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Probabilistic models of spatial fluctuations of edaphic properties in native soils in steppe zone of Western Siberia

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Abstract

Fluctuations of properties in an individuum (pedon) of a chestnut soil under different use (virgin soil, unirrigated arable soil, and irrigated arable soil) were quantitatively evaluated. It was shown that these fluctuations make up to 20-40% of the property changeability in an elementary soil area. Probability distribution functions (pdf) with high p-values were considered as probabilistic models of soil properties. Analysis of pdf regularities gives clear and stable information about difference of soil properties in the soil volumes in space in soil horizons under agricultural impacts. Information divergences quantify these regularities. Analysis of entropy value highlighted the main tendency of agricultural impact – the tendency of outstanding decreasing quantity of various microconditions of soil, which is important change of edaphic factor.

Keywords: soil, properties, fluctuation, pdf, information divergence, and statistical entropy

Introduction

The state of the art in theoretical and applied soil science requires more specific mathematical description of soil properties and their relationships with soil-forming factors, as well as the reliable evaluation and prognosis of changes induced by current anthropogenic and natural processes. The further development calls for the expansion of probabilistic thought and the mathematical specification of basic concepts, including the concept of "soil properties." It is known that soil properties show quantitative diversity even within a soil profile and that soil properties are related to soil-forming factors by probabilistic rather than functional relationships.

Multiple factors and the cumulative action of processes on different levels of organization determine not only the average values but also the oscillation of the property values; therefore, changeability should be considered as an intrinsic systemic property of the soil. On the other hand, changeability determines the quantitative measure of properties and, hence, affects the practical and economic importance of the soil, so it should be considered as biophysical attribute of the soil quality. Moreover soil changeability has very important ecological role as edaphic factor for all soil organisms, not only plants.

We have proposed considering three categories of the spatial changeability of soil properties using the concept of nesting (Figure 1): heterogeneity for significant changes in soil-forming factors, variability for their insignificant changes, and fluctuation for leveled soil-forming factors. All three changeability categories are observed at different organization levels of the soil and soil cover. In our opinion, the quantitative evaluation of relationships between different changeability categories of soil properties is also necessary for assessing the stability of the soil cover as a hierarchical system (Mikheeva, 2005).

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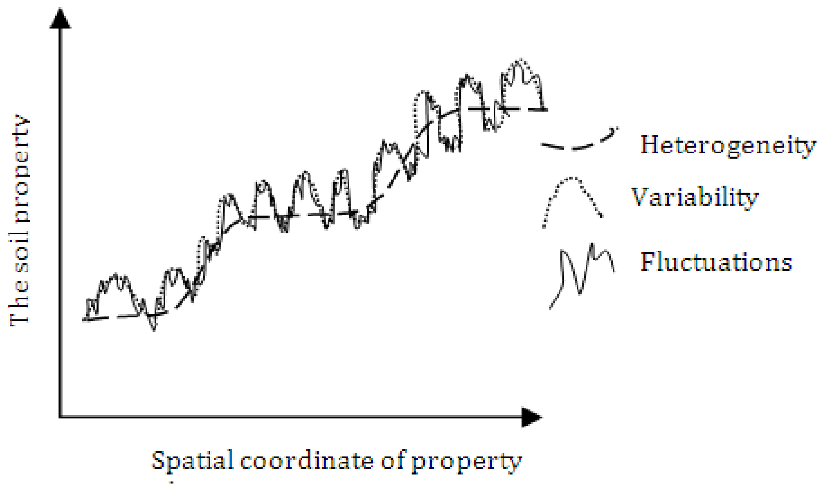

Figure 1. Categories of spatial changeability of soil properies

The variation of soil properties appears in the shortest distances. Process of soil formation, even in absolutely leveled conditions gives these fluctuations. It is known that many processes proceeding in soils, such as formation of micro and a macro- pores, structural units, cracks and microcracks and others, are stochastic by their nature. Even the smallest representative volume of the soil represents a statistical mix of the soil particles forming complicated system of channels and surfaces. At each moment the internal state of this volume under the same repeated impact has the difference. These distinctions lead to local macroscopic effects in space - to distinctions of humidity and fluctuations of the content of substances and other characteristics of the soil.

