The Resilience of Soils

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Introduction

The ever-growing importance of the soil as a substantial part of the environment and irreplaceable basis for the production of food, fodder, and raw materials is evident and more and more appreciated. It can be clearly seen that the formation of an up-to-date concept of soil resilience is highly necessary so that everybody concerned can be in a position to agree or disagree on its definition and apply it accordingly both in science and technology whenever the soil and its productivity are discussed.

We come across the term "soil resilience" more and more often without having a precise definition for this expression. When the environmental aspects, or agri-, horti- or sylvicultural value of a soil is discussed soil resilience is frequently mentioned, in most cases only as a general idea or as rhetorical rubric.

The Place and Role of Soil in Nature

It is generally accepted that the soil is a substantial part of the environment comprising different substances and forming a special kind of ecosystem, inside the given ecosystem, with various properties and attributes. It is also accepted that the soil of the continents is of high diversity which is dealt with by several branches of soil science, e.g. classification, survey, mapping, etc.

The soil, or the pedosphere, which is an environmental synonym for soils in general, has a specific place in Nature. It is a natural body, similar to rocks, waters, or biota in the sense that they, too, have their own materials, mass and energy fluxes, development, and regularities. This fact should be mentioned because, not only in newspapers but also in technical literature, soils are frequently treated either as living substances or as non-biological substances. Neither of these statements are true, because one of the characteristics of the soil is its complexity, the fact that it contains both living and non-living substances, forming due to both biotic and abiotic processes.

The soil as a natural body is inseparable from the rocks and the crust of weathering on the surface of the continents from which it has developed, on the one hand, and from the biological processes, on the other. The main characteristic that distinguishes the soil from the rocks is the result of biological processes: the production of organic matter by the activities of micro-organisms, plants, invertebrates, and other animals, and finally human beings which transforms the rocks into soils, capable of supplying plants and crops with nutrients and water.

The processes of soil formation started concurrently with the appearance of life on the continents of our globe and continued during the millions of years of interaction between living substances and rocks under the influence of climatic conditions, with particular regard to the action of water, geomorphologic patterns, and the time factor. As a result of their interaction specific mass and energy fluxes formed the different soil types in different environmental conditions.

With the appearance of the human race on the face of earth even changes in the environment became different. Due to human activities the natural processes affected by biotic and abiotic factors accelerated and several others, which were unknown or minimal before, developed.

At the very beginning, when mankind was not yet widespread on the continents, environmental changes did not differ too much from those preceding human interference. Later, however, when the number of human beings increased and great parts of the continents were already populated the effects of their activities became extended and detrimental, and the natural environment began to alter at a much more accelerated rate.

The role of soils in Nature is complex and many-sided, including biospheric, hydrospheric, atmospheric and lithospheric functions. Their interaction is illustrated in Figure 1.

The productivity of soils, when speaking of their utilization, is always determined by the properties and attributes of the whole soil body (ARNOLD et al., 1990). Evidently, top soil conditions have a special role in the nutrient and water supply of the soil biota (including organisms both above and below the soil surface).

The most important functions of the pedosphere include (but are not limited to) the following:

1. The pedosphere regulates many biotic processes, including the supply of plants with mineral nutrients and water from the soil to build up their biomass which will then become another source of nutrition underlying the food chain. This role determines the biodiversity of the soil as well as its productivity. Certain soil properties are favourable while others are unfavourable for certain types of biota and the distribution and geography of natural vegetation is con-

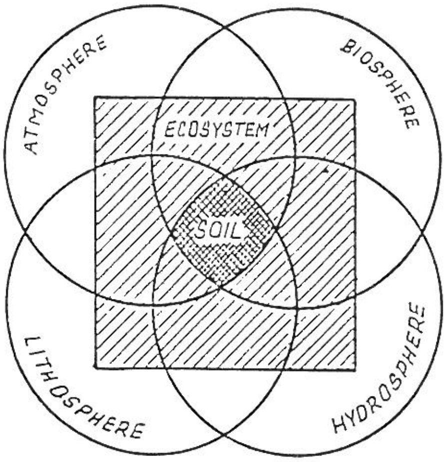

Figure 1
Schematic diagram of the interaction of lithosphere, atmosphere, biosphere, hydrosphere, ecosystems and soils (SZABOLCS, 1989)

nected with the distribution and composition of the soil cover. The pedosphere accumulates the humous materials and the chemical energy bound to them. A certain part of the dead organic matter is transformed into soil humus, which may be preserved for a long time bearing out the old saying that soil is the cradle and grave of life ("for dust thou art, and unto dust shalt thou return", Genesis 3:19). The function of the soil as a larder of the biomass is rather remarkable because, as it is shown in Table 1, in most ecosystems the bulk of organic materials is in the soil and only a smaller part of them can be found in other biological elements of the environment.

