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GENESIS AND GEOGRAPHY OF SOILS

# Regional Specificity of the Climatic Evolution of Soils in the Southern Part of Eastern Europe in the Second Half of the Holocene

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**Abstract**—The analysis of characteristic features of chernozems and chestnut soils of different ages that have been formed in the south of the East European Plain in the past 5000 years attests to the spatial and temporal heterogeneity of the rate and direction of pedogenetic processes, i.e., to the metachronous development of the soil cover. A linear zone of the retarded (before 3600–3200 years ago) and, then, enhanced development of the humus profiles of chernozems was found along the Voeikov climatic axis corresponding to the contact zone between cyclonic and anticyclonic weather conditions. It was concluded about the significant rise in the degree of atmospheric moistening of the territory took place at the end of the Subboreal–the beginning of the Subatlantic periods of the Holocene. This factor favored the more active growth of the humus profiles of chernozems in this zone in comparison with chernozems on adjacent territories.

*Keywords*: chernozem, paleosols, Chernozems, Haplic Kastanozems (Chromic)

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## INTRODUCTION

Russian paleopedology has accumulated considerable factual materials on the Holocene evolution of soils in east European regions with numerous archaeological monuments (kurgans, ramparts, ancient settlements, etc.) that serve as the main objects for reconstruction of the Holocene history of soils and the environment.

In recent years, the major attention of researchers has been focused on the chronological refinement of paleosol reconstructions in a number of east European regions, soil evolution on newly investigated territories, and on the search for new methods of the study of evolution of soils and the environment [2, 7, 17–21, 23, 38, 43, 48]. The method of soil chronosequences developed by Zolotun in his seminal work [24] is the key method to study the Holocene evolution of soils. Afterwards, analogous studies have been performed by many pedologists working in different regions. The major stages of the development of archaeological soil science in Russia have been discussed in detail in several reviews [11, 21, 26–29].

In 2007, the first results of the analysis of data on soil chronosequences for the Subboreal period of the Holocene in the southern part of east Europe and in the southern Transural region were published [46]. In this study, the climatic evolution of several profile-forming soil properties was discussed, and an attempt for mapping of the spatiotemporal patterns of the soil properties in the considered region was made. Since that time, new data on the soil properties have been obtained. They make it possible to construct longer soil chronosequences via adding paleosol data on key sites studied near the earlier investigated short soil chronosequences [14, 18, 19, 23, 37, 38, 44, 45, 48]. The problems related to the spatial and temporal changes of soils are of great interest not only for pedologists but also for climatologists (including coauthors of this paper). The views of climatologists can be important for interpreting pedochronological information in paleoclimatic reconstructions.

## OBJECTS AND METHODS

The studied territory includes the forest-steppe, steppe, and semidesert zones of the southern part of the East European Plain within 45°–54° N and 30°–53° E (Fig. 1). In terms of geomorphology, it includes foothills of the Great Caucasus; the Central Russian, Kalach, Privolzhskaya, and Stavropol uplands; the Poltava, Oka–Don, and Azov plains; and the Prichernomorskaya (Black Sea) and Caspian lowlands. Treeless landscapes predominate in these regions. Automorphic pedogenesis took place under the impact of herbaceous or shrub vegetation during the entire Holocene. Many soil scientists studied the evolution of soils in this region using the method of soil chronosequences on dated archaeological objects. For our analysis, we selected the works that contained data on definitely determined chronosequences and reliable indicative characteristics of soil evolution sensitive to

