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Ryad Bouzouidja, Gustave Rousseau, Violaine Galzin, Rémy Claverie, David Lacroix, et al.. Green roof ageing or Isolatic Technosol's pedogenesis?. *Journal of Soils and Sediments*, 2018, 18 (2), pp.418-425. 10.1007/s11368-016-1513-3 . hal-01520147

HAL Id: hal-01520147

<https://hal.univ-lorraine.fr/hal-01520147>

Submitted on 29 Aug 2017

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1 SUITMA 8

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3 **Green roof ageing or Isolatic Technosol's pedogenesis?**

4

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22 **Abstract**

1 23 *Purpose:* Green roofs (GR) offer a way to improve several ecosystem services in cities. However, the
2 24 performances of GR are basically considered as steady over time whereas they are living media subject to ageing
3 25 that are rarely managed by their owners. This study transposes a pedological approach to evaluate changes in GR
4 26 physical structure and chemical composition over time.

7 27 *Materials and methods:* A full scale experimental plot with various vegetation cover was studied. An appropriate
8 28 sampling of a four years substrate was implemented on the basis of observation. Then physical and chemical
9 29 characterization were conducted and compared to results on the original substrate.

11 30 *Results and discussion:* The top sub-layer of the substrate contained a large amount of fine and short roots
12 31 whereas the root density was much smaller in the lower layer of the substrate. There was a drastic drop of 3% of
13 32 the organic carbon content between the initial substrate and the 4 years old substrate. On contrary the nitrogen
14 33 concentration has increased of 0.4% during the same period. The total porosity decreased from 0.45 cm³ cm⁻³ to
15 34 0.38 cm³ cm⁻³. On the whole substrate the < 2 mm particles fraction was smaller after 4 years (12.5%) than in the
16 35 initial substrate (18.2%) which was especially obvious in the upper horizon (9.5%). Additionally, the monitored
17 36 properties also varied significantly as a function of soil cover (sedum, moss and bare soil). Evidences of an early
18 37 pedogenesis were highlighted.

24 38 *Conclusions:* In conclusion, the study demonstrated the effects of time, climate and vegetation on physical and
25 39 chemical properties of green roofs. They are not only classified as Isolatic Technosols due to their composition
26 40 and implementation, they also exhibit one of the major characteristic of young Technosols: a fast and intense
27 41 pedogenesis.

31 42
32 43 **Keywords** Green roof • Pedogenesis • Substrate • Temporal changes
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45 **1 Introduction**

1 46 Increasing use of green roofs (GR) on the top of the buildings of our cities rely on their acclaimed benefits
2 47 regarding local climate and storm water regulation (Mentens et al. 2006; Alexandri and Jones 2008) as well as
3 48 their contribution to urban biodiversity (MacIvor and Lundholm 2011). Such ecosystem services are
4 49 progressively evaluated in a variety of situations and climates through scientific studies (Carter and Jackson,
5 50 2007; Moran and Smith, 2005). However, the performances of GR are basically considered as steady over time
6 51 whereas they are living media subject to ageing that are rarely managed by their owners.

7 52 Considering their composition - mixing of extracted and transported materials form natural origin such as
8 53 pozzolana or peat and man-made products such as bricks and compost that all are defined as "artefacts" (IUSS
9 54 2014) – and the way they are implemented, green roofs clearly belong to the "Technosol" Soil Reference Group
10 55 (IUSS 2014). Their properties are dominated by the technical origin of their parent materials. Moreover, their
11 56 main attribute is clearly defined under the qualifier "isolatic: having, above technic hard material, above a
12 57 geomembrane or above a continuous layer of artefacts starting ≤ 100 cm from the soil surface, soil material
13 58 containing fine earth without any contact to other soil material (*e.g.* soils on roofs or in pots)" (IUSS 2014). We
14 59 already proposed to classify them as Isolatic Technosol (Drainic, Folic, and Transportic) (Bouzouidja et al.
15 60 2016).

