

Soil system and pedogenic processes: Self-organization, time scales, and environmental significance

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Abstract

The essence of pedogenesis, as a synergetic process, consists in generation, selection, accumulation and differentiation of the solids produced in the course of bio-abiotic processes functioning within a soil body. Soil formation in the broad sense is the result of synergetic processes of self-organization of an *in situ* soil system during its functioning in time and space. Soil formation, *sensu stricto*, is the transformation of the solid-phase lithomatrix (parent material) of the soil system into the pedomatrix (soil body, soil mantle). Pedogenesis is perceived as an integration of specific pedogenic processes (SPP); each of them characterized by a definite set of solid-phase pedogenic features. Each soil body is formed by a combination of some SPP. The whole set of SPP may be grouped in accordance with their essence, characteristic times (rates) and reversibility-irreversibility. In terms of *characteristic times* (rates) they may be arranged in three main groups: rapid (10^{1-2} years), medium-rate (10^{3-4} years), and slow (10^{5-6} years). Soil system functioning and soil formation are intimately linked but fundamentally different processes: the former is infinite in time, if not interrupted by external factors; the latter, as any self-organization process, is finite in time and tends to reach a steady state. The theoretical grouping of the pedogenic processes according to their essence and self-termination or quasi-equilibrium is proposed. All the diagnostic soil horizons (as defined in WRB) are perceived as more or less stable and “mature” degrees of soil self-development. They may be separated into favorable and unfavorable with respect to their suitability for biota. Favorable conditions are generally common in 12 out of 39 diagnostic horizons and properties (32%). They are mainly influenced by biotic fluxes and cycles, which are comparable to, or exceed, abiotic fluxes and cycles in their strength and capacity. In this case, biota transforms and improves the environment rather than adapts to it. Unfavorable conditions are more common in 27 out of 39 diagnostic horizons and properties (68%). They are influenced by the mutual action both of biotic and abiotic fluxes and cycles. In this case, biota adapts to the environment rather than improves it.

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1. Introduction

The behavior of a soil system in time is an old concern, and still is an actual problem in pedology (Arnold et al., 1990; Huggett, 1998). From the very beginning of pedology as a science, pedologists regarded soils as time-dependent natural bodies. In 1883 Dokuchaev included time as one of the five major factors of soil formation (Dokuchaev, 1967). Later Jenny (1941) estimated the time-scales of soil formation and proposed

an equilibrium model of soil development from incipient stages to a “climax” profile, which should be in dynamic equilibrium with actual soil-forming factors. Recent data showed that a simplified linear approach couldn’t explain adequately the temporal behavior of a soil body (Yaalon, 1970; Jacob and Nordt, 1991; Targulian and Sokolova, 1996). Recent progress in the theory of soil development has been supported by some findings in paleopedology (e.g. Bronger and Catt, 1989; Retallack, 1990). The study of paleosols clearly show that environmental changes even in a short time significantly modify the pathways of soil development, and that most surface soils are polygenetic due to temporal variations of pedoenvironments (Birkeland, 1999). A major step forward in understanding soil functioning was provided by the use of non-equilibrium

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thermodynamics in soil modelling that regards soil as an open non-equilibrium complex system, and applies synergetic approaches and terminology to studies of soil dynamics (Phillips, 1993, 1998; Phillips et al., 1996). According to these approaches, a soil system may pass through a series of largely unpredictable states toward a quasi-stable state. In a practical sense it means that a soil has more than one possible pathway of development (Phillips, 1998; Huggett, 1998). However, better understanding is still needed about soil systems behavior in time. Independent of the complexity of the models used, the principal questions remain the same: what are the pathways of soil development, what are the rates of soil-forming processes, and what environmental significance do these processes have? To answer these questions we should determine the basic terms and ideas to be used for the study of soil system behavior in time.

2. Soil formation as a synergetic process of self-organization of the soil system

Since the early works of Dokuchaev (1967) the main paradigm of pedology is based on the dependence of soil processes on soil-forming factors. Now we express this dependence in a more complete way as: factors of soil formation → internal soil system functioning → specific pedogenic processes → soil properties and features → external soil functions (Krasilnikov, 2000; Targulian, 2005). Although a good framework for soil study, the scheme lacks quantitative accuracy. The soil-forming factors are well known (Jenny, 1941; Dokuchaev, 1967) and even might be expressed quantitatively (e.g. Phillips, 1998). Soil features also can be observed and measured, however, the scheme of soil-forming processes is still rather speculative, and we need better understanding of their essence and mechanisms, reversibility–irreversibility and characteristic times (rates).

One of the most important concepts for soil formation is that of specific pedogenic processes, proposed by Rode in 1947 (see English translation: Rode, 1961) and developed by Gerasimov (1973). Many multiphase fluxes, cycles, exchange reactions (microprocesses of soil functioning by Rode) operating in the soil system are not completely closed and reversible, therefore they produce gaseous, liquid, and solid residual products of functioning (Fig. 1). While the soil gases and solutions are easily renewed by exchange with the environment, the solid microresults of soil functioning are retained and gradually accumulated within the soil system, thus forming well-expressed pedogenic solid macrofeatures over a long-term soil “life”: humus, clay minerals, pedality, porosity, soil horizons, etc. The simple model of annually fluctuating non-closed process of functioning, which creates the solid microresults in each cycle, and of the gradual accumulation of these microresults during long-term soil functioning is shown on Fig. 2.