Thus the aggregate structure of the soil has impact on a property variation in big degree, that means transition of our consideration to the lower hierarchy level. This intrinsic soil fluctuation is amplified by small fluctuations of soil forming factors, especially by variation of granulometric structure and vegetation. These factors of soil formation start acting at the lower level of hierarchy, for example, not vegetation – but separate plants, not granulometric structure – but existence of separate stones or deposits near plants at a deflation.

All these reasons, finally, lead to a variation of the quantitative values of characteristic properties of the soil quality even in very short distances in uniform conditions of soil formation. This article is devoted to quantitative studying of this phenomenon under different soil usage.

Material and Methods

The fluctuations in properties of chestnut soil of the Kulunda Steppe were studied. The region is characterized by a droughty continental climate and its relief may be defined as a gently undulating plain. The soil cover consists of chestnut soils (70%), meadow-chestnut soils, meadow soils, solonetzes, and solonchaks with different degrees of hydromorphism. The chestnut soils significantly vary in texture, from loose sands to medium loams, which is a result of the ancient limnetic alluvial genesis of the territory. Loamy sandy and sandy loamy soils are predominant; they have an evenly colored humus-accumulative horizon and display deep effervescence.

The above notion of property fluctuation describes the minimum spatial changeability of soil properties occurring under conditions of practically leveled soil forming factors at a specific level of organization. In our study, the soil fluctuations were determined by the presence of coarse pores, cracks, concretions, tongues, and micro zones with different particle-size composition, moisture contents, and chemical parameters within a pedon.

The fluctuations of the soil properties were studied using the trench method. Trenches 6 m long were dug in loamy sandy chestnut soil in absolutely level conditions (in terms of the lithology, microclimate, microtopography, vegetation, and tillage) under different use (virgin soil, arable soil, and irrigated arable soil) in close vicinity to one another (within 100-300 m).

The arable soil was tilled for more than 30 years and irrigated for 20 years; corns for silage and forage grasses were the main crops. The soil was irrigated with low-mineralized water (with salt concentration of 0.7-1.0 *g per l)* at low irrigation norms; the water was of unfavorable salt composition with the predominance of sodium hydro-carbonate.

The trenches passed through all the genetic horizons. Samples with volumes equal 10 cm^3 were taken from each horizon in 20-22 replications (Figure 2). The thickness of each horizon, the humus content, particle-size composition, cation exchange capacity, exchangeable cation composition, pH, salt composition, and some other parameters were determined in laboratory analysis of soil samples by standard methods in Russia.

The results of the laboratory studies were analyzed statistically. First we analyzed standard statistical parameters as average, standard deviation, coefficient of variation, asymmetry and kurtosis, range of changeability. Then we identified type and parameters of probability distribution functions (pdf) of soil properties by choosing the best approximation of pdf according to compromise statistical criterion, which equal the average of p-values of some nonparametric criteria: Kolmogorov's test, Smirnov's test and Ω^2- and ω^2- tests (Lemeshko, 2005). At the end we calculated and considered probabilistic indicators of pdf's like statistical entropy and information divergence.