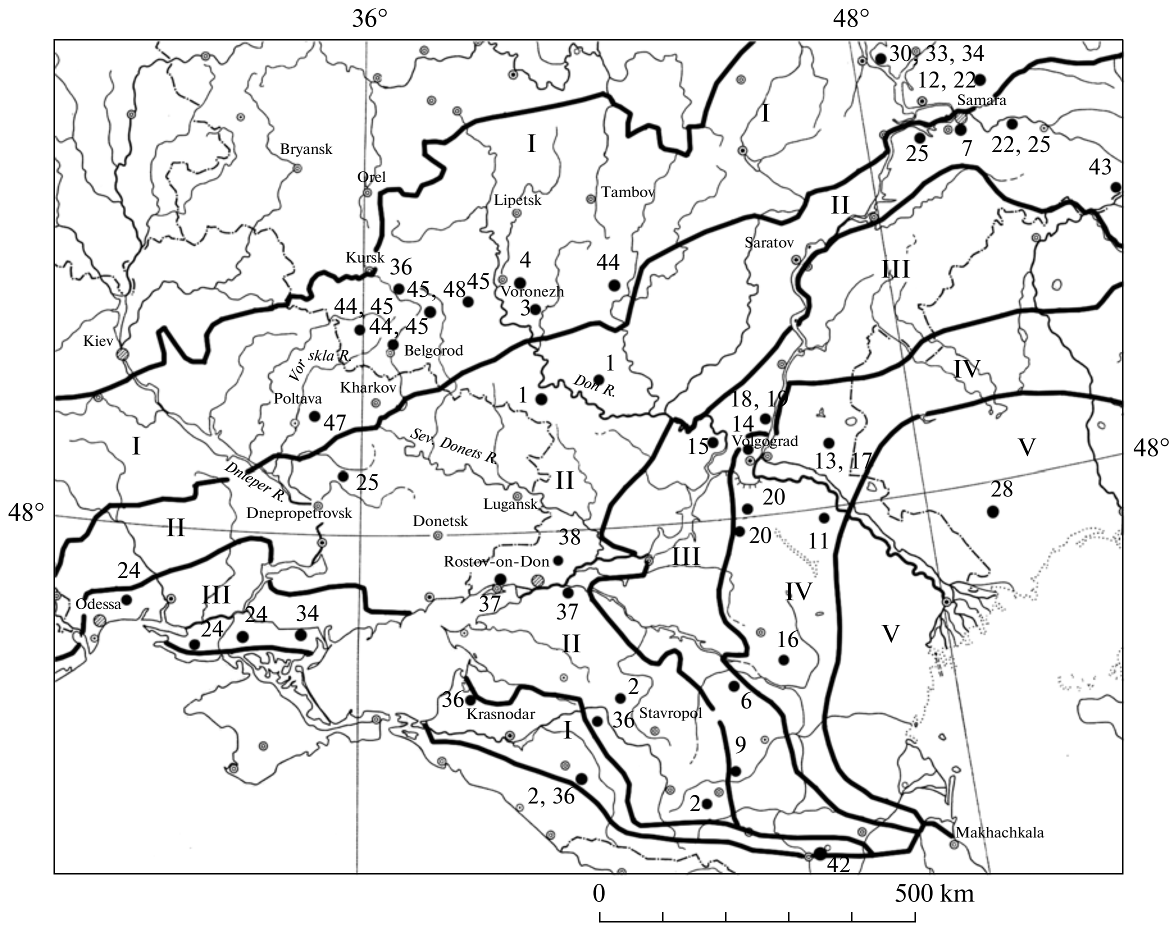


**Fig. 1.** Location of key sites to study the climatic evolution of soils in treeless landscapes in the second half of the Holocene: (I) forest-steppe, (II) forb and forb–grassy steppe, (III) dry grassy steppe, (IV) deserted wormwood–grassy steppe, and (V) wormwood semi-deserts with participation of grasses. The numbers near the points correspond to the source of information in the list of references.

climate changes, i.e., on the thickness of soil humus profiles and on the depth of soil carbonates. The thickness of the humus profiles in the forest-steppe, northern steppe, and typical steppe zones with chernozems (Chernozems) and dark chestnut soils (Haplic Kastanozems (Chromic)) was determined as the total thickness of the A1 and A1B horizons; in the dry steppe and semidesert zones with chestnut and light chestnut soils (Haplic Kastanozems (Chromic)), it was determined as the total thickness of the A1 and B1(B) horizons. The major attention was paid to the works containing data on several chronological intervals for the same site and to generalizing works with data on several neighboring key sites. Well-drained automorphic soils developed on the interfluves or river terraces with a considerable depth of the groundwater were selected for the paleosol and paleoclimatic reconstructions. The geography of the works that were used in our analysis is as follows: forest-steppe of the Poltava Plain [47], forest-steppe of the Central Russian Upland [36, 44, 45, 48], forest-steppe of the Oka–Don Plain [3, 4], forest-steppe of the Volga and Transvolga regions [7, 12, 22, 33, 34], forest-steppe of the Stavropol Upland and foothills of the Great Caucasus [2, 36, 42], steppe if the Central Russian Upland [1, 15, 44, 49], steppe of the Poltava Plain [25], steppe of the Prichernomorskaya Lowland [24, 34], steppe of the Azov Plain [37, 38], steppe of the Privolzhskaya Upland [14, 18, 19], steppe of the southwestern Cis-Ural region [43], steppe of the Stavropol Upland [2, 9, 36]. dry and deserted steppe of the Ergeni Upland [6, 16, 20], and deserted steppe and semidesert of the Caspian Lowland [11, 13, 17, 28]. Data from these works were used for compiling schematic maps of the thickness of soil humus profiles and the depth of soil carbonates in the paleosols dating back to three chronological intervals of the second half of the Holocene: 4500–5000, 3900–4100, and 3200–3600 BP. The first of these intervals characterizes the transition from the Atlantic to the Subboreal periods of the Holocene; it was marked by a general cooling of the climate and by the uneven trends of changes in the soil water supply in different parts of the studied territory. The second interval corresponds to the middle of the Subboreal period; in many studies, it is usually interpreted as the phase of a sharp worsening of climatic conditions towards cooling and drying. The third interval corresponds to the second half of the Subboreal period and is considered as the phase of increasing climatic moistening before sharp changes in the environment and soils that took place at the beginning of the Subatlantic period and transformed the soil cover up to the state close to the modern one [2, 10, 30, 31, 36, 40].