Formation, selection, accumulation, and differentiation of solid residual products within a multiphase soil system are the complex process of soil formation as an *in situ* development of a soil body (pedomatrix) from its parent material (lithomatrix), thus forming a complicated soil memory recorded on the solid carriers (Targulian and Sokolov, 1978; Targulian and Sokolova, 1996; Targulian and Goryachkin, 2001, 2004). It is important to distinguish clearly between the multiphase functioning of a soil system and the solid-phase self-organization (self-development) of a soil body in time. These are two closely related but quite different phenomena. Multiphase functioning of soil systems is potentially an endless process, if not interrupted by denudation or burial. In contrast, self-organization of the solid phase of a soil body is potentially a set of self-terminating synergetic processes.

Pedogenesis is perceived as an integration of specific pedogenic processes (SPP) each of them capable of creating a

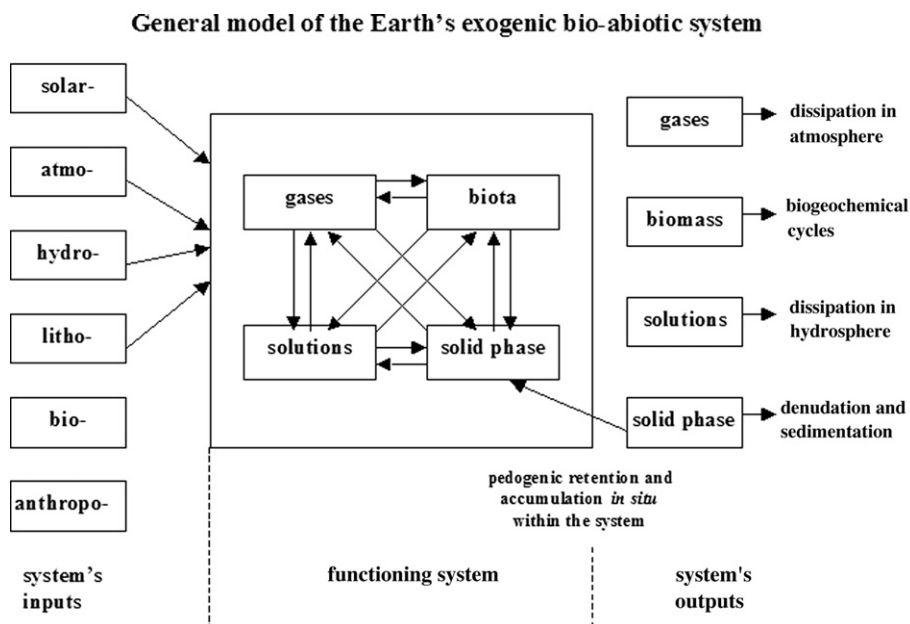


Fig. 1. General model of the Earth's multiphase bio-abiotic systems.

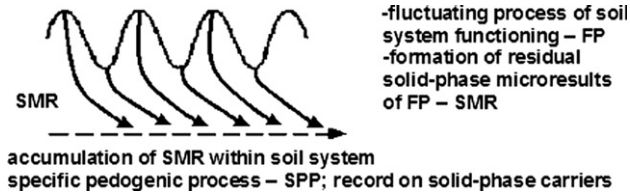


Fig. 2. The relation between fluctuating (cycling) process of soil functioning and the specific pedogenic process *sensu stricto*.

definite set of solid-phase pedogenic features. Thus, each soil body is formed by some combination of pedogenic processes. By *essence* the SPP are usually arrayed in broad groups: soil weathering, transformation of organic matter, translocation of substances within the solum, leaching from the soil, pedoturbations, gain or loss of matter on/from the topsoil, *etc.* In a more general way Simonson (1959) expressed the same idea: processes, such as gains, losses, transformations, and translocations determined by interacting factors of soil formation produce soil bodies. Soil formation (pedogenesis) is represented by the “irreversible time-arrow” of soil system functioning (Fig. 3). The latter does not mean that soil development is completely irreversible and no “reverse evolution” of soil properties occurs: it is well known, that pedoturbation (Hole, 1961; Vasenev and Targulian, 1995; Phillips and Marion, 2005), denudation, or contemporary pedogenesis (Targulian and Goryachkin, 2001, 2004) can change, destroy or mask some soil properties. But on the whole, soil formation is an irreversible phenomenon, which means that a soil never returns completely to its initial state during self-development and/or evolution. Only deep erosion down to unaltered parent material returns a soil back to a near initial stage of its development, but in that case it would be better to define it as a complete destruction of a soil body and beginning of a new one.