Table 1
Organic matter content in different ecosystems, t/ha

Type of ecosystem	Overground phytomass	Humus
Coastal marshes and terrestrial swamps	10-20	128
Tundra	3-10	320
Taiga	270	100
Grasslands	16	355

2. The pedosphere constitutes an interface between the biosphere and the geosphere sustaining, regulating, and controlling several turnovers and fluxes of substances, particularly the cycle of so-called bio-elements, the elements of mineral nutrition which, through a number of intermediate stages, are again returned into the soil. Soil is the starting point for the migration of many soluble and non-soluble substances within and through ecosystems. Most sedimentary rocks are formed from materials derived from the pedosphere and later they may give rise to new soils.

3. The soil, as a porous system, contributes to the chemistry, moisture and heat balance of the atmosphere. The pedosphere regulates the exchange of various gases between the atmosphere and the gaseous phases of soil by absorbing oxygen, exuding carbon dioxide and other gases, such as methane, hydrogen, hydrogen sulphide, nitrogen oxides, and ammonia etc. Soil evaporation influences atmospheric evaporation.

4. The pedosphere redistributes water in the various hydrological fluxes, transforms precipitation into infiltration, surface runoff, subsurface inter-soil runoff, and groundwater runoff, and also alters the chemical composition of the precipitation. The top layer of the pedosphere is often washed away by the runoff of water in the course of erosion.

5. The pedosphere has important lithospheric functions as a specific and stratified mantle of the earth's surface protecting it from destructive impacts. It buffers and regulates destructive processes, e.g. horizontally and vertically acting exogenic processes.

These two terms have often been applied as synonyms and there is no exact definition indicating the differences between them. So, somewhat arbitrarily, the word "properties" will be applied in this paper to those characteristics of the soil which can be measured directly and unambiguously, and expressed in exact weights, measures, and terms. There is no dispute about how to express e.g. the specific weight, moisture content, particle size distribution or the pH of a soil, and there are plenty of conventional methods for establishing these data. On the other hand there are important soil characteristics which cannot be measured or expressed so unambiguously like soil fertility or soil productivity. To this second group belongs the term "soil resilience" which exists beyond doubt but its interpretation requires some circumscription if we want to characterize this soil attribute in a given place and time, and for a given purpose.

When we try to characterize soil resilience as a significant attribute of the soil, it is necessary to define what resilience is in general. The latter is not a very difficult task. To define, however, the resilience of a given soil in a given place in respect of its correlation to soil forming and environmental processes, and of the targets of soil utilization and land use, including both scientific and practical aspects, it is quite another story.

The Resilience of Soils

Resilience has been defined from various points of view for various purposes. In general it means the tolerance against stress, or that proportion of the total work of deformation which the body can give back following the removal of the deforming forces. In engineering and technics "resilience" is applied as the elastic limit of a body.

These definitions are correct, however they give but little information in this general form for our purpose to analyse soil resilience as a soil attribute. The first step on the road to characterize soil resilience correctly is to pose the question of "Against what?" as soils have no resilience in general (or in absolute terms). What they have is a capability of behaving in this or that way in the face of certain more or less well defined agents, forces, or effects. The precondition of characterizing the resilience of a soil requires the definition of these agents, effects and forces.

In order to answer the above question we have to go back to the mass and energy fluxes dominating soil processes and resulting in soil behaviour in general. Soil resilience is partly a result and partly a counterpart of such fluxes. In this respect three kinds of mass and energy fluxes can be enumerated.

1. Atmospheric, including radiation, heat and precipitation from and through the atmosphere.

2. Endogenic soil fluxes, including weathering, soil formation, the synthesis and decomposition of organic matters, accumulation, leaching, and redistribution of compounds, erosion, oxidation-reduction, release and fixation of nutrients. etc.

3. Exogenic (anthropogenic) mass and energy fluxes, closely related to and overlapping endogenic fluxes, including the effects of agricultural operations (e.g. tillage, the application of chemicals, irrigation, drainage, terracing, removal of yields), as well as contamination with industrial output compounds, radioactive fission products, etc.

Soil resilience includes all the processes resulting in the behaviour of soils to counteract stress and alterations. Consequently, soil resilience includes such important properties like the buffering capacity of a soil in respect of chemical, physical, and biological impacts. It is not necessary to give a detailed definition of these three main types of soil buffering capacity but it should be noted that all of them have important theoretical and practical significance, e.g. physical buffering capacity plays an important role when the hazard of erosion is concerned, while chemical buffering capacity will come into play in case of soil acidification or alkalization. It is somewhat more complicated to define the biological buffering capacity of a soil which concerns several biotic processes as well as soil biota in total.

