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Soil Exhaustion Criteria for Central Siberia

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Abstract
The article presents the results of studying the influence of long-term agricultural use on the content of labile organic matter in arable soils. Some criteria are suggested for estimating the effective of fertility agrochernozems, black, grey and dark grey soils, the exhaustion degree and the environmental sustainability to anthropogenic loadings. For the comprehensive assessment of fertility of arable soils in Central Siberia it is recommended to use indicators of easily decomposed organic matter and mobile humic substances. The higher the content of these forms of organic matter, the more fertile and more ecologically sustainable to anthropogenic load soil is, and it can be used for agriculture for a long time. To assess the soil exhaustion degree it is used the relative content of labile organic matter, expressed as a percentage of the total content of soil organic matter.
Keywords: soil, mobile humic substances, easily decomposed organic matter, nitrate nitrogen, exhaustion degree.

INTRODUCTION

Soil fertility reduction and environmental deterioration constitute major issues in the agricultural sector today. The decrease in the volume of applied organic and mineral fertilizers led to a reduction of the content of organic matter, phosphorus, potassium and other elements of mineral nutrition of plants and an annual increase in the area of soils with insufficient provision with them in many regions of Siberia [1; 2; 3; 4]. Soil fertility depends on climate, and it varies for different crops. The currently available soil fertility indicators may be interpreted in relative terms only, considering both soil characteristics and external conditions [5]. Thus, it is necessary to develop a system of new indicators, characterizing soil fertility and the environmental situation influencing the productivity of agricultural crops. Accordingly, the existing parameters and criteria of soil quality estimation should be supplemented and specified.

Based on the concepts of heterogeneity and different levels of resistance of soil organic matter (SOM) to mineralization, Tate [6] suggested sorting it according to its mobility and decomposition speed. Thus, SOM is subdivided into two main categories according to its biodegradability and transformability: labile and highly mineralized SOM and sustainable humus SOM, which is preserved for a long period [6; 7; 8; 9]. Labile and highly mineralized SOM characterizes effective soil fertility, whereas sustainable humus SOM characterizes potential soil fertility.

Labile SOM contains two groups of components, which differ by nature and functions: easily decomposed organic matter (EDOM or mort-mass) and mobile humic substances (MHS). These are the most dynamic and easily transformable components of the organic part of soil, which take part in different soil processes and in effective fertility formation. However, in order to optimize EDOM and MHS [10], it is necessary to classify the available soil data with respect to the different types of crops, reflecting minimal, optimal and maximum EDOM and MHS content values in arable soils of different agricultural regions.

The present analysis is based on the hypothesis that the concentration of EDOM and MHS is different for every region and soil type. For example, in black soils, formed in relatively cold conditions in Siberia, a larger amount of organic substances is expected, which is optimal for crops. In Siberia, the period of microorganism reproduction is shorter, as compared with European, and falls on the second half of the summer. Therefore, organic matter accumulation is weak, and so is the release of mobile forms of nitrogen and phosphorus. Consequently, in order to form high yields, the EDOM and MHS capacity during crop sowing is expected to be higher than in European soils.

The aim of the present research is to develop some criteria for assessing the soil fertility status of agricultural lands and to determine their exhaustion degree and agro-ecological sustainability.

MATERIALS AND METHODS

In this study, the authors examined black soils and grey-forest fallow soils obtained from several farming enterprises in the agricultural part of Central Siberia (Krasnoyarsk): Minino (Yemelyanovsky Municipality), Minderlinskoye (Sukhobuzimsky Municipality), Alyonushka and Poultry Farm Barkhatovskaya (Berezovsky Municipality), Prichulymsky (Achinsk Municipality), Provintsia+ (Bogotolsky Municipality), Lazurnoye (Kozulsky Municipality) and Solyanskoye (Rybinsky Municipality). Soil samples were taken at the end of a fallow period, in the autumn and spring of 2011–2013, using a soil sampler at depths of 0–20 cm. Every farming enterprise was represented by 19–20 joint soil samples (one for autumn and one for spring), consisting of 20 individual samples.

