E3S Web of Conferences **548**, 04020 (2024) https://doi.org/10.1051/e3sconf/202454804020
AGRITECH-X 2024

Dynamics of the Lower Volga region agricultural landscapes under the influence of climate change

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Abstract. The Lower Volga region soil cover underwent changes during the Late Holocene as a result of the natural and anthropogenic factors influence. Changes in climatic conditions and soil-forming processes were imposed on the settlements construction and agricultural use of land in the XVIII century and on the organization of reservoirs on the Volga-river in the XX century. The medieval climatic optimum was characterized by humid soil formation conditions in the steppe and dry steppe zones, which contributed to the flourishing of the Golden Horde settlements, the desalinization of steppe soils and favored agriculture. The small Ice Age that began from the XVI century led to the decline of settlements and negative soil processes. The soils and cultural layers of the settlements of the Volga Germans who occupied these territories in the XVIII century are characterized by an increase in morphological signs of salinity and the content of carbonates and sodium. In addition, due to climate change and the effects of deforestation, soil erosion has intensified. Slope and landslide processes intensified as a result of the construction of reservoirs on Volga in the XX century. It led to increased degradation of soils, settlements and rural landscapes of the Volga right bank.

1 Introduction

The global anthropogenic transformation of the biosphere and lithosphere leads to changes in the factors and conditions of soil formation and natural mechanisms. The study of the evolution of the paleoenvironment, ancient natural conditions, and soil cover in historical times is of great importance for understanding climate dynamics and its impact on biodiversity change.

Agricultural development of the Volga region's soils originates in ancient times, starting with the Paleolithic people, to various nomadic tribes, then to the Golden Horde cities in the early Middle Ages and to numerous Russian and German settlements of colonists of the XVI-XVIII centuries. The intensity of agriculture increased, despite not always favorable changes in climate and soil cover. The climatic optimum of the Middle Ages contributed to the development of the settlements of the Golden Horde in the Volga region. The steppe and dry steppe zones were characterized by more humid soil formation conditions, chestnut soils

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(Kastanozems) prevailed in the soil cover. The active development of territories, the increased pace of the new cities emergence and the cutting down of floodplain forests for construction led to the accelerated development of soil erosion. The ecological situation was complicated by climatic changes [1]. Since the XVI century the little Ice Age began, the aridity of the territory increased, and gradually the settlements fell into decline. In the XVIII century, these places were occupied by Volga Germans (v. Galka, Shcherbakovka), soils and cultural layers of their settlements are characterized by an increase in the content of carbonates and easily soluble salts and morphological signs of salinity and an increase in sodium content. The change in the hydrological situation of the Volga region in the XX century was complicated by the construction of reservoirs, erosion and landslide processes intensified. This has influenced the evolution of geoecosystems and anthropogenic landscapes, in particular, the evolution of Volga settlements - many of them are now partially or completely abandoned.

2 Materials and methods

The objects of the study are the soils of settlements of different ages in the Lower Volga region (Figure 1). These are Kastanozem (B1) from the village of Nizhnyaya Bannovka (pre-XVIII-XIX centuries), Technosol (B5) from the village of Dubovka (XVIII-XIX and XIII-XIV centuries, respectively), Solonetzs (B2, B4) from the villages of Shcherbakovka and Galka (pre-XVIII-XIX centuries), as well as modern background soils - Regosols, Kastanozem and Solonetz - from the same settlements. Humus horizons are distinguished in all soils, which have more or less obvious signs of plowing in the past.
Morphological properties of the soil samples were studied; pH of water suspension (potentiometric glass electrode), phosphorus group composition (according to the method of Saunders, Williams [2]), carbonates content (volumetric method), the contents of carbon, nitrogen, sulfur, and hydrogen (on the elemental analyzer VARIO EL, Elementar GbmH, Hanau), magnetic susceptibility (based on measurements with a field kappometer (CT-5)), water extract composition, soil carbon isotopic composition were determined.