In order to study regional specificity of the natural evolution of soils in the second half of the Holocene within the considered territories, data on the known pedochronological sequences were systematized, and long soil chronosequences were deduced from them. Some data on the long chronosequences were taken directly from the published works [25, 47]. However, in most cases, they were obtained via synthesis of data from different sources. Long soil chronosequences discussed in our work were identified for the following regions: forest-steppe of the Poltava Plain, forest-steppe of the Central Russian Upland, northern part of the steppe zone within the Poltava Plain, typical steppe of the Azov Plain, and dry steppe in the south of the Privolzhskaya Upland. The particular data on the indicative soil properties for these chronosequences are summarized in the table.

It should be noted that the depths of soil humus profiles and the upper boundary of effervescence were estimated with due account for the effect of paleosol compaction under earth ramparts, as well as for the effect of compaction of background surface soils in the case of their plowing. On the plots with plowed and, hence, somewhat compacted background surface soils, the morphometric characteristics of the paleosols buried under the kurgans were taken without correction for their compaction. On the plots with virgin background surface soils, the depths of the humus horizons and the upper boundary of effervescence in the paleosols buried under the kurgans were increased by 2 cm corresponding to their compaction under the impact of surface loads (by kurgans or ramparts) and humus mineralization [25].

All the soils studied at the archaeological objects were dated by the archaeological method; the presented chronointervals are given in agreement with the noncalibrated time scale.

## RESULTS AND DISCUSSION

Data on the depths of humus profiles and upper boundaries of effervescence presented in the table are given in absolute values (cm). For our analysis, we converted them into relative values, i.e., expressed them in percent of the modern values (taken as 100%). These recalculated data are presented in Fir. 2. Its analysis allows us to conclude that the patterns of natural evolution of soils in different regions of the studied territory had both common and specific regional features.

Thus, in the forest-steppe zone of Poltava Plain and Central Russian Upland, the total thickness of the humus profiles of typical chernozems (Haplic Chernozems (Pachic)) of the Subboreal period was closer to the modern values in comparison with the thickness of the humus profiles in the ordinary chernozems (Haplic Chernozems (Pachic)) typical of the northern and typical steppe subzones on the Poltava Plain and the Azov Lowland. A comparison of evolutionary patterns of ordinary chernozems developing in these regions shows that chernozems of the Azov Lowland were characterized by more contrasting changes with time. Within the dry steppe zone in the south of the Privolzhskaya Upland, relatively stable conditions of pedogenesis have been typical of the past 3700 years; before 900 BP, the thickness of the humus profiles and the depth of effervescence in the soils of this region corresponded to somewhat wetter climatic conditions in comparison with those in the modern period. At the same time, the major tendencies of the evolution of ordinary and typical chernozems in the western and northern parts of the considered territory in the Late Holocene have been directed towards the formation of more leached and humified soils under conditions of the increasing atmospheric moistening especially pronounced in the interval from 4000 (3700) to 2800 (2500) BP.

Along with these distinctions, two common features have been typical of all the soils: a decrease in the thickness of their humus profiles and a rise in the depth of effervescence in the period from 5000–4500 to 4000–3700 BP. The minimum thickness of the humus profiles in the soils was established about 4000 BP (or in the interval from 4000 to 3800 (3700) BP.

Thus, both synchronous and synchronous (metachronous) changes in the soil properties took place in the forest-steppe and steppe regions of the East European Plain.

In order to understand the reasons for the regional specificity of the natural evolution of soils in this territory, the great volume of data on the soils of different ages within the vast area has to be analyzed. For this purpose, our data on deviations of the studied soil properties (the thickness of the humus profile and the depth of effervescence) from their modern values were put on the maps (Figs. 3 and 4).

According to the existing concepts, the depth of effervescence is a more sensitive indicator of climate changes in comparison with the thickness of soil humus profiles [2, 25]. Indeed, climate changes that took place in the southern half of the East European Plain in the Subboreal period were more distinctly reflected in the temporal changes of the depth of effervescence.

At the beginning of the Subboreal period (4500–5000 BP), the depth of effervescence in the considered soils was generally smaller than that in the modern soils, which attests to drier climatic conditions of that period. At the same time, the particular spatial patterns of this characteristic had their own regional specificity; the area of the soils with deeper leaching of carbonates was found in the Don basin and in the middle

