Information standards of contemporary soil evolution in the south of Western Siberia

I V Mikheeva

Institute of Soil Science and Agrochemistry, Siberian Branch, Russian Academy of Sciences, 8/2, Avenue of Academician Lavrentiev, Novosibirsk 630090, Russian Federation

E-mail: mikheeva@issa-siberia.ru, pulya80@ngs.ru

Abstract. In this paper it was offered to use probabilistic and information indicators to assess the soil conditions and changes under contemporary soil evolution (CSE) processes caused by anthropogenic usage and climate changes. It is necessary because the location of soil monitoring points in space does not coincide at different times, especially for legacy data. As a model of the soil state, a set of probabilistic-statistical distributions of n soil properties in k soil horizons within the studied object was introduced. The information entropy values of soil properties were used to assess the condition, and the information divergence was used to assess alterations of soils. These characteristics allow estimating the degree of influence of soil-forming factors and anthropogenic impacts on the probabilistic structure of the values of soil properties and its stability. Case studies were conducted on a large territory of the south of Western Siberia. Information assessment of soil changes during the last part of twentieth century was executed on the base of legacy data. The received models and estimates are information standards for comparison with the current and future results in the explored and neighbouring territories. Information characteristics of texture, SOM and pH indicate CSE, which is important for both agriculture and the global carbon cycle.

1. Introduction

Soils are central to all terrestrial ecosystems, so information on soil cover and its condition is an important component for agricultural and environmental management. Land degradation under intensive anthropogenic influence is a widespread phenomenon in different countries. Therefore, the scientific community faces important problems – the study, generalization and understanding of this negative process. Degradation of soils leads to disruption of soil functions in the biosphere at the local, regional and global levels of consideration that puts humanity in front of challenges in sustainable soil management [1]. Global climate changes lead to ambiguous regional climatic changes in different parts of the planet. The realization of integrated quantitative estimates demands a more differential approach to local changes to avoid gross mistakes owing to overestimation or underestimation of the contribution of various natural objects to global changes. It is important to authentically assess the risks of desertification of steppe ecosystems on reliable information about the dynamics of their parameters, according to land use and conservation. This also concerns the steppe ecosystems of internal Eurasia, like the territories located in the south of Western Siberia in the adjacent territory of Russia and Kazakhstan, which was the object of the investigation.
For improving economic and environmental activities, it is necessary to have the most objective and exact knowledge of soils properties and their alterations. The formation of databases of attributive data on soil properties at different points in time is a very important stage for this purpose. For a statistically proved quantitative estimation of soil transformations, field investigation should overcome the problem of high natural soil variability. Large-scale territorial soil studies were carried out in different years on large areas of the agricultural zone of the Russian Federation and the countries of the former USSR. Unfortunately, not all the attributive data on the soil cover obtained in these studies were entered into computer databases, although they are a national data heritage [2]. The organization of such databases for all territories is important because these data are a reference point for assessing soil changes under the influence of anthropogenic activities and climatic and ecosystem changes now and in the future. The data continuity causes the need for the development of information methods for analytical mathematical assessment of changes in the state of soils in order to identify trends in the development of contemporary processes in the soil cover.

The purpose of the study was to quantify information differences in the expression of soil properties of the most common taxonomic groups in southern Western Siberia using attributive geographical databases on legacy data on soil properties at different time. Besides, information indicators were used to carry out informational assessment of the intensity of properties formation and transformation in the soil profile under the influence of modern anthropogenic and climatic changes.

2. Materials and methods

Previous studies have shown that the structure of soil properties variability under the influence of natural and anthropogenic processes is being rebuilt, which leads to a change in the functions of their probabilistic distributions [3]. The analysis of the variability of the natural object properties can be carried out by identifying its probabilistic-statistical model, characterized by a certain type and parameters of the mathematical function of the probabilistic distribution, or the probabilistic-statistical distribution (PSD). The PSD is the most accurate and complete information (statistical) standard of the studied property of the object. For a scalar holistic assessment of variability and its changes, information characteristics calculated on the basis of the PSD were used. Information entropy is used for information characteristic of the values uncertainty of the soil object properties as an information measure of its variability, and information divergence [4, 5] is used to assess the differences in the PSD. To identify the probabilistic distribution of soil property values and calculate information characteristics, such as information entropy and divergence, free softwares – ISW (http://www.ami.nstu.ru/~headrd/) and R (https://www.r-project.org/) were used. The ISW program (Statistical Analysis of Interval Observations of Univariate Continuous Random Variables) serves the purpose of identifying the closest probabilistic distribution corresponding to the available discrete data [6].