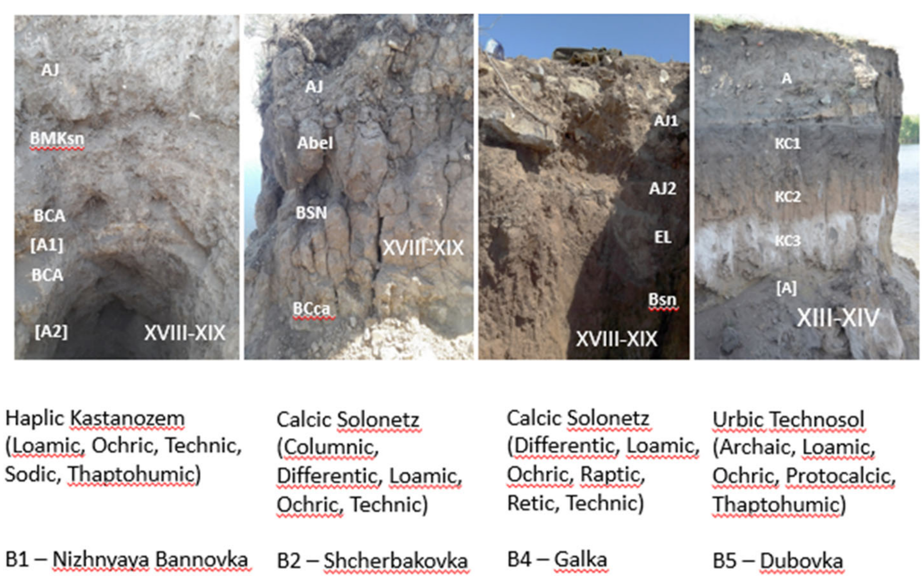

Fig. 1. Soil sections photos.

3 Results and discussion

The morphological properties of the soils of the Lower Volga region clearly indicate the differences between the cultural layers (CL) of the Middle Ages with a darker color, granular and lumpy structure and the presence of artifacts, and the cultural layers of the XVIII and XX centuries with signs which are characteristic of modern natural conditions of dry steppe zone: a structure with elements of columnar and lumpy, signs of salinization and alkaline hydrolysis of minerals.

The elements of granularity, lumpiness and nutiness of the structure of the buried horizons ([A1], [A2] in B1 section - Nizhnyaya Bannovka, CL in B5 –Dubovka) and the presence of aggregates of 0.25-10 mm in size are of relict origin, and are associated with periods of a more favorable climate. The formation of the structure and aggregate composition is associated with fluctuations in climate moisture, and in the buried Kastanozems of the Lower Volga region they persist for ~ 4000 years after burial [3].

The total sulfur content is 0.04-0.06% in soils of the Middle Ages, 0.06-0.24% in soils of the XVIII-XX centuries and 0.06-0.15 in background soils, which is due to the activation of the processes of salinization during the medieval climatic optimum and later arid conditions of southern soils, as well as progressive salinization caused by anthropogenic changes in the Volga-river hydrological regime.

The amount of nitrogen and carbon decreases naturally with depth, with the exception of local peaks in buried horizons and cultural layers (Table 1). The nitrogen content in the soils of the Lower Volga region varies from 0.1 to 0.44% (in background soils 0.07 - 0.29%), and organic carbon – from 0.37 to 4% (in background soils 0.54 – 2.89%).

Table 1. Chemical properties of the soils.

Horizon	Depth, cm	%Corg	%S	%N	Magnetic susceptibility, X*10(-6)	Organic phosphorus content, mg/kg	Carbonate content (av.), %	pH(aq.)	Chloride, %	Sulfate, %
Nizhnyaya Bannovka village, B1. Haplic Kastanozem (Loamic, Ochric, Technic, Sodic, Thaptohumic)										
AJ	0-16	3.03	0.34	0.34	8.6	465	0.9	8.19	0.004	0.034
BMKsn	16-51	1.65	0.18	0.18	16.9	355	2	8.63	0.004	0.029
B	51-78	2.56	0.23	0.23	15.8	289	0.5	8.31	0.010	0.182
[A1]	78-87	2.43	0.24	0.24	17.5	1243	1.4	8.28	0.015	0.084
[A2]	95-125	1.98	0.22	0.22	15.9	0	0	7.64	0.035	0.314
[A2]	125-160	2.7	0.29	0.29	21.3	469	0	7.53	-	-
Shcherbakovka village, B2. Calcic Solonetz (Columnic, Differentic, Loamic, Ochric, Technic)										
AJ	0-15	2.26	0.07	0.22	12.8	307	0.6	8.17	-	-
Abel	15-32	1.23	0.06	0.10	14.8	165	0.8	8.75	0.004	0.087
BSN	32-78	0.69	0.10	0.11	20.8	177	0.5	7.71	0.068	0.454
BCca	78-110	0.37	0.08	0.11	11.5	165	0	7.89	0.102	0.320
Galka village, B4. Calcic Solonetz (Differentic, Loamic, Ochric, Raptic, Retic, Technic)										

