The effect of hydromorphic processes on the soil organic matter in the Central Russia (case study of the Voronezh and Kursk regions)

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Abstract. The one of the main types of land degradation that cause the most damage to the state of soil cover is local waterlogging of soils. Only in Russia, about 9 million hectares are currently considered waterlogged, including 5 million hectares of agricultural land. On the lowland plains of the forest-steppe zone of the Central Black Earth Region of Russia, local over moistening of the soil cover creates significant difficulties in the use of arable land resources. Natural factors effects waterlogging are the amount of precipitation and the level of groundwater. The objects of research are virgin and arable soils with different hydromorphic conditions in the Central Russian Upland. The article presents results about humus content and reserves in Chernozems typical, Chernozems leached, Meadow-chernozemics soil, Chernozems-meadow soil and Chernozem wet-meadow soil. According to our investigations the most rich humus soils of the forest-steppe is semi-hydromorphic Meadow-chernozemics soils. Meadow-chernozemics leached and typical soils have an average thickness of the humus horizon of 88 and 85 cm and contain about 8.5 and 8.8% humus in the arable layer. Humus reserves in horizons A + AB is 623 and 629.5 t/ha and in a meter layer is 653.5 and 672.5 t/ha.

1. Introduction

Around the world, one of the main types of land degradation that cause the most damage to the state of soil cover is local waterlogging of soils [1, 2]. In Russia, about 9 million ha are currently considered waterlogged, including 5 million hectares of agricultural land [3]. On the lowland plains of the forest-steppe zone of the Central Black Earth Region of Russia, local over moistening of the soil cover creates significant difficulties in the use of arable and resources.

Important factor influencing the preservation of thick chernozemic humus horizons are moist/wet conditions, arising either from a high ground water table, or stagnating surface water, this factor also cannot be responsible alone for the development or preservation of thick humus horizons, because both dry Chernozems and moist/wet Black Earths, with similarly thick humus horizons, may occur in the Silesian Lowland, Poland at very close distances in one slope catena [4].

The increase in the area of waterlogged lands is due to a complex of natural and anthropogenic factors. Natural factors include, first of all, an increase in the amount of precipitation, and, associated with this, an increase in the level of groundwater [5, 6].

Eckmeier E et al found that no absolute time of formation could be stated so far, and that Central European Chernozems formed not only under steppe but also under forest vegetation; the spatial distribution of Chernozems and Phaeozems (the buried chernozemic soil) did not correlate with climate
conditions or topographic position, and until now no other factors were considered to be responsible for Chernozem development. Recent studies showed that these unknown factors could include anthropogenic activity and vegetation burning as they could form black soils or strongly affect the composition of soil organic matter [7]. At the same time Kalinina O et al showed that self-restoration of post-acrogenic chernozems in the forest steppe zone of the European part of Russia within the investigated time scale of more than 50 years was no full in comparison with natural Chernozem [8].

Labaz B et al showed that the direction of transformation of native Chernozems in the Holocene period was strongly related to their position in the landscape, which affected the erosion/accumulation intensity and water drainage conditions (soil moisture regime). As a final result of these transformations, a relief-related zonality of soils has developed with Stagnic/Gleyic Chernozems – Luvic Chernozems – colluvial “Kastanozems” – Haplic Luvisols, in the lower (moist), middle (well-drained), and upper colluvial/eroded sections of the undulating loess plain, respectively [9].