16 61 As Technosols, GR and especially their substrates are reactive media that can be submitted to an early and fast
17 62 pedogenesis that lead to an evolution of their physical and chemical properties (Séré et al. 2010; Huot et al.
18 63 2015; Leguédou et al. 2016). However, actual results about GR evolution are controversial subjects. Evidences
19 64 of the evolution with time of the chemical composition of different green roof substrates were demonstrated.
20 65 However the observations are contrasted, as some observed a decrease with time of organic matter in the
21 66 substrates (Emilsson et al. 2007), whereas others described an enrichment in both organic carbon and total
22 67 nitrogen contents (Schrader and Boening 2006). Concerning physical characteristics, a study on a 5-years-old
23 68 substrate showed that the water holding capacity has increased compared to a new one (Getter et al. 2007),
24 69 whereas Mentens et al. (2006) evidenced the lack of influence of the age of the GR on its hydraulic behaviour.
25 70 Very recent works focused on such a target as the highlighting of drastic evolution of GR's physical properties.
26 71 De-Ville et al. (2015) interestingly described the fact that the upper layers of two different aged substrates have
27 72 an increased number of finer particles whereas the lower part exhibited few changes. This increase was
28 73 attributed, amongst other factors, to atmospheric particles deposition and weathering processes. They observed
29 74 that the development of roots led to a leaching of organic constituents and a consequent local enrichment in
30 75 organic matter. Finally, the authors also demonstrated a decrease of total porosity, with antagonistic results about
31 76 the fine and the open porosities, considering one or the other substrate. As a consequence, De-Ville et al. (2015)
32 77 estimated that such an evolution could influence green roof performances, especially as water regulation is
33 78 concerned. These results are absolutely consistent with another study that suggested a decrease of the hydraulic
34 79 performances of a GR due to an evolution of its physical organization (Bouzouidja et al. 2016). All of this work
35 80 focuses on the substrate study that has most of time heterogeneous and diverse geographical origin.
36 81 Consequently, the contradictory aspect of performance may be linked to this.

37 82 Thus, it appears that soil science is progressively transposing its methods to study physical and chemical
38 83 properties of such an artificial medium as GR substrate. Beyond their WRB classification, do GR behave like
39 84 soils? Are they submitted to a fast and intense early pedogenesis like other Technosols? The present work aims

85 at: i) defining relevant sampling and measurement strategies to exhibit the evolution of an aged GR substrate
1 86 over time ii) describing such transformations in terms of pedogenic processes.
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4 88 **2 Materials and methods**

5 89 **2.1 Experimental site**

7 90 This work was based on an *in situ* experimental GR plot settled in Tomblaine (north-east of France, 48°40'N
8 91 6°13'E , under temperate climate). The local meso-climate is semi-oceanic with a continental degraded marked
9 92 influence, with an average annual precipitation of 763 mm. The average external temperature is 10°C with high
10 93 amplitude of variations between summer and winter (Bouzouidja et al. 2013)

13 94 The green roof platform, built in July 2011, is placed above an approximately 6 m height flat roof building. The
14 95 overall GR surface area is 600 m², 40 m² of which were studied for this work. (**Figure 1**). The substrate is a man-
15 96 made porous medium composed of pozzolana (60% of 3 - 6 mm particles and 20% of 7 - 15 mm particles) and
16 97 organic parts (10 % of peat dust and 10% of maritime pine bark). The thickness of this layer is comprised
17 98 between 7.5 and 9.5 cm. Vegetation plants that were installed are classically: *sedum album*, *sedum reflexumlarix*,
18 99 *sedum reflexum germanium*, *sedum sexangulare*, *sedum floriferum* (Bouzouidja et al. 2013). These plants do not
20 100 exceed 10 cm in height. In this study, the changes of the GR was observed and monitored on one plot designed
21 101 as *Stock40*.
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27 103 **2.2 Sampling and *in situ* measurement strategy**

28 104 Two time steps were studied: original substrate (S0) and 4 years old substrate (S4). We based the sampling on
29 105 the observation of the substrates vertical profiles and decided to split them into three sub-horizons: 0-2 cm, 2-5
30 106 cm, 5-10 cm. The soil cover was also taken into account by sampling on zones covered by sedums (S-sedum), by
31 107 moss (S-moss) and bare soil (S-bare). Each soil cover was replicated three times.

34 108 The measurement of plant coverage was performed using three permanent quadrats (1m × 1m) and the
35 109 photographic method according Magill (1989) .

37 110 An observation of the roots distribution was realized on the aged GR on S-sedum. The used method was based
38 111 on *in situ* mapping protocol described by Tardieu and Manichon (1986). The measurement was conducted on
39 112 three replicates, on a surface of 900 cm². For each sample a regular grid (0.5 cm × 0.5 cm cells) is chosen, the
40 113 root occurrence is defined by a coloured cell and its absence by an empty cell.
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45 115 **2.3 Substrate characterization**

46 116 The samples have been air-dried during 48h. They have been sieved at 5, 2 and 0.2 mm. All fractions have been
47 117 collected, weighted and characterized for total carbon (C_{tot}) and total nitrogen (N_{tot}) (vario Micro cube,
48 118 Elementar).