Morphometric characteristics of the chronosequences of chernozems and chestnut soils in the East European Plain

| Key site | Time, BP | Thickness, cm | | | Depth of effervescence, cm |
|---|---|---|---|---|---|
| | | A1 | A1B | A1 + A1B | |
| Typical forest-steppe chernozems, Poltava Plain, Poltava oblast [47] | | | | | |
| Storozhevoe | 3900 | 19 | 36 | 55 | 55 |
| | 0 | 41 | 29 | 70 | 38 |
| | Difference | +22 | –7 | +15 | +19 |
| | 3800 | 16 | 32 | 48 | 16 |
| | 0 | 35 | 33 | 68 | 68 |
| | Difference | +19 | +1 | +20 | +52 |
| | 3500 | 15 | 38 | 53 | 68 |
| | 0 | 35 | 33 | 68 | 68 |
| | Difference | +20 | –5 | +15 | +37 |
| | 1700 | 23 | 34 | 57 | 23 |
| | 0 | 41 | 30 | 71 | 56 |
| | Difference | +18 | –4 | +14 | +33 |
| | 900 | 32 | 25 | 57 | 32 |
| | 0 | 41 | 29 | 70 | 38 |
| | Difference | +9 | +4 | +13 | +6 |
| | 350 | 26 | 41 | 67 | 44 |
| | | 38 | 34 | 72 | 38 |
| | | +13 | –9 | +5 | –6 |
| Typical forest-steppe chernozems, Central Russian Upland, Belgorod and Voronezh oblasts [44, 45, 48] | | | | | |
| Gubkinskii | 4600 | 20 | 60 | 80 | 49 |
| | 0 | 23 | 42 | 65 | 65 |
| | Difference | +3 | –18 | –15 | +16 |
| | 4000 | 25 | 25 | 50 | 0 |
| | 0 | 50 | 15 | 65 | 50 |
| | Difference | +25 | –10 | +15 | +50 |
| | 3500 | 30 | 25 | 55 | 25 |
| | 0 | 55 | 10 | 65 | 60 |
| | Difference | +25 | –15 | +10 | +35 |
| Graivoronovskii | 3500 | 53 | 30 | 83 | 30 |
| | 0 | 65 | 35 | 100 | 55 |
| | Difference | +12 | +5 | +17 | +25 |
| Belgorodskii-2 | 3500 | 50 | 16 | 66 | 25 |
| | 0 | 67 | 21 | 88 | 45 |
| | Difference | +17 | +5 | +22 | +20 |
| Borisovskii | 2500 | 60 | 30 | 90 | 20 |
| | 0 | 43 | 29 | 72 | 53 |
| | Difference | –17 | –1 | –18 | +33 |
| Belgorodskii-1 | 2400 | 40 | 23 | 63 | 40 |
| | 0 | 55 | 16 | 71 | 50 |
| | Difference | +15 | –5 | +10 | +10 |
| Ostrogozhskii | 2400 | 45 | 22 | 67 | 18 |
| | 0 | 54 | 18 | 72 | 33 |
| | Difference | +9 | –4 | +5 | +15 |

**Table. (Contd.)**

| Key site | Time, BP | Thickness, cm | | | Depth of effer-vescence, cm |
|---|---|---|---|---|---|
| | | A1 | A1B | A1 + A1B | |
| Ordinary chernozems of the northern steppe, Poltava Plain, Dnepropetrovsk oblast [25] | | | | | |
| Shandrovka | 5100 | 28 | 14 | 42 | 42 |
| | 0 | 48 | 27 | 75 | 45 |
| | Difference | +20 | +13 | +33 | +3 |
| Bogdanovka | 4750 | 21 | 22 | 43 | 38 |
| | 0 | 57 | None | 57 | 56 |
| | Difference | +36 | – | +14 | +18 |
| | 4500 | 23 | 18 | 41 | 38 |
| | 0 | 57 | None | 57 | 56 |
| | Difference | +34 | – | +16 | +18 |
| Shandrovka | 4300 | 21 | 15 | 36 | 30 |
| | 0 | 48 | 27 | 75 | 45 |
| | Difference | +27 | +12 | +39 | +15 |
| Bogdanovka | 3950 | 20 | 15 | 35 | 35 |
| | 0 | 57 | None | 57 | 56 |
| | Difference | +37 | – | +22 | +21 |
| | 3600 | 15 | 16 | 31 | 29 |
| | 0 | 57 | None | 57 | 56 |
| | Difference | +42 | – | +26 | +27 |
| | 3400 | 24 | 12 | 36 | 30 |
| | 0 | 57 | None | 57 | 56 |
| | Difference | +33 | – | +21 | +26 |
| Chernyavshchina | 1800 | 55 | 12 | 67 | 60 |
| | 0 | 52 | 11 | 63 | 62 |
| | Difference | –3 | –1 | –4 | +2 |
| Ordinary chernozems of the northern steppe, Central Russian and Kalach uplands, Belgorod and Voronezh oblasts [1, 44, 49] | | | | | |
| Pasekovskii | 4580 | 30 | 20 | 50 | 30 |
| | 0 | 55 | 35 | 90 | 30 |
| | Difference | +25 | +15 | +40 | 0 |
| Pavlovskii | 4130 | 20 | 30 | 50 | 34 |
| | 0 | 37 | 23 | 60 | 60 |
| | Difference | +17 | –7 | +10 | +26 |
| Elanskii | 4000 | 20 | 13 | 33 | 40 |
| | 0 | 44 | 18 | 62 | 65 |
| | Difference | +25 | +4 | +29 | +25 |
| Starokriushinskii | 3500 | – | – | 50 | 46 |
| | 0 | – | – | 77 | 52 |
| | Difference | – | – | +27 | +7 |
| Koltunovka | 1250 | 39 | 12 | 51 | 0 |
| | 0 | 42 | 15 | 57 | 0 |
| | Difference | +3 | +3 | +6 | 0 |
| Ordinary chernozems of typical steppe, Azov Plain, Rostov oblast [37, 38] | | | | | |
| Rossiiskii-II | 4500 | – | – | 60 | 60 |
| | 0 | – | – | 73 | 26 |
| | Difference | – | – | +13 | –34 |
| | 4300 | – | – | 40 | 40 |

