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The system of assessment of soil degradation

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Abstract

The measurement and ecological assessment of soil quality or conversely soil degradation, is important in Russia. Thus, based on the analysis of current standards and scientific studies, we developed a set of representative soil quality (soil degradation) indicators to assess the physical, chemical, and biological degradation of soil for various anthropogenic uses of the land. We have provided a matrix of indicators for each of the three processes of degradation. The indicators are grouped into five stages of degradation: high quality (non-degraded), weakly degraded, moderately degraded, highly degraded, and very highly degraded. We have proposed a rate index as a final estimate of soil degradation. We provide examples of how to calculate the soil quality index (soil degradation) and how to interpret the index. Finally we suggest methods for displaying soil quality using soil survey maps and remote sensing procedures.

Keywords: Soil degradation; Soil quality indicators; Soil quality index

1. Introduction

Soil quality is a multi-functional phenomenon. Soil functions to cycle and supply nutrients and to store water for the production of biomass. It serves as one of the most important biogeochemical regulators of the flow of substances into, through, and out of the ecosystem. Due to their specific features, soils can influence the quality of the existence of humankind both through the quality and quantity of agricultural products and through their filtering, buffering, and transformation functions. The anthropogenic disturbance of soils can lead to critical changes in the biosphere, which, in the end, may threaten the very existence of human beings.

Table 1
The indicators of soil degradation (sign ''+'' shows that the indicator is effective for a particular type of soil degradation)

Types of soil degradation	Indicators of soil degradation											
	Thickness of organogenic layer	Thickness of abiotic layer	Soil density	Subsoil water level	Content of nutrient elements (NPK)	Content of readily soluble salts	Content of exchangable sodium	Soil redox potential	Degree of soil pollution	Phytotoxity and genotoxity	Active microbial biomass	Content of pathogenic microorganisms
Physical												
Mechanical elimination of soil layer	+										+	
Erosion	+										+	
Banks	+	+									+	
Deflation (weathering)	+										+	
Thickening			+					+				
Secondary swamping				+				+		+		
Chemical												
Soil exhaustion					+						+	
Secondary salinization and solonetzization			+			+	+			+	+	
Acidification										+		
Toxic pollution									+	+	+	
Biological												
Reduction of numbers and biodiversity of biota										+	+	
Pathogenic pollution of soil												+

The state of soil quality in Russia can be described as critical. There is no national program for land use and management. Information about soil use and soil quality, as well as the scale of pesticide and herbicide application is practically unavailable for anyone, including the Ministries and Institutions. In addition, there are no effective indicators to assess the economic value of the lands in Russia. This makes it impossible to evaluate the actual degradation of soil or to develop remedial plans for soil and related resources. The misuse of lands causes an annual average loss of about 400 000 ha of agricultural land. The loss of agricultural land is mainly due to industrialization, civil and road building, and flooding of land from the construction of dams.

About 25% of the soil is degraded by water and wind erosion, more than 20% by salinization; and almost 50% by poor irrigation practices. In the non-chernozem zone the arable lands and pastures have been degraded due to over-grazing and wetness.

These facts pose an urgent need for the development of methods for assessing the degree of soil degradation. We fully recognize the complexity of the task. Thus, our methods should be considered as a first approximation to stimulate remarks, comments, and additions. We agree completely with the statement of Lal and Stewart (1990) that ''... despite its widespread severity and global impact, soil degradation remains an emotional rhetoric rather than a precise and quantifiable scientific entity.''

2. Principal theses

The objective of the present study is to characterize the ecological state of soil regardless of its use. The soil is considered degraded if anthropogenic and natural processes occurring in soil have lowered the quantity and quality of biomass production, which, accordingly, raise the expenditure for remediation.

Soil degradation processes are divided into three types:

Physical degradation: Includes compaction, erosion, loss of soil tilth, surface sealing, and other characteristics that affect plant roots and water movement.

Chemical degradation: includes salinization, acidification, loss of organic matter, loss of nutrients, pesticide accumulation, and accumulation of toxic elements.

Biological degradation: the loss of biodiversity and optimum proportion of different species of soil mezofauna and microorganisms; and soil contamination by pathogenic microorganisms.