It follows from this that a soil may have high buffering capacity against chemical agents (e.g. a heavy textured soil or a calcareous soil against acidification) and, at the same time, it may have very low buffering capacity against biological stress (e.g. in case of vulnerable biota of the given soil).

Soil resilience also includes the important capability of the soil which is called renewability. It is very important that the soil as a natural resource is capable of conditional renewability, i.e. it can regenerate itself after several kinds of deterioration and degradation within reasonable limits. Soil renewability is also important in practical terms because in cases e.g. of overfertilization, salinization, and other destructive impacts, the soil is capable, depending on local circumstances, of regaining its original or nearly original state whenever it is permitted by natural and anthropogenic soil forming processes.

In connection with the phenomena described above the transforming ability of soils should also be mentioned. The detoxication, decomposition, and transformation of many substances in the soil contribute to its renewability, e.g. decomposition of toxic organic matters, some kinds of absorption, etc.

Perhaps it is not necessary to quote many other examples in order to argue for the statement that soil resilience should always be determined concretely, because high or low resilience has no absolute meaning as regards soil value in respect of practical purposes. Rocks in a desert may be very resilient against chemical, physical or biological agents, still they do not have much value for production. On the other hand a soil, very vulnerable to such agents, can be very valuable for agricultural purposes (e.g. a humous, loamy soil) until we do not surpass, in the course of utilization, the limits of its resilience.

When speaking of soil resilience the aspects of entropy, too, should be mentioned in brief in the form in which it has been frequently applied in connection with biological processes, with particular regard to soil forming, soil properties, and to the significance of soil in biology and the environment.

It is generally accepted that the definition of entropy is closely related to the second law of thermodynamics (i.e. the principle of entropy increase) which provides a criterion for the determination of the direction of natural processes. They proceed in the direction through which dS_{sys} increases. It also provides a criterion for equilibrium: they cease when $\int dS_{sys}$ attains to maximum, which is zero at equilibrium and positive for spontaneous processes. The heat transferred to a closed system divided by T is equal to or less than the entropy increase for any possible processes. The total entropy change in the closed system dS_{sys} is the sum of the changes inside the system dS_{int} and the entropy transferred to the system from its surroundings dS_{sur}.

$$dS_{sys} = dS_{\mathrm{int}} + dS_{sur} \tag{1}$$

$$dS_{sur} = \frac{dq}{T} \tag{2}$$

where:
q = heat transferred to the system from its surroundings.

For reversible processes of the equilibrium state of the system

$$dS_{\text{int}} = 0 \tag{3}$$

and for a spontaneous or natural process in the system

$$dS_{\text{int}} > 0 \tag{4}$$

The term "entropy" has been applied in soil science and biology based on the above regularities in a somewhat adjusted and simplified interpretation, characterizing the loss of internal energy of the system caused e.g. by decomposition of organic matter. In biology the capability of plants of transforming solar energy into chemical energy by photosynthesis has been considered as diminishing the entropy on the earth's surface. With a certain exaggeration it can be said that biological processes act against entropy.

It is accepted that soil forming processes, which are inseparable from biological processes, also reduce the entropy of the system in comparison with an environmental system without soil forming (e.g. rock).

In other words, the resilience of soils is in reverse proportion with the entropy in the soil.

This concept of soil resilience can be described in a simple equation.

$$SR = BC_{pH} + BC_{ch} + BC_b + \int_{t_1}^{t_2} \frac{dPSF}{dt} + \int_{t_1}^{t_2} \frac{dAF}{dt} \tag{5}$$

where:

SR = soil resilience;
BC_{pH} = physical buffering;
BC_{ch} = chemical buffering;
BC_b = biological buffering;
PSF = pedological soil fluxes;
AF = anthropological soil fluxes.

Such an approach can contribute not only to the interpretation of soil resilience but also, in cases of further studies, to its modelling, estimation and even measurement.

Concluding Remarks

An advanced study of soil behaviour as well as a more up-to-date interpretation of soil properties and attributes are necessary to achieve sustainable land use. It is practically soil behaviour that decides whether our attempts at effective land utilization will fail or will be crowned by success.

Soil resilience which cannot be measured by simple methods but can and should be estimated in given circumstances, is in direct correlation with the effectivity and sustainability of land use.

The better knowledge of soil forming processes and their measuring and monitoring are preconditions of an acceptable determination of soil resilience in a given place and given circumstances.

The exactness of terms and dimensions in which soil resilience can be expressed depends on how precisely those pedological and environmental factors can be measured which result in the resilience of the soil in a given place and time.

On the basis of equation (5) above, it seems to be possible that a follow-up of this paper by studies on soil resilience, by setting up models and elaborating scenarios for approaching the laboratory and in situ processes and part processes can pave the way for integrated studies resulting in an advanced concept and measurable values of soil resilience with the final aim of establishing sustainable land use.

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