Microaggregate Composition as a Factor of Variability in the Physical Properties of Gray Forest Soils in Western Siberia

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Abstract. The aim of the study was to study the variability of the microaggregate composition of the soil profile of virgin gray forest soils in the western part of the West Siberian Lowland. 330 soil sections were studied, covering all subtypes of gray forest soils. Empirical data were processed using mathematical methods of variation statistics. The results of the research showed that the humus horizon of light gray forest soils is characterized by good water resistance of microaggregates - the dispersity factor on average for the sample is 14.6%, the variation is small (Cv = 19%). Gray forest soils in the humus horizon have, on average, a dispersity factor of 12.2%. This subtype, in comparison with light gray soils, has a higher variability of the dispersity factor (Cv = 24%), which is due to the variety of combinations of soil formation factors, mainly relief and vegetation. The dispersity factor of the humus horizon of dark gray forest soils averages 7.9% for the sample, which is typical for medium structured soils; the variation is estimated as small (Cv = 18%). The microaggregate composition of gray forest soils is characterized as satisfactory throughout the entire soil profile, which makes it possible to improve structure formation during agricultural development and maintain the optimal structural-aggregate composition for a long time. The results obtained can be used in the development of an adaptive-landscape system of agriculture.

1. Introduction

The main factors that determine the structure formation of soils are the granulometric composition and humic substances. And if the organic part of the soil is constantly changing and transforming throughout the entire soil-forming process, then the granulometric and mineralogical composition of modern soils mainly depends on the parent rock and remains relatively stable for many centuries. Therefore, to understand and predict soil fertility, it is necessary to have reliable information about the role of particle size distribution in primary structure formation, which is the basis of the structural state. The formation of soil aggregates, their size and shape determine other physical indicators: the density of addition, water permeability, aeration, which have a direct impact on the growth of plants, both in natural conditions and in agrophytocenoses.

Siberia is a vast region in the Asian part of Russia. It occupies about 13 million km$^2$, which is comparable to the area of Canada and makes up 77% of the territory of Russia. The considerable extent of Siberia determines the extreme diversity of landscapes, geological and soil-forming rocks, climate, and relief. This explains the strong variability in the properties of soils formed within the same natural and climatic zone.
Thanks to the development of science and technology, new varieties of agricultural crops were created, zonal systems of tillage and fertilizers were developed [1-4]. On their basis, a system of Siberian agriculture was developed, which considered the harsh climatic conditions and low-fertile soils. And in the second half of the XX century, the subtaiga and forest-steppe zones became a territory with developed industrial agriculture [5, 6]. However, already at the beginning of the XXI century, farmers faced the problem of a shortage of land resources for agricultural land. This required the exploration of new fertile lands and gray forest soils became the first in the queue [7].

Gray forest soils in the conditions of flat relief are dominant in the northern forest-steppe and the subtaiga zone. They develop on watersheds and the upper part of slopes under birch, birch-aspen forests. They are also found under mixed-type forests (pine-birch forests), where they border on sod-podzolic soils. Under the forest canopy, there is a well-developed herbaceous vegetation, which ensures the annual supply of plant residues, both on the surface and in the upper part of the soil profile [8].

Gray forest soils differ from others by a very strong variability of properties, which makes it difficult to develop a unified farming system for them, even within the borders of one administrative district located on the vast territory of Siberia [9].

The purpose of the research: to study the territorial variability of the microaggregate composition of the soil profile of gray forest soils of the Northern Trans-Urals.

2. Materials and Methods
From an agrophysical point of view, the stability of micro- and macro-aggregates is extremely important. It is on this ability of aggregates that the erosion resistance of soils, the ability to withstand external mechanical loads, humus formation, and many other soil indicators depend. However, the study of primary structure formation has certain difficulties, which can be generally characterized as a strong variability in space. Moreover, both geographically and within the soil profile. To achieve this goal, a large amount of information is needed, covering a significant area with a detailed study of indicators for each soil profile. This is possible only when using digital technologies that allow processing large amounts of information and building predictive models based on them [10].

Our studies of gray forest soils were carried out in the Northern Trans-Urals in the south of the Tyumen region. The survey area is 160 thousand km² and is in the taiga and forest-steppes of the Trans-Urals. The object of the study was gray forest soils, which occupy 6.3% of the territory of the south of the Tyumen region. The soils under consideration were formed on carbonate mantle and loess-like lacustrine-alluvial loams and clays. Also, on the territory there are soil-forming rocks with a well-pronounced polynomial granulometric composition within a 3-5 meter thickness, which has a certain effect on the water permeability of the rocks and soils formed on them.