Table 1 shows the main types of degradation and associated indicators.

The indicators of loss of production (degradation) are considered to be those that reflect the specific soil functions. The degree of degradation is the combined effect of loss of soil function as shown by all attributes (indicators) of soil quality (i.e. the absolute decrease of the degradation indicator value, increasing ratio, etc.).

The indicators of soil degradation can be divided into two groups:

Factual indicators describing the state of soil quality during the investigation. These include the degree of erosion, the content of readily soluble salt, soil phytoxicity, etc.

Prognostic indicators reflecting the rate of ''accumulation'' of negative soil attributes and their possible display over time, for instance, the rate of soil degradation.

Among the great number of possible indicators of soil quality, the most preferable are the simplest and the most readily available for use to obtain sufficient data. Simultaneously, there is an intention to minimize the number of indicators by choosing those that are most informative and universal.

We propose five separate stages of degradation:

0 — *High quality (non-degraded) soils*: soils whose productivity corresponds to their natural fertility; the deviation of productivity from the standard does not exceed 5%.

1 — *Weakly degraded soils*: productivity is 5–25% lower than the standard.

2 — *Moderately degraded soils*: productivity is 25–50% lower than the standard.

3 — *Highly degraded soils*: productivity is 50–70% lower than the standard.

4 — *Very highly degraded soils*: productivity is more than 75% lower than the standard.

The stages of soil degradation are not defined as absolute values of indicators but as relative to some initial (or designated as the initial) state of the soil. The ranges of values used to establish the degradation classes were defined using experimental data and estimates of experts. Special attention was given to the importance of the indicator with respect to the quality and quantity of the primary biological production as well as other ecological functions of the soil.

The degree of correlation between the degradation indicator and ecological parameters with the degradation class reflects both even and uneven scales. Comparisons to an analogous soil in its natural state may be used as a norm for determining the degree of soil degradation. The data obtained from previous investigation can also be used as a datum for determination of the degree of soil degradation, especially for arable lands.

The estimation of soil degradation aims to characterize the current state of the soil, to forecast the paths of its transformation, and to propose the appropriate remedial procedures. Ultimately, the studies of soil degradation are carried out to monitor and assess the anthropogenic impacts on soil and plants.

3. Indicators of soil degradation

One of the major integral indicators of soil degradation is the reduction in quantity and quality of soil production. However, since soil productivity (yield) is a result of many natural, social, and economic factors, the interpretation of the yield indicator is not simple. The lowering of *bonitet* (degree of soil quality) which is usually defined to make economic assessment of the soil, can also indicate the degree of soil degradation but it is difficult to use because of the lack of a single system of classification of soil quality.

3.1. Physical degradation of soils

Disturbance of the soil profile is often characterized by the loss of the humus-rich organogenic layer (A horizon). This loss is caused, in part, by wind and water erosion and by mechanical rupture. Another disturbance is the accumulation of sediments (abiotic bank). The degree of soil degradation depends on the depth of the sedimentation and the properties of this material.

The disruption of soil structure caused by compaction from heavy agricultural machines and other compactive processes can be evaluated by the increase in soil density. Disruption of water movement through the soil may result in saturation and waterlogging in or above the compacted layer. The beginning of this process is depicted by soil water exceeding some critical level. Since the soil saturation process changes not only the hydrological and physical but also chemical soil parameters, redox potential at the depth of 15–20 cm is a recommended indirect indicator.

3.2. Chemical degradation of soils

The mining of soil nutrients by poor agricultural management can drastically decrease natural soil fertility. The primary consequence of this process is the reduction of the nutrients nitrogen, phosphorus, potassium, etc.

Another indicator of soil degradation is the decline of humus content. However, since organic matter content decreases sharply after ploughing a virgin soil and then reaches a new equilibrium point dependent on the amount of organic fertilizer and cropping system, it is rather difficult to specify its standard values.

The content of soluble salts reflects salinization processes. The secondary solonetzization process is shown by the change in exchangeable sodium percentage (ESP). The criterion of soil degradation is the increase in ESP.