2.1. Study area. Initial data

Outdated data from soil studies by standard methods for large-scale mapping and monitoring of soils and laboratory methods of soil properties determination were used [7]. The article presents the results of information assessment of soil properties of a significant territory of the south of Western Siberia, located at 53° 15' N – 53° 47' N; 75° 05' E – 77° 01' E. In geomorphologic terms, the territory is the central and eastern part of the Priirtyshsky uval (the endemic name of this geomorphologic region). It is composed of sandy rocks and sandy loam texture which are replaced by loams, and then clays on the slope in the direction to the East. The climate of the area is sharply continental with dry hot summers and cold low-snow winters. It is characterized by the dryness of the spring and summer period, the maximum precipitation usually falls in the middle of summer. The average annual amount of precipitation equals 275.5 mm, sometimes up to 400 mm. The mean annual moisture coefficient is 0.4–0.6, which is typical for the droughty steppe. The main area is dry steppes with multigrasses and cereals, mostly arable.

The soils are mainly Chernozems Southern (Russian Soil Classification [8]; Haplic Chernozems Pachic World Reference Base [9]), with not big areas of solonetzic and saline soil complexes. The
principal structure of the soil profile of Chernozems Southern [10] is shown in figure 1. In the studied territory, Chernozems Southern of sandy loamy and loamy texture are the most widespread soils.

Figure 1. Structure of the soil profile of Chernozems Southern.

Therefore, in this article, the conditions of these soils were estimated at the beginning of sixties (1963) and at the end eightieths (1989). The quantitative model of soil condition represents a set of probabilistic-statistical distributions (PSD) of soil properties within the studied object. The article analyzes and identifies probabilistic distributions of the clay and humus content and pH in sandy loamy and loamy Chernozems Southern in soil layers of 0–20, 20–30, 30–50 and 50–100 cm at the beginning and the end of the studied period.

The initial data were the materials of large-scale (1:25,000) soil investigations conducted in the studied territory at different times by standard techniques [11, 12]. All the data received for this territory served to create a data bank. The construction of the database, grouping and analysis of data were carried out using the statistical analysis methods. Each information line in the databases is characteristic of such soil parameters as layer depth, humus content, pH, texture fractions content, and other. The first obligatory stage of the data processing was grouping these data according to soil-genetic principle. Each group refers to one point in time and one soil variety; namely, given data belong to soil of the same taxonomical type and texture class. The volume of the received statistical samples was n = 30–130, depending on the abundance of a particular soil group and the opportunities of conducting investigations. The reliability of this grouping was proved by the unimodality of the received statistical distributions and the high level of significance. There were enough of them to carry out a probabilistic analysis.

2.2. Construction of probability distribution models. Probabilistic and information indicators

The construction of a probabilistic distribution model in practice occurs by identifying the closest known probabilistic distributions. Identification of the distribution consists of a number of stages: several statistical distributions that are most suitable for the investigated data are selected; the parameters of the selected distributions are estimated from sample data; for each distribution function, consent hypothesis of the selected and theoretical functions is tested against the selected criteria; based on the set of statistical criteria, the theoretical statistical distribution that is closest to approximate data sample is
chosen [6]. Different criteria use different measures of distributions proximity, and accepting the hypothesis of agreement on one criterion does not mean that the distributions will be close in accordance with other criteria. Therefore, this work uses a number of statistical criteria based on various proximity measures. This allows to make a decision about their totality. In the case of small samples (n ≈ 50 and n < 50), the non-parametric criteria of Kolmogorov, Smirnov and 2 modifications of the Mizes criterion were used.

Visual analysis of PSD alterations is very useful for assessing changes in the probability structure of soil properties in soil objects during anthropogenic or natural processes. But it is important to have some numerical convoluted assessments of distinction of these functions at different times or under various external conditions. Taking into account the above, probabilistic and information indicators were introduced to characterize the soil status and its alterations [13]. For soil status, they are an array of the PDF of soil properties, which could be defined from the list of usable functions by applying a statistical procedure to factual data. Such probability distribution functions as probabilistic-statistical models of soil properties were considered and used to calculate statistical (information) entropy and information divergence. Moreover, it seems that the values of these indicators are an instrument for assessing and modeling of the soil evolution (table 1).