51 119 Bulk density has been measured thanks to core-sampling. The soil water retention characteristics, *i.e.* volumetric
52 120 water content at field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}), were determined on a pressure plate
53 121 apparatus at 0.33 kPa and 15 kPa respectively (Bruand et al. 1996). The solid density was then measured with a
54 122 helium pycnometer (Quantachrome UltraPyc 1200) based on NF P18-554. Total porosity (δ) was then calculated
55 123 after (Eq. 1). Macroporosity (Mp), mesoporosity (mp) and microporosity (μp) were estimated after the previous
56 124 measurements.
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$$\delta = 1 - \frac{\rho_a}{\rho_r} \quad (\text{Eq. 1})$$

126 Where ρ_a and ρ_r are respectively apparent and real soil density (kg m^{-3}).

127 Jim and Peng (2012) described that the soil water potential is largely influenced by the poral architecture. The
128 authors determined different porosities class for green roof soils: i) the micropores have equivalent diameters <
129 0.2 μm , ii) the mesopores have equivalent diameters comprised between 0.2 and 60 μm and iii) the macropores
130 have equivalent diameters that are > 60 μm . According to Peverill et al. (1999), the relationship between porosity
131 and soil moisture explained by water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) can be
132 determined as:

$$M_p = \delta - \theta_{\text{FC}} \quad (\text{Eq. 2})$$

$$m_p = \theta_{\text{FC}} - \theta_{\text{PWP}} \quad (\text{Eq. 3})$$

$$\mu_p = \theta_{\text{PWP}} \quad (\text{Eq. 4})$$

133

134 3 Results and discussion

135 3.1 Vegetation development

136 The development of vegetation on the different plots was fast during the spring and summer of the first year
137 (2011) and reached its plateau (between 90 and 95 %) in August 2011 (**Figure 2**). The most present sedum
138 plants were of different species, mainly: *S. Spurium*, *S. Album* and *S. Floriferum* with respectively 39, 26 and
139 21%. The plant diversity exhibited small changes that were not significant over time. During this time, mosses
140 have developed themselves punctually, without being measured. Our observations are coherent with those from
141 Nicholson (2004). They make a survey of the vegetation of a GR located in London area ten years after
142 establishment; they found that mosses were also frequent in the more open areas and north-facing orientation.

143 The **Figure 3** presents three replicates of root profiles on S-sedum. Two distinct sub-layers are clearly visible.
144 The top sub-layer (0 - 5 cm) contains a large amount of roots (31.2 % \pm 4.3 %). Oppositely the root density is
145 much smaller (8.4 % \pm 4.7 %) in the lower layer (5 - 9 cm).

146 MacIvor and Lundholm (2011) reported that vegetation roots development causes the substrate restructuring. In
147 this work, the upper part of the substrate was highly colonized by roots which led to an increase in fresh organic
148 matter. Such a result is consistent with the evolution of physical parameters highlighted by Schrader and
149 Boening (2006).

150

151 3.2 Organic matter and nitrogen dynamics

152 There was a drastic decrease of the organic carbon content between the initial substrate ($[\text{Ctot}]_{\text{S0}} = 5.09\%$) and
153 the average 4 years old substrate ($[\text{Ctot}]_{\text{S4}} = 2.10\% \pm 0.65\%$) (**Figure 4**). Concentrations also varied
154 significantly as a function of soil cover, especially at the surface (0 – 2 cm). The higher content was under the
155 sedum cover ($[\text{Ctot}]_{\text{S4-sedum}} = 2.87\% \pm 0.44\%$), then the moss cover ($[\text{Ctot}]_{\text{S4-moss}} = 2.62\% \pm 0.53\%$) and the bare
156 soil at last ($[\text{Ctot}]_{\text{S4-bare soil}} = 1.98\% \pm 0.57\%$). Changes in total carbon concentrations profiles were also observed
157 with a decrease from the surface to the depth for both sedum and moss covers (**Figure 4**). Oppositely, a small
158 increase was observed under bare soil for the 2-5 cm sub-horizon compared to the surface.

159 To explain the global decrease of organic matter over time, two hypotheses could be formulated that are
160 supported by a previous work (Chow et al. 2006). Indeed, peat materials are formed under specific conditions,

161 very different from the GR environment. It appears especially that the temperature variations and the wet-dry
162 cycle effects strongly enhance the organic carbon mineralization. Nevertheless, maximum mineralization rate
163 that was measured under controlled conditions was around 1 g kg^{-1} over two months (Chow et al. 2006). Over 4
164 years, considering a constant intensity (which is unrealistic) it would correspond to a decrease of 2.4%, which is
165 below the observed 3% mentioned before. As a consequence, additional organic carbon dissolution and vertical
166 transfer probably happened in the GR following mechanisms that are described by Chow et al. (2006) and
167 Vodyanitskii (2015). Besides, some further consideration will be assessed below about particles transfer. Apart
168 from that, it can be suggested that the surface enrichment is basically due to and also depending on the
169 vegetation development.

