PEDOGENESIS AND SOIL FORMING FACTORS

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Summary

The main soil forming processes and soil forming factors based on the properties and land use limitations of the major soils groups are reviewed with reference to their effect on land use. Subsequently, their process impact on use options is discussed.

In general, it can be concluded that some soil properties, in particular those strongly related to parent material, soil depth and soil age, cannot be changed without the input of high level technologies. Other soil properties and related processes can be partly modified with specific management such as textural differentiation, podzolic, andic and ferrallitic properties and salt accumulation in subsoils. Therefore, these pedogenetic properties have a somewhat less dominating effect on land use. In a similar way this also applies for factors like flooding frequency and slope. Dikes and terraces are well-known tools to deal with these factors.

The best manageable soil properties are organic matter content of top soils and hydromorphy. Land drainage can quickly improve soil productivity of arable land and grassland. But the most used and most effective process to manage soils in order to maintain long term productivity is to increase organic matter content of the top soil.

A quick overview of the effects of land use intensification and conversion on soil properties is given. There is an overall tendency towards the decline of the favorable soil properties needed for high and sustainable productivity. The most obvious trend is a decrease in organic matter content, and because this can be a rather quick process this very vulnerable soil property requires constant attention.

1. Pedogenesis and Soil Forming Factors

Soil properties and processes can strongly affect land use options. Not all land uses are possible on all soils, and when certain uses do they often require specific management strategies. Because of this, biophysical land evaluation has always strongly emphasized on soil properties combined with climate conditions. Both are difficult to change and especially low input agriculture has to work with climate and soil conditions as given. Notwithstanding, modern technologies allow land managers to overcome a good number of basic constraints, with irrigation being a clear example to alleviate water limitations.

Soils, soil properties and soil formation are affected by: climate, parent material, vegetation, fauna and man, topography and time. The nature and importance of each of these soil forming factors vary, and most soils are still in the process of change as shown in pedogenetic profile differentiations and weathering. The terminology used in this paper refers to the terms of the World Reference Base for Soil Resources (WRB) and the FAO-UNESCO Soil Classification System **(see Soil Geography and Classification).**

The nature of a soil, its profile build-up and specific properties are the direct result of several pedogenetic processes linked to the soil forming factors mentioned above. The most important of these processes are shortly reviewed below.

1.1. Organic Surface Horizon

Organic matter (OM) accumulates in the soil as litter at the surface, and as decaying roots and microbial biomass (microbes, fungi, etc.). This is the result of the balance of production, decomposition and mixing of organic substances and soil material. Decomposition and mixing of OM are mainly due to the soil micro- and meso-fauna and are enhanced by oxygen and nutrient availability, high temperature and low amounts of Fe^{3+} and Al^{3+} bound to the organic matter. If one or more of these factors are not optimal in the soil, OM decay and mixing are hampered and this leads to organic matter accumulation. In terms of land use the nature of the top soil is essential as it contains most nutrients, and therefore land use types leading to a decline of OM in the soil deteriorate quickly.

1.2. Hydromorphism

Prolonged water saturation and seasonal alternating water logging and drainage have a pronounced affect on chemical and morphological soil properties. Changes in the degree of water saturation affect the supply of O_2 to the soil and roots, which in turn influence the oxidation state of iron and manganese and pH. Under waterlogged conditions reduction prevails, and this leads in the presence of sufficient organic matter to the dissolution of Fe^{2+} and Mn^{3+} or Mn^{4+} and to the development of typical grayish reduction colors. Upon aeration, oxygen enters the system and iron and manganese crystallize into Fe^{3+} and Mn^{3+} oxides and hydroxides, leading to the development of typical reddish colors. Under reduced conditions the pH is between 6 and 7, but it can decrease considerably under oxidizing conditions.
In strongly leached soils an alternation of oxidation and reduction can lead to a breakdown of clay minerals; this phenomenon is called *ferrolysis*. This process can help to enhance abrupt textural changes on top of a dense subsoil horizon, as can be observed in Planosols (***see below: Planosols)***.

