J Soils Sediments (2018) 18:418–425
DOI 10.1007/s11368-016-1513-3

Green roof ageing or Isolatic Technosol's pedogenesis?

Ryad Bouzouidja[1,2] · Gustave Rousseau[1] · Violaine Galzin[1] · Rémy Claverie[2] · David Lacroix[3,4] · Geoffroy Séré[1]

Received: 28 January 2016 / Accepted: 14 July 2016 / Published online: 22 July 2016

Abstract

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

Materials and methods A full-scale experimental plot with various vegetation cover was studied. A dedicated sampling strategy was implemented to monitor substrate's evolution over 4 years. Then, physical and chemical characterisation (carbon and nitrogen contents, particle size distribution, porosity, soil water retention) was conducted and compared to results on the original substrate.

Results and discussion The upper layer of the substrate (0 to 5 cm depth) contained a large amount of fine and short roots whereas the root density was much smaller in the lower layer of the substrate (5 to 10 cm depth). There was a global drop of the organic carbon content from 5 % in the initial substrate to 2 % in the 4-year-old substrate. On the contrary, the nitrogen concentration has increased by 0.4 % during the same period. The mesoporosity decreased drastically from 0.11 to 0.02 $cm^3\ cm^{-3}$. On the whole substrate, the <2-mm particles fraction was smaller after 4 years (12.5 %) than in the initial substrate (18.2 %) which was especially obvious in the upper horizon (9.5 %). Additionally, the monitored properties also varied significantly as a function of soil cover (sedum, moss and bare soil). Evidences of an early pedogenesis were highlighted such as poral evolution and fine particles eluviation.

Conclusions In conclusion, the study demonstrated the effects of time, climate and vegetation on physical and chemical properties of green roof substrate. They are not only classified as Isolatic Technosols due to their composition and implementation; they also exhibit one of the major characteristic of young Technosols: a fast and intense pedogenesis.

Keywords Green roof · Isolatic Technosols · Pedogenesis · Substrate · Temporal changes

Responsible editor: Jean Louis Morel

✉ Geoffroy Séré
geoffroy.sere@univ-lorraine.fr

[1] Laboratoire Sols et Environnement, UMR 1120 Université de Lorraine-INRA, 2 avenue de la Forêt de Haye, TSA 40602, 54518 Vandœuvre-lès-Nancy Cedex, France

[2] CEREMA DTer Est, 71 Rue de la Grande Haie, 54510 Tomblaine, France

[3] Université de Lorraine, LEMTA, UMR 7563, 2 Avenue de la Forêt de Haye TSA 60604, 54518 Vandœuvre-lès-Nancy, France

[4] CNRS, LEMTA, UMR 7563, 2 Avenue de la Forêt de Haye TSA 60604, 54518 Vandœuvre-lès-Nancy, France

1 Introduction

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

Considering their composition–mixing of extracted and transported materials form natural origin such as pozzolana or peat and man-made products such as bricks and compost that all are defined as “artefacts” (IUSS 2014)—and the way they are implemented (presence of a geomembrane), green roofs belong to the “Technosol” Soil Reference Group (IUSS 2014). Their main attribute is clearly defined under the qualifier “isolatic: having, above technic hard material, above a geomembrane or above a continuous layer of artefacts starting ≤100 cm from the soil surface, soil material containing fine earth without any contact to other soil material (e.g. soils on roofs or in pots)” (IUSS 2014). Moreover, their properties are dominated by the technical origin of their parent materials. We propose to classify them as Isolatic Technosol (Drainic, Folic and Transportic).