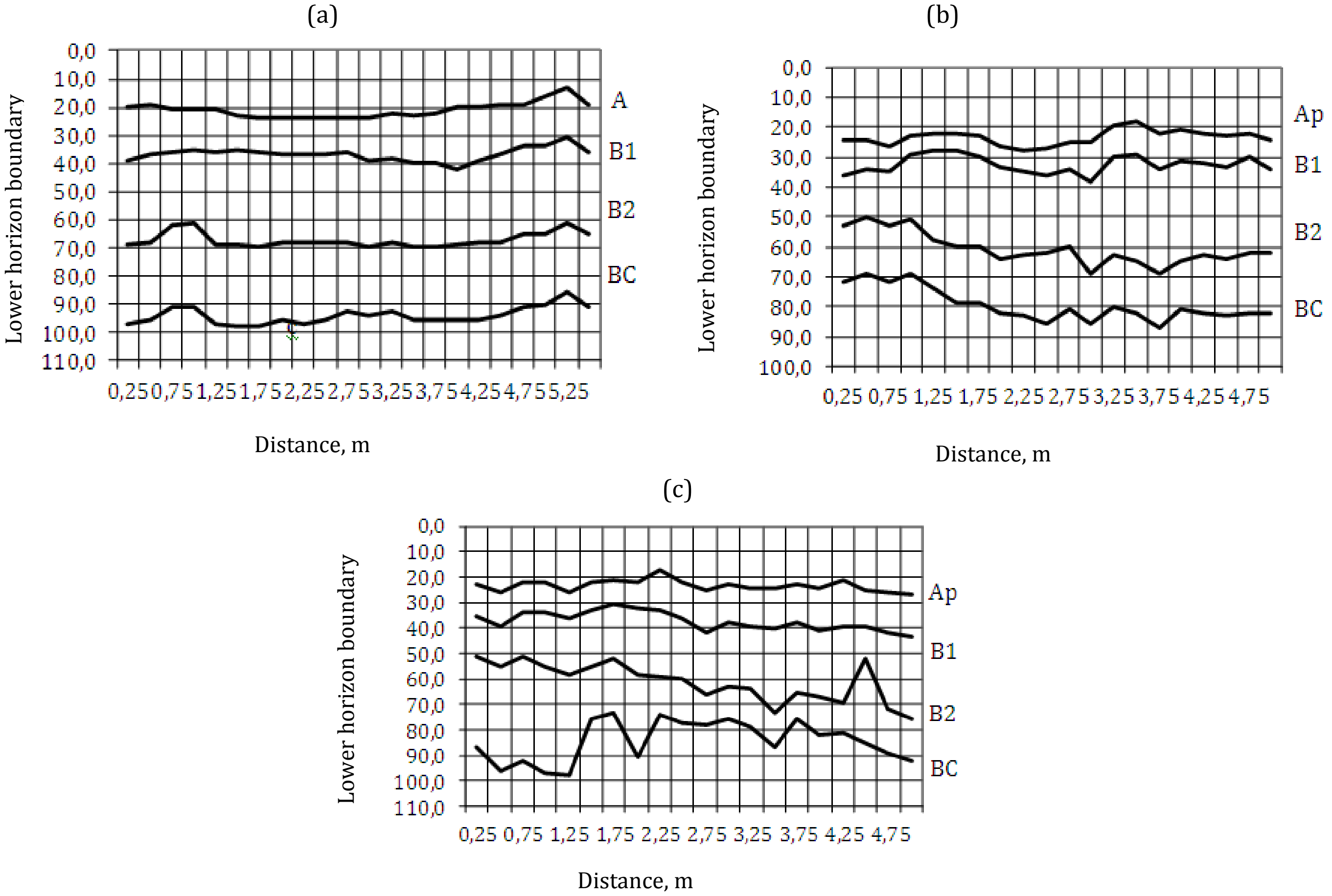

Figure 2. Trench study (lower boundaries of genetic horizons are denoted by solid lines): (a) virgin soil, (b) unirrigated arable soil, (c) irrigated arable soil.

Results and Discussion

Statistical parameters of soil fluctuations

The standard deviations of the properties fluctuations in genetic horizons of loamy sandy chestnut soil under different land-use conditions are given in Table 1 (changes in the average values are not discussed in this paper).

It is seen (Figure 2, Table 1) that the variance of the horizon thickness fluctuation in virgin soil gradually decreases down the profile. In Ap and B1 horizon of the unirrigated and irrigated arable soil this variance is some smaller than in A horizon of virgin soil. The variance of the B2 horizon thickness increases abruptly in arable soils; the thickness of BC horizon also increases strongly under irrigation. Thus, the variance of the thickness fluctuation in the illuvial horizons depends on the soil use, because it is largely determined by the water regime.

