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Soil archives: where soilscape history meets present-day ecosystems

● Boris BRASSEUR

Université de Picardie Jules Verne

● Damien ERTLEN

Université de Strasbourg

● Vincent ROBIN

Université de Lorraine

1. Introduction

The interpretation of soil archives, although complex, is nevertheless essential for understanding the impact of soils on present-day environments and deciphering the environmental history of a site. Soil archives are local, although within a continuous soilscape they allow the study of spatial structures. Compared with sedimentary archives, they do not strictly follow stratigraphic principles. Combining superficial microtopography, buried biological remains, bioturbation, and chemical evolution, these archives appear as mixed pieces of old and new disassembled jigsaw puzzles. Such puzzles are snapshots of past environments, and understanding the biological and physicochemical pedogenic processes is the main way to disentangle them. This chapter presents some key elements for understanding the archiving process through to the reconstruction of a fragment of palaeoenvironmental history. The presented key

elements are associated with our respective experiences, and we do not try to present an exhaustive list.

2. Mechanisms of soil archiving and the associated dynamics

2.1. Pedoturbations of biological and physical origins

When dealing with soil archives, a key issue to consider is that soils are dynamic entities. Biological and/or physical processes induce the mixing of the soil matrix down to a fine spatial scale (i.e., micromorphological scale). Indeed, when environmental conditions permit biological activities in soil, the related bioturbation causes a vertical transfer of elements. These transfers are mainly related to the presence of micropassages in which soil moves downward when they collapse. These spaces result from the activity of small mammals (e.g., *Talpidae*) and earthworms (e.g., *Lumbricidae*). The latter of these also move worm casts—matter excreted by the worms—upward to the soil's surface (Lavelle *et al.*, 2016). The mixing of soil also occurs through physical processes. These processes include tree uprooting, in which soil embedded in the root plate (Šamonil *et al.* 2010) moves upward through the overturning of the tree trunk and roots. Cryoturbation, which stems from the freeze-thaw-induced movement of the entire active layer portion of the soil. (Stinchcomb *et al.* 2014). Argillipedoturbation (swelling clay pedoturbation) and seismiturbation (earthquake pedoturbation) are also important physical soil disturbances. Thus, the soil matrix or soil aggregates may move in any direction, depending on the type and intensity of soil biological activities, the on-site vegetation cover, local climate, seasonality, soil clay content, and local tectonic activity. These processes sometimes preserve the soil's environmental memory, but they also represent a substantial challenge for researchers trying to read the soil archive.

2.2. Eluviation – Illuviation

The percolation of water through the soil is an important process in humid climates. This downward movement of water transports fine particles (e.g., clays, fine silt, organic matter) and molecules (e.g., organic matter, oxyhydroxides, carbonates) capable of passing through the pore spaces of the soil matrix. These two components are transported, respectively, in suspension or dissolved in the water as they pass through the pore space. A soil layer subjected mainly to the departure of particles is termed "eluvial" (E horizons) and often undergoes partial discolouration (Fig. 1). With the downward change in the texture of the horizons (i.e. clay accumulation), the disappearance of larger pores (thus a reduced movement through the soil), the pH gradient of the soil, and other physical obstacles (i.e., blocks of limestone), the eluviated soil particles are likely to flocculate and be adsorbed at depth, and the

molecules will also precipitate at a deeper soil horizon. The soil area receiving the material transported by gravity water is termed "illuvial" (B horizons). These eluviation-illuviation dynamics resulting from precipitation will, over the centuries, determine the structure and texture of soils. With these transfers/translocations of particles and molecules, many parameters fundamental to plant growth (water storage capacity of soil horizons, volume density, CEC, resistance to penetration) are influenced over these longer time scales.