As Technosols, GR substrates are reactive media that can be submitted to an early and fast pedogenesis that lead to an evolution of their physical and chemical properties (Séré et al. 2010; Huot et al. 2015; Leguédois et al. 2016). Evidences of the evolution with time of the chemical composition of different GR substrates were demonstrated, but the results are contrasted. Emilsson et al. (2007) observed a decrease with time of organic matter, whilst Schrader and Boening (2006) described enrichments in both organic carbon and total nitrogen contents. Concerning physical characteristics, a study on a 5-year-old substrate showed that the water holding capacity has increased compared to a new one (Getter et al. 2007), whereas Mentens et al. (2006) evidenced the lack of influence of the age of the GR on its hydraulic behaviour. Very recent works focused on such a target as the highlighting of drastic evolution of GR’s physical properties. De-Ville et al. (2015) interestingly described the fact that the upper layers of two different aged substrates have an increased number of finer particles whereas the lower part exhibited few changes. This increase was attributed, amongst other factors, to atmospheric particles deposition and weathering processes. They observed that the development of roots led to a leaching of organic constituents and a consequent local enrichment in organic matter. Finally, the authors also demonstrated a decrease of total porosity, with antagonistic results about the fine and the open porosities, considering one or the other substrate. As a consequence, De-Ville et al. (2015) estimated that such an evolution could influence green roof performances, especially as water regulation is concerned. These results are absolutely consistent with another study that suggested a decrease of the hydraulic performances of a GR due to an evolution of its physical organisation (Bouzouidja et al. 2016). All of this work focused on the substrate study that has most of time heterogeneous and diverse geographical origin. Consequently, the contradictory aspect of performance may be linked to this.

Thus, it appears that soil science is progressively transposing its methods to study physical and chemical properties of such an artificial medium as GR substrate. Beyond their WRB soil classification, do GR behave like soils? Are they submitted to a fast and intense early pedogenesis like other Technosols? The present work aims at: (i) defining relevant sampling and measurement strategies to exhibit the evolution of an aged GR substrate over time (ii) describing such transformations in terms of pedogenic processes.

2 Materials and methods

2.1 Experimental site

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

The green roof platform, built in July 2011, is placed above an approximately 6 m in height flat roof building. The overall GR surface area is 600 m^2, 40 m^2 of which were studied for this work (Fig. 1). The substrate is a man-made porous medium composed of pozzolana (60 % of 3- to 6-mm particles and 20 % of 7- to 15-mm particles) and organic parts (10 % of peat dust and 10 % of maritime pine bark). The thickness of this layer is comprised between 7.5 and 9.5 cm. Vegetation plants that were installed are classically: *Sedum album*, *Sedum reflexumlarix*, *Sedum reflexum germanium*, *Sedum*

Fig. 1 View of the experimental green roof platform located in Tomblaine (54), France and 10 cm deep soil profile of the 4-year-old substrate (pictures taken the 11/05/2015)

sexangulare and *Sedum floriferum* (Bouzouidja et al. 2013). These plants do not exceed 10 cm in height.

2.2 Sampling and in situ measurement strategy

Two time steps were studied: original substrate (S0) and 4-year-old substrate (S4). We based the sampling on the observation of the substrates vertical profiles and decided to split them into three sub-horizons: 0–2 cm, 2–5 cm and 5–10 cm, based on visual parameters (root density and structure evaluation) (Fig. 1). The soil cover was also taken into account by sampling on zones covered by sedums (S-sedum), by moss (S-moss) and bare soil (S-bare). Each soil cover was replicated three times. Each time, undisturbed soil cores (251 cm^3) were sampled.

The measurement of plant coverage was performed using three permanent quadrats (1 m × 1 m) and the photographic method according to Magill (1989). Every picture was analysed following the method described by Folk (1951) to assess the vegetation cover fraction.

An observation of the roots distribution was realised on the aged GR on S-sedum. The used method was based on in situ mapping protocol described by Tardieu and Manichon (1986). This measurement was conducted on three replicates, on a surface of 900 cm^2. For each sample, a regular grid (0.5 cm × 0.5 cm) was applied on the soil profile. The root occurrence is defined by a coloured cell and its absence by a white cell.

2.3 Substrate characterisation

The samples have been air-dried during 48 h. They have been sieved at 5, 2 and 0.2 mm. All fractions have been collected, weighted and characterised for total carbon (Ctot) and total nitrogen (Ntot) (vario Micro cube, Elementar).