Between 1965 and 2019 The Department of Soil Science and Agrochemistry of the State Agrarian University of the Northern Trans-Urals laid 330 full-profile sections of virgin gray forest soils of the subtaiga and forest-steppe zone of the Northern Trans-Urals, of which 96 fell on the subtype of light gray forest soils, 111 – gray and 123 - dark gray. Morphological descriptions of soil sections were carried out by soil scientists A.G. Karyakina, N.M. Sulimova, L.N. Karetin and D.I. Eremin. Simultaneously with the morphological description, soil samples were selected according to genetic horizons for more detailed study and laboratory analyses.

To determine the severity of the primary structure formation of gray forest soils, the results of granulometric and microaggregate analysis made by N.A. Kachinsky were used [11]. The soil sample was prepared for granulometric analysis by vigorously grinding the sample with a rubber-tipped pestle in a porcelain mortar with the addition of sodium pyrophosphate solution, followed by boiling in a flask. When preparing a sample for analysis of the microaggregate composition, mechanical action and chemical dispersants were not used. The soil sample was subjected to boiling in distilled water.

After laboratory granulometric and microaggregate analysis, the dispersity factor (K) was calculated according to N.A. Kachinsky, which characterizes the degree of destruction of aggregates in
water and is expressed as the ratio of elementary soil particles with sizes less than 0.001 mm to microaggregates of the same size:

$$K = \frac{a}{b} \times 100$$  \hspace{1cm} (1)

Where $K$ is the dispersity factor;
- $a$ is the content of silt particles (<0.001 mm) in microaggregate analysis, %;
- $b$ is the content of silt particles (<0.001 mm) in granulometric analysis, %.

The higher the dispersity factor, the less stable the soil microstructure. In well-structured soils, the dispersity factor is 3-5, in medium-structured soils it is 6-10, and in weakly structured soils it is 11-15, in structureless soils it can increase to 50 and even 80 [11].

Statistical processing of empirical data was carried out using the Descriptive Statistics tool of the Microsoft Excel 2013 Data Analysis package. Central tendency measures (mean, mode, median), variability measures (standard deviation, variance, range), shape deviation measures were calculated distribution (skewness, kurtosis).

To assess the spatial variability, the coefficient of variation (Cv) was determined, which represents the percentage of the standard deviation to the arithmetic mean. The variation is considered insignificant if Cv does not exceed 10%, small at Cv 10-20%, medium 20-40%, high 40-60%, very high - more than 60% [12].

3. Results and Discussion

Light gray forest soils are characterized by a low content of organic matter in the humus horizon ($A_1$). Humus formation in these soils takes place with a lack of plant residues, which accumulate mainly in the form of forest litter on the surface. The root mass of herbaceous plants is insignificant and quickly mineralized. Therefore, fulvic acids are present in humus, which are significantly inferior to humic acids in primary structure formation [13]. The dispersity factor in the humus horizon of light gray forest soils is on average 14.6% for the sample (Table 1), which indicates good water resistance of microaggregates. At the same time, the humus horizon of light gray forest soils has an unfavorable macrostructure. It is lumpy and not waterproof, but due to the relative stability of microaggregates, the humus horizon has excellent aeration and good water permeability.

Within the sample, the dispersity factor varies from 9.1 to 18.6% and depends on the humus content – the correlation coefficient is 0.89. The median (Med=15.0%) and mode (Mo=17.5%) are higher than the average for the sample, therefore, soils with a higher dispersity factor in the humus horizon than the average prevail among the studied samples of light gray forest soils. The kurtosis coefficient equal to -1.3 indicates a flat-topped distribution, that is, the spread of values relative to the average. Asymmetry is left-sided, weak. The variation can be characterized as small (Cv=19%).

Thus, the humus horizon ($A_1$) of virgin light gray forest soils in the region is characterized by a gradual decrease in the ability of primary structure formation, which in the future may lead to a deterioration in agrophysical properties and other fertility elements.

The podzolic process in light gray forest soils is not as pronounced as eluviation. Therefore, the presence of a podzolic horizon ($A_3$) is a rather rare phenomenon. Usually, because of soil formation, a humus-eluviated horizon ($A_1A_2$) or eluviated-illuviated ($A_2B$) is formed, which have a lamellar structure characteristic of weakly podzolic soils. However, in these horizons, the eluvial process is pronounced, because of silt particles and colloidal particles that are involved in the primary structure formation migrate deep into the soil profile, forming an illuvial horizon (B).