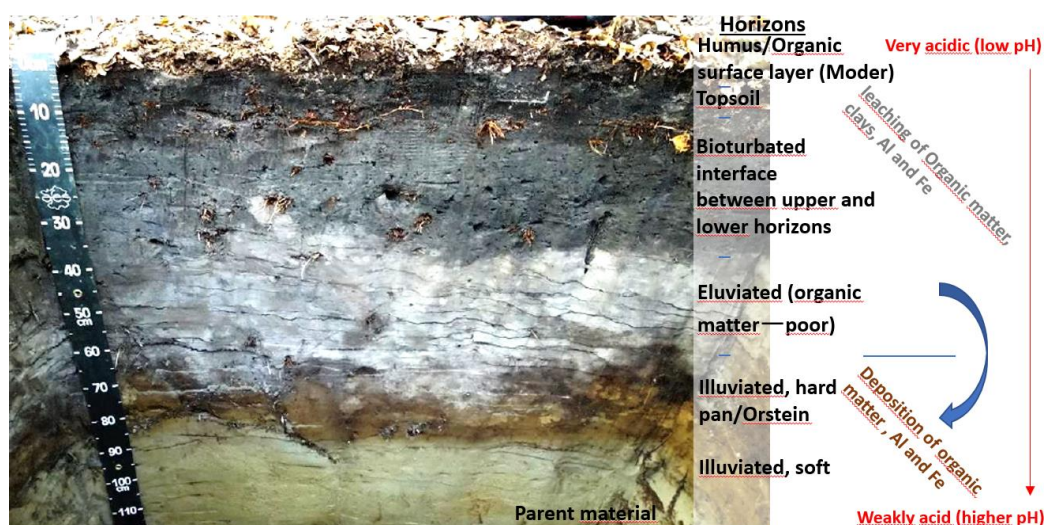


Figure 1: Soil profile showing distinct horizons (labelled on the right-hand side) that mark the eluviation and illuviation of organic matter (note the dark horizontal stripes at approx. 50 cm depth) and metal oxides (approx. 65 to 85 cm depth) at the expense of the initial parent material. This type of soil, a podzol, is dominated by these vertical redistributions and little bioturbation.

Human influence through land use (field, pasture, forest) can be very significant and long lasting. For example, human modification of pH can affect eluviation-illuviation patterns. In the case of eluviation-illuviation of clays, Ca^{2+} and Al^{3+} ions are flocculants and will prevent clay movement where these ions are abundantly available in the soil solution. The eluviation-illuviation of clays is, therefore, at a maximum under pH conditions of moderate acidity (5.5–6.5) an acidity level associated to minimum Ca^{2+} and Al^{3+} concentrations in soil water. This soil acidity is a parameter that has been controlled by humans through agriculture for several millennia (*cf.* 2.1), and thus, human activities alter eluviation-illuviation patterns and control the progressive vertical organization of fine particles, soluble molecules, and ions in the soil. These vertical redistributions are in an unstable dynamic equilibrium with natural biological mixing, which disturbs the soil's vertical organization.

2.3. Anthropogenic factors

In an anthropic landscape, various direct soil disturbances will lead to the archiving of episodes from the local land-use history. A common case is that of pits or depressions dug in the soil. Once the continual dredging/maintenance of these depressions is stopped, these features will accumulate sedimentary particles until filled. These particles, subjected to local natural and anthropogenic dynamics, originate mainly from local superficial horizons and may include plant and animal remains, as well as cultural artefacts. Such depressions can sometimes bear witness to now-truncated soils and often have unique properties (grain size texture, chemistry, structure) that affect aboveground communities.

A major anthropogenic disturbance of the world's cultivable soils, although superficial in terms of depth, concerns the impact of agricultural implements (hoes, ploughs, etc.). The effect on the surface and the superficial horizons of the soils leads to a levelling of micro- and mesotopographic landscapes and the disturbance of the superficial horizons. This anthropogenic effect will erase the inherited topography and reset the palimpsest of the microtopography of soils. Among the cultivable lands in western Europe, it is very difficult, except for mountain areas, to find areas that have not experienced past agricultural activity (Sabatini *et al.* 2018). In contrast, in a forest context characterized by a dense and continuous vegetation cover, the soil surface is protected/stabilized and therefore the conservation of its landforms is better.

The concept of anthrosol (IUSS Working Group WRB, 2015) includes all soils that have been formed or deeply modified by human activities since the beginning of the Holocene. Given the vast quantity of soils that have been affected directly or indirectly by human activities, this definition is impractical for the pedologist.