Until 2003-2005 there was a steady increase in the level of groundwater in the territory of not only the Oka-Don lowland, but also on the most aligned watersheds of the Middle Russian Upland (within the Kursk and Voronezh regions). This is confirmed by long-term monitoring of the properties of hydromorphic soils of the Central Black Earth Region in the permanent trial plots of the Voronezh, Lipetsk, Tambov and Kursk regions. Significant (last 50-60 years) increased humidity, expressed in an increase in annual rainfall (429 mm for the ten-year period from 1946 to 1955, 521 mm— from 1956 to 1965, 527 mm – from 1966 to 1975, 570 mm – from 1976 to 1985, 558 mm – from 1986 to 1995, 570 mm – from 1996 to 2005) led to the emergence of new arrays of waterlogged lands even in the territories of the Don right bank not previously affected by this process. However, from 2007 to 2011 a decrease in precipitation was observed, which led to some lowering of the groundwater level. During this period, numerous forest fires occurred. And already starting in 2014, an increase in the level of groundwater was noted at the landfills of the Voronezh, Lipetsk and Kursk regions, where hydromorphic processes have been monitored since 1999 [9].

Outwardly, an increase in the groundwater level on the upland elements of the relief of the Middle Russian Upland in the early years of increased humidity is almost imperceptible. Subsequently, intensification of the processes of waterlogging in the soil begins, which leads to the development of anaerobic conditions, deterioration of water-physical properties, and also negatively affects plants, especially valuable crops [10-12]. In addition, saucer-like depressions or ‘dishes’ (in Russian – steppe saucer) are observed on agricultural fields, the use of which, without the use of special drainage, soon becomes impossible (figure 1).

Figure 1. The evolution of the ‘dish’ (in Russian – steppe saucer) into the swale and its exclusion from arable land, April, 2012 (51°42'26.9"N 38°43'20.1"E)
Over the past 15-20 years, the appearance of such depressions on the fields of the Don river right bank of the Voronezh region (Semiluksky and Kantemirovsky districts) and Kastorensky district of the Kursk region has been noted. This is confirmed by the absence of such depressions on soil maps compiled more than 20-30 years ago and aerial photographs conducted in 2001. Subsequently, a marked increase in the degree of hydromorphism in the spring is observed. Often stagnation of water on the soil surface in the depressions lasts on open watershed areas until May, and from May to mid-July, the level of groundwater was detected at a depth of 1.5-2.0 m.

The aim of this work is to determine the effect of soil moisture regime on the soil organic matter within the forest steppe zone of the Central part of Russia (Voronezh and Kursk regions).

2. Methods and materials

Soil pits were hand dug in the midsummer to expose profiles to depths of at least 100 cm [13]. Data from selected soil profiles of Voronezh and Kursk region, including morphological and physical properties, were collected. Soil bulk samples for laboratory investigation (about 150-300 g) were obtained spaced 10-20 cm apart using a soil knife, without gaps, throughout the thickness of the section.

The objects of research are virgin and arable soils of the Don river right bank of the Voronezh region (Semiluksky and Kantemirovsky districts) and Kastorensky district of the Kursk region. In the period from 2007 to 2016, more than 42 full-profile soil pits were dug, which made it possible to distinguish the dominant soil types – Chernozems typical, Chernozems leached, Meadow-chernozems soil, Chernozems-meadow soil and Chernozem wet-meadow soil. Soil profiles (pits) were made on agricultural land in the village of Tochilnoye, Semiluksky District, Voronezh Region, the village of Novomarkovka, Kantemirovsky District, Voronezh Region, and the village of Orekhovo, Kastorensky District, Kursk Region. Totally were investigated 56 profiles, among them automorphic soils – 6 profiles, semi-hydromorphic – 20 profiles and hydromorphic soils – 30 profiles.

Soil diagnostic parameters, such as the humus content by Tyurin method and soil bulk density (g cm⁻³), were determined in all samples taken. The mass fraction of humus in the soil in percent was calculated by the formula 1:

\[ C = \frac{C_{org} \times 1.724}{1} \]

where, \( C \) – humus content (%), \( C_{org} \) – carbon of organic matter in the soil (%), 1.724 – conversion factor.

The calculation of humus reserves was carried out according to the formula 2:

\[ S = C \times B \times T \]

where, \( S \) – humus reserves (t/ha), \( C \) – humus content (%), \( B \) – soil bulk density (t/m³), \( T \) – soil layer thickness (m).