In the humus-eluviated horizon $A_1A_2$ of light gray forest soils of the Trans-Urals, the dispersity factor slightly decreases relative to the humus horizon ($A_1$) and averages 14.3 ± 3.0% for the sample. This fact indicates that the eluvial process in light gray forest soils proceeds throughout the entire humus layer ($A_1A_1A_2$). The sample variance ($\sigma^2$) increases compared to the humus horizon, therefore, the humus-eluviated horizon is less homogeneous. The coefficient of variation is 21%, which corresponds to the average variability. In the illuvial horizon $B_1$ of light gray forest soils, the dispersity factor decreases to 11.5% on average, changing in the range of 7.9–15.0%. The variability is small.
(Cv=14%). In the illuvial horizon $B_2$, the value of the dispersity factor again increases to 12.7±2.0%, while the variability also slightly increases (Cv=16%). In contrast to chernozems, in which this process manifests itself to the maximum extent, in flushing type of water regime, which reduces the processes of eluviation and enhances the sod process.

In the absence of watersheds, which causes their development in less humid conditions than light gray forest soils. In the transitional horizon $BC$, the dispersity factor varies from 9.4 to 19.0%, averaging 13.8%. The variability increases but is estimated to be small (Cv=19%).

**Table 1.** Statistical characteristics of the dispersity factor in the profile of gray forest soils in the Northern Trans-Urals.

| Horizons       | m    | Med | Mo | s    | $\sigma^2$ | Ex  | A  | min | max | min | max | Cv  |
|----------------|------|-----|----|------|------------|-----|----|-----|-----|-----|-----|-----|
| Light gray forest soil (n=96) |      |     |    |      |            |     |    |     |     |     |     |     |
| $A_1$          | 14.6 | 15.0| 17.5| 2.8  | 7.7        | -1.3| -0.3| 9.5 | 9.1 | 18.6| 19  |
| $A_1A_2$       | 14.3 | 16.0| 16.0| 3.0  | 9.2        | -1.6| -0.4| 9.3 | 8.8 | 18.0| 21  |
| $B_1$          | 11.5 | 11.1| 10  | 1.6  | 2.4        | -0.1| 0.6 | 7.1 | 7.1 | 15.0| 14  |
| $B_2$          | 12.7 | 12.5| 10  | 2.0  | 4.1        | -0.7| 0.3 | 8.1 | 9.0 | 17.1| 16  |
| $BC$           | 13.8 | 13.3| 12  | 2.6  | 6.8        | -1.2| 0.2 | 9.6 | 9.4 | 19.0| 19  |
| Gray forest soil (n=111) |      |     |    |      |            |     |    |     |     |     |     |     |
| $A_1$          | 12.2 | 11.8| 15.9| 2.9  | 8.6        | -1.1| 0.2 | 10.7| 7.6 | 18.3| 24  |
| $A_1A_2$       | 13.2 | 12.5| 16.0| 2.4  | 5.7        | -0.8| 0.6 | 9.3 | 9.9 | 19.1| 18  |
| $B_1$          | 13.0 | 12.6| 10.3| 2.4  | 5.7        | -1.2| 0.3 | 8.3 | 9.4 | 17.8| 18  |
| $B_2$          | 13.3 | 12.4| 18.8| 3.2  | 10.3       | -1.1| 0.4 | 10.7| 8.7 | 19.4| 24  |
| $B_{Ca}$       | 13.1 | 13.0| 13.4| 1.3  | 1.8        | 0.1 | 0.5 | 6.7 | 10.3| 17.0| 10  |
| Dark gray forest soil (n=123) |      |     |    |      |            |     |    |     |     |     |     |     |
| $A_1$          | 7.9  | 7.8 | 10.0| 1.4  | 2.1        | 1.1 | 0.9 | 6.8 | 5.5 | 12.2| 18  |
| $B_1$          | 7.9  | 7.5 | 7.5 | 1.9  | 3.8        | 1.6 | 1.5 | 7.7 | 5.7 | 13.3| 25  |
| $B_2$          | 10.2 | 10.0| 10.0| 1.8  | 3.3        | 0.4 | 1.1 | 7.5 | 7.5 | 15.0| 18  |
| $B_{Ca}$       | 10.8 | 10.7| 10.0| 1.4  | 1.8        | -1.0| 0.1 | 5.1 | 8.5 | 13.6| 13  |
| C              | 12.6 | 12.9| 13.3| 1.7  | 3.0        | -0.1| 0.4 | 7.9 | 9.6 | 17.5| 14  |

