson et al., 2013). The intra-
136 and inter-particle porosity are thus two important factors to be taken into account in order to promote water
137 retention. Water retention also affects substrate temperature that can affect both plant root growth and
138 functioning and building cooling. In this case, a more porous substrate likely leads to a better building cooling
139 (Lin and Lin, 2011). However, as air is a better thermal insulator than water, a trade-off exists between the
140 substrate overall porosity, substrate overall capacity to retain water, and irrigation frequencies. Efforts are
141 currently being made on searching different alternatives to design substrates from key components to achieve
142 desirable characteristics and thus better services. One example is the incorporation of substrate additives (e.g.
143 seaweed) that can enhance water retention and sorption capacity, in particular for metal ions (Vijayaraghavan et
144 al., 2015). Biochar addition in particular is viewed, and has been tested recently, as a mean to increase water
145 holding capacity and plant available water without increasing substrate weight loading (Cao et al., 2014;
146 Kuoppamäki and Lehvävirta, 2016) even if the properties of biochar can vary considerably (Kuoppamäki et al.,
147 2016).

148 Second, substrate depth by increasing substrate volume could, in absolute, linearly increase the effects of
149 substrate composition above-mentioned. The effects however are often unclear, perhaps due to the limited
150 number of available studies, and to the fact that few studies have attempted to integrate several ecosystem

151 services simultaneously. Generally, deeper substrates favor plant growth and water retention (Nagase and
152 Dunnett, 2010; Buccola and Spolek, 2010) even if they can be detrimental because of higher soil moisture to
153 certain plant species such as stress tolerant species (Rowe, 2015). However, deeper substrates can lead to higher
154 nitrogen and carbon leaching and thus decrease the quality of runoff water (Seidl et al., 2013), or have no effect
155 (Razzaghmanesh et al., 2016) e.g. by lessening water leaching and increasing nitrogen and carbon holding
156 (Vijayaraghavan, 2016). In the end, two mechanisms are confounded when depth of green roof's substrate is
157 increased. The quantity of leachable material increases, but the larger water retention allows a longer presence
158 within the substrate, which would favor a greater sorption by the substrate or a greater absorption by plants.

159

160 **5. Conclusion: what future researches on green roof substrates?**

161 Important gaps exist in the knowledge of the role of substrates on ecosystem services provided by green
162 roofs. For instance, very few authors have studied the effect of substrate composition on evapotranspiration
163 mechanisms. To our knowledge, no published study has evaluated the influence of substrate depth, substrate
164 composition or the choice of plant species on air pollution, nor on the services of supports of biodiversity or
165 pollination. No study ever projected to study the evolution of a substrate's diversity in terms of microorganisms
166 e.g. the ones involved in the realization of the nitrogen cycle. This is of great importance as substrates, that differ
167 from natural soils in their mineral composition but also in their organic compounds, can lead to particular
168 abundances, activities and strategies (such as oligotrophic vs. copiotrophic) of microorganisms (Ditterich et al.,
169 2016). Beyond studying the successions of microbial communities within substrates, the delivery of ecosystem
170 services by green roofs could benefit from studies focusing on i) how exactly certain substrate components can
171 modify microbial communities and functions (e.g. the addition of biochar can promote plant performance by
172 increasing diversity and modifying metabolic potential in the rhizosphere microbiome – Kolton et al., 2017), and
173 ii) how harsh environments as green roofs could be improved by manipulating microbial communities such as
174 mycorrhizal fungi and microbial mixtures (Molineux et al., 2014; John et al., 2017).

175 Project managers as well as building owners indeed agree that there is a lack of tools to design and manage
176 green roofs associated with "quality" ecosystem services. Studies that explicitly sought to evaluate the effect of
177 vegetation type, composition, or substrate depth on ecosystem functions and services provided by green roofs are
178 scarce (e.g. Graceson et al., 2014; Young et al., 2014; Aloisio et al., 2016; Eksi and Rowe, 2016; Ondoño et al.,
179 2016). In relation to substrate (composition or depth combined), there are about fifteen studies concerning
180 thermal services, about ten concerning the reduction of runoff, a dozen concerning water quality, only one

181 concerning the quality of air, none concerning other services. How can this low interest in the relationships
182 between the components of a green roof and service levels be explained? A first explanation is the technical
183 nature of green roofs. As mentioned above, the vast majority of commercialized green roofs are off-the-shelf
184 systems, the design of which is highly standardized. This explains the homogeneity of systems throughout the
185 world, and the scarcity of comparative studies. Moreover, the influence of the components of a green roof on the
186 associated services is by essence multidisciplinary, and this also explains a part of the apparent scarcity of the
187 specialized literature.