Soil formation, ideally, is a synergetic process of self-organization of a soil system in time, which tends toward a

mature soil body in balance with the matter and energy fluxes in its environment. In this process initial components and structures of a lithomatrix are transformed into new more stable components and structures of a pedomatrix or pedomemory (soil body, soil mantle). The pedomatrix after its formation becomes a powerful regulator of the further functioning of the soil system (see Fig. 3). It is still an open question if soil development has limits. According to the classical model (Jenny, 1941; Yaalon, 1970), soil develops towards a steady state, balanced with existing factors of soil formation. However, within geological time scales very few soils develop in stable environments (Jacob and Nordt, 1991). Most soil profiles undergo geological burial and/or denudation processes (Butler, 1982; Birkeland, 1999). During the Anthropocene many soil bodies have been completely “poisoned” with technogenic residues, thus terminating their natural development (Fig. 4). Long-term soil formation in stable environments seems to be an exception, and such soils have recently been called Vetusols (Cremaschi, 1987). Still, even if we consider only soil development of land surfaces in relatively stable environments, it is not clear, if soil can reach a steady state. We consider that a soil body reaches a steady state only if all the specific pedogenic processes (including the slowest ones) are already terminated, or are in a dynamic equilibrium with the external environment. Let us try to find out, if such a situation is theoretically possible. To do so we propose a subdivision of SPP according to whether or not they are self-terminating.

- a) *Resource-self-terminated SPP*. These processes are irreversible, and are limited by the reserves of certain components in parent material. The most evident example is the weathering of primary minerals in soils. The reserve of such minerals cannot be renewed without new geological material accumulation, and the process of weathering in soils terminates when this reserve is finished. To some extent

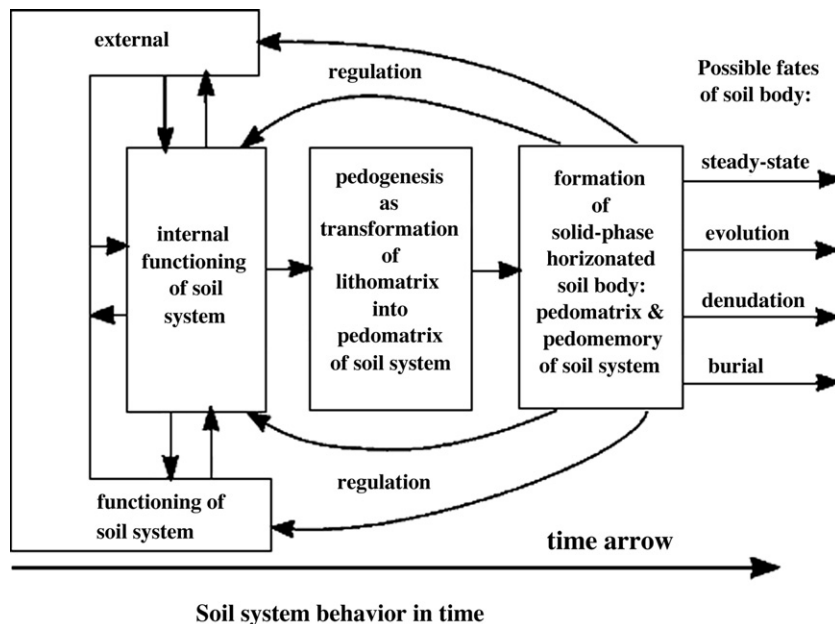


Fig. 3. Soil system behavior in time.

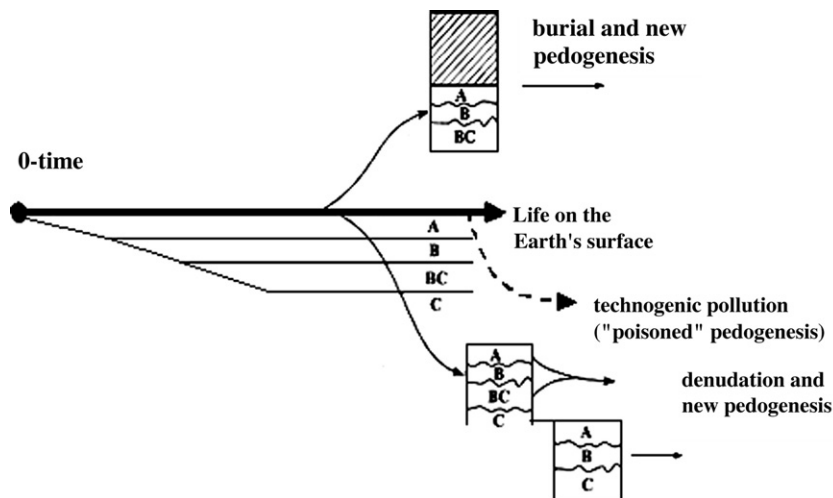


Fig. 4. Possible fates of soil body in a geological time scale ($n \cdot 10^4 - 10^6$ years).

clay translocation in soil profile is also limited by its initial presence in a parent material if no pedogenic clay formation occurs. If pedogenic clay forms, its translocation is limited by the initial quantity of clay plus the presence of minerals able to produce pedogenic clay.