The soil humus content was determined according to Turin's method. In order to extract MHS 0.1N, sodium hydroxide was used with a soil to solvent ratio of 1:20, whereas a heavy liquid ($P = 1.9–2.0\ g/cm^3$) was used for the extraction of EDOM. Humic acids (HA) in the soil humus content were precipitated with sulfuric acid, and the fulvic acid (FA) content was calculated from the difference between the total concentration of humic substances, extracted with an alkaline medium,and the HA content. The amount of HA determined the HA:FA ratio. The nitrate nitrogen ($N\text{-}NO_3$) concentration was determined by the ion-selective method.

In order to determine the soil exhaustion based on the organic matter transformation and to estimate the nitrification capacity, a model experiment was carried out. The experimental scheme included the following variants: 1, 4 – soil without composting (control); 2, 5 – soil with 15-day composting and 3, 6 – soil with 30-day composting. In variants 1–3, the soil samples were taken from a summer fallow, whereas in 4–6, they were obtained from a wheat field. The soil type was minor-to-heavy loam black soil with a humus content of 3.89%. Soil composting (300 g) was done in a thermostat at a temperature of 25°C and soil moisture of 60%–80% of the field moisture capacity.

RESULTS AND DISCUSSION

Humic substances increase the absorption capacity of the soil. In addition, they are plant food elements and a source of carbon dioxide, which is necessary for photosynthesis. Furthermore, humic substances contribute to the microbiological degradation of pesticides, and their sufficient content contributes to mineral fertilization and ecological balance.

Humus content in black soils and grey forest soils changes rather dramatically in variants 3 and 6 (Table 1), from low to very high, according to the classification of Grishina and Orlov [11]. All black soils and dark soils exhibit high humus content, whereas grey soils show low humus content. Moreover, the estimated fertility differs significantly in the examined samples; in fact, the humus content differs by 1.3–2.3 times.

EDOM originates from plant litter, detritus, remains of organisms and organic fertilizers. A decrease in EDOM leads to degradation of the nutritional content and the physical characteristics of soils. The analysis of humus group composition shows that detritus is the main source of mobile FA [12]. Therefore, low EDOM indicates soil exhaustion [13].

The EDOM content varies widely from 0.1% to 1.64% in the study's areas. Indeed, based on the large dataset obtained, the EDOM content in arable soils of Central Siberia (C, %) is in the following ranges: < 0.30 – very low; 0.31–0.60 – low; 0.61–0.90 – average; 0.91–1.20 – increased; 1.21–1.50 – high and > 1.51 – very high. The authors attribute this gradient to the fact that the organic matter content in the soil depends on temperature and humidity. In Siberian soils, due to the short warm period, there is less advanced processing of vegetative matter than in European soils. The mineralization degree of vegetative matter during a vegetative period was only 45% – 50% in the soils of Western Siberia and 65% – 70% in the soils of the European part of Russia [14]. In soils of Central Siberia, the process of decomposition and mineralization of vegetative matter was also observed to slow down; 43% – 54% of the initial stock of vegetative matter was decomposed in fallow soils without fertilizers in the Krasnoyarsk forest-steppe with in a period of only one year.

The EDOM average content in soils fluctuates strongly as well depending on the type of soil. In dark grey soil, the EDOM content is significant due to the annual production of a large amount of plant residues, as a result of leaving the soil fallow. The EDOM content in grey soil is estimated as high. A sufficient amount of EDOM is found in the soil of Poultry Farm Barkhatovskaya, fluctuating between increased and high values. The soil in this area is not exhausted by land use; on the contrary, organic matter is returned to the soil. In the soils of Prichulymsky and Minino, labile SOM is estimated as low and very low. The EDOM content in soils is subject to dramatic changes (by 2–4 times) and shows critical values. The authors propose that the EDOM content should be widely used in agricultural practice because it provides significant information.

A decreasing trend of the nitrate nitrogen content in soils means that nitrate accumulation in fallows is less likely to occur, and thus the soils are expected to become exhausted [15]. Nitrate nitrogen content in fallow soils changes drastically, in some cases by many times. In the soils of Poultry Farm Barkhatovskaya and Provintsia+, the nitrate nitrogen content is very high due to fertilizer use; organic fertilizers are used in Poultry Farm Barkhatovskaya, whereas mineral fertilizers are employed in Provintsia+ (Table 2). Thus, nitrate nitrogen accumulation in the soil of Poultry Farm Barkhatovskaya was due to the heavy use (up to 300 t/ha) of fresh poultry litter. The minimum and maximum values of nitrates changed here by 17 times during the studied interval, which shows strong fertility diversity.

