Six factors of pedogenesis

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The formation of soils is the consequence of weathering of various geological materials (the "parent materials" formerly called "mother rocks") particularly under the action of precipitation and living beings, over a long period of time. This article details the six factors that determine their formation, appearance, properties, and functioning. In our climates, the main factor is the lithology of the parent material, which initially determines the morphology and main properties of soils for a long time. But other factors play a role: the local climate, the position within the terrain, the spontaneous vegetation, not to mention the time factor. In France, many soils are relatively "young" (10,000 to 15,000 years old) but others correspond to weathering that have lasted for several million years. Since the Neolithic period and the development of agriculture, humans have also become important agents of pedogenesis. Ploughing, drainage, irrigation, fertiliser and pesticide application, liming, etc. are all interventions that profoundly modify the hydric, physical and biological functioning of soils.

1. Pedogenesis: the result of multiple interactions

A first article (See Soil formation in temperate climates) defined what soils are and their main specificities, in particular their organization into aggregates and the presence of a multiform porosity favourable to the activity of living beings.

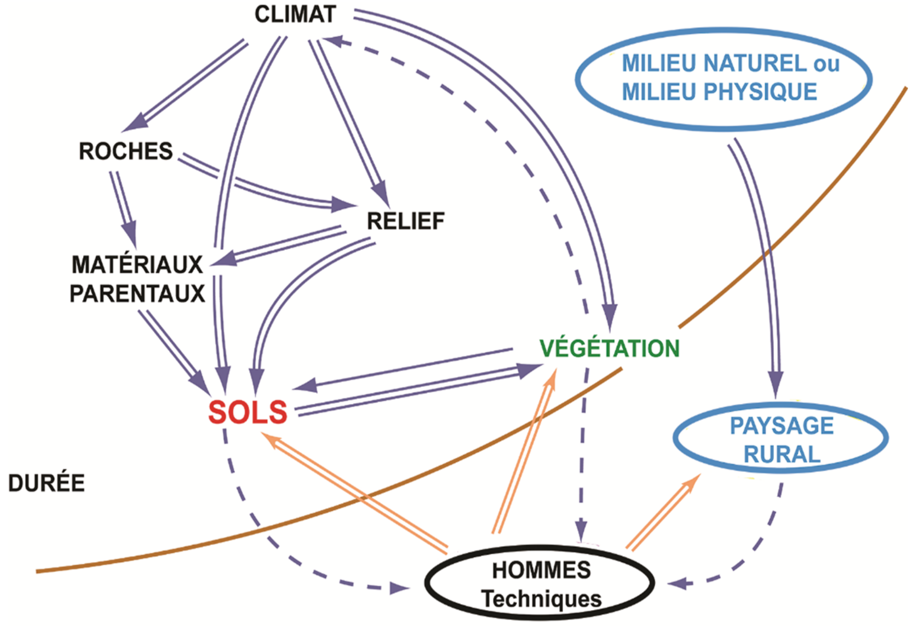

Figure 1. Simplified diagram of the relationships between soils and the different factors of pedogenesis. The brown line separates the phenomena that characterize the "natural environment" and everything related to human actions leading to the creation of the "rural landscape". [Source: © Denis Baize]

Conventionally **six main factors are taken into consideration in the formation of soils**, whatever the climate in which they have developed. Figure 1 presents these different factors of pedogenesis but also their interrelationships. Indeed, for example, the existence of **parent materials** depends closely on the combination of the **nature of the rocks** and the position in the **relief**; soils have a significant impact on vegetation, but the latter in turn has an influence on soils via the **form of humus**. As a final example, while it is obvious that the **climate** strongly determines the vegetation, the latter, in turn, has an influence on the local climate (cooler and wetter mesoclimate in a forest area).

Beware of the word "humus", an ambiguous term with various meanings. The **Comifer** (*French Committee for the Study and Development of Reasoned Fertilization*) has given this definition: "all the organic constituents of the soil that no longer have a biological organization (plant, animal, bacterial, etc.) identifiable and which are the result of the slow biochemical evolution of the various organic matter in soils." For this restricted meaning, scientists now prefer the formula "**soil organic matter**" (SOM).