- b) *Resistance-self-terminated SPP*. This group includes the processes that lead to the formation of products that are rather stable in soils. Clay transformation to kaolinite or gibbsite may be a good example. The process is mainly irreversible; however, regradation of gibbsite to kaolinite has been reported (Furian et al., 1999) indicating that a reverse process is possible in particular pedoenvironments.
- c) *Self-inhibiting SPP*. There are processes that create conditions preventing their future development. For example, plinthitization forms an impermeable layer that does not allow groundwater to penetrate to the upper layers, and, thus, prevents iron oxide precipitation.
- d) *Dynamically equilibrium SPP*. These processes are rather common in soils, with humus formation to be a good example of that. The accumulation of humus is a result of equilibrium in organic residues deposition, humification and mineralization rates. Mainly such processes are biologically induced and correspond to matter and energy fluxes through soil. Some other examples include the formation of forest litter, biogenic structure, saturation of the exchange complex etc.
- e) *Fluctuating-reversible SPP*. These processes are rather rapid and depend mainly on external factors, such as seasonal groundwater level fluctuations. Examples are seasonal or perennial dissolution and translocation of carbonates or salts in soil profile, and freezing and thawing in cold soils or in an active layer of permafrost soils.
- f) *Unlimited SPP*. Very few soil processes can be regarded as continuous and unlimited in time. The only example may be pedoturbations, including biologically induced ones.
- g) *Self-activating SPP*. Some processes can activate themselves: e.g. oligotrophic peat accumulates in water, and produces inhibitors of microbial activity, which favor the growth of *Sphagnum* mosses etc. Ferrollysis is another

example: this process destroys clay particles, increasing the difference in texture between the surface and underlying horizons, thus increasing surface water accumulation, which, in its turn favors the development of ferrollysis.

- h) *Quasi-equilibrium SPP*. These are processes, which lead to the formation of quasistable complex products, such as clay-organic matter complexes. These complexes, though not absolutely stable from a thermodynamic point of view, might be surprisingly resistant for hundreds or even thousands of years. Short-ranged silicates (such as allophane and imogolite) in Andosols should be rather unstable, but in the form of complexes with organic matter their stability is much higher.
- i) *Quasi-static SPP*. These processes, once occurred, keep a soil profile in a relatively stable state, if the environments do not change. For example, gleyzation, which is a fast process, leads to Fe and Mn reduction and their loss from soil horizons. However, soil horizons under reducing conditions do not undergo any important changes after the initial loss of these elements. At least, if no seasonal changes in oxidative-reductive conditions occur, no specific alteration of soil material has been reported.

Each soil is developing and evolving due to activity of all these specific pedogenic processes but the relationships among them and duration of their actions are very different in different soils. Due to the variations in the kinds and interactions of these processes there is great diversity of soils on the Earth (Targulian, 2005; Phillips and Marion, 2005). Characteristics of some important pedogenic processes are summarized in Table 1.

We clearly perceive that this subdivision of SPP can be proposed only as the debatable working hypothesis. We try to use it to discuss how can such a division of SPP help us to understand if soil development has limits? We consider that under a constant environment, soil development should be a self-terminating process directed towards a steady state because all specific pedogenic processes are either terminated due to depletion of initial resources, or come to dynamic/quasi

Table 1
The list of some specific pedogenic processes in Russia and in USA

Russia (Targulian, 2005)	Essence	USA (Bockheim and Gennadiev, 2000)
Litter formation	Accumulation of poorly decomposed organic debris on soil surface in aerobic conditions	–
Peat formation	Accumulation of poorly decomposed organic debris on soil surface in anaerobic conditions	Paludization
Humification	Transformation of organic debris into specific dark-colored humus compounds	Melanization
Gleyzation	Reduction of Fe and Mn in anaerobic conditions in soils saturated with water	Gleization
Salinization	Soluble salts accumulation in soil	Salinization
Pedoturbation	Turbation of soil material by various biotic and abiotic forces (bio-, cryo-, vertiturbations)	Cryoturbation
Structuring	Formation of soil structure from parent material	–
Cementation	Cementation of loose soil material by various compounds (Fe, Si, Ca)	Silicification
Calcification	Accumulation of Ca(Mg)CO ₃ in soils	Calcification
Podzolization	Leaching of Fe, Al and humus from surface horizon in dissolved form and consequent precipitation in a subsurface horizon	Podzolization
Lessivage	Translocation of clay from overlaying soil horizons in a subsurface horizons	Argilluviation
Fersiallization	Transformation of soil material <i>in situ</i> , with moderate desilication, formation of 2:1 clays	–
Ferrallitization	Transformation of soil material <i>in situ</i> , with strong desilication, formation of 1:1 clays and Fe and Al (hydr)oxides	Ferrallitization

equilibrium with the environment. But under an evolving environment without strong erosion and deep burial, soil evolution is a continuous process because many specific pedogenic processes change in response to the driving changes of the environment.