170 In a very different way, nitrogen concentration increased over time between the initial substrate ($[\text{N}_{\text{tot}}]_{\text{S0}} =$
171 0.13%) and the average 4 years old substrate ($[\text{N}_{\text{tot}}]_{\text{S4}} = 0.54\% \pm 0.20\%$) (**Figure 4**). Similar trends as for carbon
172 were observed: higher concentrations under vegetation (even if the nitrogen content was higher under moss than
173 under sedum) and decreasing concentrations from the surface to the bottom part of the substrates.

174 Organic matter mineralization is a logical explanation to explain nitrogen increase over time. Consistent
175 observations have been made, especially by repeatedly measuring higher nitrogen concentrations in runoff water
176 from green roofs when compared to control roofs (Van Seters et al. 2007; Hathaway et al. 2008; Retzlaff et al.
177 2008). Apart from the mineralization, another mechanism could explain such phenomenon: the deposition of
178 nitrogen oxides coming from airborne (Oberndorfer et al. 2007).

3.2 Fine particles eluviation

181 In all situations, the $< 2 \text{ mm}$ particles fraction were smaller after 4 years ($12.5\% \pm 2.9\%$) than in the initial
182 substrate (18.2%) (**Figure 4**). Potential vertical transfer of fine particles leading to an accumulation on the
183 geotextile and an eluviation through the drainage layer has already been described (Schwager et al. 2015).
184 Despite that fact, the solid density was almost the same for S0 (2.84 g cm^{-3}) than for S4 ($2.85 \text{ g cm}^{-3} \pm 0.03 \text{ g cm}^{-3}$),
185 suggesting an equal loss of all kind of substrate's constituents.

186 A very clear pattern, if not statistically tested, was observed under all soil covers on the aged GR. Indeed, there
187 was an enrichment of fine particles ($< 2 \text{ mm}$) in the second sub-horizons ($2 - 5 \text{ cm}$) ($14.6\% \pm 2.3\%$) compared
188 to the top sub-horizons ($9.5\% \pm 2.1\%$) and the bottom horizons ($13.9\% \pm 0.5\%$) (**Figure 4**). The eluviation
189 process was the most pronounced in the bare soil, whereas it was the least visible under moss cover. Under
190 sedum cover, the particles transfer was intermediate. The most probable assumption is that the fine particles
191 were eluviated from the surface by the rain. The presence of vegetation would limit the intensity of the process
192 by covering the soil surface and slowing down the velocity of the water flux.

193 The novelty in our approach was the strategic sampling in three sub-horizons of the thick substrate layer. Indeed,
194 we performed previous tests, before the profile observations, by dividing only into two layers and only small
195 grain size's differences were visible as indicated by De-Ville et al. (2015).

3.3 Poral architecture

196
197 The total porosity of S0 ($0.45 \text{ cm}^3 \text{ cm}^{-3}$) was higher than for S4 ($0.38 \text{ cm}^3 \text{ cm}^{-3} \pm 0.02 \text{ cm}^3 \text{ cm}^{-3}$) (**Figure 5**). The
198 moisture at the field capacity indicated that the macroporosity remained almost constant over time (S0 = 0.26
199 $\text{cm}^3 \text{ cm}^{-3}$; S4 = $0.24 \text{ cm}^3 \text{ cm}^{-3}$). The microporosity (calculated after the volumetric water content at permanent
200

201 wilting point) increased in S4 ($0.12\text{cm}^3\text{ cm}^{-3}$) compared to S0 ($0.07\text{cm}^3\text{ cm}^{-3}$). The decrease in total porosity was
1 202 mainly explained by the drastic decrease of mesoporosity between S0 ($0.11\text{cm}^3\text{ cm}^{-3}$) and S4. Considering the
2 203 size of the sampling core and the shallow depth of the substrates, it was not possible to study the effect of depth
3 204 on such parameters.

4 205 These measurements indicated modifications of the structure and consequently an evolution of the association
5 206 between the particles of the substrates. Furthermore, such results suggested not only a small decrease of the
6 207 water holding capacity of the substrate with time as already highlighted (Bouzouidja et al. 2016), but also a
7 208 major decrease of the available water for plants in the aged substrate. This would require confirmation by
8 209 observation of the vegetation behaviour during drought events.