Beware of the other meanings of this word:

In common parlance, humus is the "blackish earth formed by the decomposition of plants" (from the french dictionary *"Petit Robert"*);

In soil science, it was mistakenly used to refer to all surface horizons that are entirely organic and organomineral and contain a lot of organic matter. From now on, the term "humus-bearing episoleum" will be preferred.

2. Nature and state of parent materials

Parent materials are the geological formations, little or not altered, actually observed under the soil, at the bottom of a pedological pit. (See [Soil formation in temperate climates])

Figure 2. Cryoturbated paleosols typical of the chalky Champagne region. Note that the "urns" are more coloured and filled with finer material, separated by chalk "chimneys".[Source : © M. Jamagne, with the author's permission]

If this underlying material is indeed the one that gave rise to the soil (and this will only be proven after a somewhat detailed study), it must be called **the parent material** of the soil (formerly it was called "mother rock"). The parent materials can be **rocks** such as granites, gneisses, basalts, marls, chalks, sandstones, argilites, etc. or, for some, their alterites. An **alterite** is a formation resulting from the weathering and fragmentation of a rock in place, without the acquisition of a significant specific soil structure. The **growan** is a good example of this.

But the parent materials are also all kinds of **superficial deposits** that are very often the real materials in which the soils have developed:

Alluvium (stony or fine) and colluvium (fine);

Loess and deposits that resemble them (calcareous formations redistributed by the wind during the Quaternary), silty deposits covering the terraces of the Garonne or the Pyrenean rivers;

Glacial moraines;

Coarse slope formations (scree, "*grèzes*", "*graveluche*"), but also fine slope formations or formations with significant fine components (geliflucted formations with boulders, clay-stony slope formations);

Paleosols and cryoturbated paleosols (Figure 2);

Residual clays issued from the decarbonatation of hard limestone (clay with cherts, "*Terres d'Aubues*" of Lower Burgundy (Figure 3), "silty materials in Auxois") or soft calcareous rocks (clay with flints).

Figure 3. "Terre d'Aubue" of Lower Burgundy. Non-calcareous soil, moderately thick (1 m), silty-clayey in the uppermost horizons, clayey at depth, developed in a clay resulting from the carbonate dissolution of a hard limestone (Yonne). [Source: © Denis Baize]

Many of these formations are deliberately neglected or poorly marked by geological maps (especially the older ones, which show only an "écorché" and focus on intact rocks located deeper).

In the temperate climates of Western Europe, the parent material determines most of the properties of the future soil very strictly. For a long time, the influence of climate and vegetation remain limited. Important characteristics of the parent material, which will influence the composition and structure of the soil, are:

its grain size (pebbles, heavy clay, sandy sediment, aeolian silt);

the particle size of the decarbonatation residue in the case of calcareous parent materials;

the more or less alterable nature of primary minerals (e.g. quartz is unalterable while black mica, biotite, is rapidly alterable);

the mineralogical nature of inherited or newly formed clay minerals (kaolinite, illite, smectites, etc.);

the petrographic nature of the parent material and the resulting physico-chemical characteristics. For example, chalky soils inherit an extremely limy composition that lasts for a very long time;

its fine geochemistry: for example, soils developed from "green rocks" (peridotites, serpentinites), which are very rich in chromium and nickel, are themselves very rich in these two metals.

When it comes to the role of the state of an underlying material, we will take the example of hard limestones. It is clear that the different states of dislocation of the same hard rock (Figure 4) have a major influence on the rooting capacities of perennial plants [1] such as forest trees or vines. The same goes for annuals (wheat, rapeseed) which can find a little (or a lot) of interstitial earth between the stones, which can provide some water during dry periods. Thus, vegetation will be able to settle more easily in a stony formation than on undislocated rock, and the soil will form more quickly.