2.4. Effects of geomorphological processes on soil archives

In the three previous sections, we described the biological, physical, and anthropological archiving elements of pedological processes. Geomorphological processes also affect the soilscape and can produce excellent soil and sediment archives or ...destroy them. Aeolian, fluvial, and gravitational processes are the major erosional forces that affect a soil's environmental memory. Soilsapes lacking the protection of vegetation are very sensitive to ablation (Fig. 2 b). Consequently, biomes with little vegetation and agrosystems with denudated soils are not favourable to directly preserving soil archives.

Tracing soil archives is difficult in the case of transport by aeolian processes or by large fluvial systems because the constituents are mixed over a large area and the spatiotemporal information is lost entirely. In a small catchment or at the slope scale, soil material is often stored as pedosedimentary layers, and the properties of eroded soils can be traced. Even if the soil architecture is lost, some chemical parameters or

organic botanical remains (e.g., seeds, charcoal, phytoliths) can be preserved (Fig. 2d).

The former soil properties can be even better preserved when the horizons are buried under other layers of sediment (Fig. 2 c). In these cases, the soil parameters or constituents can be considered as fossilized (Yaalon, 1971). These palaeosols are no longer influenced by present-day climate, vegetation, farming, etc. and can be precisely dated. This is not the case of preserved soils that are in equilibrium with present-day conditions. The surficial soils also contain inherited properties and archives (*cf.* 2.1, 2.2, 2.3), but these soils are often difficult to date because they are the result of a temporal continuum (Fig. 2a).

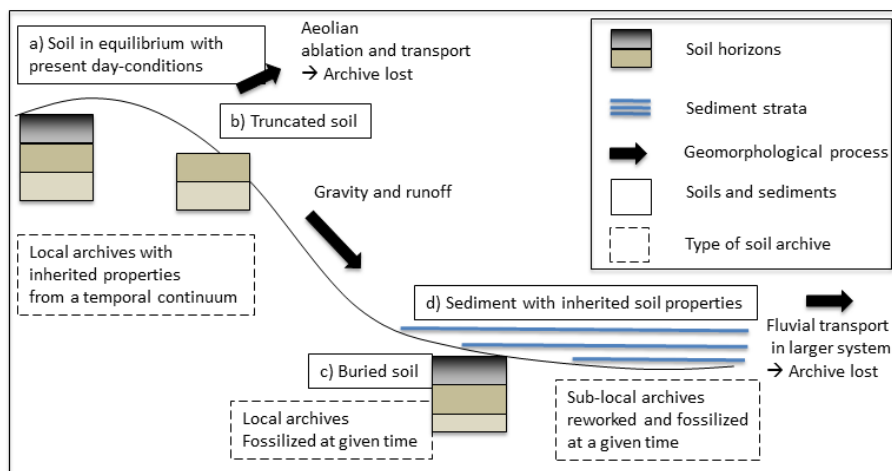


Figure 2: The effects of the main geomorphological processes on the preservation and quality of soil archives.

On the other hand, because they are still part of the present-day ecosystems, these soils remain relevant for historical ecology studies.

When looking for archives in soils, the main error to avoid is confusing soil horizons with soil strata. Both appear as a vertical succession of layers; however, the strata are the result of successive deposits in time that are fossilized. They can therefore be read as a relative chronology from the bottom (oldest) to the top (youngest) of the sequence. This is not the case of soil horizons that are still subjected to reorganization processes (*cf.* 1.1, 1.2, 1.3). Consequently, no relative chronology can be read from the soil horizons, and the age or residence time of every incorporated constituent must be considered.

3. Examples of soil archives and their influence on current ecosystems

3.1. Chemical archives, witnesses of progressive soil transformations

The chemical parameters of soils (i.e., pH, C, N, P, exchangeable cations) are very rarely in equilibrium and are therefore subject to evolutionary dynamics at an annual to millennial scale. The inherited initial state is the starting point for these dynamics; for example, this could be a parent material newly accessible to pedogenesis. It can also be a tipping point, such as climate or land-use change. For the chemical parameters of soils, the subsequent evolutionary dynamics will tend towards a new equilibrium state. The history of a soil is therefore important for explaining the state of current chemical characteristics but also for understanding the successions of past and future states. The associated soil biotas are subject to the influence of these chemical parameters and are likely to be structured by the achieved evolutionary trajectory.