13 210 14 211 **3.4 Early pedogenic evolution**

15 212 Various changes over time of physical and chemical properties have been noted in the GR substrates. Our results
16 213 are consistent with the existing literature cited above, but the soil science methods – observation / adapted
17 214 sampling / measurement – added an explicit identification and quantification of the involved processes. Thus,
18 215 such pedogenic processes as organic matter transfer, transformation and degradation, fine particles eluviation,
19 216 and structure evolution have been highlighted in Technosols that are analogous to what happened in natural soils.
20 217 But, in accordance to what Legu dois et al. (2016) described, most of the Technosols are known to be submitted
21 218 to a notably quick evolution. This is due to the disequilibrium between their parent materials and the
22 219 environmental forcing factors that lead to an internal response that induced a high-energy state of such artificial
23 220 media (S r  et al. 2010). This is the case for GR substrates that mix different particulate materials from various
24 221 origins, with much contrasted properties.

25 222 The preliminary results currently available, including the one presented here, suggest that there are concomitant
26 223 processes that happened with a significant intensity shortly after the substrate implementation. However, very
27 224 little is presently known about i) the kinetic of such processes, ii) the influence of external factors (*i.e.* climate,
28 225 vegetation), iii) the influence of internal factors (*i.e.* nature and ratio of the parent materials) that would require
29 226 further investigations.

30 227 31 228 **4 Conclusions**

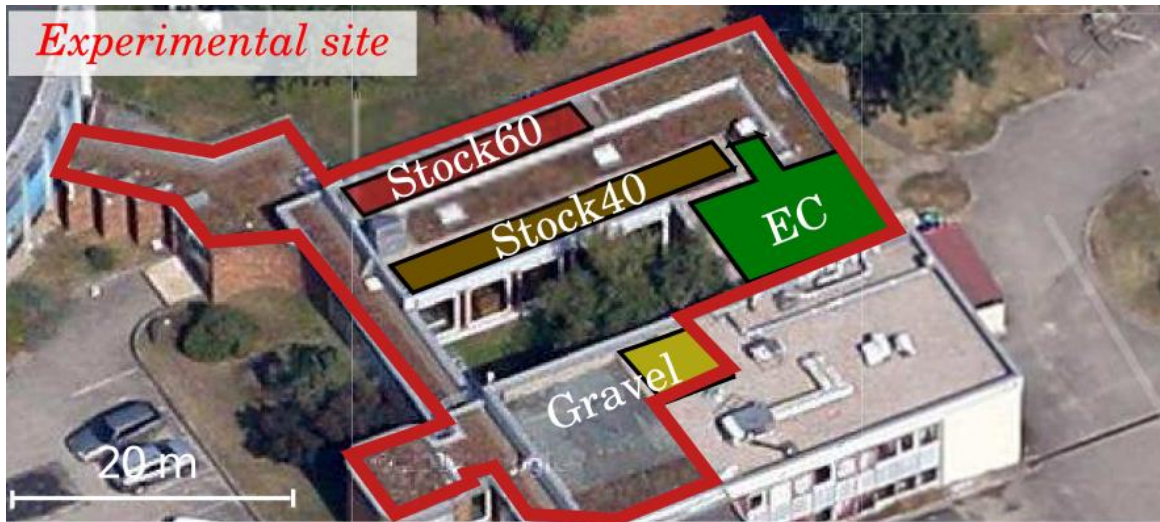
32 229 The study of an aged GR substrate led to the evidences of drastic transformations of both physical and chemical
33 230 properties compared to the original substrate. The results show that over 4 years, the organic carbon has
34 231 decreased from 5.0% to 2.10% and that the nitrogen concentration has increased from 0.13% to 0.54%. At the
35 232 same time, a loss of fine particles was also observed. The implementation of an adequate sampling protocol into
36 233 representative sub-horizons based on the observation and pedological measurements enabled an explicit
37 234 quantification of active soil forming processes. Indeed, organic matter transformation and fine particles
38 235 eluviation, structure evolution have been reported that depend on both the vegetation cover or the depth. The
39 236 acquisition of a vertical organization of the GR substrate over time is now suggested. In addition to the Isolatic
40 237 Technosol definition, such criteria promoted the idea to consider GR as urban soils. As Technosols, GR are
41 238 submitted to fast and significant changes that can affect their performances. Further researches are needed either
42 239 to assess more precisely such evolution and to develop new technical solutions for GR conception and
43 240 management.

