Forests advancements to grasslands and their influence on soil formation: Forest Steppe of the Central Russian Upland

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Forests advancements to grasslands and their influence on soil formation: Forest Steppe of the Central Russian Upland

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Abstract. Natural replacement of grasslands by forests during the Late Holocene and in the modern period was observed. Soil changes as reaction to this phenomena were analyzed. Long-term transformation of steppe Chernozems into forest Phaeozems and Luvisols has been studied in archaeological landscapes in 5 key sites by comparison of paleosols buried under Early Iron Age defensive ramparts, with modern background soils of broad-leaved natural environments. Short-term changes of Chernozems covered by tree cover were studied in 3 key sites, presented by 55 yrs broad-leaved shelterbelts, planted on initially open spaces with Chernozems in agroforestry landscapes. Long-term (during the last 2800-2000 yrs) steppe Chernozems transformation into the forest categories of soils leaded to decrease of humus pools in the soil profiles more than 2 times. After 55 years of steppe Chernozems existence under a tree canopy (in shelterbelts) soil profiles exhibited an increase of humus stocks to depths 1 m in average on 13% at initial values. Stages of Chernozem evolution in response to changing land cover from forest to grassland is discussed. Natural advancement of forest over grasslands continues in the contemporary period. From 1970–2014 rates of climatically determined frontal advancement of forests edges onto grasslands, studied in 6 key sites in different regions of forest steppe, have linear connection with the hydrothermal coefficient (HTC). According to this linear trend, rate of forests advancement to grasslands in modern period declines to zero at HTC 0.75 (the index of the center of steppe zone).

1. Introduction

Relationships between forests and grasslands in space and time in transitional zone between forests and steppes – prairies in Eurasia and North America is one of the most discussed questions in ecological and geosciences issues over the last century. The disclosure of the patterns of development over time of these two spatially conjugated types of vegetation and corresponding them types of soils has fundamental importance since it solves the problem of the origin, formation and functioning of the forest-steppe as a geographic zone, large geosystem and natural ecoton. One of the first scientists who begun discussion was Korzhinskii, studied steppe animals signs (mole holes, krotovinas) in grey forest and podzolic soils under native forests of the East-European plain [1]. Many authors then investigated responses of soils to contrast changes in time of forest and grass vegetation. Buol et al. [2] presented examples of soils transformation in different regions of North America as a result of bioclimatic changes in Middle and Late Holocene. Bettis III et al. [3], used a complex of scientific approaches including the study of soil chronosequences, for Upper Missouri Valley. They reconstructed dry climatic conditions with prairie vegetation in the Middle Holocene and humid conditions with forest vegetation in the Late Holocene [3]. Alexandrovskiy and Chichagova [4] analyzed ^{14}C dates of organic matter of the Holocene soil chronosequences allowed two main stages of Holocene soil formation within East-European plain center and Northern Caucasus: a humus-accumulative steppe stage Early and Middle Holocene and a humus-degradation - Luvisol-forming forest stage after 3500 BP. Vyslouzilova et al. [5] according to comparative analysis of soils buried under mounds of Bronze Age and their modern background analogies in Czech Republic, reconstructed dry steppe conditions about 4000 BP in places covered by contemporary broad-leaved forests. Eckmeier et al. [6] discusses different points of views on origin and development of Chernozems in the Central Europe, and in their turn – bioclimatic changes in the Holocene as a factor of these soils development. Spore-pollen reconstructions also indicate essential spatial-temporal variations of forest and steppe areas in the Holocene. For example, Shumilovskikh et al [7] are marked the Middle Holocene expansion of steppe formations from the south to the north in the central part of Eastern Europe, and shift of the forest-steppe boundary with broad-lived forests to 50–70 km further north-west during the period 7,000–4,500 cal yr BP.

Among other regions, the Central Russian Upland is one area that generated discussions in the development of a number of hypotheses in soil science and biology. One of the first hypothesis was forest assimilation of grasslands as a natural phenomenon of relationships between forest and steppe vegetation resulting in the evolutionary transformation of Chernozems into Phaeozems and Luvisols (soils are named according to WRB-2015 [8]) [1]. Another scientists explained isolated distribution of forest and steppe areas in the forest-steppe zone by the influence of human economic activities. It has been suggested that the areas of Chernozems could appear as the result of forest cutting and replacement of former forests by agricultural lands [9]. The third hypothesis explains that Phaeozems and Luvisols (forested soils) are quite specific soils in the forest-steppe zone, whose development under insular areas of broadleaved forests began since the first half of the Holocene together with the development of Chernozems under meadow steppe ecosystems, and whose areas were stable during the entire Holocene [10]. Recent research by Rusakov et al. [11], based on the study of soil chronosequences within the archaeological site - settlement of Early Iron Age in Vorskla River basin, continues the development of this point of view – assuming of vast forest areas existence in the forest steppe at least since the Middle Holocene [11]. The forth hypothesis is pointed at climatically determined evolution of Chernozems into Phaeozems–Luvisols as a result of cooling and moistening of the climate. Authors proof that the invasions of forests into steppes in the forest-steppe zone for the last 10 millennia developed intensively only during the Late Holocene - as a result of climatic moistening [4,7].