**Table.** (Contd.)

| Key site | Time, BP | Thickness, cm | | | Depth of effervescence, cm |
|---|---|---|---|---|---|
| | | A1 | A1B | A1 + A1B | |
| | 0 | – | – | 73 | 26 |
| | Difference | – | – | +33 | –14 |
| | 4000 | – | – | 37 | 10 |
| | 0 | – | – | 73 | 26 |
| | Difference | – | – | +36 | +16 |
| | 3800 | – | – | 40 | 26 |
| | 0 | – | – | 73 | 26 |
| | Difference | – | – | +33 | 0 |
| Scythian Necropolis | 2400 | 33 | 20 | 53 | 10 |
| | 0 | 38 | 37 | 75 | 32 |
| | Difference | +5 | +17 | +22 | +22 |
| Beglitsy | 2400 | – | – | 53 | 0 |
| | 0 | – | – | 67 | 0 |
| | Difference | – | – | +14 | 0 |
| Rossiiskii-II | 1800 | – | – | 52 | 0 |
| | 0 | – | – | 73 | 26 |
| | Difference | – | – | +21 | +26 |
| Semenovskaya fortress | 1200 | 24 | 16 | 40 | 0 |
| | 0 | 38 | 37 | 75 | 32 |
| | Difference | +14 | +11 | +35 | +32 |
| Chestnut soils of the dry steppe, south of the Privolzhskaya Upland, Volgograd oblast [14, 18, 19] | | | | | |
| Ilovlya-2 | 5000 | – | – | 32 | 35 |
| | 0 | – | – | 26 | 27 |
| | Difference | – | – | –6 | –8 |
| | 4800 | – | – | 32 | 23 |
| | 0 | – | – | 26 | 27 |
| | Difference | – | – | –6 | +4 |
| | 4000 | – | – | 31 | 0 |
| | 0 | – | – | 26 | 27 |
| | Difference | – | – | –5 | +27 |
| Ilovlya-1 | 3900–3600 | 12 | 15 | 27 | 25 |
| | 0 | 12 | 18 | 30 | 27 |
| | Difference | 0 | +3 | +3 | +2 |
| | 2300 | 14 | 18 | 32 | 35 |
| | 0 | 12 | 18 | 30 | 27 |
| | Difference | –2 | 0 | –2 | –8 |
| Ilovlya-2 | 1950 | – | – | 34 | 32 |
| | 0 | – | – | 26 | 27 |
| | Difference | – | – | –8 | –5 |
| | 1800 | – | – | 30 | 31 |
| | 0 | – | – | 26 | 27 |
| | Difference | – | – | –4 | –4 |
| | 750 | – | – | 34 | 35 |
| | 0 | – | – | 26 | 27 |
| | Difference | – | – | –8 | –8 |

Dashes denote the absence of data.