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299 **Figure**



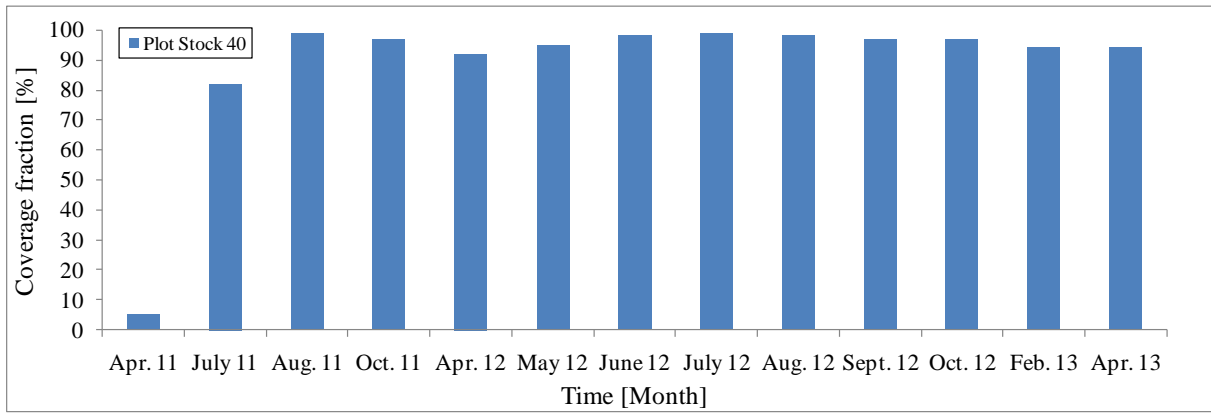
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301 Figure 1: Overview of the experimental platform, comprising four green roof plots including Stock40

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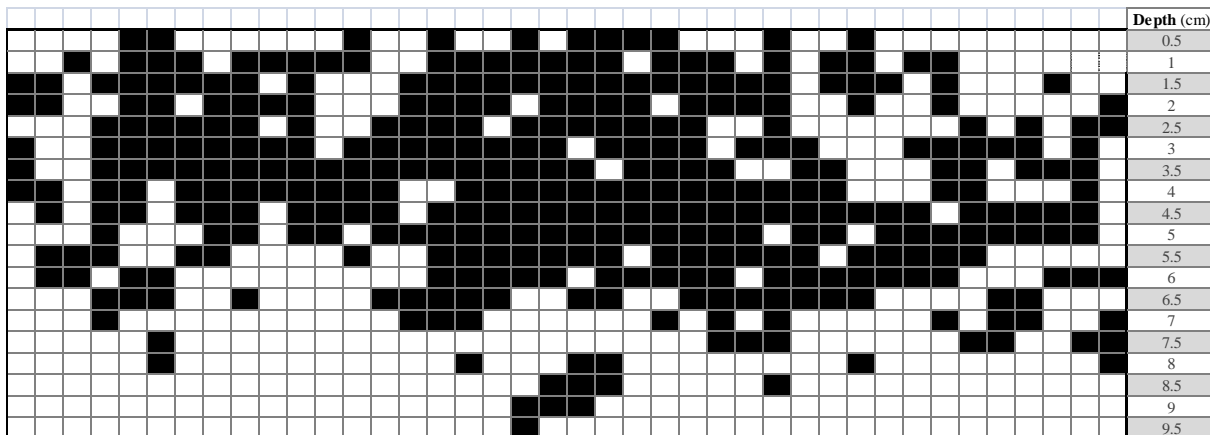
Figure 2: Evolution of coverage fraction of vegetation for the plot Stock40 between April 2011 and April 2013

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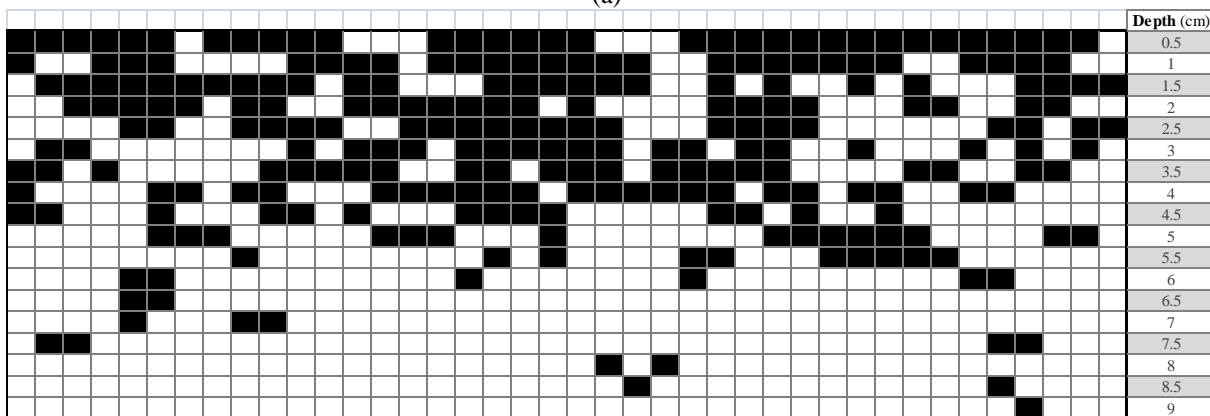
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(a)