**Table 1.** Probabilistic and information indicators of status and changes of soil objects.

| Category                          | Indicator                              | Calculation                                                                 |
|-----------------------------------|----------------------------------------|----------------------------------------------------------------------------|
| State of soil at time points t1,  | Probability-statistical distributions  | \( W_{t1}(x) = W_{t1}(x, \theta_{0t1}, \theta_{1t1}, \theta_{2t1}, \theta_{3t1}) \)  |
| time points t1, t2                | soil property at time points t1, t2    | \( W_{t2}(x) = W_{t2}(x, \theta_{0t2}, \theta_{1t2}, \theta_{2t2}, \theta_{3t2}) \) |
|                                   | Information (statistical entropy), h at | \( h_{t1} = -k \int_{A} W_{t1}(x) \ln W_{t1}(x) dx + h_{0} \)            |
|                                   | t1, t2                                 | \( h_{t2} = -k \int_{A} W_{t2}(x) \ln W_{t2}(x) dx + h_{0} \)            |
| Change of soil during period      | Increment of informational entropy, Δh | \( \Delta h = h_{t2} - h_{t1} \)                                          |
| Δt = (t2 - t1)                    | during period Δt = (t2 - t1)            |                                                                            |
| Informational divergence          | d = ΔW(x) during period Δt = (t2 - t1) | \( d = \int_{A} \frac{(W_{t2}(x) - W_{t1}(x)) \ln \left( \frac{W_{t1}(x)}{W_{t2}(x)} \right)}{W_{t2}(x)} dx \) |

3. Results and discussion

The values of soil properties in each soil horizon at any point in space are the cumulative effect of various factors and processes at different scales, which is the reason for the multi-scale variability of the soil, which appears differently at distances from several centimeters to tens and thousands of meters and kilometres [14]. The variability of soil properties at the field level is defined by the mutual effect of elementary soil and elementary landscape processes, micro- or meso- heterogeneity of soil formation factors, the difference between the anthropogenic factor and the reaction of soil to it. Indeed, there is stochasticity at each separate point of the soil, but the soil system as a whole is rigidly determined by the result of the sum of many factors that determine soil properties. The integrity of this system is given by the presence of specific and deterministic external conditions in which the elements of the system exist. It is necessary to consider at least two levels of organization of such system – the macro state and microstate. The macro state is the condition of the soil cover of the soil object as a whole, microstate is the condition of individual soil profiles or pedons. The macro state is defined by the probabilities of their microstates. Therefore, it is logical to use the probability distribution functions (PDF) of properties that reflect two structural levels – the internal structure of microstates with different display of soil properties and the deterministic macro states of the system. As a consequence, it characterizes the holistic property of the system. The transformation of the macro state of the soil system arises from a set of individualistic changes in microstates; the quantitative characteristic of which is a change of the PDF.
3.1. Clay (particles with \(d < 0.001\)) content in the soil profile of Chernozems Southern

The granulometric structure is one of the lithogenic properties of soils. It is considered to be one of the most conservative properties of soils with a rather long time of native changes – \(10^2 - 10^4\) years. The genetic aspect of the modern soils development is estimated by the difference in the content of granulometric fractions in soil horizons, which vary very much in space [15]. Various variants of changing the probability distribution functions and information characteristics of the content of granulometric fractions in the soil profile are possible due to the processes of sedimentation, rock destruction and soil formation, as well as geological and contemporary deflation [16]. Changes in the solid phase of the soil indicate soil evolution processes, so alterations of the granulometric composition, especially the content of fine particles, are very important for assessing the contemporary soil evolution (CSE). Modern changes in the PSD of the clay content are mostly associated with the arable use of these soils. Ploughing leads to mixing of the top soil horizon with the below layer and homogenizes the top layer. Intensive cropping provokes contemporary soil-forming mineralogical processes. Mutual effect of all reasons is reflected by the PSD of the clay content (figure 2).

![Probability distributions of the clay content in Chernozems Southern in 1963 and 1989](image)

The reached probability \(p\) according to the statistics of nonparametric criteria for identifying the closest pdf functions is rather high in all layers of both sandy loamy and loamy soils. This means that the set of pdf functions chosen for modelling soil variability is adequate to the soil data. The peculiarity of the change in the PSD of the clay content in Chernozems during three decades of intensive arable use lies in a significant increase in this indicator in the layer of 0–20 cm of both sandy loamy and loamy varieties. This phenomenon is associated with the mechanical homogenizing impact on the upper soil horizon during their arable use, the involvement in the arable layer of soil material from the subsurface illuvial horizon, which naturally contains more clay.