Our aim was to identify the most plausible of these hypotheses, to reveal the modern trend of spatial-temporal interrelations between forests and steppes, and to study reactions of soils to contrasting changes of plant cover within forest-steppe zone. We completed this interdisciplinary research study in the southern area of the Central Russian Upland.

2. Objects, approaches, materials

Key site locations of the study area (figure 1) were grouped into three blocks – in accordance with the approaches developed to address the objectives of the research. In the first block, including plots 1–6 modern (since 1970 until 2014) tendencies of naturally determined changes in forest areas were studied. The second block of key sites (7–23) was selected for analysis of long-term changes in vegetation and soils that occurred in the Late Holocene. The second block is divided into two groups of key sites: areas of palaeogeographic reconstructions of soils and vegetation within archaeological landscapes (7–11), and key sites with soil pits (12–23) in which stocks of organic matter (humus) for modern zonal soils of the forest-steppe (Chernozems, Phaeozems and Luvisols) were determined. The third block of key sites (24–26) consists of plots in which transformation of Chernozems occurred under forest vegetation during the first several decades of tree cover growth.

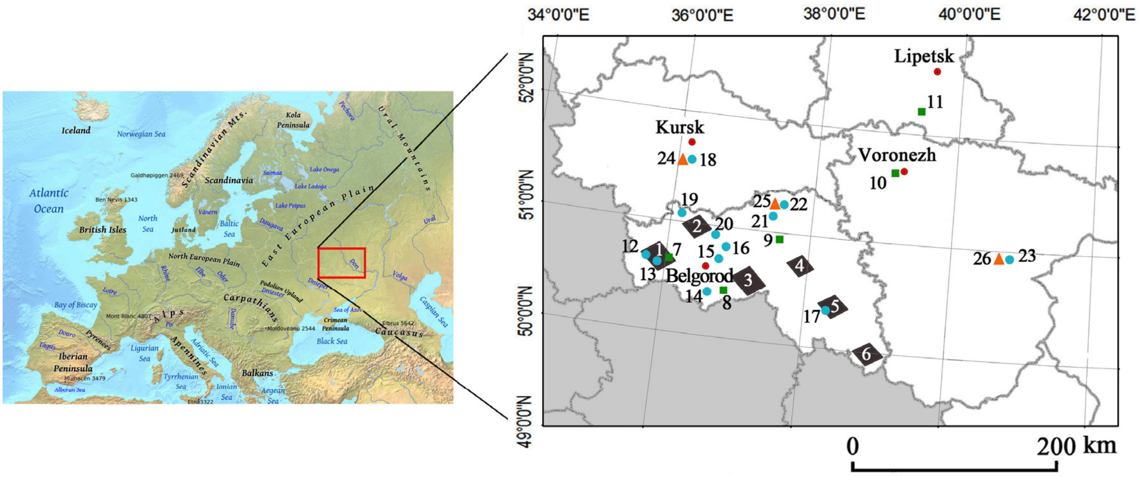


Figure 1. Location of key sites. Plots of research of spatial-temporal changes of forest area during contemporary period: 1 – 6. Plots of study of long-term changes of forest area and evolution of soils within archaeological landscapes: 7 – Borisovka; 8 – Dmitrievka; 9 – Petropavlovka; 10 – Voronezh; 11 – Podgornoe. Plots of sampling for identification of humus stocks in zonal soils of forest-steppe: Phaeozems and Luvisols: 12 – Kazachya Lisitsa; 13 – Hotmyzhsk; 14 – Polyana; 15 – Melikhovo; 16 – Shehovtsevo; 17 – Samarino; Chernozems: 18 – Kursk; 19 – Safonovka; 20 – Zhimolostnoe; 21 – Yur'evka; 22 – Gubkin; 23 – Talovaya. Plots of study of Chernozems transformation under tree cover during first decades of tree growth: 24 – Streletskaya Steppe; 25 – Yamskaya Steppe; 26 – Kamennaya Steppe. Note: key sites 1-6 are shown at the scale of the site map, but the other sites are not to scale.