Bulk density has been measured thanks to core-sampling. The solid density was measured with a helium pycnometer (Quantachrome UltraPyc 1200) based on NF P18-554. Total porosity (δ) was then calculated after (Eq. 1).

$$\delta = 1 - \frac{\rho_a}{\rho_r} \quad (1)$$

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

The soil water retention characteristics, i.e. volumetric water content at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), were determined on a pressure plate apparatus at −10 kPa (−100 cm) and −1500 kPa (−15000 cm), respectively (Bruand et al. 1996). Macroporosity (Mp), mesoporosity (mp) and microporosity (μp) were estimated according to Peverill et al. (1999). The relationship between porosity and soil moisture explained by water content at field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) can be determined as:

$$Mp = \delta - \theta_{FC} \quad (2)$$

$$mp = \theta_{FC} - \theta_{PWP} \quad (3)$$

$$\mu p = \theta_{PWP} \quad (4)$$

All results are presented with the average value and the standard error over the three replicates except C and N contents of the initial substrate (S0) because a single sample was characterised.

3 Results and discussion

3.1 Vegetation development

The development of vegetation on the different plots was fast during the spring and summer of the first year (2011) and reached its plateau (between 90 and 95 %) in August 2011 (Fig. 2). The most present sedum plants were of different species, mainly: *S. spurium*, *S. album* and *S. floriferum* with respectively 39, 26 and 21 %. The plant diversity exhibited small changes that were not significant over time. During this time, mosses and unvegetated zones have developed themselves punctually due notably to local floodwater events. The vegetation cover fraction slightly decreased after 2013 (88 % in April 2013, 82 % in April 2014 and 72 % in April 2015). Our observations are coherent with those from Nicholson (2004). They made a survey of the vegetation of a GR located in the London area 10 years after establishment; they found that mosses were also frequent in the more open areas and north-facing orientation.

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

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

3.2 Organic matter and nitrogen dynamics

There was a drastic decrease of the organic carbon content between the initial substrate ($[Ctot]_{S0} = 5.09$ %) and the average 4-year-old substrate ($[Ctot]_{S4} = 2.10$ % ± 0.65 %) (Fig. 4). Concentrations also varied significantly as a function of soil

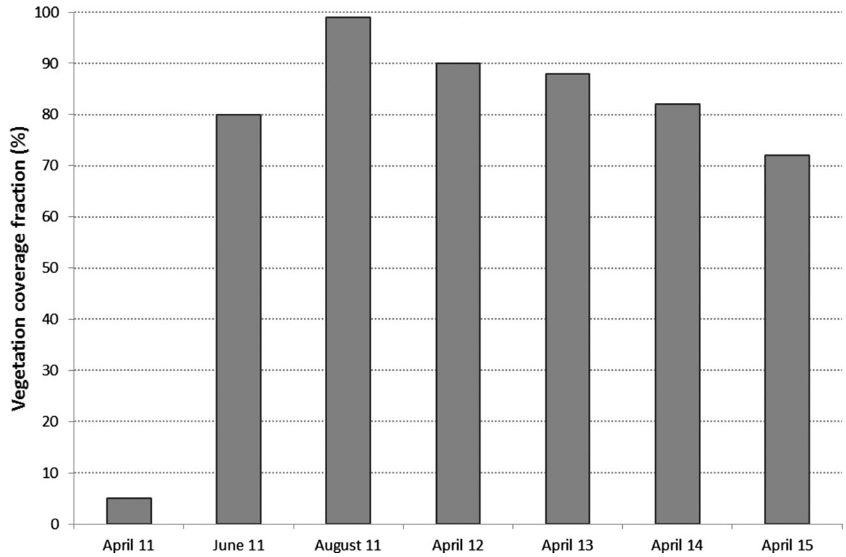

Fig. 2 Evolution of the vegetation coverage fraction of the experimental green roof platform between April 2011 and April 2015

cover, especially at the surface (0–2 cm). The higher content was under the sedum cover ($[Ctot]_{S4\text{-}sedum} = 2.87\ \% \pm 0.44\ \%$), then the moss cover ($[Ctot]_{S4\text{-}moss} = 2.62\ \% \pm 0.53\ \%$) and the bare soil at last ($[Ctot]_{S4\text{-}bare\ soil} = 1.98\ \% \pm 0.57\ \%$). Changes in total carbon concentrations profiles were also observed with a decrease from the surface to the depth for both sedum and moss covers (Fig. 4). Oppositely, a small increase was observed under bare soil for the 2–5 cm sub-horizon compared to the surface.