Soil bulk density is an indicator of soil compaction. It is calculated as the dry weight of soil divided by its volume. This volume includes the volume of soil particles and the volume of pores among soil particles. Bulk density is typically expressed in g/cm³ [14].

The relative humus distribution over the vertical soil profile was also calculated (relative to the upper 20 cm layer, the humus content of which was taken as 100%).

Analytical data were processed by methods of mathematical statistics using application programs MO Excel and STATISTICA.

3. Results and discussion

To date, there have been clear ideas about the nature of the relationship between soil humus and zonal bioclimatic conditions. The relationship between humus and the degree of soil moisture within the forest-steppe zone is much less studied. It is known that the humidity and aeration mode is one of the main factors regulating the speed and nature of the humification of plant residues. The degree of humification depends on the correlation of the processes of aerobiosis and anaerobiosis and reaches its
maximum expression with periodic saturation of the soil with water, followed by its complete desiccation. Such conditions are formed in the forest-steppe zone under meadow-steppe vegetation, but their degree of severity, the ratio of soil moisture and aeration are far different in spaces with different drainage.

The water relationships of Chernozems typical and leached belong to the periodically flushing type. The depth of groundwater beneath them is 10-12 m on the Central Russian Upland. The depth of spring soaking of Chernozems varies from 50-100 cm in the years of low humidity to 100-200 cm in normal. Only in certain particularly wet years does it reach the upper boundary of the zone of increased humidification with humidity exceeding the field moisture capacity, which is located at Chernozems below 5-6 m. In dry years or periods, the entire soil profile of Chernozems dries to wilting moisture. According to the international soil classification – Chernozems typical and Chernozems leached (Voronic Chernozems or Haplic Chernozems).

Meadow-chernozemics soil (Voronic Chernozems or Haplic Chernozems) are characterized by a water regime of the flushing type. The groundwater level varies between 3-5 m (during the growing season) with an average deviation of 1.5-2.5 m for years. The depth of spring soaking annually reaches the upper boundary of the zone of increased moisture, which is usually located 2-2.5 m from the surface of these soils. Even in the driest periods, the profile of Meadow-chernozemics soil does not dry out to wilting moisture. From a depth of 2-2.5 m, the natural humidity is equal to or greater than the field moisture capacity.

Chernozem-wet-meadow soil characterized by increased wetting of the entire soil profile, and the level of groundwater during the growing season ranges from 1-1.5 m and even in sharply arid years does not fall below 2 m.

These differences in moisture in a series of soils: Chernozems, Meadow-chernozemics, Chernozems-meadow, Chernozem-wet-meadow have a definite imprint on their soil organic matter content (humus profile, content, reserves and composition of humus).

According to statistical data, Chernozems typical and Chernozems leached with medium-humus content have a horizon thickness of A + AB of 78.5 and 80 cm, respectively, and contain 6.5% humus in the plow layer. The humus supply in the A + AB horizons is 432.5 and 464.5 t/ha, in a meter layer – 497 and 512 t/ha (table 1).

Under semi-hydromorphic conditions, Meadow-chernozemics leached and typical soils with medium-humus content have formed on the Oka-Don lowland plain, which have an average thickness of horizons A + AB of 83 and 84 cm, which is 4 cm more than that of the corresponding Chernozems. The humus content in the arable horizon is 7.1 and 6.9%, its reserve in the A + AB horizons is about 538 and 534 t/ha (which is more than in the Chernozems by more than 70 t/ha), and in the 1-meter layer - 574.5 and 568.5 t/ha (which is more than more than 50 t/ha in Chernozems).

The most common Meadow-chernozemics leached and typical soils with high humus content have an average thickness of the humus horizon of 88 and 85 cm and contain about 8.5 and 8.8% humus in the arable layer. Its stock in horizons A + AB is about 623 and 629.5 t/ha. And humus reserve in the 1-meter thickness is 653.5 and 672.5 t/ha. The given indicators show that the most rich humus soils of the forest-steppe are not automorphic Chernozems, but semi-hydromorphic Meadow-chernozemics soils.