*Note: n – number of soil cuts; m – mean values, %; Med – median, %; Mo – mode, %; s – standard deviation, %; $\sigma^2$ – sample variance, %; Ex – kurtosis; A – coefficient of asymmetry; min – minimum, %; max – maximum, %; Cv – coefficient of variation, %.*

The subtype of gray forest soils is mainly formed on elevated sloping or slightly undulating plains of watersheds, which causes their development in less humid conditions than light gray forest soils. In the forest-steppe zone, gray forest soils are found in places of slight depressions on high gently undulating terraces of large rivers or places with a well-defined gully-beam network. In the absence of a natural drainage system, gray forest gley soils form. Gray forest soils develop with a periodically flushing type of water regime, which reduces the processes of eluviation and enhances the sod process. However, in contrast to chernozems, in which this process manifests itself to the maximum extent, in gray forest soils proper, the role of woody vegetation remains significant. A well-developed herbaceous cover provides a stable supply of plant residues in the form of above-ground and root mass. This ensures the formation of humus in greater quantities than in light gray forest soils. The composition of humus is dominated by humates, which provide structure formation. The
macrostructure of the humus horizon \( (A_1) \) of gray forest soils is usually cloddy or silty-cloddy, not water-resistant. In light varieties (light loamy and sandy loam) the structure is silty.

The gray forest soils of the Northern Trans-Urals in the \( A_1 \) humus horizon, on average for the sample, have a dispersity factor of 12.2\% with a variation range of 10.7\% (Table 1). Negative kurtosis \((E_x=1.1)\) indicates a flat-topped distribution, the asymmetry is insignificant. Gray forest soils are less homogeneous in terms of dispersity factor compared to light gray ones, the conclusion about this is based on a higher sample variance \((\sigma^2)\) and coefficient of variation \((C_v=24\%)\). This fact is explained by the variety of combinations of soil formation factors, mainly relief and vegetation. The degree of influence of the parent rock and its mineralogical composition on the formation of gray forest soils in the Trans-Urals is manifested to a lesser extent.

In the \( A_1A_2 \) horizon of the gray forest soil, eluviation is not as pronounced as in the light gray soil. However, the dispersity factor within the sample varies from 9.9 to 19.1\% with an average value of 13.2\%, the variation is small \((C_v=18\%)\). This indicates a strong influence of local conditions on soil formation, which will be the main reason for the diversity of fertility within the boundaries of land use when gray forest soils are involved in agricultural circulation.

In the illuvial horizon \( B_1 \) of gray forest soils, the dispersity factor varies from 9.4 to 17.8\%, with an average value of 13.0\%. The variation is small \((C_v=18\%)\). In the lower part of the illuvial horizon \( (B_2) \), the dispersity factor averages 13.3 ± 3.2\%, which determines the good water resistance of microaggregates. This has a positive effect on the water permeability of the illuvial horizon and significantly reduces the risk of surface waterlogging, both in the virgin state and in arable land. However, in the territory of the Northern Trans-Urals there are places where the probability of overmoistening of gray forest soils is quite high. This is due to the genetic characteristics of the soil-forming rock, which will need to be considered when conducting agricultural activities. The dispersity factor variability is estimated as average \((C_v=24\%)\).

In the lower part of the soil profile in the \( B_{Ca} \) horizon, the dispersity factor averages 13.1±1.3\%, the variation is insignificant \((C_v=10\%)\).

The dark gray forest soils of the Northern Trans-Urals in terms of morphological features, physicochemical, and water-physical properties do not have regional distinctive features in relation to other regions of Siberia [14]. Dark gray forest soils are characterized by a significant accumulation of organic matter in the upper part of the soil profile due to well-developed legume-grass plant associations, which are not inferior to the herbaceous cover of chernozems in terms of root biomass. Woody vegetation is represented mainly by birch and very rarely by aspen, which indicates the absence of even short-term waterlogging. Humus in dark gray forest soils is of the fulvate-humate type, but in the southern forest-steppe there are soils with a humate type like chernozems.

The profile of dark gray forest soils has weak eluvial-illuvial differentiation into horizons. It is quite difficult to distinguish visually, but podzolization is clearly visible by laboratory tests. Thus, favorable conditions are formed in the humus horizon for primary structure formation at the microaggregate level. The dispersity factor of the \( A_1 \) horizon averages 7.9\% for the sample, which is typical for medium structured soils. In visual terms, this is also clearly noticeable - the macrostructure of the humus horizon \( (A_1) \) of virgin dark gray forest soils is granular, less often cloddy-granular. But, unlike chernozems, dark gray forest soils quickly lose it during mechanical processing [15, 16].