To explain the global decrease of organic matter over time, two hypotheses could be formulated that are supported by a previous work (Chow et al. 2006). Indeed, peat materials are formed under specific conditions, very different from the GR environment. It appears especially that the temperature variations and the wet-dry cycle effects strongly enhance the organic carbon mineralization. Nevertheless, maximum mineralization rate that was measured under controlled conditions was around 1 g kg^{-1} over 2 months (Chow et al. 2006). Over 4 years, considering a constant intensity (which is unrealistic and overestimated), it would correspond to a decrease of 2.4 %, which is slightly below the observed 3 % mentioned before. As a consequence, it is reasonable to suppose that an additional organic carbon dissolution and vertical transfer probably happened in the GR following mechanisms that are described by Chow et al. (2006) and Vodyanitskii (2015). Besides, some further consideration will be assessed below about particles transfer. Apart from that, it can be suggested that the surface enrichment is basically due to and also depending on the vegetation development.

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

Organic matter mineralization is a logical explanation to explain nitrogen increase over time. Consistent observations have been made, especially by repeatedly measuring higher nitrogen concentrations in runoff water from green roofs when compared to control roofs (Van Seters et al. 2007; Hathaway et al. 2008; Retzlaff et al. 2008). Apart from the mineralization, other mechanisms could explain such phenomenon: (i) bird droppings (Charzynski et al. 2015) and (ii) the deposition of nitrogen oxides coming from airborne (Oberndorfer et al. 2007). In France, during the 4-year period, the average concentration of NO_2 in the atmosphere of urban areas was 21 μg m^{-3} (Geod'Air 2014).

3.3 Fine particles eluviation

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

A very clear pattern, if not statistically tested, was observed under all soil covers on the aged GR. Indeed, there was an enrichment of fine particles (<2 mm) in the second sub-horizons (2–5 cm) (14.6 % ± 2.3 %) compared to the top sub-horizons (9.5 % ± 2.1 %) and the bottom horizons (13.9 % ± 0.5 %) (Fig. 4). The eluviation process was the most pronounced in the bare soil, whereas it was the least visible under moss cover. Under sedum cover, the particles transfer was intermediate. The most probable assumption is that the fine particles were eluviated from