The key sites to assess spatial-temporal changes of forests in the modern period (1–6; figure 1) were situated in Belgorod oblast (one of administrative units in the south of the Central Russian Upland). These key sites were selected taking into account differences in climatic conditions. The hydrothermal coefficient was chosen as an indicator by which climatic differences were determined. The hydrothermal coefficient (HTC) of Selyaninov [12] calculated as HTC = $\Sigma Q/0.1\Sigma T$, where Q and T are precipitation (mm) and temperature (ºC), respectively, during the growing season (defined as $T >$ 10 ºC). The range of HTC values was between 0.99 (northern part of steppe zone, key site 1) and 1.2 (moist part of forest-steppe, key site 6). The change in forest cover was detected by satellite images for two periods in 1970 (http://earthexplorer.usgs.gov) and in 2014 (https://map.yandex.ru). The resolution of the satellite images for both study dates was 1.8 m/pixel. Satellite images were similarly geographically referenced into the WGS 84 coordinate system (Projection UTM, Zone 36N). Geo-referencing and geometric correction was performed by using the software package ERDAS IMAGINE. The study key sites were delineated using ArcGIS 10.1, resulting in an integrated archive of satellite images and vectored layers of data (for each study period and location). Wooded lands were delineated at the scale 1: 9000 enabling the assessment of linear change at the one square meter level. This image resolution allowed for an accurate quantitative assessment of forested area and the rates of deforestation or afforestation. Total area of all six key sites was 2043 km^2.

The rate of forest edge advancement (m/year) was estimated in places where forest areas contacted with grasslands. Analysis of a subset of sites within slopes of ravines and river valleys for northern and southern exposures was performed. For those sites the following selection criteria were included that the area of the forested slope could not be dissected by roads or railways, settlements, or croplands, and must have grassland connectivity. Forest area linear increment was determined in ArcGIS by measuring the distance between forest borders for the period 1970–2014. The distance between adjacent linear measurements of forest edge increments in satellite images in real terrain ranged from 15 to 30 m.

For the study of long-term changes of forest area and evolution of soils within archaeological landscapes the following approaches were used. Archaeological landscapes were represented by ancient settlements, which were studied jointly by archaeologists and soil scientists. These settlements appeared in the Scythian epoch at the beginning of Subatlantic climatic period of the Holocene in the interval from 2800–2000 BP. Some of them (Dmitrievka, Podgornoe) ended their functioning in the medieval epoch, and have defensive earth ramparts created in different periods. For soil scientists these sites hold valuable palaeoenvironmental information in the soils buried under the defensive earthen ramparts surrounding the settlements. The studied settlements have similarities in environmental factors including parent material, relief, and vegetation. All the settlements in the area are covered by loesslike loams and are situated on elevated plateau interfluves. The surface of the ancient settlements is under oak broadleaved forests typical of forest-steppe landscapes in the center of the Eastern Europe and the Central Russian Upland in particular. At all the sites, buried palaeosols have been well preserved under earth deposits of ramparts of the Early Iron Age and the Early Medieval epoch. These profiles were studied in order to reconstruct the history of soil development and the palaeoenvironmental conditions. In the study we used the method of soil chronosequences, which is widely applied by Russian soil scientists and archaeologists [4,11]. This method is based on the comparative analysis of ancient soils buried under archaeological monuments and natural surfaces of modern soils near the archaeological sites. Buried soils were isolated from active pedogenesis and factors of soil formation (climate and vegetation) and retained their properties reflecting environmental factors before their burial over a long period (millennia) – untill the moment of their study. A comparison of buried palaeosols with background surface soils that continued their natural development up to the present period makes it possible to identify the direction and intensity of soil evolution as well as changes of plant cover over time. Absolute dating of ramparts was conducted by the radiocarbon method with samples analyzed at the radiocarbon laboratory in Kiev. At the Dmitrievka site, dating of buried soils was completed using archaeological methods due to absence of dating objects on radiocarbon (coal, bones), extracted during archaeological excavations.

In addition to the study of soils within archaeological landscapes, the authors conducted studies of organic matter (humus) stocks to 1 m depth of modern zonal soils of forest steppe in six key sites represented by natural broadleaved forests, and in six key sites in virgin grasslands (meadow-steppe landscapes). All of these sites are situated within flat interfluves with parent materials of loesslike loams.

The third aspect of our studies concerned transformation of Chernozem soil in places of former grasslands and crops, which recently (55 yrs ago) were converted to tree plantations. As a model of natural process of forest invasions of steppes, we used artificial shelterbelts plantings on fields of agricultural management in the northern (Streletskaya Steppe site), central (Yamskaya Steppe site) and southern (Kamennaya Steppe site) parts of the forest-steppe zone. At the Streletskaya Steppe the shelterbelt consists of black poplar (*Populus nigra*) and silver birch (*Betula verricosa*), at the Yamskaya Steppe – American maple (*Acer negundo*), at the Kamennaya Steppe – English oak (*Quercus robur*) and balsam poplar (*Populus balsamifera*). Within Streletskaya Steppe the key site study soils are presented by Chernic Luvic Chernozems, and in the other 2 key sites – by Chernic Haplic Chernozems [8].