The highest variance of the humus content fluctuation was observed in the A horizon of the virgin soil because of the irregular influx of organic matter. In the B1 and B2 horizons, the variance was significantly lower. In the Ap horizon of the arable soils, the fluctuation range of the humus content decreased abruptly, especially under irrigation. This is explained by the long-term tillage, mechanical mixing, and uniform wetting of the upper horizons. The variance of the humus content fluctuation decreased down the profile in the unirrigated arable soil and increased in the irrigated arable soil because of the translocation of humus substances within the soil profile under the effect of the alkaline irrigation water.

Table 1. Standard deviations of fluctuations of properties in genetic horizons of loamy sandy chestnut soil

Feature	A(p)			B1			B2			BC		
	1	2	3	1	2	3	1	2	3	1	2	3
Horizon thickness, cm	2.86	2.49	2.31	2.75	2.13	2.54	2.11	5.88	5.33	1.66	1.83	11.6
Humus, %	0.27	0.11	0.07	0.11	0.09	0.11	0.09	0.06	0.11	nd	nd	nd
Clay,%	0.70	0.60	0.60	0.80	1,00	1,00	1,00	1.20	1.40	1,00	2,00	4.20
Fine sand, %	2.14	2.83	2.08	1.48	4.23	5.55	6.11	3.16	7.85	4.09	8.52	9.08
Salt, %	0.006	0.002	0.005	0.004	0.004	0.016	0.01	0.007	0.022	0.008	0.005	0.082
pH	0.12	0.13	0.19	0.2	0.14	0.11	0.38	0.18	0.43	0.73	0.1	0.24
CEC, meq/100 g	0.41	0.3	0.43	0.81	0.86	1.07	1.47	0.92	1.33	0.62	0.95	3.22

Note: (1) virgin soil, (2) unirrigated arable soil, (3) irrigated arable soil.

The variance of the fluctuations of the content of particles of different granulometric fractions significantly increases down the profile; hence, the pedogenesis in upper part of soil profile results in the smoothing of the fluctuations of the particle-size composition, which is manifested for all the types of soil use. Variance of clay content especially increases in irrigated arable soil as consequence of transferring clay particles under influence of irrigation water. Regularity of change of variance of sand particle content is defined by genesis of soil forming breeds.

The variance of the salt content in the A horizon of the arable soil is significantly lower than in the virgin soil; under irrigation, it increases abruptly compared to unirrigated case. This is due to the mixing and more uniform rainfall penetration in the former case and due to the influx of salts with low-mineralized irrigation water in the latter case. The variance of the salt content fluctuation sharply increases in the deeper horizons.

Localization of soil carbonates and the quality of irrigation water affect change of the variance of pH in soil profile. It authentically increases in the arable horizon of the irrigated soil versus unirrigated soil, owing to input of the hydro-carbonate ion with irrigation water. But it is bigger in virgin soil in deeper horizons relatively of arable cases because of ununiform localization of soil carbonates in natural conditions. The variance of capacity of cationic exchange in soil profile of chestnut soil isn't identical in soils of different use. But there is the general tendency of increasing of variation of CEC down on soil profile.

Apparently from the provided data the characteristic of fluctuations of properties of the soil, its profile distribution depend on conditions and factors of soil formation and, in fact, is a genetic sign of the soil. Therefore it needs to be displayed quantitatively for the purpose of a better understanding of spatial distribution of properties in soil profile. Thus, the trench study of the soil properties and the statistical analysis of the results showed that fluctuations of soil properties regularly change along the soil profile and depend on the soil-forming conditions and soil use; hence, they are features or properties (hyper properties) of the soil.