3. Characteristic times of the formation of WRB diagnostic horizons and specific pedogenic processes

The concept of characteristic times of soil forming processes was proposed by Armand and Targulian (1974), and claimed the co-existence in a soil body of the processes of different temporal scales: fast, medium-rate, and slow. Independently, Richter (1987) proposed to divide soil processes into long-term, medium-term, and short-term ones. Though the idea was almost identical, his classification of processes comprised some mistakes; for example, together with laterization he included humus decomposition, podsolization, and gleying in the long-term processes, while clay formation and transformation are included in the medium-term processes. Further development of the concept (Targulian and Sokolov, 1978; Arnold et al., 1990) defined a characteristic time of a pedogenic process as a medium time required to reach the finite steady-state or quasi-equilibrium with the environment and to produce pedogenic soil features stable in time.

General knowledge allows a tentative grouping of pedogenic processes in terms of *characteristic times* into three main classes; rapid (10^{1-2} years), medium-rate (10^{3-4} years), and slow (10^{5-6} years) (Fig. 5). Consequently, soil profiles might be tentatively classified according to their “maturity”. The soils where only rapid pedogenic processes have occurred can be regarded as “young” soils: these are mainly soils formed on recently deposited sediments (alluvial, colluvial, aeolian, or volcanic). The characteristic time of a process is not a constant value; it depends on the pedogenetic potential of the environment. For example, soils formed in regions where the climatic potential of pedogenesis is low (e.g. in cold and hot deserts) show only evidence of “rapid” processes, and the soils should be considered “young”, although the time of pedogen-

esis may be long. More developed soils are found in humid boreal regions, even more mature soils are found in humid temperate areas, and the most developed ones — in humid tropics. This general scheme gives a frame for classifying soil properties and features according to their characteristic times. The parent rock also affects the rate of soil development, because different materials have different “sensitivity” to bioclimatic factors of soil formation (Targulian and Sokolov, 1978).

We tried to arrange the diagnostic horizons and properties used in World Reference Base for Soil Resources — WRB (FAO–ISRIC–ISSS, 1998) according to characteristic times (CT) of their formation (Fig. 6).

4. Two main concepts of soil system behavior in time

Soil formation is the emergence and development of soil systems and bodies from “nonsoil” systems and bodies interacting on the land surface. Functioning (or “life”) of a multiphase soil system starts immediately at time-zero in the zone of multiple atmo–hydro–bio–litho-interactions within the

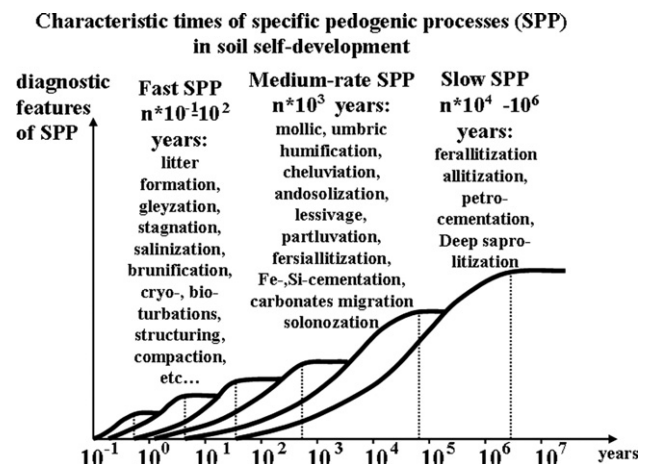


Fig. 5. Characteristic times of specific pedogenic processes (SPP) in soil self-development.

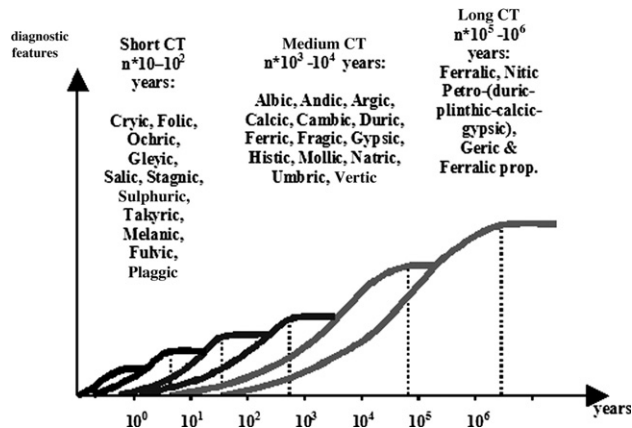


Fig. 6. Characteristic times (CT) of the main diagnostic horizons and properties used in WRB.

parent material (lithomatrix of the soil system). The future development of soil (if it is not truncated or buried by geological processes, or made completely dysfunctional by anthropogenic pollution) was regarded initially as a more or less gradual quasi-equilibrium process under the constant soil-forming factors. That is what we call now a steady-state model of soil development (Jenny, 1941; Rode, 1961; Dokuchaev, 1967; Yaalon, 1970). Several recent considerations have modified a steady-state model of pedogenesis.