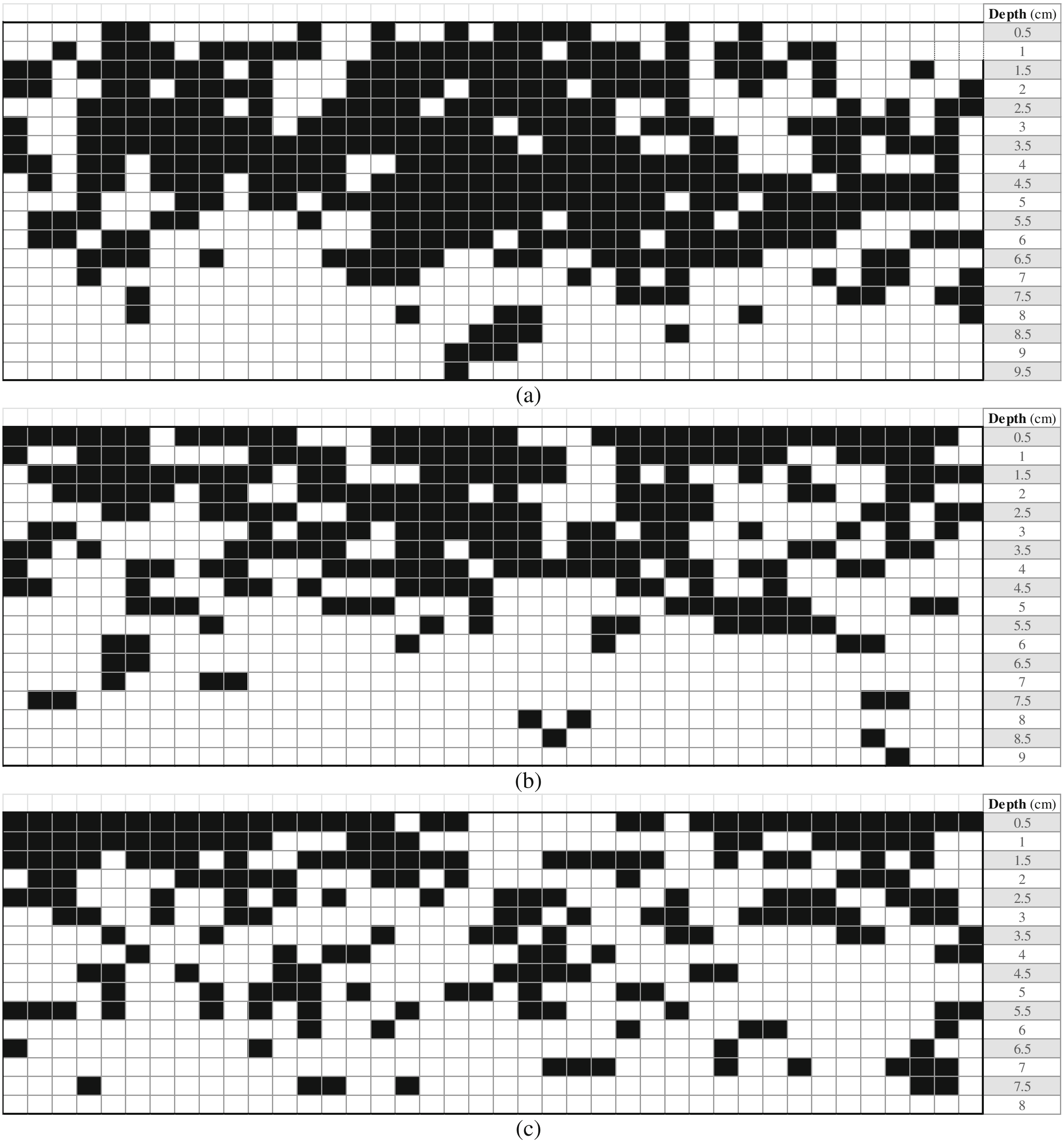

Fig. 3 Root distribution profiles extracted from three samples of the S4 substrate on S-sedum measured on the experimental green roof platform in June 2015, after the method of Tardieu and Manichon (1986) (Roots occurrence is represented by *black cells*)

the surface by the rain. The presence of vegetation would limit the intensity of the process by covering the soil surface and slowing down the velocity of the water flux, as well as by increasing evapotranspiration and thus limiting water loss.

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

3.4 Poral structure

The total porosity of S0 (0.72 cm^3 cm^{-3} ± 0.02 cm^3 cm^{-3}) was similar than for S4 (0.72 cm^3 cm^{-3} ± 0.04 cm^3 cm^{-3})