AJ1	5-30	1.35	0.06	0.18	10.6	368	3.6	8.33	0.004	0.061
AJ2	30-49	4.06	0.12	0.38	18.8	714	0	7.15	0.004	0.106
EL	50-53	1.44	0.06	0.18	51.4	419	0	5.92	0.008	0.061
Bsn	50-85	0.89	0.06	0.13	31.7	360	0.8	7.14	0.013	0.140
Dubovka village, B5. Urbic Technosol (Archaic, Loamic, Ochric, Protocalcic, Thaptohumic)										
AJ	0-15	1.49	0.05	0.16	27.1	269	0.2	7.81	0.003	0.103
KC	15-35	1.74	0.06	0.19	32.4	529	0	8.17	0.001	0.055
RJ1	35-70	1.29	0.04	0.13	18.1	490	2.3	8.2	0.001	0.108
RJ2	70-110	0.77	0.06	0.07	11.3	0	0.3	7.88	0.002	0.206
[A]	110-175	0.74	0.04	0.06	17.8	65	0	8.25	0.003	0.069

The pH of the Lower Volga region steppe soils is mainly neutral and medium alkaline, which is due to salinity, as well as the content of carbonates and gypsum, the presence of limestone boulders – remnants of the foundations of old settlements. In buried horizons and cultural layers, the pH is weakly and medium alkaline: from 7.5 (Nizhnyaya Bannovka, 95-125 cm) to 8.25 (Dubovka, 110-175 cm). The acidity of the studied samples and background soils differs slightly, mainly in the direction of pH reduction in background soils, that is, anthropogenic soil development naturally shifts the reaction of the medium to the alkaline side. The largest change was noted for the section in the Nizhnyaya Bannovka – the pH of the section of the background soil is less alkaline: 6.9 versus 8.2 in the upper horizon.

Salinity of the profiles and the presence of accumulations of easily soluble salts are characteristic features of the soils of the Lower Volga region.

A large amount of CaCO3 is observed in the Volga region soils (Table 1): in the soils of Nizhnyaya Bannovka the CaCO3 content ranges from 0 (in the buried horizon at a depth of 95-125 cm) to 3% (BCA, 87-95 cm). The absence of carbonates in the buried horizon may indicate its bulk nature – it could have been brought from other places or abundantly fertilized humus material for creating vegetable gardens. In the soil of Shcherbakovka village, the amount of carbonates ranges from 0 (78-110 cm) to 0.8% (15-32 cm), in Galka village – up to 3.6% in the upper horizon (5-30 cm, next to the limestone slab), in Dubovka – from traces of CaCO3 to 2.3% (at a depth of 35-70 cm).

Carbonates were not found in the background (modern) soils of Verkhnyaya and Nizhnyaya Bannovka settlements; in the background soil of Shcherbakovka village their content is about 2%; for the background soil of Galka village– 0.3-3.9% (maximum value in the Bt horizon); in the horizon B (60-90 cm) of the background soil of Dubovka, the largest amount of carbonates is observed – about 8%. Naturally, there is a slight increase in the content of carbonates in soils as they approach the Caspian Sea.

The content and features of salts profile distribution reflect the degree of atmospheric and soil moisture content, mark the direction of soil-forming processes in various historical epochs of settlement existence.