In the soils of most of the farming enterprises, the average nitrate nitrogen content is low to very low. Thus, fallow soils do not accumulate a sufficient amount of nitrate nitrogen for crops. In order to figure out the reason for such low level of nitrates, the authors perform quantitative and qualitative characteristics of MHS.

MHS are presented in soil either as free substances or bound with sesquioxides [16]. The authors consider this humic compound fraction to be labile and easily mineralized. The MHS content is determined based on the nitrogen-phosphorus concentration [17] and the structural condition of the substances. Therefore, optimization of the MHS content in soil is of practical importance for agriculture.

Table 1 – Organic matter content in fallow soils

Farming enterprise	Soil	Humus, %	SOM, C%	EDOM, C%			MHS, mgC/100g			
				min	max	x	sum	HA	FA	HA: FA
Minino	Black soil with clay illuviation	4.03	2.58	0.10	0.40	0.24	101	40	61	0.66
Minderlinskoye	Black soil	7.02	4.74	0.50	0.78	0.67	527	329	198	1.66
Alyonushka	Grey	2.50	2.48	0.77	1.22	1.03	415	274	141	1.94
Poultry Farm Barkhatovskaya	The same	2.73	2.77	1.10	1.30	1.19	308	195	113	1.73
Prichulymsky	Black soil with clay illuviation	7.70	4.84	0.25	0.50	0.37	382	259	123	2.11
Provintsia+	The same	8.33	5.51	0.45	0.90	0.70	452	184	268	0.69
Lazurnoye	Dark grey	9.01	6.63	0.97	1.64	1.40	1223	954	269	3.55
Solyanskoye	Black soil with clay illuviation	8.61	5.75	0.45	1.20	0.76	952	702	250	2.81

Table 2 – Nitrate nitrogen content in fallow soils and degree of their exhaustion

Farming enterprise	Soil	N-NO_3, mg/kg			Soil exhaustion, grade
		min	max	X	
Minino	Black soil with clay illuviation	5.6	7.9	7.1	5.7
Minderlinskoye	Black soil	5.6	10.4	7.4	0.9
Alyonushka	Grey	5.6	8.2	7.3	0.0
Poultry Farm Barkhatovskaya	The same	9.4	156.7	45.7	0.0
Prichulymsky	Black soil with clay illuviation	13.6	25.4	19.2	7.4
Provintsia+	The same	21.6	53.1	33.2	2.3
Lazurnoye	Dark grey	2.2	9.7	5.5	0.0
Solyanskoye	Black soil with clay illuviation	3.5	7.0	4.4	1.8

The MHS content in fallows varies significantly between the different study areas. According to the classification the mobile humus content in all cases is estimated as high to very high. Black soil with clay illuviation is the exception (Minino), where the total MHS content is low. The low MHS content does not allow nitrate nitrogen accumulation in fallow soil. The highest MHS content is found in dark-grey soil, which, being fallow, annually produces a vast amount of vegetative matter that is the source of MHS. High MHS content also does not provide nitrate nitrogen accumulation in fallow. The authors hypothesize that weak nitrification capacity of fallow soils is largely connected with the quality of MHS. HA:FA correlation of mobile humus is indicative of the soil characteristics. The main source of mineral nitrogen in the soil is mobile nitrogen-containing organic matter of non-specific nature and the most mobile fractions of humic substances [18]. Gamzikov [19] proposed that in all arable soils of Siberia, there is clearly defined dependence of nitrate nitrogen accumulation on the content of non-specific organic substances. Soil treatment with 0.1N NaOH allows extracting humic substances and non-specific organic substances. While separating HA and FA, non-specific compounds are grouped together in FA, and therefore, HA:FA correlation to some degree is also indicative of the relative content of non-specific organic substances. When this correlation is high, more non-specific compounds pass to alkaline extract, relative to the total MHS content, and the more actively these substances are involved into the mineralization process, providing energy and food for microorganisms, and thus, increasing the nitrate nitrogen accumulation in soils. In most cases, HA:FA correlation is very wide, which indicates the weak availability of MHS for mineralization by microorganisms.