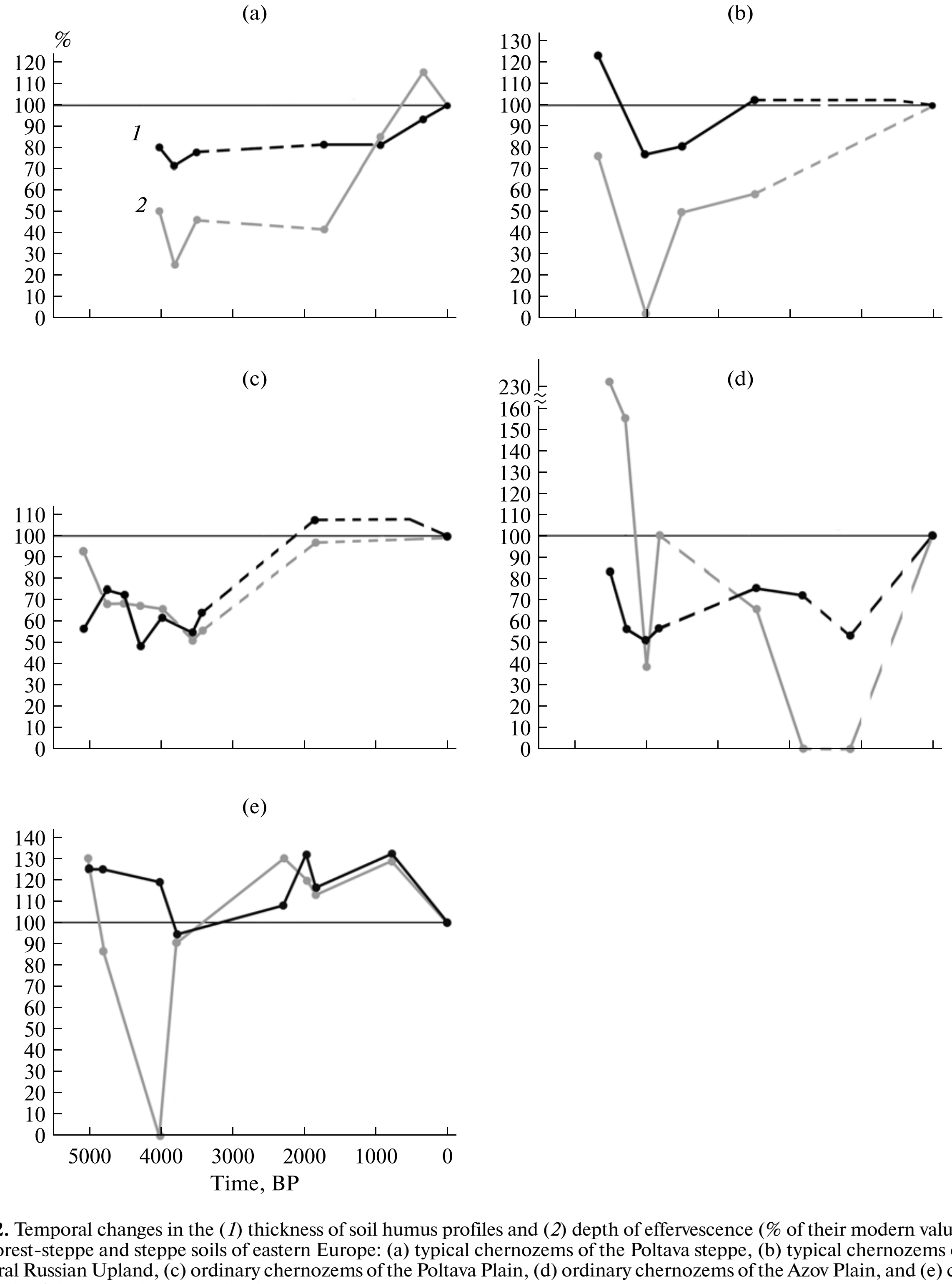


**Fig. 2.** Temporal changes in the (*1*) thickness of soil humus profiles and (*2*) depth of effervescence (% of their modern values) in the forest-steppe and steppe soils of eastern Europe: (a) typical chernozems of the Poltava steppe, (b) typical chernozems of the Central Russian Upland, (c) ordinary chernozems of the Poltava Plain, (d) ordinary chernozems of the Azov Plain, and (e) chestnut soils of the Privolzhskaya Upland.

reaches of the Volga River. The width of this area was about 200–250 km in the south and up to 500 km and more in its northern part.

It is probable that the enhanced leaching of carbonates within this area was specified by the increase in the atmospheric moistening of the territory because of the more pronounced cyclonic activity. The stretching of this area from the southwest to the northeast allows us to assume that its increased moistening was caused by cyclones moving in the same direction. In