The lowering of soil redox potential can lead to a decrease in the productivity of an ecosystem (Snakin, 1992). Thus the change in redox potential is a measure of soil quality due to waterlogging in soils and the resulting anaerobic conditions.

Toxic pollution of soil lowers the quantity and quality of the yield. This kind of degradation is assessed by the index of excess of permissible pollutant concentration (PPC) in soil (the degree of soil pollution). Other standard indicators include degree of permissible radioactive pollution, the index reflecting the complex effects of heavy metals pollution, public health standards, and other legislated standards. The intensity of soil pollution estimated by exceeding PPC should be differentiated in accordance with the toxicity of the analyzed pollutant (toxic group). Since there are no PPC standards for many soil pollutants (e.g. for cadmium and many pesticides in Russia), the PPC index could be used, with some adjustment, for natural waters as compared with the content of pollutants in the soil liquid phase (soil solution).

Phyto- and genotoxicity of soil can also serve as indicators of soil degradation as previously discussed.

Soil acidification processes are indicated by changes of pH value in the soil liquid phase. However, the quantitative assessment of this indicator in the context of soil degradation in not well defined and is still disputable.

3.3. Biological degradation of soils

Living organisms in the soil play the key role in cycling nutrients, in decomposition of organic debris in soils, in detoxification of pollutants, and in suppressing pathogenic microorganisms.

Microbiological tests often provide early diagnosis. They can be used to quickly assess an anomaly in the soil functioning even after a slight change of the environment.

Therefore the content of the active microbial biomass is used as an informative indicator of soil biological function.

Biological pollution of soil can be characterized by the content of pathogenic microorganisms. Soil phytotoxicity is an indicator of biological function. The indicator depends on the total soil pollution and the content of phytopathogenic and toxicogenic microorganisms.

In addition to phytotoxicity, genotoxicity of the soil is an important indicator that reflects the ability of the soil to influence the structural and functional state of the genetic structures of soil biota. Genotoxicity is a measure of the effect of pesticides on the soil biological function and is important with respect to food quality for human consumption.

4. Determination of the degree of soil degradation

4.1. Determination of the degree of physical soil degradation

The physical degradation of soil is determined by the following parameters:

- the depth of the organogenic layer;
- the depth of sedimentation;
- soil density;
- the percentage of subsoil water (saturation), Table 2.

The depth of the organogenic layer (A) is determined in situ. The soil is considered non-degraded if the depth of its layer A is equal to or greater than that of the non-disturbed soil or if it has lost no more than 1/10 of the layer depth as compared to the non-disturbed soil. The soil is considered very highly degraded if it lacks layer A and the degradation process proceeds in the underlying layers.

Table 2
Indicators and criteria of physical degradation of soil

Indicator	The degree of degradation				
	0	1	2	3	4
Thickness of organogenic layer: reduction in terms of the total profile thickness	< 0.1A *	(0.1–0.2)A	(0.3–0.5)A	(0.6–1.0)A	> A
Thickness of abiotic bank (cm)	< 1	1–3	4–10	11–20	> 20
Soil density (multiple increase)	< 1.10 times higher	1.10–1.20 times	1.21–1.30	1.31–1.40	> 1.40 times
Subsoil water level (excess of critical level, %)	below critical level	0–15	16–30	31–50	> 50

* All types of organogenic layers.

The depth of sedimentation is determined in situ. Sedimentation in the non-degraded soil is less than 1 cm deep, and in very highly degraded soil is more than 20 cm (i.e. close to the depth of the arable layer).

The density of soil is determined by the method of cutting cylinders (Agrophysical Methods, Anonymous, 1966). The increase in density for non-degraded soil is less than 1.1 times greater than the norm, and in very highly degraded soil is more than 1.4 times greater.

The subsoil water level is evaluated in relation to some critical index. The critical level is determined as the sum of major root-inhabited depth and maximum level of capillary water (Zaidelman, 1987). The soil is non-degraded if subsoil water does not reach the critical level. If subsoil water exceeds the critical level by 15% the soil is considered weakly degraded and if the critical level is exceeded by over 50%, the soil is considered very highly degraded.