All field studies of soils included morphological analysis of the soil profiles, the comparative geographic analysis, and statistical methods. In every sub-area of each key site, indexes of soil properties were calculated as arithmetic mean from 2 duplicate soil profiles. Soil profiles were studied in large (1.2×2 m) and deep (up to 2 m) soil pits. The morphological description of soil profiles was accompanied by morphometric measurements of genetic horizon depth and soil sampling from given depths (every 10 cm). Soil bulk density was determined by sampling of soil with steel rings of known volume in triplicate for all sampled profiles.

The content of soil organic carbon was determined by method of Tyurin (wet combustion) according to State Standard (GOST 26213-91). Sample pH in H_20 was determined using the potentiometric method (GOST 26423-85).

3. Results and discussion

In all key sites of soil-archaeological research (Borisovka, Dmitrievka, Petropavlovka, Voronezh, Podgornoe) soils buried under the ramparts of Early Iron Age settlements at the beginning of Subatlantic period of the Holocene have been identified as dark-humus soils. In Borisovka and Voronezh sites they can be classified as steppe Chernozems. In Dmitrievka, Petropavlovka, and Podgornoe sites buried Chernozems were on the initial stages of transformation under forest vegetation with such indicators of forest pedogenesis as angular blocky structure of buried B horizons and glossy films or cutanas, which formed as the result of downward migration of organo-mineral substances in a cool microclimate under a forest canopy. The modern analogies of the Early Iron Age palaeosols are represented by Phaeozems and Luvisols that developed under influence of long-term forest soil formation. As an example, in figure 2 pairs of soil profiles (buried and background) from the Borisovka key site are compared. Data of the classification position of buried and background soils at all study sites are summarized in Table 1.

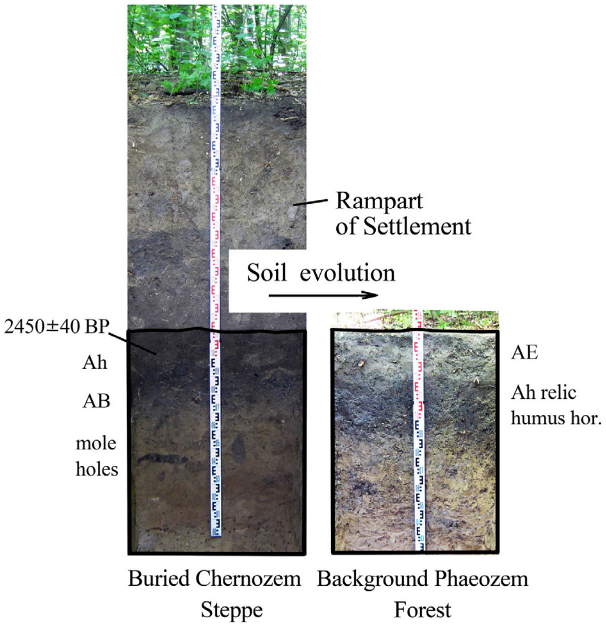


Figure 2. Buried and modern soils studied in the archaeological landscape Borisovka. The arrow shows the direction of the bioclimatic evolution of soils as a result of steppe replacement by forest (data from Chendev [13]).

Conclusive evidence of the steppe past of the soils buried under the studied ramparts is the presence of burrows (krotovinas) of typical steppe animals – mole rats. Krotovinas in buried soils are often filled with well-structured loamy humus-rich material of Chernozems. Examples of some of these krotovinas are shown in figure 2. The importance of information about krotovinas and their filling in buried soils for paleoclimatic and paleogeographic reconstructions is discussed in Pietsch [14].

Table 1. Classification status of soils (according to WRB-2015 [8]) studied at archaeological landscapes in the Central Russian Upland.

Key site	Buried paleosols		Background modern soils
	VIII–I centuries BC	VIII–X centuries AD	
Podgornoye (Lipetsk oblast)	Chernic Luvic Chernozem 2030±50 BP	Chernic Greyzemic Luvic Phaeozem 1150±110 BP	Greyzemic Haplic Luvisol
Dmitrievka (Belgorod oblast)	Chernic Luvic Chernozem VIII–VI centuries BC	Chernic Greyzemic Luvic Phaeozem VIII century AD	Greyzemic Haplic Luvisol
Voronezh (Voronezh oblast)	Chernic Luvic Chernozem 2790±70 BP	No	Greyzemic Luvic Phaeozem
Borisovka (Belgorod oblast)	Chernic Haplic Chernozem 2450 ± 40 BP	No	Greyzemic Luvic Phaeozem
Petropavlovka (Belgorod oblast)	Chernic Luvic Chernozems 2450±60 BP, 2380±50 BP	No	Greyzemic Luvic Phaeozem

In our early studies genetic differences in the morphological properties of buried and background soils have been discussed [15]. In other works they also were complemented by differences in their physical and chemical properties: the evolutionary transformation of Chernozems into Phaeozems and Luvisols is accompanied by the increase in the coefficient of textural differentiation of clay (ratio of clay content / reserves in horizon B to that in horizon A), leaching of carbonates, and acidification of the soil profile [13,16].