The distribution and concentrations of salts along the soil profile of the Lower Volga region (Figure 2) show that the sulfate and chloride-sulfate type of salinization mainly prevails in soils. Moreover, the sulfate type of salinization dominates in the soils of Dubovka village, which are the closest of the studied objects to the Caspian Sea, which may be an indirect proof of the ideas about the aerial-aeolian genesis of chloride salinization of the Volga region soils [4], which most actively occurred during maximum aridization in the subboreal period of the Holocene (~4-5 thousand years ago). In the subsequent time, a downward migration of salts was established in the soils.

According to the classification of soils based on toxic salts content [5], the soils of Nizhnyaya Bannovka village are slightly saline, and the soils of Shcherbakovka village are medium–saline; in other soils, the salt concentrations do not exceed the toxicity threshold. The heterogeneity of salts distribution along the profile indicates a complex picture of the periods of salinization and desalinization of soils during the Holocene, which were also corresponded to climatic changes and the formation of different types of soils.

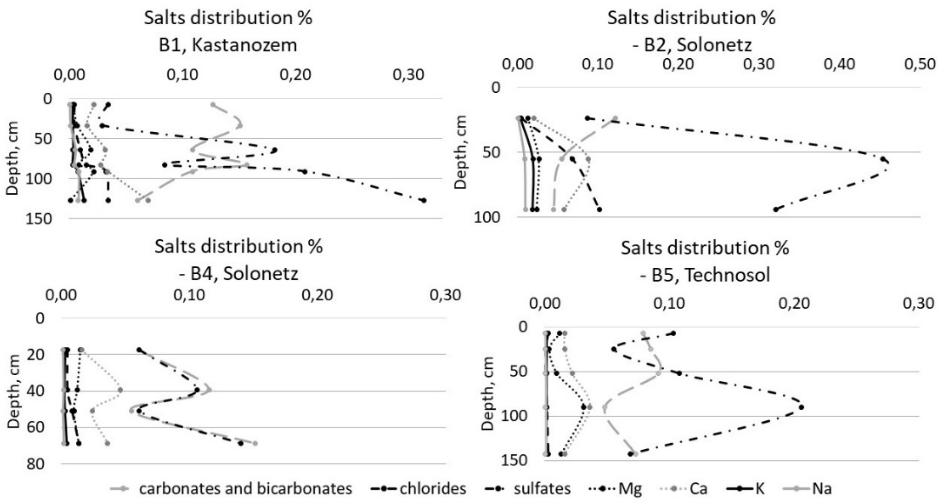

Fig. 2. Salts distribution (%) in soil profiles.

The maxima of organic phosphorus content in soils are an indicator of humus accumulation processe intensity, as well as diagnose traces of human activity. Inorganic phosphorus can accumulate as a result of alluvial processes, as well as in connection with local manifestations of anthropogenic impact – perhaps this is due to the heterogeneity of its distribution along the profile. The maximum proportions of organic phosphorus are up to 40-60% of the total, and the depths mostly correspond to the maximum content of organic phosphorus.

The maximum of organic phosphorus in section B1 (Kastanozem, Nizhnyaya Bannovka) occurs at a depth of ~80 cm (1240 mg/kg) and after 140 cm, which corresponds to the cultural layer highlighted in color and structure. Section B2 (Solonetz, Shcherbakovka) does not contain pronounced maxima, despite the fact that bones and fragments of ceramics were found at a depth of 70-80 cm. Inorganic phosphorus has a regressive-accumulative distribution (max. – 2300 mg/kg). In B4 section (Solonetz, Galka), the maxima of organic and inorganic phosphorus fall on the horizon at a depth of 30-49 cm (750 and 11350 mg/kg, respectively) – under the remains of limestone foundations of buildings; at the same depth, remains of decomposed wood, inclusions of brick and coal were found. In the section B5 (Technosol, Dubovka, Beldjamen) The maxima of organic and inorganic phosphorus can also be traced at a depth of ~30-40 cm (about 500 and 4600 mg/kg), which corresponds to a cultural layer with numerous fragments of brickwork, ceramic dishes and bone material.