Within the sample, the value of the studied indicator varies along the \( A_1 \) horizon in the range from 5.5 to 12.2\% (Table 1). The kurtosis is 1.1, indicating a peaked distribution. It should be noted that the increase in the dispersity factor occurs not due to eluvial processes and a decrease in humus content, but due to relict salinization in the territories where soils of the saline series are located. The hypothesis of modern salinization of gray forest soils cannot be rejected either, since the conditions for this process in some areas are present at the present time.

Among the dark gray forest soils, samples with a dispersity factor index below the average predominate, as evidenced by the average right-sided asymmetry. This allows us to assume that the dark gray forest soils of the Northern Trans-Urals develop according to the soddy type in the direction
of increasing potential fertility [17]. The variation of the dispersity factor index within the sample is estimated as small (Cv=18%).

The illuvial horizon is stretched and indistinctly expressed. The soil aggregates inside are well stained with humus, forming a brownish-black color, which turns into a dark brown color with depth. Its upper part is stained with humus. Black humus films are often present on the edges of structural units, indicating the movement of humic substances from the humus horizon deep into the soil profile. The presence of humus and clay fraction ensures the formation of organomineral colloids in the B1 horizon, which has a beneficial effect on the primary structure formation and the formation of a finely nutty macrostructure. The dispersity factor in the B1 horizon does not strongly differ from the values of the A1 horizon and is 7.9%, which corresponds to the average structure. However, the variation range of the dispersity factor in horizon B1 is wider (from 5.7 to 13.3%). The asymmetry is also right-sided but is assessed as strong. The median and mode equal to 7.5% allow us to conclude that soils with a smaller dispersity factor than the average for the sample predominate. Statistical calculation confirms the development of dark gray forest soils of the Northern Trans-Urals according to the soddy type towards the formation of chernozems. The coefficient of variation is 25%, which corresponds to the average degree of variability.

In the second half of the illuvial horizon (B2), the dispersity factor was 10.2% with a variation range of 7.5%. The distribution of values in the sample has a strong right-sided asymmetry (A=1.1), which indicates the predominance of dark gray forest soils with a dispersity factor in the B2 horizon below the average. The variability is lower than in the upper part of the illuvial horizon (B1), the coefficient of variation is 18%.

In the BCa horizon, the value of the dispersity factor on average for the studied sample was 10.8±1.4%, the variation is estimated as small (Cv=13%). The presence of calcium carbonates had no effect on the primary structure formation - the dispersity factor was within the error. Nevertheless, comparing the values with the parent rock material it can be argued that the modern process of soil formation had a positive effect on the microaggregate composition of the illuvial horizon. In the soil-forming rock (C), the dispersity factor was significantly higher, 12.6%, with a variation coefficient of 14%.

4. Conclusion

Based on large-scale studies of gray forest soils of the Northern Trans-Urals, it was established:

1) The humus horizon of light gray forest soils is characterized by good water resistance of microaggregates – the dispersity factor on average for the sample is 14.6%. The study area is dominated by light gray soils with a higher dispersity factor in the humus horizon than the average, which is associated with a gradual decrease in the ability of primary structure formation and indicates a gradual deterioration in agrophysical properties and other fertility elements.

2) Gray forest soils in the humus horizon, on average for the sample, have a dispersity factor of 12.2%. This subtype, in comparison with light gray soils, has a greater variability of the dispersity factor (Cv=24%), which is due to the variety of combinations of soil formation factors, mainly relief and vegetation.

3) The dispersity factor of the humus horizon of dark gray forest soils is 7.9% on average for the sample, which is typical for medium structured soils. Among the dark gray forest soils, samples with a dispersity factor index below the average predominate. This gives the right to assume that the dark gray forest soils of the Northern Trans-Urals develop according to the soddy type in the direction of increasing potential fertility.

4) Light gray and gray forest soils of the Northern Trans-Urals are characterized by an unfavorable macrostructure of humus horizons. It is cloddy, cloddy-dusty, non-water resistant and quickly destroyed by precipitation. The macroaggregate composition of the dark gray forest soil is granular-cloddy with good water resistance. At the same time, the microaggregate composition of gray forest soils is characterized as satisfactory over the entire soil profile, which makes it possible to improve
structure formation during agricultural development and maintain an optimal structural-aggregate composition for a long time.

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