When studying the soils buried under the ramparts compared with background soils, it was impossible to compare their humus status, since after burial, diagenetic changes in soil organic matter occurred, accompanied by a decrease in their stocks due to microbial activity. Therefore, we conducted a study of humus stocks in a meter-thick stratum of natural zonal soils of the forest-steppe in the modern period, which are formed under virgin steppe vegetation and under broadleaved forests. The validity of comparing the humus status of these soils from the point of view of evolutionary changes in Chernozems after land cover change from steppe to forests is based on the fact that at the beginning of the Subatlantic period of the Holocene (in the early Iron Age), according to the humus state, the Chernozems of meadow-steppe areas of the forest-steppe zone had already reached modern characteristics and were in quasi-equilibrium with the combination of environmental factors [13, 15]. Stocks of organic matter in 0–1 m layer of modern virgin Chernozems are from 380 to 550 ton/ha, and in profiles of virgin Phaeozems and Luvisoils under broadleaved forests – from 176 to 310 ton/ha (Table 2). Based on these results, it can be concluded that the natural evolution of Chernozems to Phaeozems and Luvisoils was accompanied by the decrease of humus stocks by more than double.

Table 2. Stocks of organic matter (humus) in natural soils (0–1 m, ton/ha) in the modern period: forest-steppe of the Central Russian Upland. Geomorphic positions – flat interfluves, parent materials – loess-like loams.

Meadow-steppe sites, Chernozems	**Stocks of humus** (t/ha)	Broadleaved forests sites, Phaeozems and Luvisols	**Stocks of humus** (t/ha)
Kursk	420	Kazachya Lisitsa	191
Safonovka	550	Hotmyzhsk	210
Zhimolostnoe	384	Polyana	234
Yur’evka	500	Melikhovo	255
Gubkin	541	Shehovtsevo	310
Talovaya	589	Samarino	176
Mean	497	Mean	229

On the basis of paleoecological and palaeosol reconstructions carried in archaeological landscapes of the forest-steppe zone in the south of the Central Russian Upland before the Subatlantic period, Chernozems of steppe genesis were the dominant component of soil cover in areas that were late covered by forests. Consequently, our research confirms the point of view of climate-related forest advance onto steppes over the last 2–3 millennia.

In the light of the research conducted, it is of great interest to study the relationship between forest and steppe in the modern period of formation of ecosystems in the forest-steppe zone.

Comparative analysis of high-resolution satellite images taken at 6 key sites (figure 1) in 1970 and 2014 (time interval of 45 yrs) showed that there was an overall increase in forest area within all study areas (Table 3). These observations also confirmed that cultivation of fields at the forest edge restrained forest advancement. This was clearly demonstrated by differences in forest expansion between cultivated and non-cultivated edges. Forest growth appeared to be primarily in ravines, which were previous grasslands (pastures or hayfields). Forest edge advancement within the study sites was observed from different relief positions (northern and southern slopes of ravines, watersheds and watershed slopes) during the period 1970–2014. Rates of forest advancement on slopes of polar exposures did not have essential differences and the mean index for all key sites was equal 5 m/10 yrs (Table 4). The calculated hydrothermal coefficient (HTC) for the study period (1970–2014) within each key site (from 0.99 to 1.2) showed an obvious connection of this indicator with rates of linear increment of forest edges.

Table 3. Characteristics of changes in forest area, estimated at key sites in the period 1970-2014.

Key site	Area of forests, ha		Forest cover,% of total area	
	1970	2014	1970	2014
1	9103	12100	21	29
2	2855	4595	9	15
3	8943	10824	22	26
4	5829	7172	22	27
5	3195	5134	10	16
6	940	1907	3	6