The values of magnetic susceptibility (Figure 3) confirm the results of cultural layers selection and correlate with the maxima of organic phosphorus content in the soils of the Volga region. In addition, magnetic susceptibility has maxima in the surface humus horizons, which is associated with the content of organic matter. This may be due to favorable environmental conditions, the simultaneous accumulation of humus and magnetic minerals, and the presence of iron compounds in the form of organo-mineral complexes.

In most cases, humus horizons have increased values of magnetic susceptibility due to the possible accumulation of magnetite and maghemite during the soil formation process [6,7].

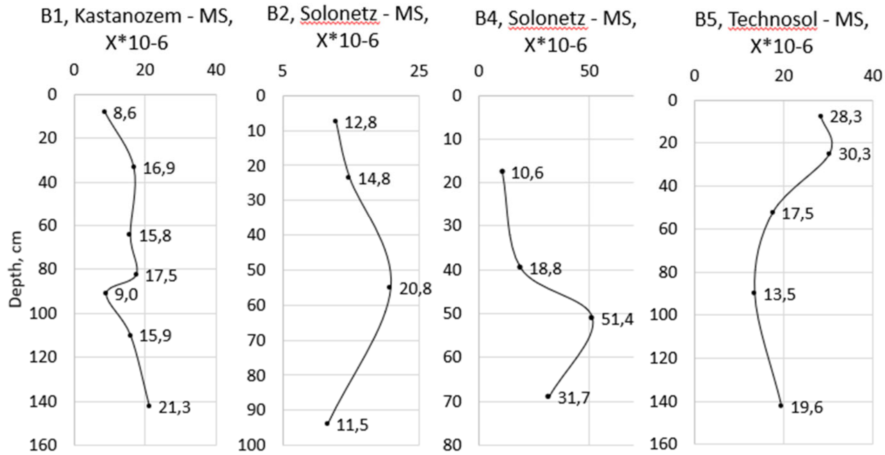

Fig. 3. Magnetic susceptibility of soils.

Alekseev A.O. [8] revealed a correlation between the magnetic characteristics of steppe soils and the amount of precipitation according to the formula: the average annual precipitation rate = 86.4Ln(Xb-Xc)+90.1; where Xb is the magnetic susceptibility of the soil, Xc is the magnetic susceptibility of the rock.

Calculations of the average annual precipitation rate based on the magnetic susceptibility of different-aged cultural layers of Lower Volga region reveal a distinct medieval pluvial, aridization of landscapes during the era of formation of cultural layers of Russian and German settlements (during the Little Ice Age) and the modern moderately humid environment (Figure 4). It is obvious that the processes of salinization-desalinization of soils followed the identified periods.

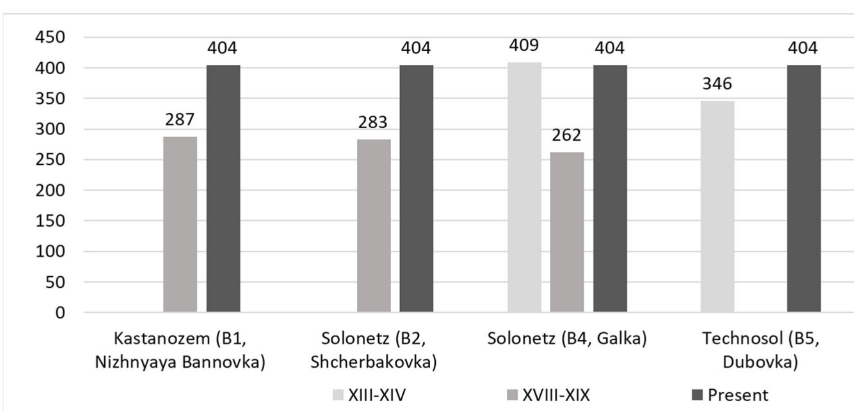

Fig. 4. The average annual precipitation (mm) in the XIII-XIV centuries and XVIII-XIX centuries, calculated from the magnetic susceptibility of cultural layers of Lower Volga. (Current values - Volgograd weather station data).

Isotope curves have been obtained for some of the sections, and they diagnose the polygenetics of the studied soils. In all cases, there is a well-traced rhythm in change in vegetation following climate change.