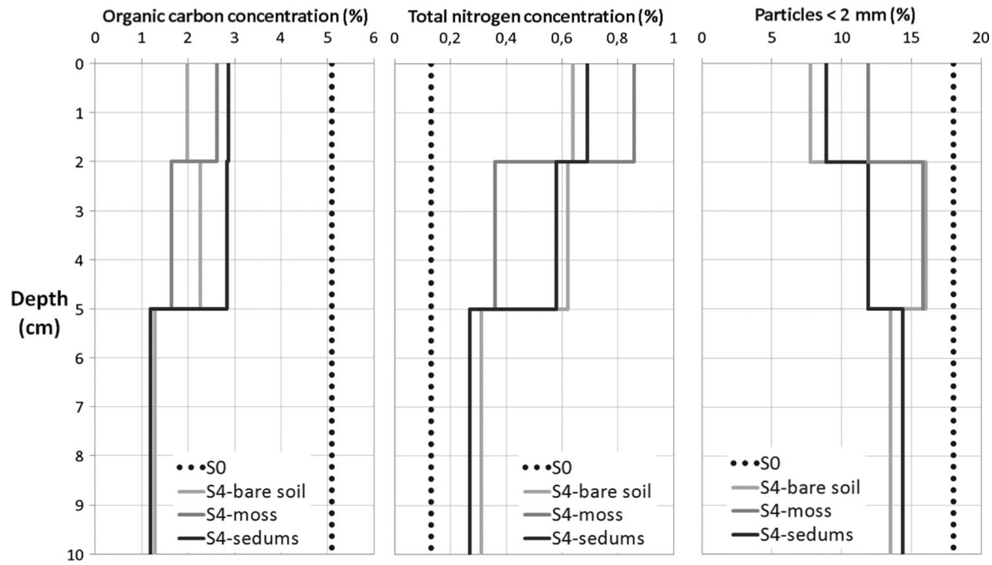

Fig. 4 Evolution with depth of the fine particles, the organic carbon concentration and the total nitrogen concentration in the initial (S0) and 4 years aged substrates (S4) over different soil cover (bare soil, sedums, and moss)

(Fig. 5). The moisture at the field capacity indicated that the macroporosity slightly increased over time ($Mp_{S0} = 0.53$ cm^3 cm^{-3} ± 0.03 cm^3 cm^{-3}; $Mp_{S4} = 0.58$ cm^3 cm^{-3} ± 0.03 cm^3 cm^{-3}). The microporosity (calculated after the volumetric water content at permanent wilting point) increased in S4 ($\mu p_{S4} = 0.12$ cm^3 cm^{-3} ± 0.03 cm^3 cm^{-3}) compared to S0 ($\mu p_{S0} = 0.07$ cm^3 cm^{-3} ± 0.01 cm^3 cm^{-3}). On the contrary, there was a drastic decrease of mesoporosity between S0 ($mp_{S0} = 0.11$ cm^3 cm^{-3} ± 0.02 cm^3 cm^{-3}) and S4 ($mp_{S4} = 0.02$ cm^3 cm^{-3} ± 0.01 cm^3 cm^{-3}). Considering the size of the sampling core and the shallow depth of the substrates, it was not possible to study the effect of depth on such parameters.

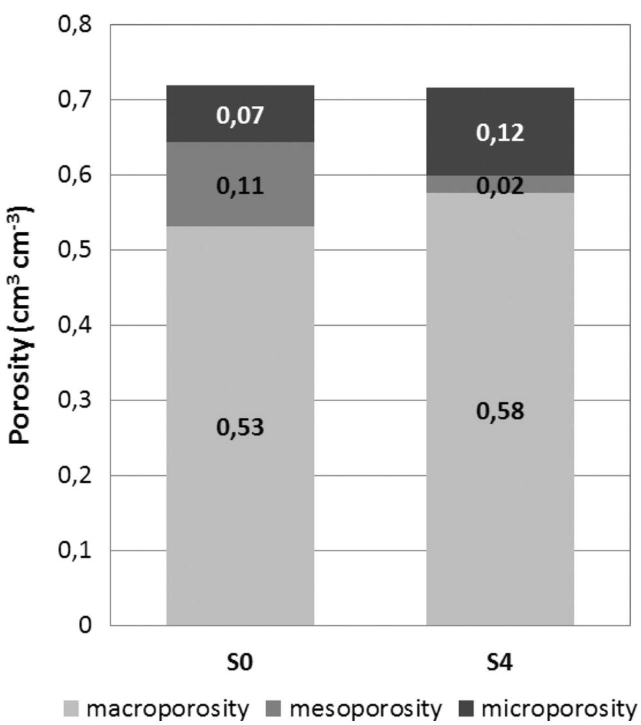

Fig. 5 Evolution of the macro, meso and microporosity of the initial (S0) and 4 years aged substrates (S4)

These measurements indicated modifications of the structure as a potential result of particles transfer and particles associations. Furthermore, such results suggested not only a small decrease of the water holding capacity of the substrate with time as already highlighted (Bouzouidja et al. 2016), but also a major decrease of the available water for plants in the aged substrate.