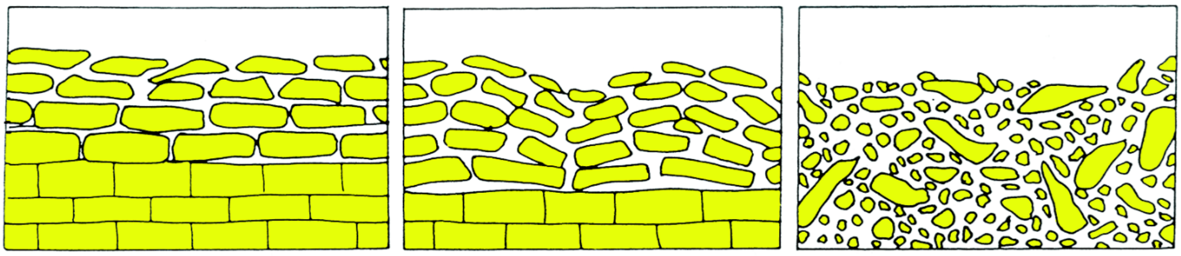

Figure 4. Three possible states of the same hard limestone, seen in cross-section. [Source : © Denis Baize]

3. Microclimate and pedoclimate

The general climate (major climatic zones of the globe) is more or less modified by the local conditions in which each soil is located (relief, topographical position, aspect): this is the **microclimate.** The latter is modified by certain intrinsic properties of the soil itself (e.g. its surface colour, the presence of impermeable layers generating long-term waterlogging). In this way, the internal climate of the soil or **pedoclimate** can be defined.

The pedoclimatic conditions of the distant past have governed the oldest pedogenetic processes. They are generally very different from the current conditions that govern the present functioning of soils. As a result, some soils today have red hues that correspond to much warmer and drier climates than the current one.

3.1 Rainfall

Potentially percolating flow (likely to percolate vertically) is defined as the input flux (precipitation) minus the evapotranspired flux (direct evaporation from soil + transpiration from vegetation). In temperate climates, the potentially percolating flow is positive because precipitation is much higher than evapotranspiration. The greater these water flows, the greater the transfer of materials (solutions, clay particles), either vertical or lateral. (see Plants water needs).

The potentially percolating flow is more or less modified depending on the topographic position. For example, lower slopes are likely to receive runoff from higher elevations.

Snow plays a special role:

it causes a delay in the flow (the precipitation will flow well after it has fallen) and it causes the soil to become waterlogged when it melts;

It is an insulating coat that protects the ground from frost as long as it has fallen before the temperature drops.

3.2 Mean annual temperature and seasonal temperatures

The higher the temperature, the faster the chemical and biochemical reactions (alteration of primary minerals, biological activity, mineralization of organic matter); on the other hand, cold water is the best dissolver of limescale because, all other things being equal, cold water dissolves more CO_2 than warm water. (see Karst, a renewable water resource in limestone rocks).

Conversely, prolonged or permanent freezing has mechanical effects (disintegration, cryoturbation) but slows down or stops all biological activity and weathering.

4. Position in the landscape

TThe functioning of the soil (therefore its general evolution in the long term) depends on its position in the relief. This is the case, in particular, with the vertical or lateral orientation of the flows of water and displaced materials. The shape of the slopes depends on the more or less hard nature and the succession of the underlying rocks. As a result, different soils follow one another on these slopes [2] depending solely on their position (soil toposequence or soil chain – Figure 5) or also on the variation of the rocks (soil topolithosequence).