Comparison of fluctuations and variability

The variability data (in the sense of the concept, mentioned above) were received by statistical analysis of the materials of regular large-scale (1:25000) soil survey at the investigated territory (All-Union Guidelines for Soil Survey and Compilation of Large-Scale Maps of Land Tenure, 1973). The comparison of the variability ranges, variability coefficients, and standard deviations (Table 2) shows that the fluctuations of the properties within the soil individuum (pedon) are significantly lower than their variability within soil taxonomic variety at the territory (elementary soil areal).

Table 2. Fluctuation and variability of properties in the A(p) horizon of loamy sandy chestnut soil

Property	Changeability range		Variability coefficient,%		Variability standard deviation*	F**	Fluctuation variance contribution ***, %
	fluctuation	variability	fluctuation	variability			
Horizon thickness, cm	18-28	11.0-35.0	11	34	6.9	7.7	36
Humus, %	1.26-1.74	0.8-2.61	7	21	0.31	7.9	35
Clay; %	10.8-13.0	4.7-13.2	5	15	1.51	6.3	40
Fine sand, %	53.6-65.7	37.4-73.2	5	20	9.23	10.6	31
Salt, %	0.013-0.02	0.01-0.33	12	146	0.01	25.0	20
pH	6.3-6.9	6.2-7.6	2	4	0.27	4.3	48
CEC, meq/100 g	10.7-11.7	7.7-16.0	3	18	2	44.4	15

*For fluctuation standard deviations, see Table 1. ** F-ratio. *** Contribution was evaluated by the Mill's equation (Dmitriyev, 2000)

In the A horizon of the loamy sandy chestnut soil, the variance of fluctuation makes up 15-40% of the total variance of the variability (Table 2). From the point of view of geostatistics variance of fluctuations could be considered as reliable minimum of expected nugget-effect for real soil surveys. Hence, the variability of the soil properties within the elementary soil areas is 20-40% determined by the local fluctuations of the elementary soil processes and 60-80% determined by changes in the soil-forming factors at territory. The contribution of the fluctuations in the horizon thickness, humus, clay and fine sand contents, and pH to their variability (31-48%) is larger than that of the chemical properties like the content of exchangeable cations and salts (15-20%). The obtained results do not contradict the opinion about the compatible variability's within small and large areas: they are comparable but not equal. In the soils studied, this is an appreciable portion, close to the golden section ratio, which characterizes studied soils as stable hierarchical systems.

Probabilistic models of humus content

The simplest mathematical model of a soil property taking into account its variation in the space is the model of random value. The frequencies structure of the occurrence of quantity values in the range of variation of a property is described by a statistical distribution. Its mathematical function or probability distribution function (pdf) is the model of the random value. Often it is proposed Gaussian function of pdf, but it is not obligative function and in many field cases it contradicts to pedogenesis. The model of changes in the statistical distributions of soil properties under anthropogenic and natural processes, proposed by us earlier, indicates that pdf of soil properties can be of various shapes and have a regular character (Mikheeva, 2001; 2005). Developments have been made in the field of mathematical statistics (Lemeshko, 2005); they helped us identify and analyze pdf of various soil properties at different territories.

There are types and parameters of probability distribution functions of humus contents in loamy sandy chestnut soil in trenches at fields of different usage in Table 3.

Table 3. Types, parameters, and statistical entropy of probability distribution functions of humus contents in loamy sandy chestnut soil in trenches at fields of different usage

Usage	Horizon	Type of function*	Parameters	p-value**	Statistical entropy
Virgin	A	S_u-Johnson's	θ_0=-3.9; θ_1=1.76; θ_2=0.09; θ_3=1.18	0.9	-0.03
	B1	-"-	θ_0=0.93; θ_1=1.19; θ_2=0.07; θ_3=0.98	0.8	- 0.9
	B2	Nakagami	θ_0=0.17; θ_1=0.46; θ_2=0.43	0.6	-1.0
Arable	A	S_u-Johnson's	θ_0=-0.3; θ_1=1.01; θ_2=0.07; θ_3=1.48	0.8	-0.9
	B1	D. of maximal value	θ_0=0.72; θ_1=0.08	0.9	-0.9
	B2	Nakagami	θ_0=0.1; θ_1=0.53; θ_2=0.51	0.8	-1.6
Irrigated arable	A	Double exponential	θ_0=1.57; θ_1=0.08; θ_2=1.46	0.6	-1.2
	B1	S_u-Johnson's	θ_0=-2.20 θ_1=3.87 θ_2=0.34 θ_3=0.62	0.8	-0.8
	B2	Nakagami	θ_0=0.17 θ_1=0.29 θ_2=0.45	0.8	-1.2