First, it was understood, that the whole combination of irreversible pedogenic processes (SPP) could lead to qualitative alteration of a soil body. These processes were generally regarded in a “normal” steady-state model as gradual quantitative changes in soil composition and properties (Buol et al., 1973). However, some SPP can qualitatively change soil functioning, like hardpan formation in the development of Calcisols, Durisols, Gypsisols, and Plinthisols, which results in the transformation of a developed profile to a “shallow soil” from an ecosystem point of view. In a general way the phenomena may be presented as a scheme of the various interactions of SPP with the different characteristic times (Fig. 7). Direct interactions of the fast, medium-rate and slow processes form well-known SPP chronosequences or chronochains, whereas during feedback interactions slow processes with the faster ones can form “pedogenic time bombs” by gradual accumulating feedback results of “slow” pedogenesis that cannot be observed or calculated directly from fast or medium-rate processes.

Second, significant fluctuations occur in the course of pedogenesis, some of them completely stochastic, and others caused by soil-landscape co-evolution (Burgess, 1960; Ibáñez et al., 1990; Jacob and Nordt, 1991; Kozlovskiy and Goryachkin, 1996). We agree with Phillips (1998) that a factorial steady-state model cannot counter a short-term process oriented approach; they are complimentary ones. The main difference is in the time scale of the processes to be studied.

Finally, recent developments produced a new model of soil development and evolution (Johnson and Watson-Stegner, 1987; Johnson et al., 1990). This model stressed the uncertainty of pedogenesis, which even might express a chaotic behavior

(Phillips, 1993; Phillips et al., 1996). It led some authors to contrast concepts of “soil development” with “soil evolution” (Huggett, 1998) relating the first one to simplified equilibrium models, and the latter to more complex, nonlinear dynamical system models. In our opinion, such a division does not contribute much to understanding pedogenesis. On one hand, uncertain, chaotic behavior may be observed only at small temporal and spatial scales: nobody has described extensive areas of soils characterized by uncertain, nondeterministic development for a significant period of time. Moreover, the feedback of such uncertainty on soil features is not very important: we speak on the variation in soil properties, not on a complete change of the pathway of pedogenesis. Uncertainty cannot produce, e.g., a Phaeozem instead of an Acrisol, such a drastic change is always determined by evident factors. On the other hand, the term “uncertainty” often masks lack of knowledge, when we are unable to find the factors determining the spatial distribution of soil properties. That is why Phillips et al. (1996) preferred to use “deterministic uncertainty” to describe variations in paleosol properties which could be ascribed to microtopography we cannot actually reconstruct.

5. Environmental significance of soil self-development

A common view is that fertility is the main unique property of soils (Williams, 1939), though we know that external soil functions are much more diverse. As a logical continuation of the idea of soil fertility, usually it is believed that the development of pedogenic processes increases the ecological “comfort” for soil biota and the fertility of soil. Hence, soil formation is perceived as a form of expansion of terrestrial biota into the upper layer of the lithosphere with the “main goal” to change and improve the living conditions in the belowground tier of ecosystems. This view was supported by the Gaia hypothesis (Lovelock, 1979): biota transforms and regulates the abiotic environment rather than adapts to it. Thus, soil formation should be regarded as the transformation of parent material by biota with a consequent increase in its fertility and ecological suitability (Ponomareva, 1969; Van Breemen, 1992, 1993).

However, not all pedogenic processes are favorable for plants and soil biota. Some SPP can induce an almost complete extinction of biological activity (strong salinization); other SPP

Interactions of the specific pedogenic processes

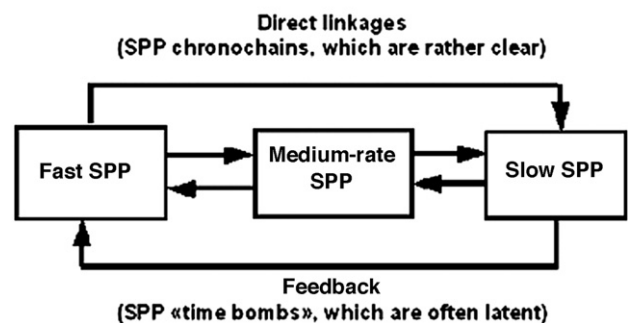


Fig. 7. Interactions of the pedogenic processes having different characteristic times.

can strongly reduce biodiversity and bioproduction (strong leaching, gleyzation), or restrict the rooting zone thickness (hardpan formation). The most “aggressive” SPP – ferrallitization and podzolization – produce very unfavorable soil media for biota (low activity clays in Ferralsols and Acrisols, acid albic and free Al-enriched spodic horizons in Podzols). It has been reported that the most tectonically stable tropical regions are unsuitable for agriculture because of accumulation of final soil weathering products, such as kaolinite and gibbsite (Fyfe et al., 1983). If denudation processes develop, transported highly weathered material also gives rise to rather nonproductive soils (Gracheva et al., 2001). Trofimov and Sedov (1997) indicated that from the thermodynamic point of view pedogenic processes should always lead to an accumulation of stable, inactive products in soils.