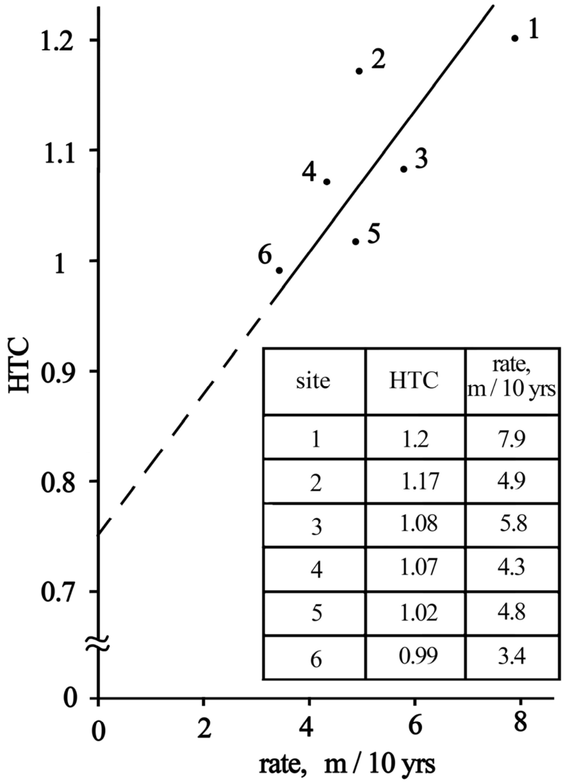
Sites are numbered in accordance with figure 1.

Table 4. Characteristics of changes in forest area, estimated at key sites in the period 1970–2014.

Key site	Number of measurements		Mean length of advancement, m		Rate of advancement, m/10 yrs		
	Northern exposure	Southern exposure	Northern exposure	Southern exposure	Northern exposure	Southern exposure	Mean
1	175	137	33.1	35.9	7.5	8.2	7.9
2	176	115	19.6	23.5	4.4	5.3	4.9
3	147	91	26.9	24.3	6.1	5.5	5.8
4	121	87	24.9	13.3	5.6	3.0	4.3
5	121	105	21.9	20.4	5.0	4.6	4.8
6	150	86	15.1	15.0	3.4	3.4	3.4
Total	890	621	23.7	23.2	5.3	5.2	5.2

The numbering of sites is the same as for Table 3.

This relationship is approximated by a linear trend (figure 3). With increasing values of the HTC, the rate of forest edge advancement increased. The slope of the trend line is such that the zero advance of forest vegetation corresponds to the HTC value of 0.75, i.e. climatic conditions of the northern part of the steppe zone. In our opinion, this HTC value can be used as a spatial reference point between the regions of Eastern Europe, where forest advancement is absent and where there is currently forest advancement onto the steppes taking place. The main reason for growth of forest cover, detected in 1970-2014 in the south of the Central Russian Upland forest-steppe, is the favorable climatic changes due to an increase in the average annual air temperatures and increase in annual precipitation at the end of the 20th - beginning of the 21st centuries. These results are consistent with observations over the entire Subatlantic period of the Holocene with climatologically driven advancement of forests on steppes in the East European forest-steppe zone.



site	HTC	rate, m / 10 yrs
1	1.2	7.9
2	1.17	4.9
3	1.08	5.8
4	1.07	4.3
5	1.02	4.8
6	0.99	3.4

Figure 3. Linear trend between hydrothermal coefficient (HTC) and rate of forest edge advancement (1970–2014). Sites are numbered in accordance with figure 1.

As we have determined the actual rate of forests advancement on steppes in the modern period, it seems a natural question - how quickly does this change of vegetation affect the transformation of Chernozem soils, recently covered by forest? We tried to provide an answer to this question by studying Chernozems under shelterbelts of 55 years of age (key sites 24-26 in figure 1).

Within all sub-areas each of the three studied key sites Chernozems, fall into one category of classification status. In grasslands, cultivated fields, and under the shelterbelt at the Streletskaya Steppe site, Chernic Luvic Chernozems were identified, and in the same sub-areas of Yamskaya and Kamennaya Steppe sites Chernic Haplic Chernozems were identified. None the less, according to comparative analysis, some essential changes of soil properties within the studied sub-areas have been revealed.

The soils of the studied key sites are somewhat different and should be analyzed separately as they cannot be included in one statistical sample. However, the fact that we found similar tendencies of changes in the soil properties (in the thickness of humus profiles and in the content and total storage of organic matter) under the shelterbelts in comparison with the adjacent cropland and grassland at all the key sites suggests that the shelterbelts exert quite definite influence on soils.

An important morphogenetic indicator characterizing the direction of change over time of the studied soils in the sequence “grassland – arable land – shelterbelt”, are the thickness of their humus profiles (A+AB horizons; Table 5). In the areas of the three study key sites humus profile thickness of virgin Chernozems varies from 70–75 cm. In Chernozems under shelterbeltss humus profile thickness is significantly higher than in virgin grasslands (in Streletskaya Steppe – by 11 cm, and in Yamskaya Steppe – by 5 cm). This index is significantly lower in the area of Kamennaya Steppe – by 9 cm on comparison with the shelterbelt’s Chernozem. At each location, there were significantly greater thicknesses of the A+AB horizons in soils beneath tree plantings compared to the adjacent cultivated soils (Table 5). It is likely that these differences in thickness of the A+AB horizons are due to both continued humus loss from cropping practices, especially tillage, humus accumulation beneath the trees where there is greater biomass, and also, probably humus migration downward in the more cool microclimate under the shelterbelts canopy.