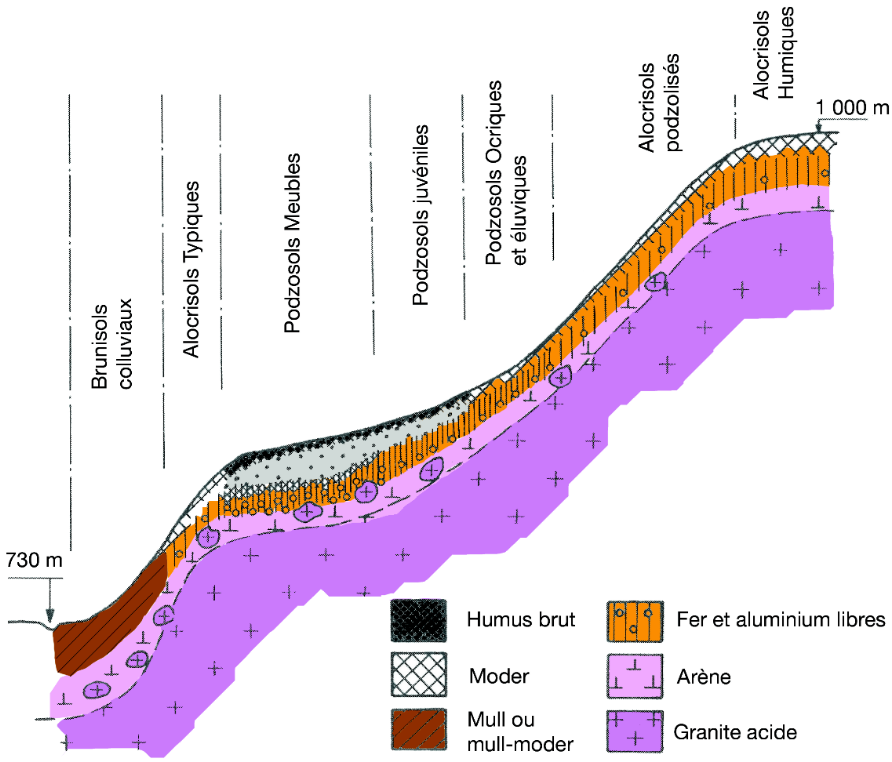

Figure 5. Chain of soils on an acidic granite slope in the Hautes-Vosges. Upslope: steep slopes, thin growan , oblique leaching, development of alocrisols. On flat areas: thicker growans vertical migrations, development of podzosols. Downslope: thicker soils, colluvial brunisols with "active mull", enriched with fine particles and soluble elements (Ca^{++}) coming from soils and materials located higher up the slope. [Source: © Denis Baize, after Jamagne]

4.1 Flatbed positions (plateaus)

On the plateaus, the dynamics of the water and transfers are rather **vertical**. So there is little or no erosion. However, there are few plateaus that do not have any relief at all, and there is no need for much slope for runoff and erosion to develop.

This is what happens when the surface horizons have very fragile aggregates as a result of a silty grain size and a low organic matter content. The sealing of the soil surface can occur under the impact of raindrops. A thin, finely bedded crust (0.5 to 5 mm) is formed, more or less continuous. This **slaking crust** prevents water from seeping into the soil. This results in puddles and, often, surface runoff into the plot, the initial stage of water erosion. This is the case, for example, of the plateaus of the Petit Morin catchment area in Seine-et-Marne or those of the Pays de Caux.

4.2 Upslope and mid-slopes

Upslope, there is loss of water and dissolved or suspended matters without compensation. Generally the soils are rather dry and thin (because they are more or less eroded). In the middle of the slopes, the losses of water and dissolved matters downwards are compensated by inputs from above, resulting in a neutral balance.

The south-facing slopes are hot and drier (the vegetation is rather thermophilic, even xerophilic). The north-facing slopes are rather cold. (see How do plants cope with alpine stress?).

4.3 Downslope and valley bottoms

Downslope and in the valley bottoms, water flows are much higher than precipitation, which generates more or less prolonged or even permanent or almost permanent waterlogging (peat bogs). There are also accumulations of displaced solids (colluvium) and the formation or presence of specific parent materials (fluvial alluvium, lacustrine alluvium). In these situations, thick or even over-thickened (colluvial) soils are generally observed.

The lower part of the slopes and the bottoms of the valleys correspond to areas of accumulations of dissolved products higher upslope which precipitate (iron and manganese oxides, calcium bicarbonate in the form of lime) or bind to the adsorbing complex (calcium-saturated soils – the case of the brunisols in Figure 5).

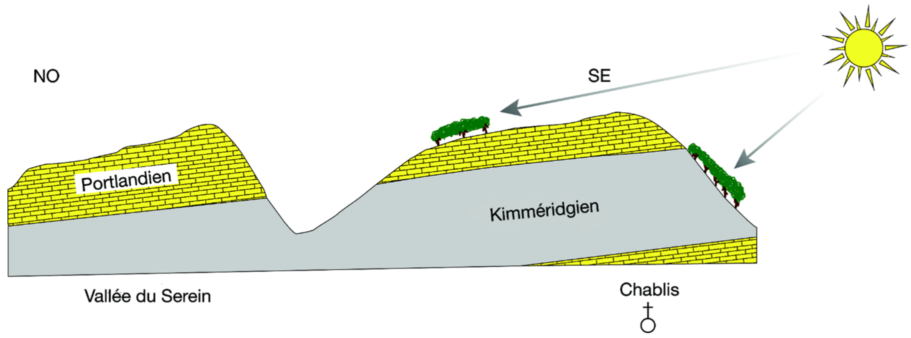

Figure 6. Slope aspect and angle of incidence of solar radiation. The case of the Chablis vineyards. [Source : © Denis Baize]