In order to assess the MHS content in soil objectively, it is important to correct the class of their content relative to the HA:FA ratio. This can be achieved by calculating the average of two quantitative and qualitative classes. Quantitative assessment of the MHS content is carried out according to the following: 1) < 100 – very low; 2) 100–200 – low; 3) 200–300 – middle; 4) 300–400 – high and 5) > 400 – very high. It is possible to assess the MHS quality using the HA:FA ratio according to the following classification: 1) > 2.5 – very wide; 2) 2.5–2.0 – wide; 3) 2.0–1.5 – middle; 4) 1.5–1.0 – narrow and 5) < 1.0 – very narrow. However, there are five classes of the MHS content and two classes of the MHS quality for black soil. The average of two classes is 3.5; when rounding off (always down), we will get the average (class 3) content of MHS.

Soil exhaustion is a simple process in soils, caused by long and continued tillage, which leads to the reduction of humus sources, quantitative and qualitative deterioration of soil properties and, finally, soil fertility decrease. Both cultivated and native soils, having high and low humus content, can become exhausted. Exhaustion is the first stage of soil fertility degradation. This process is reversible, because after optimization of the organic substances in exhausted soils, their effective fertility recovers rather quickly. Low EDOM can be considered a criterion of soil exhaustion. Low EDOM leads to the deterioration of nutrient content and of the physical properties of the soil. Therefore, optimization of the EDOM quantity in soil has practical significance.

For the qualitative assessment of the soil exhaustion degree, the EDOM relative content is used, expressed as a percentage of the SOM general content. A 25-point scale is used to characterize the soil exhaustion degree [13]. On this scale, unexhausted soils are those with an EDOM content of 25% or more of the SOM content. Such soils have a zero point of exhaustion. While calculating the exhaustion points for soils, in which the EDOM content relative to the total SOM content is less than 25%, the ratio obtained should be deducted from 25. Thus, the soil exhaustion degree increases with the exhaustion points. Studying the EDOM content in fallows reveals that using a unified 25-point scale for soils of different types is not effective. Therefore, at the present time, different scales are used; a 25-point scale is used for sod-podzol, light grey and grey forest soils, a 15-point scale is used for dark grey forest soils and for black soils of forest-steppe and steppe zones and a 20-point scale is used for chestnut soils.

The authors propose that the following point scale can be used for assessing the exhaustion degree of black soils and dark grey soils of agricultural part of the study region: < 3.0 – very weak; 3.0–6.0 – weak; 6.0–9.0 – average; 9.0–12.0 – strong and > 12.0 – very strong. The soil exhaustion degree shows a close reverse conjugation with the MHS content ($r = -0.84 \pm 0.24$), which proves the information value of the first figure. The authors suppose that this new indicator can be widely used for assessing the effective fertility and characterizing the ecological condition of soils.

The SOM and EDOM contents are given in Table 1. According to the suggested approach, black soils in Minderlinskoye and Provintsia + and Minino have very weak exhaustion degrees, and black soils in Prichulymsky have an average exhaustion degree. Thus, an additional parameter has to be taken into account in order to assess the exhaustion degree of fallow soils. Although the soil in Prichulymsky appears to be exhausted, it has accumulated a significant amount of nitrate nitrogen while being fallow. Thus, it cannot be considered to be exhausted, because during the fallow period, the vegetative matter, which makes up most of EDOM, decreases dramatically. Moreover, in soils of Central Siberia, stocks of plant material decrease by 50% or half as much during the fallow period [20]. This means that at the beginning of a fallow period, the EDOM content in soils is twice as high. Consequently, in order to assess the EDOM content and to obtain comparative data on the soil exhaustion degree, it is necessary to define the proper time for soil sampling, either in autumn or in early spring at the beginning of the fallow period. Thus, all of the examined soils exhibited EDOM content twice as high and were not exhausted at the beginning of the fallow period. The only exception is the black soil with clay illuviation in Minino, where the MHS content is very low and, despite the narrow HA:FA ratio, during the fallow period, a small quantity of nitrate nitrogen was accumulated in the soil.