Recent work shows that not only weathering and leaching can cause the formation of unfavorable conditions for soil biota (Targulian and Krasilnikov, 2004). If we consider soil horizons during soil evolution as suitable or favorable habitats from an ecological point of view, then degrees of suitability or favorability could be recognized in the course of pedogenesis. Favorable horizons represent those states of a soil system at which it becomes more favorable for biota than in previous states (in terms of biological productivity, biodiversity, and reproduction). Unfavorable horizons represent those states of the soil system at which it becomes less favorable for biota than in previous states (in terms of biological productivity, biodiversity, and reproduction).

Pedogenic processes approaching unfavorable conditions can be grouped as: a) loss and/or destruction of soil components, which are essential for biota (strong weathering, removal of substances), or b) excessive accumulation of products of pedogenesis (salts, gypsum, iron, aluminum, silica, acid peat). The majority of unfavorable conditions of soil formation are associated mainly with self-limiting irreversible processes. In contrast, mainly reversible quasi-equilibrium processes favor biota. From an ecological point of view it is important to monitor not only rapid and medium-rate PP, but also pay attention to the slow ones which can latently overcome some ecologically important soil thresholds (chemical, mineralogical, textural) and reduce soil quality, thereby acting as a kind of “pedogenic time-bomb” (see Fig. 7).

We estimated the suitability of diagnostic horizons, properties, and materials used in WRB (FAO–ISRIC–ISSS, 1998). The division of the horizons into favorable and unfavorable for soil biota was done tentatively on the basis of our own expert judgment. This division corresponds well with the data on roots density in different soils reported by Schenk and Jackson (2002).

We believe that only 12 WRB diagnostic horizons (32% of the total amount of horizons, properties and materials listed) are generally ecologically favorable for biota, namely: *mollic*, *umbritic*, *chernic*, *melanic*, *histic* (eutrophic), *hortic*, *terric*, *andic*, *cambic*, *calcic*, *nitic*, and *vitric* horizons. However, even these horizons are not always favorable for biota. For example, *histic* horizons are permanently or seasonally saturated with water, and biota suffers from oxygen deficiency. Also some varieties of *histic* horizons, containing *Sphagnum* peat produce inhibitors of

microbiological activity, and, thus, may be toxic. *Vitric* horizon in places lacks sufficient surface activity, and the excess of Ca in *calcic* horizons may cause Mg deficiency in plants. The favorable conditions are mainly influenced by biotic fluxes and cycles that are comparable to, or exceed, abiotic fluxes and cycles in their strength and capacity. In this case, biota transforms and improves the environment rather than adapts to it.

The list of unfavorable conditions is more extensive including 27 out of 39 diagnostic horizons and properties (68%). These horizons are listed in Table 2, together with their properties, limiting their “ecological comfort”. We should remember that in particular cases some of these horizons may play a positive role in plant growth (like the presence of an *argic* horizon in sandy soils may facilitate the capture of water by plants roots); however, most of them limit the development of higher vegetation. They are influenced by the mutual action of biotic and abiotic fluxes and cycles. The latter ones have minor impact on pedogenesis, because very few pure abiotic soil-forming processes are known. It is known that weathering, strong leaching, and salts accumulation are mostly biologically induced in soil. In this case, biota adapts to the environment (to a great extent “spoiled” by itself) rather than improves it.

Does it mean that pedogenesis is a negative process from an ecological point of view? We do not think so. First, biotically dominated dynamic quasi-equilibrium processes, though few in quantity, are a strong counterpart to irreversible pedogenic processes. Many horizons (favorable for biota) formed by these processes are usually situated on the topsoil, giving fertile rooting zones. Second, in a long-term frame, denudation processes refresh the land surface, eliminating stable products of pedogenesis and giving rise to incipient soil formation. At certain stages of soil development the functional significance of certain pedogenic processes may change. The external functions of soils depend on the quality and/or quantity of the pedogenic products, which change in the course of pedogenesis. For example, in initial stages of pedogenesis, clay mineral transformations lead to an increase of clay surface activity due to the formation of low-charged 2:1 layer silicates (illites, vermiculites, smectites, and their intergrades). Advanced stages of long-term humid tropical pedogenesis lead to a decrease in surface activity due to the accumulation of final weathering products (kaolinite, gibbsite). Another example is gypsum accumulation in soils. Minor contents of secondary gypsum might favor soil productivity (Laya et al., 1998), however, further accumulation of gypsum up to the formation of a petrogypsic horizon, is definitely unfavorable for living organisms.