The upper part of the profiles corresponding to the daytime soil develops under conditions of increasing moisture. The values of the isotope ratio are reduced from -23 % at the upper boundary of the buried soil to -25 - -27 % in the daytime horizon (Figure 5).

The lower buried soil diagnoses a distinct aridization of the climate and an increase in the proportion of C4 plants. Isotopic ratios increase from -24- -25 in the lower buried part of the profile to -23 % (on contact with the day soil).

At the same time, the lower part of all the studied sections also reveals an increasing moisture content of the climate in terms of the isotope ratio: from -23 to -24 - -25 %.

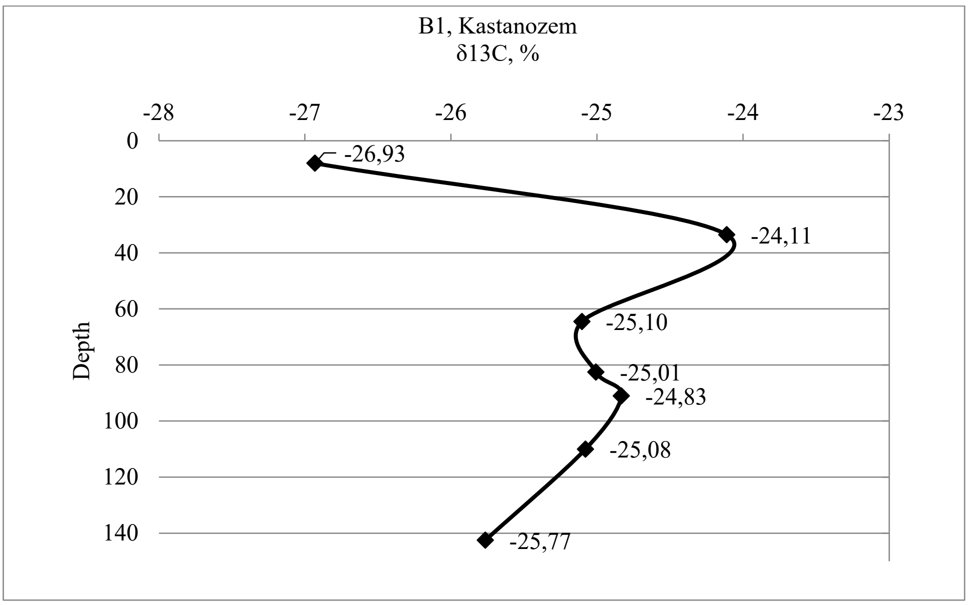

Fig. 5. The isotopic composition of carbon in Haplic Kastanozem (Loamic, Ochric, Technic, Sodic, Thaptohumic) (Nizhnyaya Bannovka village, section B1).

4 Conclusion

The natural and agricultural landscapes of the Volga region during the Holocene were subject to changes associated with climate fluctuations, a change in the direction of soil-forming processes, and increased anthropogenic activity. The nature of soil cover also changed - the processes of salinization and increase in sodium content began to reveal gradually and with varying intensity in the chestnut soils (Kastanozems) prevailing in the region in the early Middle Ages. In the Middle Ages, a favorable climate and fertile soils were one of the factors that led to the flourishing of the Golden Horde cities in the Volga region. One of them is the trading town of Beldjamen (now Dubovka village). There was a desalinization of the soils and active humus accumulation, chestnut soils (Kastanozems) suitable for development prevailed in the soil cover. With the beginning of the Little Ice Age, the deterioration of the soil began, and at the same time the Volga Germans came to the region territory, whose settlements are now partially abandoned (Galka village, Shcherbakovka village). Despite the negative processes of salinization and erosion, frequent crop failures and droughts, soil cultivation actively continued and increased, new areas for arable land were developed. The next stage in the transformation of landscapes was the construction of reservoirs on Volga in the XX century, which caused the flooding of many lands and villages, landslide processes and degradation of soils and water, aggravation of the arid conditions of the region.

The work was carried out within the framework of the Moscow State University state assignment № 122011800459-3.

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