Table 5. Statistics of humus profiles (A+AB horizons) thickness of soils within three key sites.

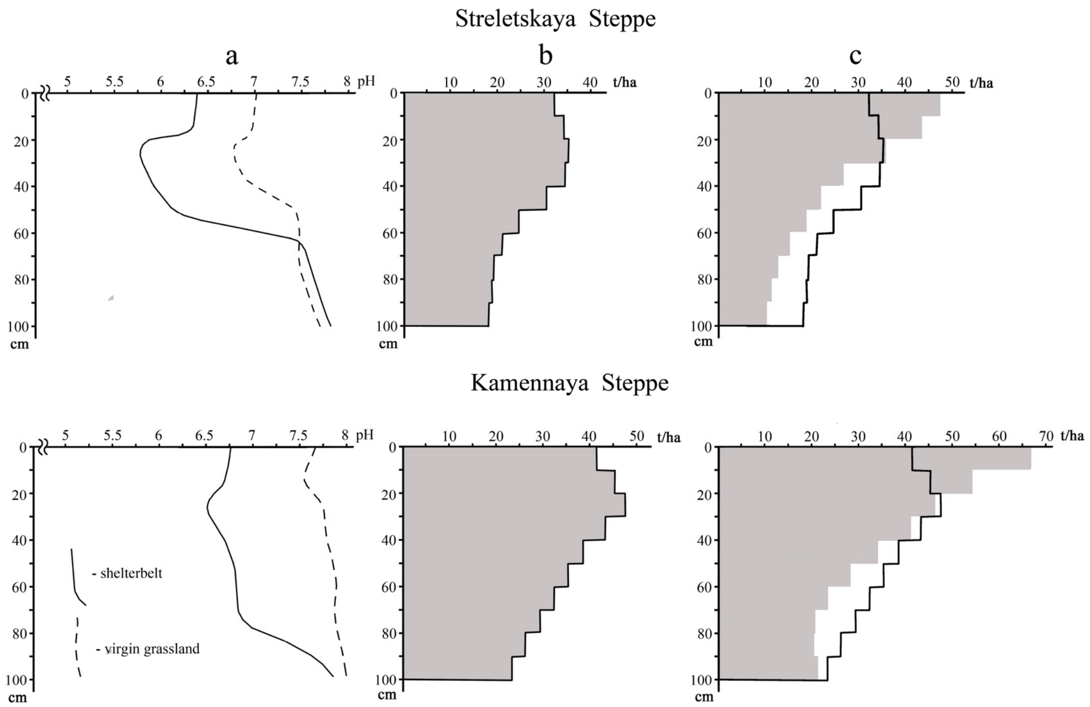
Sub-area	n	Lim, cm	$X \pm \delta_X$, cm	δ, cm	RSD, %
		Streletskaya Steppe			
Grassland	15	60–77	70.3±1.0	3.9	5
Shelterbelt	15	75–85	81.4±1.0	3.8	5
Cultivated land	30	47–80	63.1±2.0	10.8	17
		Yamskaya Steppe			
Grassland	15	69–80	75.5±0.9	3.4	5
Shelterbelt	15	71–92	80.1±1.6	6.3	8
Cultivated land	30	54–82	69.2±1,3	6.9	10
		Kamennaya Steppe			
Grassland	15	69–88	75.5±1.3	4.9	6
Shelterbelt	15	57–70	64.1±1.0	3.8	6
Cultivated land	30	49–64	58.5±0.6	3.5	6

Characteristics of individual soil profiles of humus stocks to a depth of 100 cm, which have been studied in three sub-areas within the three key sites, are presented in table 6. At every key site organic matter in Chernozems under shelterbelts are higher than in background virgin grasslands (Table 6). Vertical redistribution of humus stocks was detected in Chernozems beneath shelterbelts. We can explain this effect (the growth of relative stocks of humus in 50–100 cm layer of soils beneath tree plantations) as a result of some part of tree roots dying and their transformation to humus (figure 4b and 4c).

Table 6. Humus stocks in study soil profiles (0-1 m, t/ha) under virgin grasslands, shelterbelts, and adjacent crop fields.

	Key site	
Streletskaya Steppe	Yamskaya Steppe	Kamennaya Steppe
	Grasslands	
421	541	589
	Shelterbelts	
488	650	614
	Cultivated lands	
486	539	491

The results indicate that, at least during the first decades of Chernozems development under forest vegetation, there is an accumulation of humus. This accumulation process is apparently temporary since we have previously shown that in the long-term trend of the evolutionary transformation of Chernozems into Phaeozems and Luvisols, humus stocks are reduced by more than 2 times.