3.5 Early pedogenic evolution

Various changes over time of physical and chemical properties have been noted in the GR substrate. Our results are consistent with the existing literature cited above, but the soil science methods—observation/adapted sampling/measurement—added an explicit identification and quantification of the involved processes. Thus, such pedogenic processes as organic matter transfer, transformation and degradation, fine particles eluviation and structure evolution have been observed in the aged green roof, which was previously described as an Isolatic Technosol (Drainic, Folic, and Transportic). Such processes are analogous to what happened in natural soils. But, in accordance to what Leguédois et al. (2016) described, most of the Technosols are known to be submitted to a notably quick and intense evolution. GR substrates mix different particulate materials from natural origins, various locations, with much contrasted properties, that were crushed, sieved and mixed together, before being sowed and exposed to climatic conditions and to biological activity. As a result, there is a strong thermodynamic disequilibrium between the substrate and the environmental forcing factors. It leads to an internal response that induced a fast and intense evolution (Séré et al. 2010). Distinct sub-layers have been observed inside the substrate;

however, from our point of view, they did not exhibit enough discontinuities in their physic-chemical properties to be already called pedological horizon.

These preliminary results suggest that there are concomitant processes that happened with a significant intensity, few years after the substrate implementation. Some similarities appeared between GR and other technogenic soils—Edifisols (Charzynski et al. 2013, 2015) shallow soils naturally developing on buildings and constructed Technosols (Séré et al. 2010) that result in the deliberate mixing of artefacts—that shed light on their pedogenesis. Three main questions arise from them: (i) what is the kinetic of such pedogenic processes, (ii) what is the relative influence of external factors (i.e. climate, vegetation, biological activity) and (iii) what is the relative influence of internal factors (i.e. nature and ratio of the parent materials). Hereby, only two points where analysed (initial time and 4 years), inside the chronosequence. Other data on physical and hydraulic properties of the GR substrate were measured after 3 years (Bouzouidja et al. 2016) and were very similar to S4 (data not shown) suggesting that most of the pedogenic processes happened within the first year. Concerning the external factors, the influence of the vegetation has been assessed. Sedums and moss prevented fine particles eluviation and contribute to the C_{org} and N enrichment of the soil surface. The contribution of soil fauna was not studied yet in itself. Despite that, observations on the GR platform was conducted and brought to light the presence of decomposers (woodlice and snails). Knowing their role in the cycle of organic matter, we can hypothesise a functional impact due to the presence of these organisms on the evolution of GR. At last, a single kind of GR substrate was studied and it would be necessary to monitor various ones (e.g. containing some compost, crushed bricks, coconut fibres) to evaluate the nature, intensity and kinetic of pedogenic processes.

4 Conclusions

The study of an aged GR substrate led to the evidences of drastic transformations of both physical and chemical properties compared to the original substrate. The results show that over 4 years, the organic carbon has decreased from 5.0 to 2.1 % and that the nitrogen concentration has increased from 0.13 to 0.54 %. At the same time, a loss of fine particles was also observed. The implementation of an adequate sampling protocol into representative sub-layers based on the observation and pedological measurements enabled an explicit quantification of active soil-forming processes. Indeed, organic matter transformation, fine particles eluviation and structure evolution have been reported as a function of depth. The intensity of such pedogenic processes appears to depend on the presence, density and nature of the vegetation. The acquisition of a vertical organisation of the GR substrate over time is now suggested. In addition to the Isolatic Technosol definition, such criteria promoted the idea to consider GR as dynamic urban soils. As Technosols, GR are submitted to fast changes that can significantly affect their expected performances (e.g. water holding capacity, reservoir of biodiversity, water filtration). Further researches are needed to assess more precisely such evolution and to develop new technical solutions for GR conception and management.

References

Alexandri E, Jones P (2008) Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Build Environ 43:480–493

Bouzouidja R, Claverie R, Sere G, Lacroix D (2013) Characterization of the thermo-hydric functioning of *in situ* green roof. Houille Blanche 5:62–69

Bouzouidja R, Séré G, Claverie R, et al (2016) Green roof ageing: quantifying the impact of substrate evolution on hydraulic performances. Submitt. Ecol. Eng

Bruand A, Cousin I, Nicoullaud B et al (1996) Backscattered electron scanning images of soil porosity for analyzing soil compaction around roots. Soil Sci Soc Am J 60:895–901