*Mathematical expressions of functions are given in next small table

**Compromise criterion, the p-value equal average of p-values of Kolmogorov's test, Smirnov's test and Ω^2- and ω^2- tests

Mathematical expressions of functions

Name	Function
S_u-Johnson's	$f(x)=\frac{\theta_1}{\sqrt{2\pi}\sqrt{(x-\theta_3)^2+\theta_2^2}}\exp\left\{-\frac{1}{2}\left[\theta_0+\theta_1\ln\left\{\frac{x-\theta_3}{\theta_2}+\sqrt{\left(\frac{x-\theta_3}{\theta_2}\right)^2+1}\right\}\right]^2\right\}$
Nakagami	$f(x)=\frac{2}{\Gamma(\theta_1)}\left(\frac{\theta_1}{\theta_0^2}\right)^{\theta_1}(x-\theta_2)^{2\theta_1-1}\exp\left\{-\frac{\theta_1(x-\theta_2)^2}{\theta_0^2}\right\}$
Double exponential	$f(x)=\frac{\theta_2}{2\theta_1\Gamma(1/\theta_2)}\exp\left\{-\left(\frac{\lvert x-\theta_0\rvert}{\theta_1}\right)^{\theta_2}\right\}$
D. of maximal value	$f(x)=\frac{1}{\theta_1}\exp\left\{-\frac{x-\theta_0}{\theta_1}-\exp\left(-\frac{x-\theta_0}{\theta_1}\right)\right\}$

P-values are very high and significantly exceed standard means of significance levels (usually 0.01, 0.05, or 0.1), so we consider these functions as probabilistic models of humus contents in pedons of chestnut soil. Because it is difficult to understand they in form of mathematical functions, let's do graphical visual analysis of results (Figure 3).

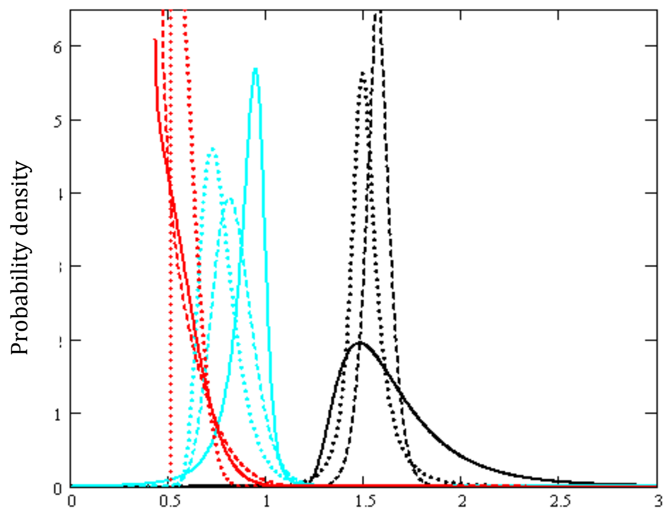

Figure 3. Probability distribution functions of humus content

Note. Solid lines – virgin soil, dotted lines –arable soil, dash lines - irrigated arable soil; Three curves appointed in right side belong to humus content in A horizon, middle three curves – in B1 horizon, and left curves – in B2 horizon

Looking to Figure 3, it became clear that tillage decreases humus content in soil profile. Though the characteristic remain in the same range of variation, but probabilities of high values extremely decrease and aspire to zero. So the range of humus content in Ap horizon become close and shape of pdf become tight. In irrigated arable soil this tendency keeps, but growth of values in the left part of range of variation leads to shift of left branch of pdf, and do the tendency more expressed.