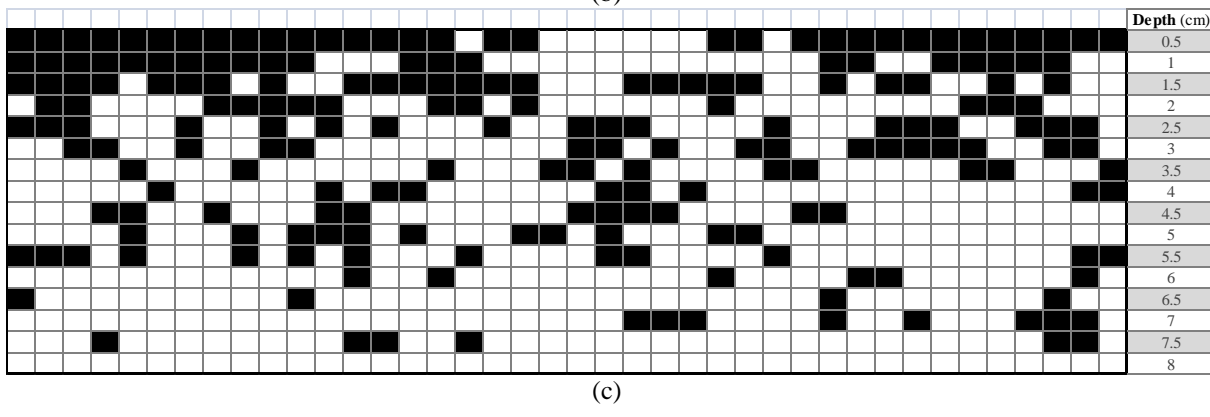
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(b)

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(c)

Figure 3: Root distribution profiles extracted from three samples of the S4 substrate on S-sedum, Black and White square are designed respectively as roots occurrence and voids.

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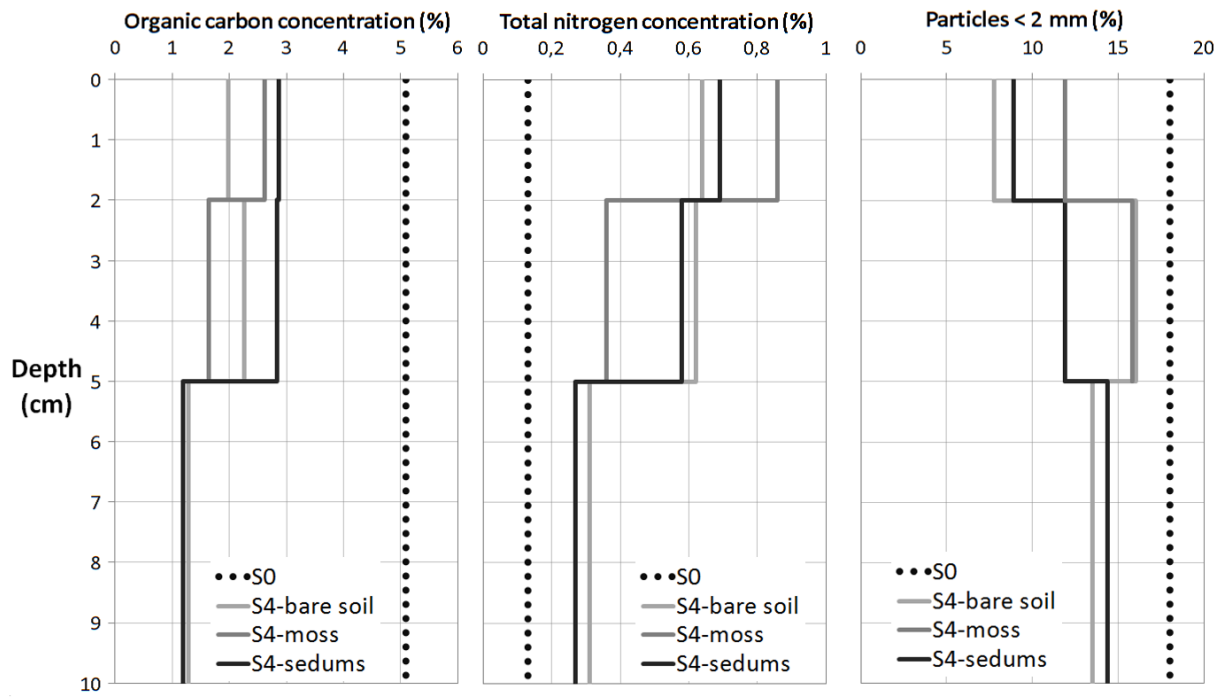