In other layers of sandy loamy soils, changes in the PSD consist in some frequency rearrangement of the values that does not lead to a shift in the distribution function. But this alteration of the PSD of 30–50 cm is expressed significantly, which identifies an increase in the clay content in this layer of sandy loamy soils. In the loamy variety, there is a tendency to increase the clay content in the layer of 20–30 cm, which is expressed by a shift of the PSD. The tendency to increase the clay content, which is expressed in an increase in the probabilities of higher values of this indicator within the continued range of variation, is possibly associated with the intensification of intra-profile movement of clay fraction particles due to an increase in the amount of moisture entering the arable soil for a long time. This is also indicated by the difference in the expression of this change within the textural soil varieties, which is most likely caused by differences in moisture conductivity. However, the assumptions made require a more detailed investigation of internal soil processes, which was not the purpose of this study. Another
visually noted feature of the PSD changes is a slight decrease in the scattering of clay content values, which will then be estimated using the value of information entropy.

3.2. *Humus content in the soil profile of Chernozems Southern*

The group of processes of receipt, transformation and mineralization of organic substances in the soil are one of the main groups of soil processes. They define both the soil profile formation, and the functioning and fertility of soils. Therefore, the content of humus is an important factor in the quality standard of soils, and is one of the obligatory indicators for their monitoring. Moreover, the great interest represents the change in the soil organic matter content because this soil parameter is connected with the regional and global carbon cycle [17].

Due to regional features, Chernozems Southern in Western Siberia are usually low-power, that means organic substance mostly allocates in the top part of the profile, and in the lower layers - the content of humus is small. Basic types of the PSD of the humus content in soil layers are Ln-normal, Maximum values – the distributions, which are characterized by an essential right asymmetry and a more or less wide center. Another group of distributions: Normal, Double-side Exponential (DE), Logistic, Laplace, Cauchy – are symmetric functions, with various degrees of expressiveness of the central part – from a wide central part in the normal distribution to a very narrow center in the Laplace and Cauchy's distributions (figure 3).

![Figure 3](image-url)

*Figure 3.* Probability distributions of the humus content in Chernozems Southern in 1963 and 1989: left – sandy loamy; right – loamy.

The happened transformation of the humus content of 0–20 cm in the PSD characterizes the tendency to decrease the humus content in the top soil layer as a whole in the soil cover presented by sandy loamy Chernozems. It transformed from Ln-normal in 63rd to Double Exponential in 89th year. Changes of the PSD of the humus content in loamy Chernozems are similar, but they are expressed to a lesser extent. Here, the type of the PSD in 89th year remained the same as it was in 63rd – Ln-normal, the changes concerned only the parameters of the function. Indeed, in arable agricultural use, there is a decrease in the humus content in the soil surface horizon, which is a natural consequence of changes in its physical state and intensive removal of substances with a harvest.

A graphical analysis and comparison of the PSD of the humus content in 63rd and 89th showed the positive tendency, consisting in a slight increase in the humus content in layers of 20–30, 30–50 and 50–100 cm (figure 3). Apparently, the reason was the mitigation of climatic conditions in the territory, at least temporarily, within the optimum periods of climatic recurrence (more heat and precipitations), which promotes the best conditions of soil formation, from the point of view of energy [18]. There are
the best conditions for growth of vegetation, development and depth of root systems of crops, activities of microorganisms and their penetrations are deeper into the soil; it promotes an increase of the SOM content. This growth is not big, but the alterations of the PSD of the humus content in the soil profile are obviously expressed.

In a layer of 30–50 cm, the transformation of the PSD of the humus content during a thirty-year period is characterized not only by a reorganization of the probabilities of values, as in the overlying layers. It is very important that there is an essential change in the intervals of variation, both in sandy loam and in loamy soil versions, which is expressed in an essential increase in the lower limits of the variation intervals. Despite this, the type of the PSD in the sandy loamy soil does not change, it remains the Maximum value with a considerable change in the parameters of the function. In the loamy soil version, despite less expressed changes, the PSD type is transformed from a symmetric function of Laplace to distribution with a right asymmetry – the Maximum value.

3.3. pH in the soil profile of Chernozems Southern

One of the most important characteristics of the soil is its acidity (pH). It shows the concentration of hydrogen ions that determine the acid-alkaline balance of the soil. Figure 4 shows that in the upper part of the profile, the variation intervals are entirely located in the range of values characterizing the neutral reaction of the medium.

However, in soils of different granulometric composition, the types of distributions are different. Moreover, in soils of both varieties, they change significantly in the soil layers down the profile, naturally, but not equally shifting towards a more alkaline reaction of the medium. For more than a quarter of a century, both the types and parameters of probabilistic pH distributions have changed, especially in deep soil layers.