The humus content in B1 horizon in steppe soils is sharply less than in surface horizon. Difference of pdf here, according to soil usage, is very clear. Though the values of humus content are small but they increase in irrigated study case, because of additional humidity.

Differences between study cases of soil usage become smaller in B2 horizon, though it is obvious the decreasing of probability of heightened values in unirrigate arable soil is lower than in virgin and irrigated arable soil.

Visual analysis of pdf regularities gives us clearer picture of difference of soil properties in the soil volumes in space under the agricultural impacts, than standard statistical characteristics, like the average and the variance; moreover pdf information is more stable to some big deviations. Nevertheless we should have some another quantitative characteristics to evaluate features and differences of pdf's as themselves. Statistical entropy and information divergence could help us.

Statistical entropy as indicator of soil changeability

Entropy is derivative concept from the concept "condition of object" or "phase space of object". It characterizes degree of variability of microconditions of object. Qualitatively, if the entropy is higher, then in bigger number of significantly various microconditions an object at this macrocondition can be. Studying of pdf brought us the idea that statistical entropy of soil properties, which is calculated from pdf, can serve as the numerical characteristic of soil variation (Mikheeva, 2004). We have shown that statistical entropy is more stable characteristic than other characteristics of variability (Mikheeva, 2005).

Known Shannon's formula is applicable in case of discrete systems, therefore its use is justified for high levels of the organization of soil cover. We consider natural fluctuations of soil properties which cannot be considered as discrete as they are continuous. Therefore we have used definition of statistical entropy for continuous random quantity values. The value of statistical entropy may be calculated by the formula, where W (x) – pdf of random variable x; k and h0 are constants (Gubarev, 1992):

$$h = -k \int_{-\infty}^{+\infty} W(x) \ln W(x) dx + h_0$$

At calculations of entropy we have accepted while a constant h0 = 0, factor k = 1. For the bottom limit of integration have accepted the minimal values, or, in case of Nakagami pdf, θ_2; and for top limit - the maximal values of properties, because outside of this interval they are not determined. The value of entropy thus was interpreted as measure of a quantitative variety of inwardness of soil, owing to continuous spatial fluctuations. Because of small humus content in soils in semiarid steppe zone and small size of investigated pedons, intervals of definitions of humus's pdf are tight (Figure 3) and statistical entropy is small and only in horizon A of virgin soil have little negative value close to zero. In other cases it is considerably negative (Table 3). Negativity of entropy value do not contradicts taken definition of entropy. Smoothing of pdf leads to growth of entropy, but at decreasing of area of definition, the entropy are decreasing and can have negative value. Data show that entropy of humus content in A horizon catastrophically decrease in arable soil, it decrease still in irrigated arable soil. Value of entropy is more or less equal in B1 horizon in cases of study; in B2 it decrease especially in arable soil, and apparently increase in irrigated arable soil. Thus, analysis of entropy value highlighted the main tendency of agricultural impact – the tendency of outstanding decreasing quantity of various microconditions of soil. This is important change of edaphic factor.

Divergence of pdf as indicator of holistic change of soil properties

The concept of divergence is interpreted after Darwin more often in biology as concept connected with evolutions of organisms kinds. However in methodological works the divergence concept is given more fundamental systemic meaning. All area of life on the Earth can be considered in its whole as one system of divergences; it is believed that increase of distinctions conducts to more and more steady structural parities. We proposed that it is reasonable to name process of soil forming and modern changes of soil properties by term "divergence" and investigate it quantitatively.