In fact, the term “ecological comfort” is almost as speculative as the expression “soil fertility”. Without specifying the organisms feeling “comfortable”, it makes little sense. For example, deeply weathered acid tropical soils (Acrisols and Ferralsols) support the most productive and diverse ecosystems on Earth, though in the terms of limiting factors for potential agricultural use they are rather unproductive (poor in nutrients, with toxic Fe and Al concentrations and unfavorable physical properties; Arnold et al., 1990). With only imprecise empirical criteria related to potential agricultural production of soil, we conclude that most “fertile” soils are relatively young ones; they form on recent sediments in dynamic environments. The ancient

agricultural civilizations appeared on soils formed on recent alluvial sediments and flood plains (Egypt, Mesopotamia, China, and India) or volcanic ashes (Java, Mesoamerica). In contrast, “old” highly weathered soils on ancient stable surfaces are mostly unsuitable for agriculture (Fyfe et al., 1983) in their natural state.

It is important to remember that the uncertainty of soil development of the soil evolution model of Johnson et al. (1990) contributes to the formation of more stable, sustainable structures in the biosphere. Both factor-determined soil diversity and “uncertain” variability create the mosaic structure of the soil mantle (Fridland, 1974, 1976), which determines the organization of a landscape (Kozlovskiy and Goryachkin, 1996), and increases its biological diversity (Krasilnikov, 2001). Consequently, the mosaic structure of the biosphere provides for its own self-organization and sustainability (Watson and Lovelock, 1983).

6. Soil formation — the myths and reality

Though soil formation has been studied for a long time, there still are gaps in our knowledge. Moreover, several myths about

Table 2
WRB diagnostic horizons, properties, and materials, unfavorable for roots and soil biota development and their limiting attributes

Horizons (properties, materials)	Limiting attributes
Albic	Acidity, lack of nutrients
Argic	High density, impermeability, low hydraulic conductivity
Cryic	Low temperatures
Duric	Compaction
Ferralic	Lack of nutrients, low CEC
Ferric	Fe toxicity, periodical lack of oxygen
Fragic	High density, impermeability, low hydraulic conductivity
Gypsic	S competition with N and P
Natric	Alkalinity, compaction, Na toxicity
Ochric	Lack of structure, unfavorable physical properties
Petrocalcic	Complete impermeability
Petroduric	Complete impermeability
Petrogypsic	Complete impermeability
Petroplintic	Complete impermeability
Plintic	High density, impermeability, Fe and Al toxicity
Salic	Soluble salts toxic concentration
Spodic	Al toxicity
Sulfuric	Extreme acidity
Takyric	Impermeability, compaction
Vertic	High density, impermeability
Yermic	Low nutrients content, unfavorable physical properties
Abrupt textural change	High density, impermeability
Alic properties	Al toxicity
Geric properties	Lack of nutrients, low CEC
Gleyic properties	Deficit of oxygen, high Fe and other metals activity
Stagnic properties	Deficit of oxygen, high Fe and other metals activity
Permafrost	Negative temperatures

pedogenesis are rather resistant in the mind of the scientific community, having been repeated in various forms since the beginning of pedology as a science. Even now they are strong and are periodically refreshed.

6.1. The first myth: Pedogenesis may be expressed as a mere function of factors of soil formation

It is not true. The five-factor model formulated in 1883 by Dokuchaev (1967) and presented as an equation by Jenny (1941) gives a good frame for soil study. But correct prediction is complicated by the lack of quantitative expression of most factors, the absence of correct information on past pedoenvironments, and so forth.

6.2. The second myth: Pedogenesis is an uncertain, mainly chaotic process, and synergetic approach the best way to describe it

It is true, but only partially. Soil is a self-organizing body since it receives fluxes of matter and energy, thus, irreversible processes should be described using non-equilibrium thermodynamics. However, many long-term macroprocesses in soil, such as weathering, are well described by classical thermodynamics, based on the idea of increasing entropy in closed systems (Trofimov and Sedov, 1997). General pathways of pedogenesis can be predicted using a simplified equilibrium approach. In most cases “uncertainty” means that we lack adequate knowledge about the factors determining soil development. The term “deterministic uncertainty” (Phillips et al., 1996) characterizes the situation more adequately.

6.3. The third myth: The pathway of pedogenesis may be “calculated” from actual short-term soil processes

Pedogenesis cannot be reduced to simple chemical and physical processes functioning in a soil body. Soil system functioning and soil formation are intimately linked but fundamentally different processes. Soil system functioning is infinite in time, if not interrupted by external factors, and soil body formation is self-organizing process of gradual accumulation of solid products of soil functioning; it is finite in time and tends to reach a steady state with its environment.

6.4. The fourth myth: The development of pedogenic processes usually increases the ecological “comfort” for soil biota and the fertility of soil

Simple review of the WRB soil horizons indicates that many pedogenic processes lead to the formation of properties unfavorable for biota. It is not only true for ancient deep-weathered soils, well known for their low potential productivity, but also for the soils of intermediate stages of development (e.g. soils characterized by the presence of hardpans, Al and Fe toxicity, salinity, sodicity etc.). Thus, pedogenesis is a very complex phenomenon consisting of many diverse and contrary processes and in its “biotic” and agricultural sense may either increase or decrease soil fertility. It should be taken into

consideration, when we try to elaborate our strategy to sustain or improve soil quality.

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