4.2. Determination of the degree of chemical soil degradation

Change in the following parameters indicates chemical soil degradation:

- the content of nutrient elements (NPK);
- the content of readily soluble salts;
- the content of exchangeable sodium;
- the value of the redox potential;
- the degree of soil pollution (Table 2).

The content of nutrient elements is defined by standard methods. The degree of soil degradation is evaluated by the amount of major nutrients of the soil in question as compared to non-disturbed soils. If the content of nutrient elements in the soil in question is less than 1.2 times lower than the non-disturbed soil, it is non-degraded. If it is more than 5 times lower, the soil is considered very highly degraded.

The content of readily soluble salts is evaluated by standard methods. The soil is considered non-degraded if the content of readily soluble salts does not exceed 0.10% and very highly degraded if the content is more than 0.8%.

The content of ESP is also determined by standard methods. The accumulation of ESP of 5% or less is characteristic of non-degraded soils. The secondary accumulation of ESP of more than 50% reflects a very highly degraded soil.

The redox potential is evaluated in situ at a depth of 15–20 cm (Snakin et al., 1991). A lowering of redox potential by 50–100 mV compered to the non-disturbed soil characterizes a non-degraded soil. A decrease of 400 mV reflects a very highly degraded soil [1].

The degree of soil pollution is determined as the ratio of the content of soil pollutants to the PPC value or other accepted standard. The content of soil pollutants is calculated

[1] Here it is important to notice that non-disturbed (natural) soils are characterized by a high degree of heterogeneity of soil redox potential. Thus, its value on the surface of soil particles can be 200–400 mV higher than inside them. During soil degradation one can observe leveling of the soil redox potential value.

by standard methods (Goncharuk and Sydorenko, 1986; Methodic Guidelines, Anonymous, 1992).

In the absence of PPC values for soils, indicators for water are suggested. For these indicators, concentration of pollutants in soil solution is determined using physical and chemical methods (Antipov-Karatajev, 1968).

The indicator of soil pollution is differentiated according to the toxic group of the analyzed substances. For instance, in the non-degraded soil this indicator is not higher than 1 regardless of the toxic group, for the highly degraded soils this figure will be 5 times higher for the first toxic group, 20 times higher for the second, and 100 times higher for the third class.

4.3. Determination of the degree of biological soil degradation

Biological soil degradation is evaluated by:

- the content of active microbial biomass,
- phyto- and genotoxicity, and
- the number of pathogenic microorganisms (Table 4).

The content of the active microbial biomass is determined by the methods reported by Anderson and Domsch (1978). The degree of soil degradation is evaluated by the decrease of the content of active microbial biomass relative to a standard. The non-degraded soil has a less than five-fold decrease and the very highly degraded soil has a more than 100-fold decrease in biomass.

Soil phytotoxicity is estimated by the method of ''soil plates'', that is, the reduction of the number and height of seedlings in relation to non-disturbed soil (Yevdokimova et al., 1984; Zvyagintzev et al., 1989). The decrease of germinating capacity and length of the seedlings in non-degraded soil is less than 1.1 times lower than in non-disturbed soil, and in very highly degraded soil the reduction is 2 times that of non-disturbed soil.

Genotoxicity of soil is appraised by the increase of the number of gene mutations in comparison with non-disturbed sites. Genotoxicity is evaluated in short-term tests (Fonstein et al., 1977; Anonymous, 1989). In non-degraded soil the number of mutations is up to 2 times higher than in standard (non-disturbed) soil and in very highly degraded soil mutations are more than 1000 times higher than the standard.

The number of pathogenic microorganisms contained in 1 gram of soil is estimated by standard methods (Mishustin et al., 1979). The standard is 1000/g of soil.

4.4. Dynamics of soil degradation

Specific measures for soil remediation require knowledge on the intensity and trend of the degradation process. The decline of soil properties in a unit of time is one measure of the rate of degradation. In order to unify all of the indicators, the rate of degradation could be expressed as the rate of decline from one degradation degree to another. However, as the calculation is made mainly with uneven scales (Tables 2–4), the calculated rate will be different for each stage of degradation. Thus it is more correct to determine the degradation rate by the length of the degradation period. Some hypothetical time (in years) during which the analyzed soil transformations from 0 to the 4th stage of degradation for each indicator is defined as the degradation period.