Visual graphical analysis of pdf dynamics under anthropogenic impacts (Figure 3) have shown that within one soil the property can both weaken and intensify in different localities, though, a prevailing tendency is observed. Quantitative comparison of pdf of soil properties gives holistic estimation of changes of their fluctuations. For such holistic estimation of changes of soil properties we proposed to use mathematical value of divergence of pdf. This value is the quantitative measure of difference of pdf (Mikheeva, 2009). To estimate how the pdf of soil properties differ in different horizons and different state of soil (virgin, arable, irrigated) we used the value d:

$d = \int_{-\infty}^{+\infty} (W1(x) - W2(x)) \ln\left(\frac{W1(x)}{W2(x)}\right) dx$,where *W1(x) и W2(x)* – pdf of property in compared objects (Gubarev, 1992).

The degree of difference of genetic horizons is one of important morphological features of soil body. In field condition it could be evaluated by visual perception of investigator. Information divergence help quantify this feature. Information divergence of humus content in horizons A and B1 is very big, but it shows less value in unirrigated arable soil. Divergence of horizons B1 and B2 is not so big, and it is equal in different cases of study (Table 4). Divergence of the humus content in the pedon of unirrigated arable soil as compared with a virgin soil happens because of a decrease in the upper limit of variation, with the value of divergence in B1 horizon being higher than in Ap horizon. On the contrary, in the pedon of irrigated soil versus unirrigated one, the changes happen because of an increase in the low limit of variation (Table5).

Table 4. Information divergence of humus content in soil horizons

Usages / Horizons	Virgin		Arable		Irrigated arable	
	d*	dr	d	dr	d	dr
A v. B1	35.2	- -	15.4	- -	36.1	- -
B1 v. B2	6.2	- -	6.5	- -	6.2	- -

Note. In this and text table: d – value of information divergence; dr – direction of difference, which is shown by to symbols, which reflect directions of differences, accordantly, of left (minimum) and right (maximum) boundaries of variation: - -decrease; + -increase; 0 –not change.

Table 5. Information divergence of humus content in soil of different usage

Horizons / Usages	A(p)		B1		B2	
	d	dr	d	dr	d	dr
Virgin v. Arable	1.0	0 -	2.6	- -	0.4	0 -
Virgin v. Irrigated arable	3.9	+ -	0.9	- -	0.5	0 0
Arable v. Irrigated arable	1.1	+ 0	0.5	+ 0	0.7	0 -

Thus, the impact of mechanical treatment and irrigation influences the change of pdf of the humus content in opposite directions, and their combined effect increases the divergence owing to the total restructuring of the probability distribution in Ap horizon. Irrigation in the B1 horizon moderates the differences caused by tillage. Thus, divergence as a quantitative parameter of the similarity of pdf of the soil properties can be used under different conditions for estimating the degree of differences of soil related to the fluctuations of natural and anthropogenic processes. This characteristic can help to single out the most changing and vulnerable soils, as well as to range the natural and anthropogenic changes according the degree of their influence on the soil properties. In summary, we note that increase of fluctuations of genetic soil properties down on the soil profile is the regularity for chestnut sandy soils in semiarid zone of Western Siberia. It is explained by a smaller engagement of the bottom horizons by soil forming process because of sharp continental climate. But reduction of fluctuations of horizon thickness and humus content, in virgin soil at the left asymmetry of their pdf testifies a stationary of this horizon. Soil indicators here don't vary enough in space as they are close to the limit under constant external conditions, and, therefore, they vary a little and in time. Machining and irrigation of the soil break the dynamic balance that had been reached in the virgin soil during natural evolution. Increasing homogeneity of the superficial horizon, these influences cause processes of transferring of substances in a profile and lead to sharp increase of fluctuations of properties of the soil in the bottom horizons, and more in the irrigated soil. Thus the right asymmetry of pdf of soil properties, testifying that considerable changes of properties were occurred only in small part of the distributed in space volumes of the genetic horizons, obviously, because of small quantity of an atmospheric precipitation and small irrigation and irrigating norms. Humus content is exception from this rule, because its fluctuation decreases down to the soil profile; that is displayed at different soil use. Statistical parameters and probabilistic models investigated in our paper would be considered as statistical standard of chestnut soils.

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