A comparison of the humus content and reserves in the profile of Meadow-chernozemics soils with the depth of groundwater revealed that the optimal conditions for humus accumulation in the forest-steppe develop with a slight additional surface moisture and groundwater level in the range 3.0-4.0 m.

A further increase in the degree of hydromorphic processes and the rise of groundwater leads to the formation of Chernozem-meadow soils, which, according to the main indicators of the humus profile, begin to gradually give way to Meadow-chernozemics soils.

The Chernozem-meadow leached and typical soil of the Oka-Don lowland plain are characterized by the following statistical data: thickness of horizons A + AB is about 77.5 and 76.5 cm, humus content in the arable layer 6.75 and 7.33%, humus reserve in horizons A + AB – 447 and 469 t/ha, in the 1-meter layer – 486 and 509 t/ha respectively.
Table 1. The main indicators of the soil organic matter depending on the intensity of hydromorphism.

| Soil type                        | Thickness of horizons A+AB, cm | C$_{org}$* 1.724 0-20 cm % | Humus reserves, t/ha       |
|----------------------------------|--------------------------------|-----------------------------|-----------------------------|
| **Automorphic soils**            |                                |                             |                             |
| Chernozems leached medim-humus   | 78.5                           | 6.5                         | 432.5                       | 497                          |
| Chernozems typical medim-humus   | 80                             | 6.55                        | 464.5                       | 512                          |
| **Semi-hydromorphic soils**      |                                |                             |                             |
| Meadow-chernozemics leached medium-humus | 83                        | 7.1                         | 538                         | 574.5                        |
| Meadow-chernozemics typical medium-humus | 84                        | 6.9                         | 534                         | 568.5                        |
| Meadow-chernozemics leached high-humus | 88                        | 8.55                        | 623                         | 653.5                        |
| Meadow-chernozemics typical high-humus | 85                        | 8.8                         | 629.5                       | 672.5                        |
| **Hydromorphic soils**           |                                |                             |                             |
| Chernozems-meadow leached medium-humus | 77.5                     | 6.75                        | 447                         | 486                          |
| Chernozems-meadow typical medium-humus | 76.5                     | 7.33                        | 469                         | 509                          |
| Chernozems-meadow typical high-humus, virgin land | 83                        | 9.895                       | 572                         | 610.5                        |
| Chernozems-wet-meadow leached    | 55                             | 6.85                        | 320                         | 393                          |
| Chernozems-wet-meadow typical    | 55                             | 6.5                         | 304                         | 378                          |
| Chernozems-wet-meadow typical, virgin land | 58                        | 11.12                       | 375                         | 437                          |

On virgin lands, Chernozem-meadow soils contain about 10% humus in the 0–20 cm layer. Its stock in the horizons A + AB with a thickness of 83 cm is 572 t/ha, and in the 1m thickness – 610.5 t/ha.

So, in comparison with semi-hydromorphic Meadow-chernozemics soils in hydromorphic Chernozem-meadow soils, the total thickness of the humus horizon (by 5-10 cm) and humus reserves (on average by 80-90 t/ha) are reduced.

A further increase in moisture content negatively affects the humus accumulation in the soils of the forest-steppe. Chernozem wet-meadow leached and typical soils with a groundwater level of 1 - 1.5 m have a thickness of humus horizons A + AB of 55 cm and contain 6.8 and 6.5% humus in the arable layer. Its stock in humus horizons is significantly lower than that of Chernozems and amounts to 320 and 304 t/ha, and in the 1-meter layer it is about 393 and 378 t/ha. On virgin lands, a high humus content in the 0–20 cm layer (an average of 11%) and a slightly higher thickness of the A + AB horizons (58 cm) are observed. Stock of humus in the humus horizon is 375 t/ha, in the 1-meter soil layer– 437 t/ha. This shows a sharp decrease in the thickness of the humus profile (by 20-40 cm) and humus reserves (by 250-300 t/ha) in Chernozem wet-meadow soils compared with Meadow-chernozemics soils.