Streletskaya Steppe

Kamennaya Steppe

Figure 4. Vertical distribution of pH in H_2O in soils under shelterbelts and virgin grasslands (a), humus stocks of Chernozems under shelterbelts (b) and under virgin grasslands (c). In the diagram, reflecting virgin Chernozems, line border area represents the distribution in soils beneath shelterbelts. Panels represent a contrast in variants of soils forming in the northern and southern parts of the forest-steppe zone (Streletskaya and Kamennaya Steppes, respectively).

A study completed in the USA confirmed this assumption, i.e. accumulation of humus in soils under shelterbelts does not occur indefinitely. Sauer et al. [17] observed the maximum rate of increase in soil organic carbon (SOC) accumulation at 4 locations in Iowa, under artificial forest plantations 30 years after planting, after which the average rate of accumulation was decreased (figure 5).

Along with the established increase in humus stocks in Chernozems under newly established tree plantations, these soils also show an increase in acidity (figure 4 a), which can be explained by the chemical features of forest litter turning into humus, as well as the relatively humid microclimate under the forest canopy.

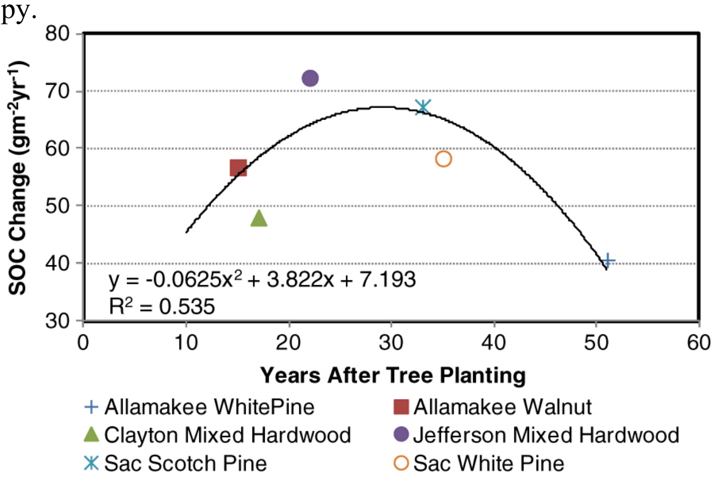


Figure 5. Average annual increase in soil organic carbon (SOC) for the 0–30 cm layer with time after tree planting assuming that the cropped SOC was at equilibrium (according to Sauer et al. [17]).

Recent results of Kalinina et al. [18,19] confirm trends, close to have discussed in this work, but in appliance to broad-lived forest zone - after arable Luvisols abandonment and their covering by young natural forests. During restoration, the former plow horizons showed the newly developed Ah and O horizons; within the Ah horizons soil organic carbon and plant available nutrients (P, K) enrichment was observed [18]. Restoration of Luvisols under broad-lived forests led to SOC increase within both active (free and occluded particulate organic matter) and passive (clay fraction) pools, and as a result - with total organic carbon accumulation. These dynamics reflect an initial ecosystem disturbance after abandonment, which slows down with time [19].

4. Conclusions

The process of forest expansion into grassland (steppe) areas both in the long-term trend (during the Subatlantic period of the Holocene) and over recent decades is observed in the southern part of the Central Russian Upland. The direct relationship between climatic humidity in the forest-steppe zone and the rate of frontal displacement of forest edges towards the grasslands is revealed. Rates of forest advancement on topographic slopes of polar exposures did not have essential differences and mean index for all key sites was equal 5 m/10 yrs. According to our calculations the trend line between the HTC and the rate of forest edges advancement shows a zero value of advancement at HTC 0.75 (northern part of the steppe zone).

Chernozems of the Early Iron Age covered by forest after the beginning of humid climatic conditions of the Late Holocene, during the last two millennia have been transformed into other soil categories - according to WRB-2015, to Phaeozems and Luvisols. Stocks of soil organic matter in this evolutionary transformation decreased by not less than two times. Chernozems of the modern period recently covered by forest vegetation (under 55-yrs old shelterbelts) have not transformed into another soil category. But changes of a number of soil properties have been detected. Thickness of A+ AB horizons, stocks of humus in layer 0–100 cm as well as acidity of soil profiles increased in time.

The accumulation of humus in soils under shelterbelts can occur during the first decades after planting and then may be followed by a change in soil evolution including potential degradation. Our working hypothesis requires further research that can solve an important fundamental soil-geographic problem, which consists in developing the concept of “soil formation factors – soil formation processes – soil properties”.

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