The value of a land's slope, combined with its aspect, determines the amount of solar radiation brought to the soil and vegetation. It is for this reason that the most famous vineyards, such as the of Champagne (*Barséquanais* areas) or Chablis, favour south-east and south aspects and fairly steep or steep slopes. It is under these conditions that solar radiation is maximum [1] because it reaches perpendicular to the ground (Figure 6).

5. Vegetation and biological activity (broadly defined)

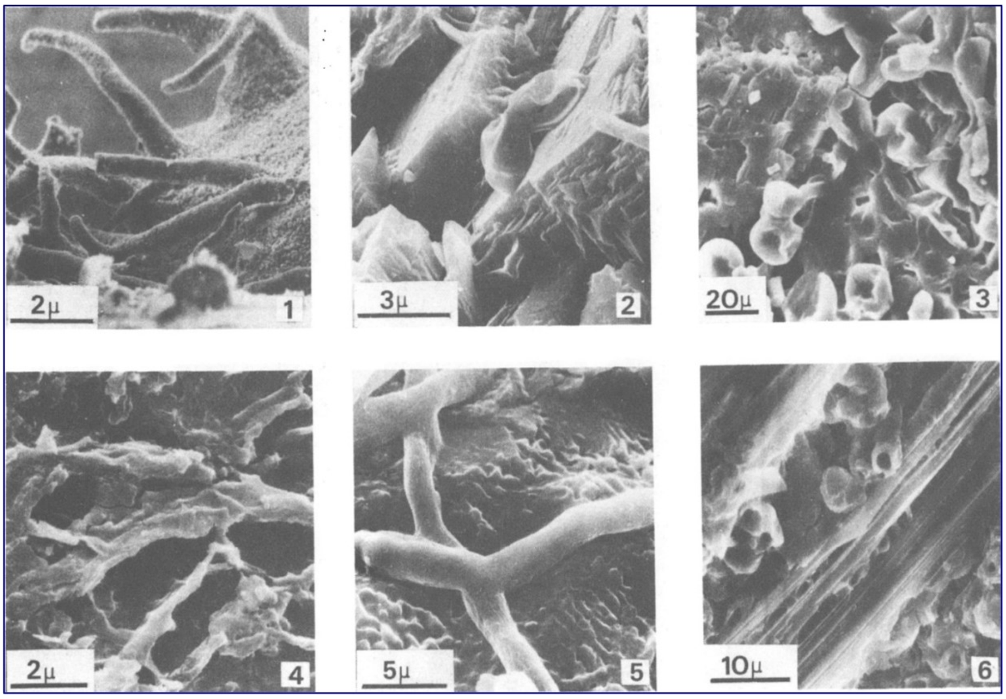

Figure 7.. Interactions between living beings and minerals. 1: Umbilicaria cylindrica (foliaceous lichen) on mica. 2: Algae (or cyanobacteria) inside a quartzite. 3: Algae colony on altered plagioclase. 4: fungal hyphae. 5: Hyphae of Rhizocarpon (a lichen) on feldspar. 6: Rhizocarpon penetration into micas. [Source : © Robert et al, ref. 3]

TThe pioneer microflora consists of bacteria, algae, hyphae, fungi or lichens. Thanks to its adhesion to the surfaces of rocks and minerals, and to bacterial biofilms, it initiates the first alterations, the figures of which are visible under an electron microscope [3]. The first effect of hyphae penetration is a disintegration or microdivision of minerals, e.g. by developing between the leaflet packets of micas. Dissolution phenomena then appear, localized to microsites in contact between living beings and minerals (Figure 7).