Carter T, Jackson CR (2007) Vegetated roofs for stormwater management at multiple spatial scales. Landsc Urban Plan 80:84–94

Charzyński P, Hulisz P (2013) Soils forming on the buildings in Torun. In: Charzyński P, Hulisz P, Bednarek R (eds) Technogenic soils of Poland. Polish Society of Soil Science, Toruń, pp 81–94

Charzyński P, Hulisz P, Bednarek R, Piernik A, Winkler M, Chmurzyński M (2015) Edifisols—a new soil unit of technogenic soils. J Soils Sediments 15:1675–1686

Chow E, Meldrum CJ, Crooks R et al (2006) An updated mutation spectrum in an Australian series of PJS patients provides further evidence for only one gene locus. Clin Genet 70:409–414

De-Ville S, Menon M, Stovin V (2015) Using X-ray microtomography to identify physical changes in green roof substrates as a result of ageing. In: the annual postgraduate research student conference. Sheffield, UK, pp 8–13

Emilsson T, Berndtsson JC, Mattsson JE, Rolf K (2007) Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. Ecol Eng 29:260–271

Folk L (1951) A comparison chart for visual percentage estimation. J Sediment Petrol 21:32–33

Geod'Air (2014) http://www.statistiques.developpement-durable.gouv.fr/lessentiel/ar/227/1101/pollution-lair-oxydes-dazote.html

Getter L, Rowe B, Anderson A (2007) Quantifying the effect of slope on extensive green roof stormwater retention. Ecol Eng 31:225–231

Hathaway A, Hunt W, Jennings G (2008) A field study of green roof hydrologic and water quality performance. Trans ASABE 51:37–44

Huot H, Simonnot M-O, Morel JL (2015) Pedogenetic trends in soils formed in technogenic parent materials. Soil Sci 180:182–192

IUSS WG (2014) International soil classification system for naming soils and creating legends for soil maps. WRBWorld Reference Base for Soil Resources 2014, FAO, Rome

Leguédois S, Séré G, Auclerc A et al (2016) Modelling pedogenesis of Technosols. Geoderma 262:199–212

MacIvor JS, Lundholm J (2011) Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. Ecol Eng 37:407–417

Magill AW (1989) Monitoring environmental change with color slides. Gen. Tech.Rep.PSW-117.Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S.Department of Agriculture; 55 pp

Mentens J, Raes D, Hermy M (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21\textsuperscriptst century? Landsc Urban Plan 77:217–226

Moran, an Hunt WA, Smith J (2005) Green roof hydrologic and water quality performance from two field sites in North Carolina. Manag Watersheds Hum Nat Impacts 1–12. doi: 10.1061/40763(178)99

Nicholson B (2004) CUE building. Horniman Museum: Botanical survey, London

Oberndorfer E, Lundholm J, Bass B, et al (2007) Green roofs as urban ecosystems: ecological Structures, functions, and services. BioScience 823–833

Peverill KI, Sparrow LA, Reuter DJ (1999) Soil analysis: an interpretation manual. CSIRO Publishing

Retzlaff W, Ebbs S, Alsup S, et al (2008) Evaluation of the thermal benefits of green roof systems. In: Proceedings of the 6th Annual Greening Rooftops for Sustainable Communities Conference. Baltimore, MD, p 12

Schrader S, Boening M (2006) Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans. Pedobiologia 50:347–356

Schwager J, Schaal L, Simonnot M-O et al (2015) Emission of trace elements and retention of Cu and Zn by mineral and organic materials used in green roofs. J Soils Sediments 15: 1789–1801

Séré G, Schwartz C, Ouvrard S et al (2010) Early pedogenic evolution of constructed Technosol. J Soils Sediments 10:1246–1254

Tardieu F, Manichon H (1986) Caractérisation en tant que capteur d'eau de l'enracinement du maïs en parcelle cultivée. Agronomie 6:345–354

Van Seters T, Rocha L, Mac Millan G (2007) Evaluation of the runoff quantity and quality performance of an extensive green roof in Toronto. Minneapolis, MN 2007

Vodyanitskii YN (2015) Organic matter of urban soils. Eurasian Soil Sci 48:802–811