To illustrate this point, we can look at soil pH, one of the most structuring parameters for edaphic ecosystems. Under humid climates, soil pH is subject to acidification by the leaching and/or the input of protons (from atmospheric precipitation, litter decomposition, root exudation, and respiration) in the upper part of the soil (Slessarev *et al.* 2016). This acidity increase reduces the quality and quantity of the harvests of many food crops. To fight against this natural process of acidification, farmers, especially in north-western Europe, have added limestone amendments for more than two millennia, thus neutralizing the acidity of the soil (see Pliny the Elder: Book XVII-Chapter 4). A spatiotemporal study of silty soils in northern France compared two chronosequences of land-use change (Fig. 3). The authors compared plots that had been deforested and cultivated within the past few years to several centuries and plots where afforestation (on cultivated land) occurred recently to nearly 1.6 millennia ago (Brasseur *et al.* 2018). The soil pH of the deforested chronosequence revealed that the tilled surface horizon, initially acidic, will require a few years to approach neutrality, whereas this neutralization will take one to three centuries at more than one-metre depth.

Conversely, when cultivated land (with neutral pH) is abandoned and afforested, the natural acidification dynamics are slower. Indeed, after 1.6 millennia of afforestation of previously cultivated land, although the pH at the surface has decreased, the pH of deeper horizons has lowered to a much lesser extent, indicating a slow process that is still underway.

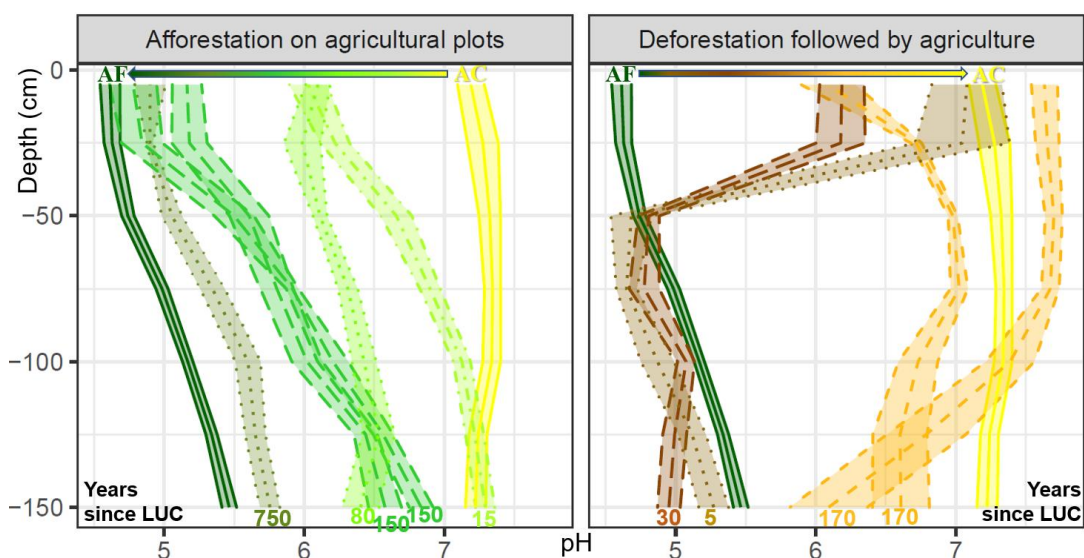


Figure 3: Mean ($n = 6$; \pm SE) pH(water) profiles in luvisols from the loess plateau in northern France characterized by differences in deforestation and afforestation ages. Left-hand graph: pH(water) profiles for agricultural plots that were afforested at various times in the past. Right-hand graph: Plots deforested at various times in the past for agricultural use. AF: ancient forest (circa. 1600 years BP), AC: ancient culture (>500 years BP), LUC: Land-use change.

The characterization of these evolutionary soil dynamics makes it possible to identify the successions of ongoing and forthcoming chemical states for soils in similar contexts (parental material, climate, land use). This work also reveals that the past agricultural use in the now-forested lands of northwest Europe can still be characterized owing to this very gradual acidification of the soil. Lowland temperate forests with a primaeval character no longer exist in Europe (Peterken, 1996) and most European forests have been cultivated in a more or less distant past (Sabatini *et al.* 2018). Thus, soil pH profiles may be an indicator of afforestation oldness in many forested areas. A wealth of literature also describes the long-lasting inherited chemical effects of past human agricultural activities on soils that can be deciphered from the present-day plant community composition (e.g., Dambrine *et al.* 2007).