Table 3
Indicators and criteria of chemical degradation of soil

Indicator	The degree of degradation				
	0	1	2	3	4
Content of main nutrient elements (multiple decrease)	< 1.2	1.2–1.5	1.6–2.0	2.1–5	> 5
Content of readily soluble salts resulting from secondary salinization (increase by %)	< 0.10	0.11–0.20	0.21–0.40	0.41–0.80	> 0.81
Content of exchangable sodium resulting from secondary solonetzization (increase by % of CEC)	< 5	5–10	11–25	26–50	> 50
Soil redox potential (decrease, mV)	< 50	50–100	101–200	201–400	> 400
The degree of pollution (multiple excess of the toxicant PPC value)					
I toxic group	< 1	1–2.0	2.1–3.0	3.1–5	> 5
II toxic group	< 1	1–3.0	3.1–5.0	5.1–10	> 20
III toxic group	< 1	1–5.0	5.1–20	21–100	> 100

Therefore the degradation period is the reciprocal of degradation rate.

The degradation period is calculated by the formula:

$$T_d = X_{max} * T/(X_c - X_p),$$

where: T_d is the degradation period (years); X_{max} is the indicator value of the 4th stage of degradation; X_p is the indicator value at previous survey; X_c is indicator value of current survey; and T is the period between the two surveys (years).

The degradation period is evaluated by the data collected during the several years of monitoring. Its value can be negative which indicates improvement of the soil quality for the specific parameter. Therefore, based on the degradation period, it is possible to

Table 4
Indicators and criteria of biological degradation of soil

Indicator	The degree of degradation				
	0	1	2	3	4
Content of active microbial biomass (multiple decrease)	< 5	5–10	11–50	52–100	> 100
The amount of pathogenic microorganisms in 1 g of soil	$< 10^3$	$10^3–10^4$	$10^4–10^5$	$10^5–10^6$	$> 10^6$
Phytotoxity (multiple reduction of the number of seedlings, the degree of their growth suppression)	< 1.1	1.1–1.20	< 1.21–1.4	1.41–2.0	> 2.0
Genotoxity (multiple increase in the number of mutations as compared with the standard)	< 2	2–10	11–100	101–1000	> 1000

forecast, approximately, the short-term changes in soil qualities, assuming that the direction and the rate of the current processes in soil are constant. For instance, if the soil degradation is estimated as the 3rd state of degradation for the limiting factor (the indicator with the highest value), and the degradation period is 10 years, the soil is likely to transform from the highly degraded state to the very highly degraded state during a period of about 2 years. This rate of transformation requires immediate remedial measures.

Together with the limiting indicator, the analysis of degradation dynamics should be conducted using the other indicators, since the limiting factor can change over time.

The final assessment of the degree of degradation should include the degradation value, the degradation period (as its index) and the indicator based on which value is calculated. Furthermore, it is necessary to indicate the degradation value and period in terms of the indicator characterized by maximum degradation rate (i.e. minimum degradation period).

4.5. The final assessment of the degree of degradation

The degree of degradation can be assessed by any of the proposed indicators. In the case of two or more degradation factors, the evaluation is carried out by the indicator showing the maximum degree.

While making the final assessment of soil degradation, the process characterized by the maximum degradation stage (and its rate index) as well as that of maximum degradation rate and the degree of degradation should be indicated.

When the value of the index of biological degradation rate is high, it is necessary to state the indicators used, since they (excluding the number of pathogenic microorganisms, Table 4) are mutually dependent and reflect the cumulative action of a number of factors.

Two examples of the final estimates of degradation follow:

(a) 3^{20} (physical density); 2^{5} (chemical pollution).

This is a highly degraded soil with a tendency to increasing compaction. The degradation period for density is 20 years. With respect to chemical pollution, the soil is moderately degraded; however, the chemical degradation progresses so quickly that in 1–3 years the degradation for chemical and physical degradation will be the same. Therefore, a set of remedial measures to address the problem of toxic substances should be developed immediately.