188 In the end, one of the main stumbling block is that the variable influence of certain components of green
189 roofs on the expected services underlines the possibility of trade-offs between these services. In other words,
190 optimizing a particular service is likely to reduce the level of another service. This possibility of compromise
191 results mainly from the cycles of nutrients and water within a green roof. First and foremost, it is necessary to
192 avoid as much as possible the flow of water in liquid form while promoting its evacuation in gaseous form *via*
193 evapotranspiration. Second, it is necessary to facilitate the storage of carbon and nitrogen by plants and the
194 substrate by limiting substrate leaching. Water cycle and nutrient cycle are intrinsically linked through different
195 ecosystem functions. For example, transpiration depends on leaf area and the total biomass of the plants, which
196 are themselves the result of the availability of nutrients, this ultimate being determined by the moisture of the
197 substrate, conditioned by plant transpiration.

198 To better understand these trade-offs, while information on the links between components of a green roof
199 substrate and the functions or services it fulfills remains fragmented, studies that have sought to cross just two of
200 these components are rare. Until recently (Dusza et al., 2017), no study had evaluated the influence of
201 interactions between substrate depth, substrate composition, and plant species on any of the functions or services
202 of a green roof (Figure 1). In 2015, Lundholm was the first author to explicitly use the term “multifunctionality”
203 in the context of green roofs. By observing how plant species, in monoculture or in combination of plants,
204 simultaneously alter substrate temperature, retention and biomass production, Ludholm has established an index
205 of multifunctionality representing an average of functions. Lundholm considered three types of treatment in
206 relation to the desired services: the least and most effective for a given service, as well as those with the highest
207 multifunctionality index. This approach is very innovative in the disciplinary field of green roofs and calls for
208 more multifunctionality studies while we now know that substrate–plant interactions induce trade-offs between
209 ecosystem functions, and that substrate type and depth interactions are major drivers for green roof
210 multifunctionality (Dusza et al., 2017).

211

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216

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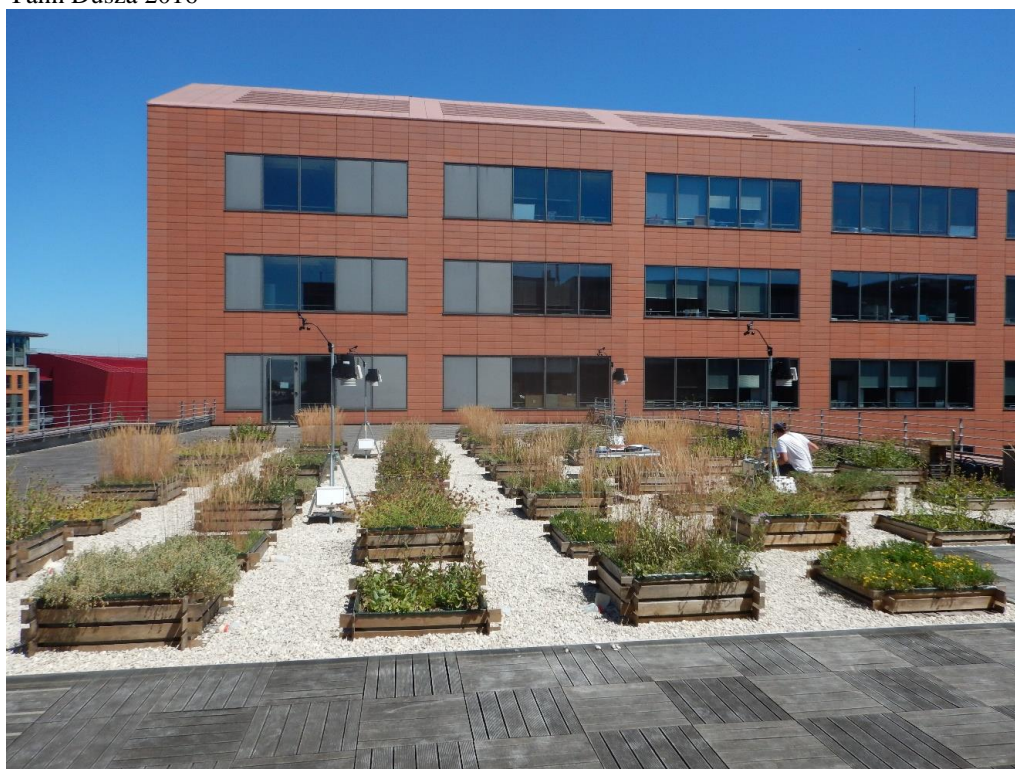
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329

330 **Table 1**
 331 Ecosystem services associated with green roofs (Dusza, 2017).

Service category	Expected services of green roofs
Regulation (City scale)	Fighting urban heat island effects Reduction of rainwater run-off Improved water and air quality Carbon storage
Regulation (Building scale)	Thermal protection of building Protection of waterproofing membranes Sound protection
Support	Support of biodiversity Pollination
Production	Urban Agriculture
Cultural	Aesthetics Psychological services (resistance to stress, attention restoration)

332
 333 **Fig. 1.**
 334 Experimental green roof in Paris City, France, manipulating substrate type, substrate depth and plant diversity ©
 335 Yann Dusza 2016



336