Figure 4: Evolution with depth of the fine particles, the organic carbon concentration and the total nitrogen concentration in the initial (S0) and 4 years aged substrates over different soil cover (bare soil, sedums and moss)

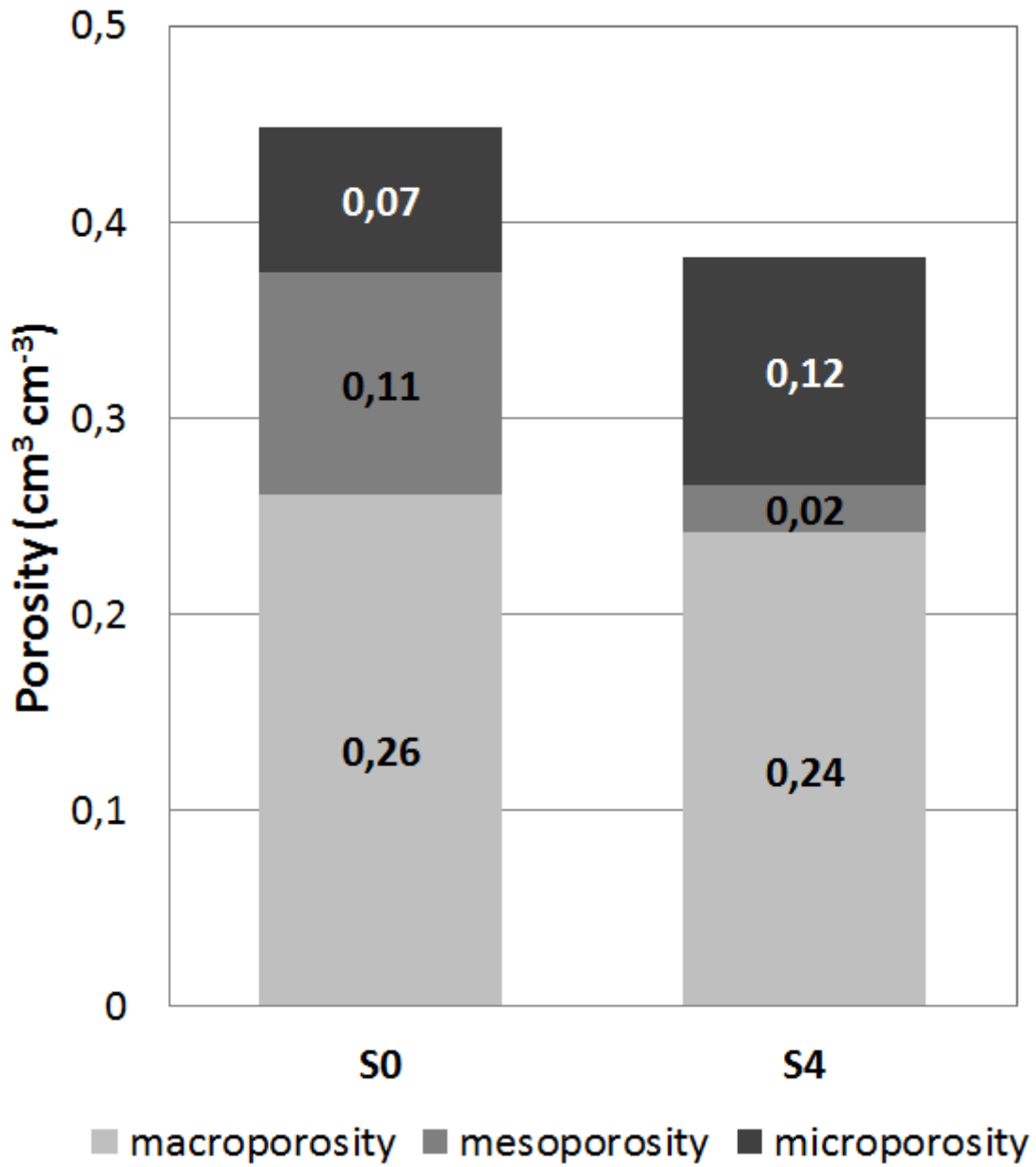


Figure 5: Evolution of the macro, meso and microporosity of the substrates over time