The given main parameters of the humus profile indicate that semi-hydromorphic conditions are optimal for humus accumulation over the entire profile of forest-steppe soils. With an increase in the degree of hydromorphic processes, humus accumulation in the upper soil layer gradually increases, decreases in the middle part of the profile, and the thickness of the humus horizon decreases. In addition to the main indicators of the humus profile, this is evidenced by the data of the relative distribution of
humus along the vertical profile of soils (table 2). Chernozems and Meadow-chernozemics soils are close in the vertical distribution of humus. They are characterized by a high humus content in the 0-20 cm layer and a very smooth decrease in depth. In hydromorphic Chernozem-meadow soils, a sharper decrease in the humus content with depth is already observed, especially in the AB horizon. For Chernozem wet-meadow soils, a very high humus content in the layer of 0-20 cm, a double decrease at a depth of 20-40 cm, and a further rapid decrease in the underlying layers are specific. So, at a depth of 50-60 cm, the humus content is almost 5 times less than in the 0-20 cm layer, while in Chernozems-meadow soil it decreased 1.9 times, in Meadow-chernozemics in 1.7 and in Chernozems in 1.5 times.

| Layers, cm | Chernozems | Meadow-chernozemics soil | Chernozems-meadow soil | Chernozems wet-meadow soil |
|------------|-------------|--------------------------|------------------------|---------------------------|
| 0-20       | 100         | 100                      | 100                    | 100                       |
| 20-40      | 86          | 85                       | 75                     | 43                        |
| 40-50      | 74          | 70                       | 63                     | 34                        |
| 50-60      | 67          | 59                       | 53                     | 21                        |
| 60-70      | 57          | 53                       | 42                     | 14                        |
| 70-80      | 40          | 42                       | 25                     | 12                        |
| 80-90      | 29          | 30                       | 22                     | 10                        |
| 90-100     | 24          | 23                       | 14                     | 7                         |

The main factor ensuring this process is, apparently, a more active accumulation of humus in the top horizons of excessively moistened soils compared with Chernozems. This is due to both an absolutely higher number of roots in the upper horizons of soils of increased moisture, and a lower degree of mineralization of organic matter. Here, the humus content of semi-decomposed organic residues increases, which was revealed by morphological studies of Chernozem-meadow soils.

Similarly, findings have been described by Kabala C et al. that moist conditions influencing strongly the preservation of thick chernozemic humus horizons, arising either from a high ground water table, or stagnating surface water, this factor also cannot be responsible alone for the development or preservation of thick humus horizons.

Thus, an increase in hydromorphic processes to the stage of semi-hydromorphic soils is accompanied by an increase in humus accumulation along the entire soil profile to a depth of about 1 meter and an increase in the thickness of the humus horizon. At this stage, the distribution of humus retains a chernozemic character, although a tendency toward a more rapid decline in its content with depth begins to be traced. Further intensification of hydromorphism contributes to the intensification of humus accumulation in the upper part of the humus horizon with a sequential reduction in its power and disturbance of the uniform distribution of humus along the vertical soil profile.

4. Summary
According to the paper aim we studied 10 types of soil with different soil moisture regime and compared them with 2 typical automorphic soils. The main parameters were humus contents (Corg) and humus reserves.

Our findings proved that moist conditions influencing strongly the preservation of thick chernozemic humus horizons. For the forest-steppe zone in Central Russia the most rich humus soils are not automorphic Chernozems, but semi-hydromorphic Meadow-chernozemics soils. At the same time further increase in moisture content negatively affects the humus accumulation in the soils of the forest-steppe zone.

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