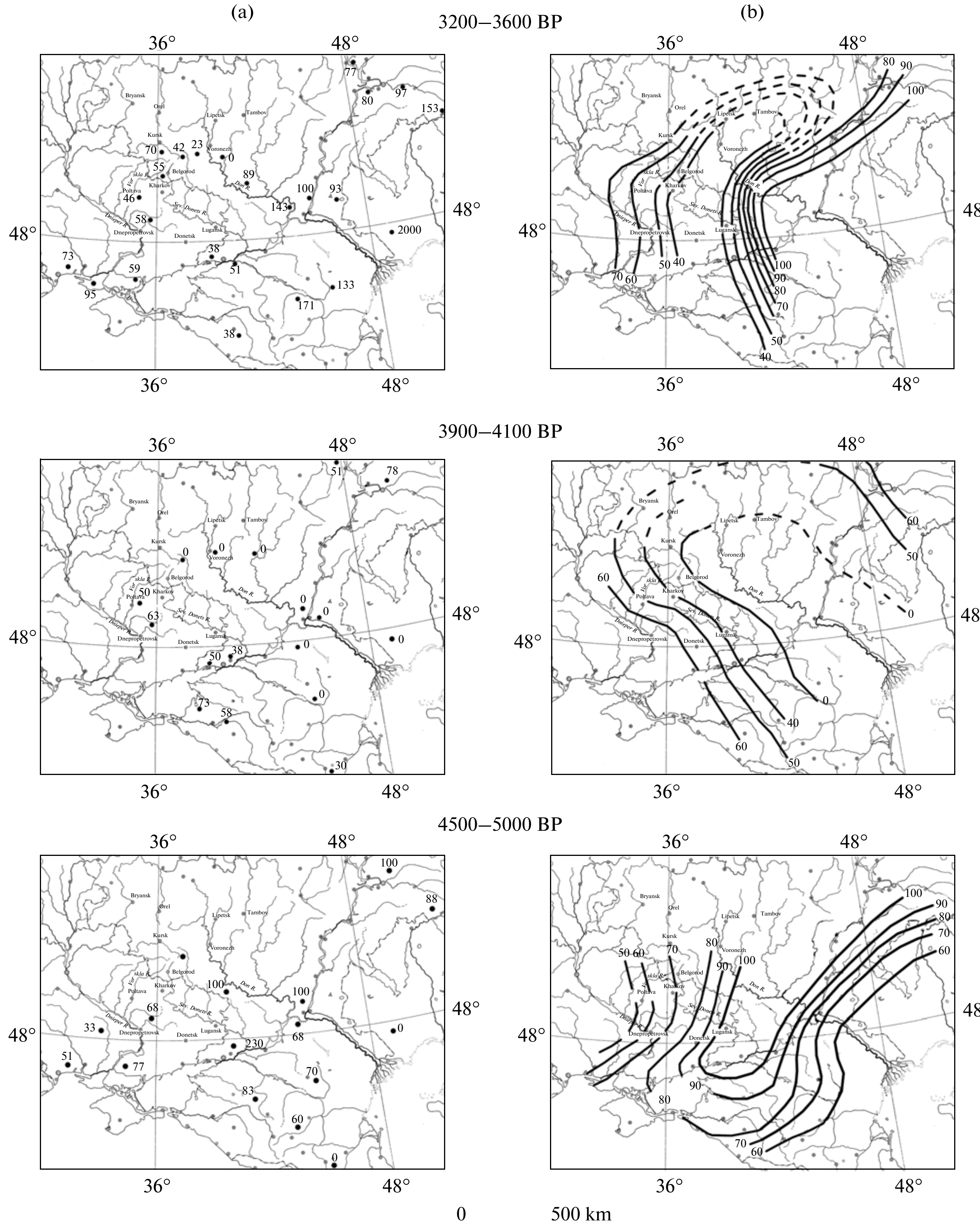


**Fig. 3.** Depths of effervescence in the paleosols of three chronointervals of the Subboreal period on the south of eastern Europe. Here and in Fig. 4, (a) numerical values characteristic of the investigated key sites and (b) isolines of deviation of the depth of effervescence in the paleosols from that in the modern soils, %. The maps are based on literature data.