The SOM content in all variants of the model experiment is assessed as low (Table 3).

In the process of soil composting over the period of 15 and 30 days, the SOM content definitely does not change, indicating its stability and sustainability to mineralization. The EDOM content in soil samples varies slightly and is assessed as being very low; therefore, it appears to be weakly to very weakly exhausted. In the process of composting, the EDOM content decreases and the exhaustion degree increases by two points, becoming weak to average.

The MHS content in soil is also assessed as low. In the process of composting, the number of humic substances does not change. The total MHS content does not mineralize intensively. The mobile humic acid content also does not change. Low MHS content may result in that humic acids become inert and tightly bound with heavy hydrolyzable condensed humus fractions. At the same time, soil composting leads to the decrease in the mobile fulvic acid content and increase in the HA:FA ratio.

Table 3 – Transformation of organic matter of black soil and accumulation of nitrate nitrogen under the influence of composting

Experiment variant	SOM	EDOM	N-NO_3, mg/kg	MHS, mgC/100g of soil				Exhaustion degree, point
	C, %			Total	HA	FA	HA:FA	
1 (control)	2.26	0.23	4.5	168	70	98	0.72	4.8
2	2.37	0.20	9.2	165	75	90	0.83	6.6
3	2.34	0.19	9.7	157	73	84	0.87	6.8
4 (control)	2.25	0.28	3.2	176	61	115	0.53	2.5
5	2.32	0.25	7.6	162	73	89	0.82	4.3
6	2.37	0.15	7.5	168	70	98	0.71	4.4
LSD_{05}	0.16	0.04	1.7	27	22	5	-	-
Sx,%	2.3	6.2	8.3	5.5	10.7	12.5	-	-

Thus, despite a low initial EDOM and MHS, these contents increased significantly. The EDOM mineralized, and the MHS underwent qualitative changes.

Nitrate nitrogen accumulation as a result of fallow or composting does not occur in exhausted soils. The nitrate content in the soils of the control samples is low and very low. Summer fallowing does not contribute to nitrate accumulation. Soil composting increases the nitrate content moderately, but still remaining low, as indicated by the report on soil exhaustion. Such nitrate quantity in soil does not lead to the high productivity of crops.

Thus, the EDOM and MHS values can be used for assessing the effective fertility, the exhaustion degree and the ecological sustainability of soils. The authors hypothesize that the higher (to a certain degree) the content of these forms of organic matter, the more fertile and more ecologically sustainable to anthropogenic load soil is, and it can be used for agriculture for a long period of time. A greater degree of exhaustion is observed in soils, where the mineralization process of organic matter is nearly completed, and the mineral nitrogen is immobilized, to a large extent, in the biomass of heterotrophic bacteria, which are able to use ammonium and nitrates.

CONCLUSIONS.

1. For the comprehensive assessment of fertility, exhaustion degree and ecological sustainability of arable soils of Central Siberia, it is recommended to use the values of EDOM and MHS content in soils. At the same time, MHS absolute values should be supplemented with qualitative characteristics using the HA:FA ratio.
2. In arable (black, dark grey and grey) soils, the EDOM content ranges from 0.10% to 1.64%. EDOM fluctuation is determined by the soil formation conditions and different aspects of land management. To assess the EDOM content, the following classification is offered (%): < 0.30 – very low; 0.31–0.60 – low; 0.61–0.90 – average; 0.91–1.20 – increased; 1.21–1.50-high; >1.51 – very high.
3. To assess the soil exhaustion degree, we recommend using the EDOM content relative to the total SOM content. With regard to the arable (black and dark grey) soils of Central Siberia, the following classification of the soil exhaustion degree (point) is offered: < 3.0 – very weak; 3.1–6.0 – weak; 6.1–9.0 – average; 9.1–12.0 – strong; > 12.1 – very strong. High exhaustion degree is observed in soils, where organic matter mineralization is nearly completed and in the inhibited condition, while the mineral nitrogen formed during this process is immobilized to a large extent.
4. Fallowing and composting of black soils with low EDOM and MHS content does not assure intensive mineralization of organic matter and sufficient accumulation of nitrate nitrogen quantity for future crops.

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