The alteration of the parent material also takes place under the action of the roots. Indeed, in the rhizosphere (volume of soil directly under the influence of exudates and associated bacteria and ectomycorrhizae), organic acids and CO_2 released are likely to alter certain minerals and dissolve lime.

The fauna (micro, meso and macrofauna) is also adapted to the nature of the soil. (see Soil biodiversity).

It also plays a major role in soil formation:

by breaking down plant debris into small molecules;

by the absorption of nutrients (P, K, Ca, Mg), or potentially polluting trace elements at the root level;

by the formation of aggregates with a crumb structure of certain humus-bearing surface horizons by the reorganization of earthworm castings.

In turn, the soil has an important influence on the living beings it hosts. In particular, spontaneous natural vegetation is closely dependent on certain properties of this soil: acidity, waterlogging, relative dryness, richness in exchangeable calcium, nitrogen, and fine "active" calcium carbonate. This is why, depending on the nature of the soil, plant species and associations known as acidiphilous, hygrophilous, xerophilous, calcicolous, nitrophilic, calcaricole or calcarotolerant are observed.

The above-ground parts of plants that fall to the soil surface can be "acidifying" or nitrogen-rich (so-called "improving"). After a long period of time (centuries, millennia) a balance is created between the soil, the spontaneous vegetation and the climate.

The natural biogeochemical cycle (soils-plants-soils)

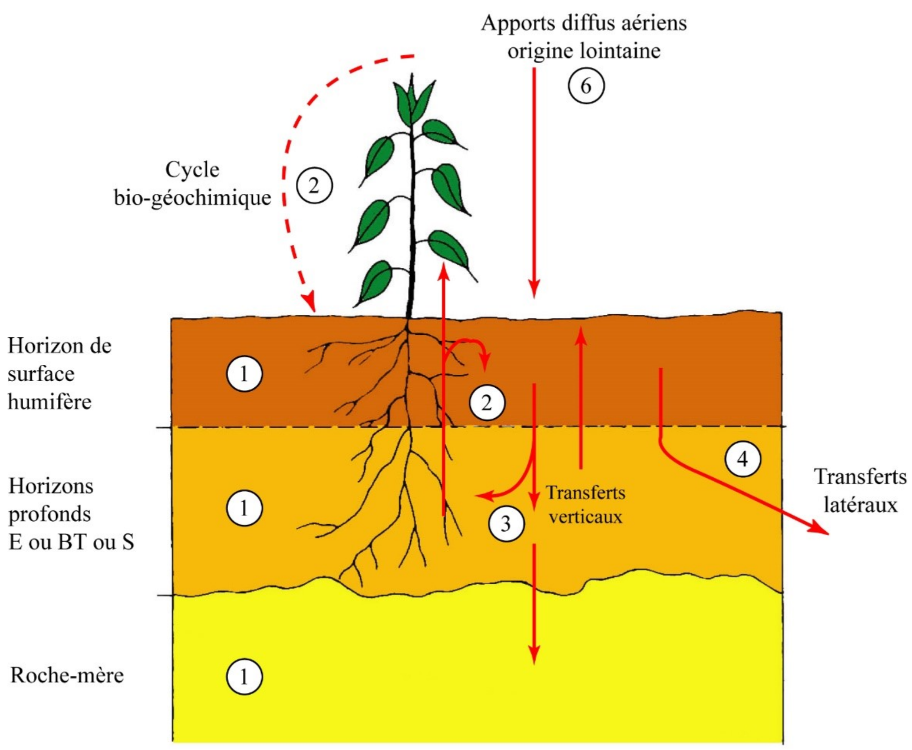

Figure 8. The arrows numbered □ to □ to (6) symbolize the movement of matters in soils in the natural environment. The biogeochemical cycle corresponds to the arrows □. [Source : © Denis Baize]

Elements dissolved in the soil solution, which are essential for plant development (such as phosphorus, potassium, calcium, trace elements) or useless or even potentially toxic (such as certain trace elements), are absorbed by plant roots, and this in all the horizons actually explored by these roots (Figure 8).

Once absorbed by the plants, these elements are transferred to their various organs (stems, leaves, fruits, seeds, branches, trunks).