Soils affected by hydromorphism are usually not suitable as arable land because of the unfavorable rooting conditions and increased acidity after drainage.

1.3. Textural Differentiation

Textural differentiation between parent material, topsoil and subsoil are common in soils under all climatic conditions. It affects root development and internal hydrologic properties of the soil, in particular permeability and water retention capacity. Abrupt textural changes can also lead to local hydromorphism at levels with important porosity changes.

There are at least eight different reasons for a textural differentiation in the profile: (1) physical and chemical weathering; (2) vertical transport of fine soil particles through biological activity; (3) eluviation and illuviation of clay suspended in the soil water; (4) superficial removal of fine soil particles by erosion; (5) superficial removal of clay due to tillage in wetland rice agriculture; (6) clay formation in the subsoil; (7) weathering of primary minerals in some subsurface horizons; and (8) vertical movement of soil matrix material.

1.4. Calcic, Gypsiferous and Saline Properties

Many soils in low rainfall areas accumulate relatively soluble minerals that affect both their own properties and the plants and crops that grow on them. Calcite, gypsum, chlorides and sulfates are commonly accumulating salts. The depth of accumulation is a function of the precipitation and evaporation balance. The more soluble salts only accumulate under real arid conditions.

Plant growth is usually not much hampered by calcium and magnesium carbonates, and to a lesser extent by gypsum (calcium sulfate). More soluble salts, however, cause problems with plant growth and create so-called saline soils. In sodium-dominated (or alkaline) soils, clays become unstable and may cause severe structural degradation (***See below: Solonetz).*** Arable farming in saline soils is therefore only possible when irrigated, and with a good drainage system for leaching the harmful salts.

1.5. Vertic Properties

Soils dominated by swelling clay minerals and affected by a contrasting seasonal climate often develop vertic properties. These are expressed by a combination of (1) deep cracks when dry; (2) intersecting slickensides in the subsoil; (3) the presence of wedge-shaped structural aggregates in depth; (4) and the occurrence of a ‘nutty’ surface structure.

The strong cracking and self mulching makes these soils not very suitable for perennial crops. Moreover, the presence of a micro-undulating micro-relief (gilgaï) requires additional planning measures in irrigation projects.

1.6. Podzolization

Podzolization occurs through transport of organic matter, iron and aluminum in a soluble form and under acid conditions from the surface to deeper horizons. The process consists of a phase of mobilization followed by an immobilization of these compounds. Unsaturated organic acids dissolve Fe and Al. The immobilization is either caused by saturation of the organic acid complex by these metals or by microbial breakdown of the carrier.

Podzols develop under conditions where the production of soluble organic acids is not neutralized by divalent cations. This occurs mainly in sandy parent materials holding few weatherable minerals. Low temperature and high rainfall during the growing seasons also stimulate podzolization. Other contributing factors are unpalatable litter, as produced by conifers, heather etc. and impeded biological mixing due to poor fertility, periodic water stagnation and/or cold climate.

The low nutrient content and low pH conditions of soils with podzol characteristics are not favorable for agricultural use.

1.7. Andic Properties

The formation of amorphous aluminum silicates and/or Al-bound organic matter gives rise to so-called andic properties. The key factor governing this process is the rapid weathering of easily weatherable materials (often volcanic glass). The Al-Si gel (allophane) has a considerable potential anion exchange capacity leading to phosphate retention in these soils. Allophane has strong aggregation, which increases upon drying, high water retention and high pore volume with non-rigid pores.

Andic properties are not unfavorable for agricultural use, though phosphate retention can become a problem.

1.8. Ferralitization

Typical for this process is the removal of silica from primary minerals. This leads to a residual accumulation of (hydr)oxides of iron (Fe), manganese (Mn) and aluminum (Al). Ferralitic weathering involves a strong depletion of basic cations and a low pH. The soil is dominated by low activity clays and hydr(oxides). As a result the chemical status is poor, and soils have a pH-dependent exchange capacity. Given the low pH these soils typically have an anion exchange capacity leading to phosphate retention. Ferralitization causes inherent poor soils with unfavorable chemical properties for agricultural use.