3.2. Physical archives: Reading the soil pit profile and microtopographic features

An essential method for accessing the *in situ* physical properties of the soil archives, e.g., horizonation, soil structure and disturbance, and density anomalies, is studying soil pits. This approach is the best way to describe the spatial relationships between horizons, the soil and parent material, pedofeatures (e.g., redoximorphic and textural characteristics, secondary precipitations), and biological and physical pedoturbations. Reconstructing the history of the soil then consists of unravelling the spatial relationships to derive a chronological sequence of events that have affected the soil. We can do this using simple logical principles borrowed from stratigraphy, including superposition (limited use, see Part 1.2, 1.4), inclusion, and cross-cutting. The progression in horizon individualization from the initial parent material is also a key criterium. As an example, the podzol profile (Fig. 1) evolves through the following steps: 1- the parent material is accessible to pedogenesis, 2- acidification, horizonation, and podsolization, 3- formation of dark horizontal stripes, 4-intense reworking (cross-cutting) of topsoil & eluviated horizons by the intrusion of roots and burrows following a possible local nutrient enrichment. Such enrichment can reactivate the biological activity (and bioturbation) of these very nutrient-poor soils (Robin, 2005).



Figure 4: Aerial photography and DEM of the same area with ancient forested (1, 2, 3) and deforested (4, 5; cleared ca. 150 years ago) sectors. 1-Track ways, 2-Charcoal kilns, 3-Demarcation of old (probably Roman) agricultural plots, 4-Less visible under pasture, 5-No demarcation under culture, darker spots are former charcoal kilns.

Since the 2000s, laser remote sensing techniques have revolutionized the observation of soil microtopography. The generated digital elevation models (DEM)

offer the opportunity to observe and interpret landscapes invisible to the eye, especially for land having a forest cover. In the Thiérache forest (near franco-belgian frontier), for example, DEM (Fig. 4) has revealed numerous old agricultural parcel limits, ancient trackways, and charcoal kilns. In recently deforested areas, such memories of land use disappear gradually under pastures and much more quickly under the recurrent impact of ploughing in cultivated fields.

3.3. Soil organic matter

Soil organic matter (SOM) is a functional category of soil constituent. Its quality, chemical structure, quantity, and age vary within the soil profile and the succession of horizons. Transport processes and biological and anthropological transformations (*cf.* 1.1 and 1.2) control these distributions. Vegetation and the microbial mass that transforms this vegetation are the main sources of OM (Kögel-Knabner, 2002). The OM derives mainly from the degradation of plant fragments within the litter or from root exudates. The extraordinary biochemical diversity of the plants is partly reflected by the SOM even after transformation and microbial degradation. When researchers manage to trace and date SOM, it can serve as a proxy of past vegetation and past landscape dynamics. SOM contains thousands of different organic molecules. The classification of these complex components depends on the tools at hand and the scale of the study.

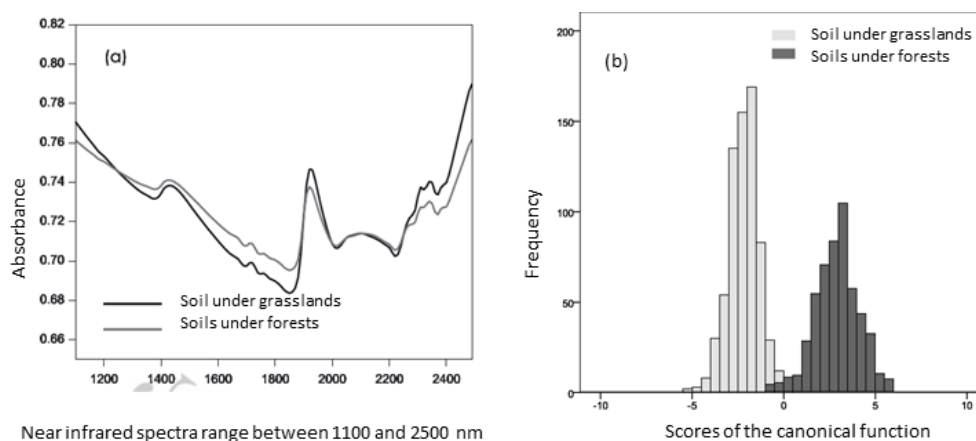


Figure 5: Soil organic matter determined by near-infrared spectroscopy. (a) Near-infrared spectra of soils; (b) multiple discriminant analysis on a set of 1333 reference spectra from 75 sites under temperate forest and grassland cover.