After the death of the plant, these elements finally return to the soil either directly into the soil (in situ decomposition of dead roots) or by falling to its surface (debris from above-ground parts, forest litter). It is there that fresh organic matter will be decomposed more or less quickly by biological activity (microarthropods, nematodes, springtails, earthworms, fungal filaments, algae, bacteria) until, in the most "active" forms of humus, complete mineralization and therefore the release of chemical elements in fairly mobile and more easily bioavailable forms.

This results in a cycle of matter from soil to soil through vegetation. However, it should be noted that the majority of the elements absorbed over the entire thickness of soil prospected by the roots fall to the surface. This, together with the good ventilation that prevails, explains why the most intense biological activity can be observed in the first few centimetres. In a natural environment, even if it is chemically poor (Amazon rainforest, temperate forests on acidic soils), the biogeochemical cycle is sufficient to keep the ecosystem in equilibrium.

What happens when the cycle is broken, for example when humans take some or all of the plants (ears of wheat, lettuce, carrots, potatoes, fodder, tree trunks), whether they are cultivated or not, and take them elsewhere? A more or less important part of the biomass is "exported" with the elements it contains. Very generally, food products (flour, vegetables, fruit), wood and their waste (wheat husks, peelings, human or animal excrement, sawdust, ashes from fireplaces) are not returned to the place where they were taken. This results in a gradual impoverishment of the environment as the harvests progress. "Poor" ecosystems are quickly thrown out of balance and wither. Under intensive agriculture, where exports are massive, it is therefore essential to bring back to the soil all the elements (N, P, K, Ca, trace elements, organic matter) that have been removed from them, which is the reason for the addition of fertilizers and amendments (organic, calcareous). (See How to feed plants while polluting less?).

6. Human activities

Figure 9. The Chablis vineyard is a good example of a monoculture introduced by man. [Source : © Denis Baize]

Since the Neolithic period, with the development of agriculture, humans have had an impact on the nature and functioning of the soil. This impact is growing under the influence of ever more powerful and disruptive technical means and because of the need to produce more to feed an ever-growing population.

Action on vegetation: Man directly disturbs vegetation, in particular its diversity, by voluntarily installing:

monospecific forest plantations (Douglas fir, Christmas trees, poplars);

monocultures (wheat, barley, maize, apples, vines – Figure 9);

"natural" grasslands (where livestock graze selectively);

sown meadows;

... or it allows wastelands to develop...

In forests that seem natural to us, it favours certain species at the expense of others, eliminates certain layers of vegetation...

Chemical actions: voluntary application of fertilizers, trace elements, organic amendments (manure, slurry, compost, sewage sludge), calcium (liming), hence the rise in pH and the resaturation of the soil mainly by calcium ions; involuntary inputs of mineral or organic pollutants.

Repeated inputs of organic or mineral matter (salts contained in irrigation water) that accumulate.

Human interventions altering completely the initial natural water regime: drainage (by underground pipes or ditch networks), lowering of the water table (marshes, peat bogs), flooding of rice fields, irrigation.

Agricultural mechanical actions:

Figure 10. Rutting caused by timber unloading in a forest environment. Deep horizons can be affected by irreversible compaction. [Source: © Jacques Ranger, with the author's permission]

Ploughing;

Superficial or deep compaction (Figure 10);

Subsoiling: tillage of the soil with the aim of loosening it in depth without bringing elements to the surface;

Very deep ploughing (40 cm to 1 m) carried out exceptionally to dislocate deep indurated horizons or hard rocks located at depth and thus improve the rooting of vines or fruit and forest trees.

Creation by the farmer of different micro-reliefs raised to avoid excess surface water.These mechanical actions result in the homogenization of the ploughed horizon and sometimes the mixing of horizons

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Other mechanical actions (public works): restructuring of steep slopes into terraces more or less narrow (this has been the case since Antiquity), scraping, tarmacking.

Displacement of earthy materials for the construction of reconstituted urban soils, refitting of abandoned quarries or gravel pits.

7. Duration

Time is a major player, not to be forgotten, in the formation of soils. This is always slow and takes thousands or tens of thousands of years to generate a few decimetres of soil.