1.9. Chronosequences

Pedogenesis progresses in time and the longer it acts the better a logical evolution in soil development can be observed, from young to older and more mature soils in time. This is reflected in so-called chronosequence studies, like on river terraces where all conditions are assumed to be equal except time. A good example of such a study was made by Jongmans *et al*. (1991) in the Allier basin in France where a shift was observed from recent soils with only an organic surface soil development, towards a textural differentiation in a later phase, and leading in time to temporary water stagnation and hydromorphic conditions; ultimately, it involved further leaching, texture differentiation and finally podzolization. As a result, the agricultural soil potential also changed in time. As these soil property changes are much more gradual than land use change we will not look further into soil profile evolution.

It should also be noted that the present-day properties of many soils are due to long term development under changing conditions. For example, deep tropical red soils can be found in NW Europe (Vogelsberg Germany) as a result of a past climate. Consequently many soils are not always in equilibrium with current conditions. Likewise, highly weathered tropical soils are nowadays found also in semiarid environments, being an indication of much wetter conditions in the past.

In the next paragraph an overview is given of the major world soils as grouped in the WRB and FAO-UNESCO classification systems (***see: Soil Geography and***

Classification), their properties and their use limitations.

2. Soil Properties affecting Land Use Potential

2.1. Properties affected by Climate

2.1.1. Wet (Sub) Tropical Climates

The mineral soils conditioned by wet (sub)tropical climates belong to 6 major soil groups. They have the following properties and land use potential:

Plintosols are soils that contain ‘plinthite’, i.e. an iron-rich humus-poor mixture of kaolinite clay with quartz and other constituents, that can change irreversibly into a hardpan or irregular aggregates on exposure to repeated wetting and drying.

Plinthite forms in perennially moist subsoil horizons in the tropics. It involves an accumulation of sesquioxides and a segregation of iron mottles by alternating reduction and oxidation conditions. The irreversible hardening of plinthite to petroplinthite happens when the land becomes dryer and is due to the crystallization of amorphous iron compounds into oxide minerals and to the dehydration of goethite and gibbsite. Plinthosols with soft plinthite are characteristic for the tropical rain forest zone, while soils with (hard) petroplinthite are abundant in the transition zone from rainforest to savannah.

Overall, Plintosols have a poor natural soil fertility; are waterlogged in bottomlands and suffer from drought in the uplands. Their shallow depth is another serious limitation.

Ferralsols are extensively weathered, deep, well drained soils of the humid tropics. They have a clay assemblage dominated by kaolinite and a high sesquioxide content. The process of ferralitization leads to low soil pH and low concentrations of dissolved weathering products, causing de-silication and build-up of residual Fe and Al. Stable micro-aggregates behave as pseudo-sands and give them similar soil physical characteristics as sandy soils explaining their excellent porosity and good permeability. Ferralsols are chemically poor and their pH-dependent exchange capacity gives them a significant anion exchange capacity at low pH values, causing phosphate retention.

The natural fertility of Ferralsols is poor, and therefore good management of the top soils with all the organic matter and nutrients is of utmost importance. Ferralsols are generally low in macro- and micro-nutrients; they are open for all types of deficiencies and toxicities; due to low pH, toxic levels of manganese and zinc can occur. The good physical properties of Ferralsols and the commonly level topography often encourage for a more intensive land use if the chemical soil properties can be overcome by investments.

Alisols consist of strongly acid soils with an accumulation of high activity clays in their subsoil. They occur in humid (sub)tropical and warm temperate regions on basic parent materials that contain a substantial amount of unstable Al-bearing minerals. These soils have more than 50% of Al saturation of the exchange complex. They have undergone a process of clay transformation in the sense that the original high-activity clays are weathered into low-activity clays, causing low pH values and high amounts of free Al in the soil.