In the last 20 years, numerous studies using gas chromatography–mass spectroscopy (GCMS) and other powerful methods have identified some very specific

molecules or isotopic ratios that identify particular categories of vegetation or sometimes specific species (Trendel *et al.* 2010). Because they are time-consuming, these methods are often applied to only a few soil profiles and are of little use for landscape-scale studies. The fingerprinting approach of SOM by near-infrared spectroscopy is less accurate and functions as a black box in regard to SOM molecular chemistry, but it is fast and effective and provides an overall picture of the SOM. As well, the existence of an extensive catalogue of reference soil samples with a well-known ecological history (Ertlen *et al.* 2010; Fig. 5), allows near-infrared spectroscopy to discriminate SOM according to its plant-association source. It is thus an effective tool for historical and landscape ecology.

3.4. Botanical remains

Soils are not well suited for the long-term preservation of organic botanical remains. Biogeochemical activities induce the degradation of organic material, limiting their retrospective representativeness. Such is the case of plant macroremains that are assimilated into the carbon cycle by organic degradation. Nonetheless, several botanical remains have specific features that make them resistant to biogeochemical degradation. Once these botanical remains are extracted from soil, taxonomic analyses of these samples can shed valuable insight into the studied organisms and provide a portrait of the environmental context (Ferguson, 2005). This resistance to degradation is observed with certain microfossils such as pollen grains, owing to their exine composed of sporopollenin, or phytoliths, being microscopic structures composed of silica. These microfossils, when found in significant quantities in soils, can provide information about past land use and vegetation history (e.g. Contreras *et al.* 2014; Robin *et al.* 2012).

These indicators are often difficult to use, however, because establishing the chronological framework is a challenge in a soil. Assessing the chronology of an archive is a key step in any retrospective study. Indeed, most soils are continuously mixed (*cf.* 1.1); therefore, soils do not present a chronologically structured stratification (Carcaillet, 2001). This contrasts with chrono-stratified sedimentary sequences, such as those recovered from lakes or mires, in which chronological archiving is nearly continuous from the sequence bottom to the sediment surface. Only in the case of pedosedimentary accumulation that have clear boundaries (Fig. 2d) is it possible to identify a relative stratigraphy in soil archives (Robin *et al.* 2014). However, more precise chronological insights can be obtained from charred botanical remains. Such indicators can be preserved for a long period and are datable directly by ^{14}C measurements (*cf.* 1.4). The carbonization of botanical remains, possibly related to anthropic or natural fires, transforms them into inorganic carbon remains, allowing them to resist biogeochemical degradation. Moreover, charcoal remains

taxonomically identifiable, as its anatomical structures are well preserved during carbonization, except for some deformation and shrinkage (Braadbaart & Poole, 2008). Quantitative and qualitative analyses of the charcoal assemblages from soils provide insight into fire and forest vegetation history (Nelle *et al.* 2013). Charcoal pieces must be large enough to be taxonomically identifiable (i.e., megacharcoal, >800 µm). Therefore soil megacharcoal assemblages are relevant in fine-scale studies (Feiss *et al.* 2017) or at a catchment scale when, for example, studying erosive events (Robin *et al.* 2014).

Overall, investigations that combine diverse types of botanical remains or diverse types of indicators are the most relevant to obtain the best possible, reliable, and complete picture of past environments (Contreras *et al.* 2014; Robin *et al.* 2012).

4. Conclusion

Soils are a complex environmental interface where the chronological succession of environments can produce distinct archives having a complex interpretation, much like studying an environmental palimpsest. In this context, it is best to combine the skills of different specialists in the (archaeo-) environmental sciences. The combined study of the different soil archives (plant remains, soil organic matter, chemical parameters, macro- and micromorphological features, microtopography, archaeology) lets an increasingly less lacunary picture to emerge of the environmental history and its legacies in the soil; an environmental story whose heritage, while fading, still structures today's terrestrial ecosystems.

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