Some recent changes are more rapid (on favourable materials) and can affect the upper part of the soil by a few decimetres. For example, from a soil that is already highly acidified, neo-podzolization can only take a century to express itself clearly over about fifteen centimetres.

In northern Europe, many pedogenesis began at the end of the last deglaciation (10,000 – 12,000 years ago). Either the old soils have been completely eroded (e.g. scraped by glaciers), or new surface deposits have formed new parent materials and a new pedogenesis has then begun (new loess or slope formation deposition).

But there are also much older soils. Here are two sets of examples, but there are many more.

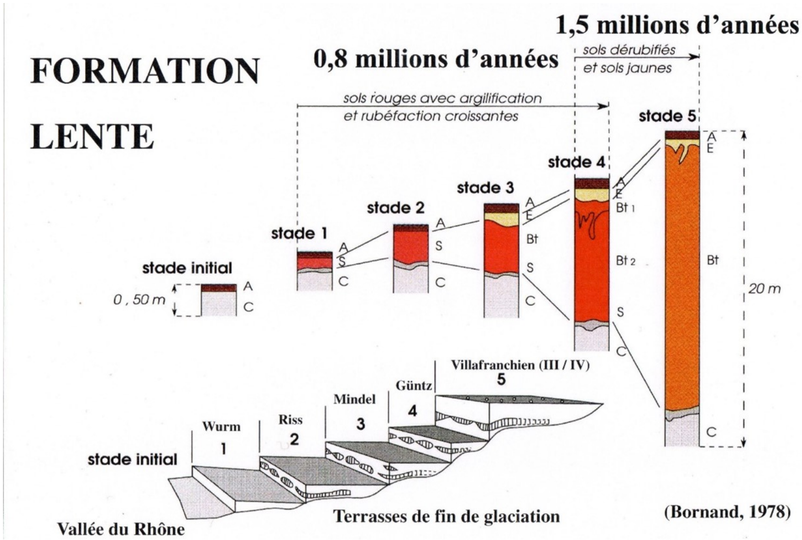

Figure 11. Reconstruction of the formation of the very old soils of the highest terraces of the Rhone pebbles. For a period of evolution of the order of two million years, the thickness of the residual soils can approach 20 m. [Source: © Michel Bornand, with the author's permission]

Exemples 1: A certain number of soils are developed in residual clay formations accumulated following the total decarbonatation of calcareous rocks: clay with flint, clay with cherts, clayey and ferruginous soils of the Sinemurian platform in *Auxois* [4], the "*terres d'Aubues*" of the plateaus of Lower Burgundy [5] (see Figure 3). All of these soils are at least one to two million years-old (probably more).

Examples 2: The soils of the very high terraces of the Rhone pebbly alluvium. The parent material of these deposits consists of fluvio-glacial pebbles from the Alps, containing calcareous stones but also fragments of crystalline rocks. The latter are the main source of all residual weathering products, including clays. Bornand [6] (Figure 11) described 5 stages of pedogenesis that he studied on the various terraces of the middle Rhone valley, dated from the Würm (for the lowest) to the Villafranchian (for the highest). The total evolution time of soils developed in the oldest deposits has been estimated to be between 1.8 and 2.3 million years.

When it comes to soil age, the question is: what soil is it?

To form a *Fluviosol Brut*, i.e. an alluvium vaguely impregnated with organic matter at its surface (as in the major bed of the Loire), it takes 30 years. To form a *Luvisol Typique* from a loess deposited at the end of the Würm, it took about 12,000 years. But to form a 15 m thick ferrallitic red soil in Côte d'Ivoire, resulting from the weathering of granites, it took several million years.

8. Messages to remember

The crossing of the 6 factors of pedogenesis, in particular the great variety of parent materials in France, explains the great diversity of soils that can be observed from one point to another: thickness, colours, texture, particle size contrast, pH, mineralogical composition, richness in organic matter, etc. This also explains their variability in space, which can be very rapid (decametric).

Man is increasingly an important factor in the modification (morphology and functioning = "artificialization") or even the total destruction of soils.

Soils are a non-renewable heritage on the human time scale. Any soil that is totally or partially destroyed is an irreversible loss of patrimony.

Notes et références

Cover image. Tuscany landscape [Source : © Denis Baize]

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