3.4. Information indicators of alterations of probabilistic-statistical distributions of soil properties in the soil profile of Chernozems Southern

The above-described visual tendencies in the change in the PSD can be quantitatively estimated by such information indicators as increment of statistical entropy and information divergence. The results of calculations of these characteristics are visualized in figures 5–6.

During the studied thirty-year period, the statistical entropy of the humus content decreased: in general, in the profile of sandy loam soil for 63%, and in loamy soil for 66% of the reference value. This means that the condition of Chernozems has significantly changed, in spite of the fact that the absolute values of the humus content practically did not go beyond the variation intervals at the beginning of the
studied period. A significant decrease in statistical entropy testifies a decrease in the variety of micro conditions in the soil.

In layers of 0–20 cm and 20–30 cm, changes in the PSD of pH are minimal (information divergence is less than 1.0), but are characterized by a significant decrease in entropy (figure 5). In the layer of 30–50 cm and to a greater extent in the layer of 50–100 cm, a shift of the PSD towards a more alkaline reaction of the medium was observed. The information divergence is high and is approximately 4.5. At the same time, the pH entropy decreases in 30–50 cm, but less than in the top layer, which is more pronounced in sandy loamy soils. In the 50–100 cm layer, the pH entropy is practically stable.

Figure 5. Relative (%) increment of entropy properties of Chernozems Southern: left – sandy loam texture; right – loamy.

A quantitative assessment of the transformation of probabilistic distributions is given by the value of information divergence (figure 6). This value does not depend on the dimension of the property, so it makes it possible to assess the intensity of changing different soil properties. Information changes in the clay content are maximal in the top layer, the divergence is more than 5.0. Below it smoothly decreases, and in the layer of 50–100 cm it is close to zero. But in sandy loamy soils, there is a second maximum of divergence in the layer of 30–50 cm, equal to about 3.0. The entropy of the clay content varies slightly during this period. On the contrary, information changes in the humus content in the top layer are small (<< 1.0), they are maximal in the layer of 30–50 cm (4.5–2.5), the entropy of the humus content changes significantly, and this difference is rather various in different layers. Information alterations of pH are insignificant in the upper horizon, and below become bigger with a maximum of 50–100 cm. Change in the pH entropy, on the contrary, is very strong in the top part of the soil: its values decrease below it and become zero in the deep horizon. Thus, information changes in different soil properties are different, they depend on the physical nature of the properties, soil-forming factors and anthropogenic impact.
4. Conclusions
Accurate knowledge of the condition of soils and their changes is necessary to solve important state problems, including food and ecological security in Russia and neighboring countries. For this purpose, it is essential to carry out repeated monitoring researches of the soils of agricultural territories. It is suggested to consider probabilistic and information indicators for assessing soil conditions and soil alterations. These are probabilistic-statistical distributions (PSD) of soil properties, their information entropy and divergence. The probabilistic-statistical distribution is the best mathematical function among probability distributions (according to a set of parametrical and non-parametrical statistical criteria) with parameters that supply excellent goodness with the histogram of factual data on soil properties obtained as a result of soil monitoring investigations. Our experience shows that when identifying probability-statistical distributions on the basis of legacy and new data from large-scale soil investigations, it is preferable to use a number of non-parametric criteria - Kolmogorov's, Smirnov's, Mises's.

The case study was conducted on a large territory of the South of Western Siberia, situated on the Priirtyshsky uval. It reveals that the contemporary soil evolution occurs under the influence of climate changes, natural processes and anthropogenic impact and leads to changes in the PSD of soil properties. Analysis of the PSD transformation of the soil organic matter (SOM) content (namely, humus content) in Haplic Chernozems Pachic in the studied territory over a 30-year period revealed a decrease in the SOM content in the top layer and its increase in the underlying soil layers. The transformation of the PSD of the SOM content is followed by a very essential decrease in the statistical entropy up to 60% of the initial value, which indicates a significant change in the condition of Chernozems, in spite of the fact that the soils have not changed taxonomically. Analysis of information divergence showed that the revealed tendencies in the sandy loam version of the soil are more pronounced than in loamy soils. Moreover, the greatest transformation of the PSD of the SOM content during the studied period occurred in the layer of 30–50 cm due to an increase in the low boundary of the variation interval. The revealed transformations of the PSD are interpreted as "process-result" of the interaction of soil forming, landscape and anthropogenic processes. They are important for assessing soil changes throughout the study area and are useful for investigating individual probable "processes-mechanisms" that realize contemporary soil evolution.

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