(b) 3^{-5} (chemical pollution); 2^{5} (physical density)

The soil is highly degraded due to chemical pollution and moderately degraded due to compaction. However, the degradation period for chemical pollution is −5 years, which indicates an improvement during the last monitoring period. Therefore, remedial measures should address physical degradation processes of compaction.

5. Mapping of degraded soils

Maps of degraded soils spatially depict quantitative and qualitative changes in soil quality resulting from anthropogenic use. These maps are most useful when overlain on soil maps of appropriate scales.

Depending on the purposes of the studies, stage of degradation, and the territorial coverage of the maps, maps of soil degradation are divided into several types:

- detailed maps, scale = 1:200–1:2000
- large-scale maps, scale = 1:5000–1:50 000
- medium-scale maps, scale = 1:100 000–1:200 000
- small-scale maps, scale = 1:300 000–1:1 000 000

The content of the maps is determined by the types of soil degradation prevailing in the studied area.

The maps of soil degradation are compiled in combination with soil surveying, according to Anonymous (1973). Remote sensing (RS) and field and laboratory research data make it possible to specify, along with soil units, the outlines of degraded soils without the more rigorous on-site sampling of indicators.

With qualitative 2–3-year-long records it will be sufficient to revise and refine the outlines according to RS data and the collection of selected soil samples for laboratory testing. The selection and preparation of soil samples are carried out by standard methods. Considering the annual variation of the soil state indicators, it is preferable to collect the information at the beginning of the vegetation season, since this period is most vulnerable and determines the future development of the ecosystem.

6. Summary

Based on the analysis of current legal rules and documents, literary sources and original data, a set of representative indicators has been developed, which makes it possible to assess physical, chemical and biological degradation of soil adequately.

The indicators are scored on a 5-point scale. When making a final estimate of soil degradation it is proposed to ad the ''rate index'' (the degradation period). The article gives some suggestions concerning the methods for defining the soil degradation indicators and explains some special terms used in the work.

7. Glossary

Abiotic (sedimentation) bank — in the context: the upper layer of the soil profile which does not result from soil formation and is less fertile than the underlying organogenic layer.

Content of active microbial mass — the biomass of microorganisms living in soil.

Criterion of degradation — criterion, on the basis of which the degree of degradation is assessed (absolute decrease in soil degradation indicator, multiple increase, etc.).

Critical level of subsoil water — in the given work: the subsoil water level which does not cause anaerobic processes in the rooted layer.

Degradation period — hypothetical time (years) in which the analyzed soil transforms from 0 to 4 degradation degree (in terms of the considered indicator).

Degraded soils — soils in which steady negative processes, both anthropogenic and natural, have led to the lowering of the quantity and quality of soil production with the correspondent increase in expenditure for remediation.

Degree of soil degradation — the interval between the values of degradation indicator in which some fixed lowering of soil productivity is registered. In order to compare the different types of degradation the indicator is defined by a graduated scale.

Degree of soil pollution — impoverishment of nutrient elements caused by the irrational use of soil.

Genotoxicity of soil — the capability of soil to influence the structural and functional state of genetic organs of soil biota.

Indicator of soil degradation — soil parameter or attribute reflecting the influence on the soil of adverse factors causing the lowering of its fertility or worsening of its production quality.

Non-disturbed soil — soil whose composition and properties coincide with its natural state.

Pathogenic microorganisms — microorganisms causing sickness of animals and people.

Phytotoxicity of soil — the capability of soil to suppress the growth and development of higher plants.

Rate of soil degradation — the change of the value of the degradation indicator in a unit of time.

Secondary salinization of soil — accumulation of readily soluble salts in soil caused by their entering into soil with mineralized irrigating and subsoil waters.

Soil degradation — worsening of the parameters of soil considered as the habitat of biota, caused by natural and anthropogenic factors.

Soil density — the ratio of soil dry mass, taken in its natural consistency, to its volume.

Soil organogenic layer — the upper layer of the soil profile formed by activity of biota and containing the organic matter decomposed to a variable extent (humus-accumulative, soddy, turfy).

Soil pollutant — a substance accumulated in soil in quantities which can adversely influence the characteristics and fertility of soil or the quality of agricultural production.

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