These soils are often found on unstable landscape positions making them prone to water erosion. Aluminum levels are often toxic at shallow depth and this, together with poor natural soil fertility makes them less suitable for intensive cropping. Consequently, Alisols only allow cultivation of shallow rooting and Al tolerant crops. Only with fully fertilizing and liming can these soils become productive. They are also used for acid tolerant estate crops such as tea and rubber.

Nitisols are deep, well drained, red tropical soils with more than 30% clay in the subsurface. Although strongly weathered they are far more productive than most other red tropical soils. Nitisols are formed by ferralitization combined with nitidization (formation of angular shiny peds), and homogenization by termites and other soil fauna. Their cation exchange capacity is relatively high because of their high clay content (> 30%) and high organic matter content in the topsoil. The pH varies typically between 5 and 5.5. As a result, phosphate fixation may occur although P-deficiency is rare.

These soils are among the most productive soils in the humid tropics. They have excellent physical and chemical properties allowing intensive agriculture with perennials such as cocoa, coffee, rubber and pineapple and are also widely used for food crop production by small holdings. High P-sorption calls for additional P-fertilization (often in combination with a correction of the pH by liming) apart from the commonly used N fertilizers for higher yields.

Acrisols are characterized by an accumulation of low activity clays and a low base saturation. They occur generally in the (sub)humid tropics, most often on acid parent materials. Acrisols have only a thin surface horizon especially in areas with a dry season. Their subsurface horizon is generally depleted in clay and has a weakly developed structure which is often less stable than the underlying clay-enriched layers. Their microstructure is weak and they have a poor chemical fertility (low pH, Al toxicity and P-sorption).

Surface soil preservation is a precondition for the successful farming of Acrisols. The subsoil can contain toxic levels of aluminum and, thus, be unfavorable for root development and crop production in general. Adapted cropping systems with complete fertilization are required for farming. The widely used ‘slash and burn’ agriculture is a well adapted form of land use on Acrisols, if the occupation is short (only one to two growing seasons) followed by a long regeneration period (> 10 years). Acid-tolerant cash crops such as pineapple, cashew, or rubber can be grown with some success.

Lixisols consist of strongly weathered soils in which clay has washed out from an eluvial (e.g. clay-depleted) horizon down to an argic clay-enriched subsurface that has low activity clays and moderate to high base saturation. They have generally a thin surface horizon. The clay- enriched subsoil has a stronger structure than observed in Acrisols; the clay depleted sub-horizon is commonly quite massive and very hard when dry. The chemical properties are somewhat better because, due to the higher pH, Al levels are generally not toxic. Slacking and caking of the surface soil are serious problems with Lixisols.

These soils are found in tropical, subtropical and warm temperate climates with a pronounced dry season; savannah or open woodland are the common natural vegetation. Many Lixisols are polygenetic soils with characteristics formed under a more humid climate in the past. Preservation of the surface soil and its organic matter is important. Degraded top-soils have a low aggregate stability and are prone to crust formation causing run-off (erosion). Heavy tillage of wet Lixisols will cause compaction. The low absolute level of nutrients and the low cation retention makes recurrent inputs of fertilizer and/or lime a precondition for continuous cultivation. Degraded Lixisols regenerate very slowly, if at all. Consequently, perennial crops are preferred over annuals, particularly on sloping land.

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Biographical Sketch

Antonie Veldkamp is a professor and a chairperson in the Soil Inventory and Land Evaluation Department of Environmental Sciences at Wageningen University (The Netherlands). He has been active for twenty years in teaching and research in quaternary geology, geomorphology, soil science and land use changes. In all those fields he combines fieldwork with quantitative analysis and process modeling. He developed several models and wrote over 100 international peer reviewed papers. He is a member of the SSC of LUCC (Land Use/Cover Change Project) and the GLP Global Land Project (IGBP and IHDP).

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