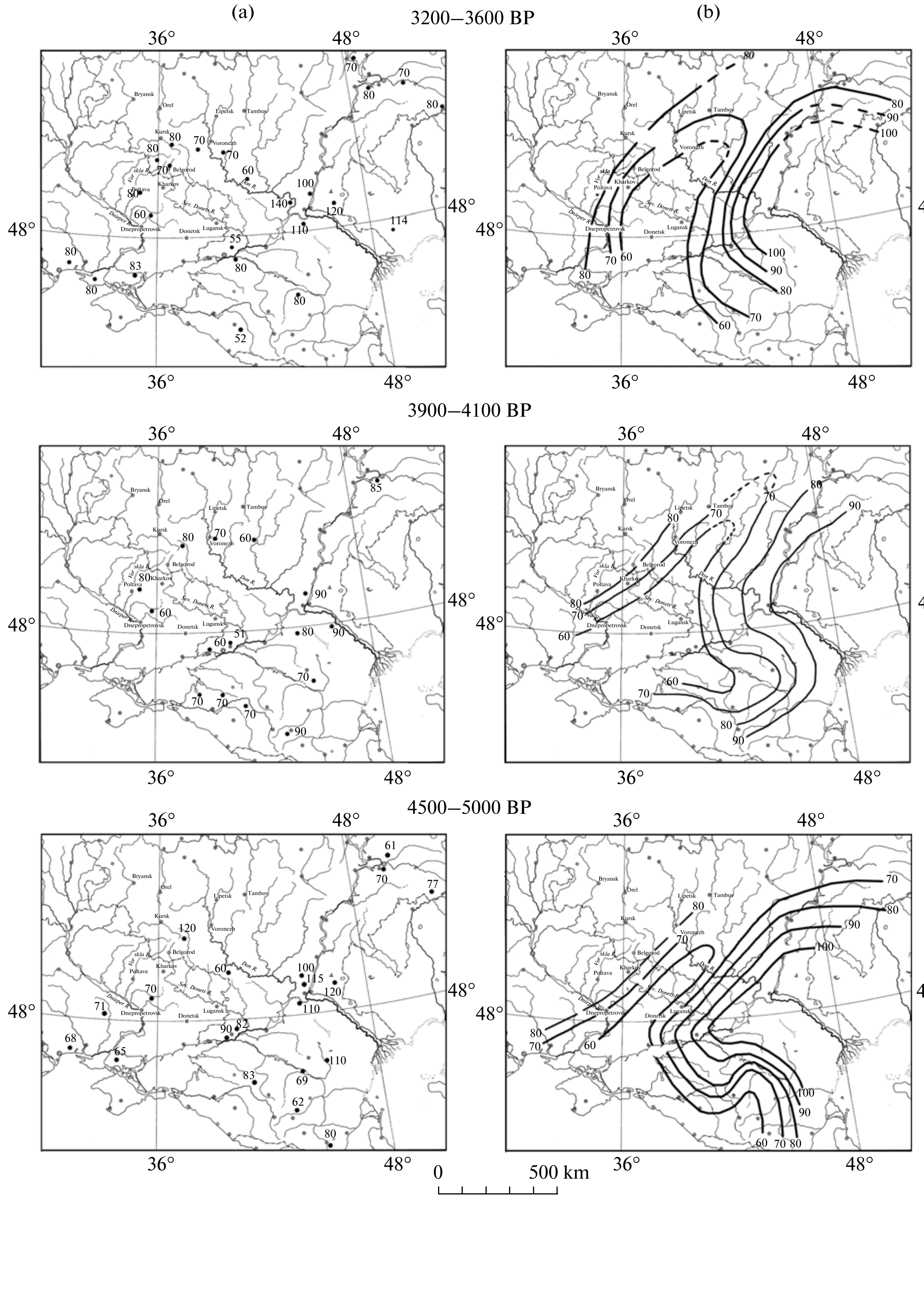


**Fig. 4.** Thickness of soil humus profiles in the paleosol space for three chronointervals of the Subboreal period in the south of eastern Europe, % of the modern values.

fact, this is a typical path of modern cyclones, which is clearly seen on synoptic maps of the European part of Russia.

Our conclusion about the increased climatic moistening in the specified region at the beginning of the Subboreal period is confirmed by findings of other researchers. Thus, paleoenvironmental reconstructions based on the palynological study of soil and peat samples from the middle Don reaches allowed Spiridonova and Aleshinskaya [40, 41] to conclude that forest vegetation in the considered period propagated far to the south; the zone of broadleaved forests was formed on the territory of the modern Voronezh oblast and neighboring areas. In the Middle Volga region (the Buzuluk pine stand), the interval from 6000 to 4500 BP is considered the optimum period with respect to the balance of the heat and moisture supply in the Holocene [32]. The palynological and radiocarbon analyses of peatlands from the Privolzhskaya Upland also suggest that the climatic optimum of the Holocene with the warm and relatively moist climate in this region was observed 6000—4500 years ago [5]. In the forest zone of the Kama basin, to the north of the Middle Volga forest-steppe, the transition from the Atlantic to the Subboreal period is considered the beginning of the moist climatic phase (more humid than that at the end of the Atlantic period).

On the schematic map of deviations of the depths of effervescence in the paleosols dating back to 3900—4100 BP from their modern values, a large depressed area extending from the northern Caspian Lowland towards Voronezh, Tambov, Lipetsk, and Kursk is clearly separated from neighboring territories by the shallow depths of effervescence. In the central part of this area extending for more than 1000 km in length and 500 km in width, the paleosols in the considered chronointerval effervesced from the surface. Some authors consider this chronointerval as the time of ecological crisis in the northern and northwester Caspian region with strongly developed wind erosion and soil salinization. There are no analogues to these paleosols in the modern soil cover of the region [6, 16, 17]. According to the palynological analysis performed by Spiridonova, the semidesert zone in that time shifted northward towards the southeastern part of the central chernozemic region [40].

The following interpretation of the synoptic conditions existing in the southeastern Europe in that time (3900–4100 BP) can be suggested. The formation of a vast zone of the accumulation of carbonates in soils could be due to the enhanced meridional transfer of air masses and the development of anticyclonic weather conditions above the considered area with the low precipitation and the high potential evaporation. These anticyclones extended from the southern Kazakhstan and Central Asia, i.e., from the areas of high air pressure in the tropics. Aridization of the climate in that period was observed in many other regions of the northern hemisphere, including China, Middle Asia, and northern Africa [52[. Thus, we may suppose that there were several centers, from which continental tropical air masses penetrated into northern regions, where they contacted with air masses of the temperate zone. The northward shift of the tropical centers of high air pressure could be the consequence of (or the reason for?) the activation of Indian monsoons about 4000 years ago [51].

If we look on the map showing the depths of effervescence in the chronointerval of 3200–3600 BP (Fig. 3), we can see a considerable change in the spatial patterns of this characteristic in comparison with that during the arid phase 3900–4100 BP. Even within the Caspian Lowland, the soils were more leached than those at present. At the same time, a new area of soils with a shallow depth of effervescence was shaped to the north of the Black Sea and the Sea of Azov. Hypothetically, its development could be related to the activation of the Azores High with penetration of its ridges into the considered area in summers.

The spatiotemporal regularities of the behavior of soil humus profile during the three considered chronointervals (Fig. 4) reflect a higher stability of this characteristic, its smaller changes both in space and in time in comparison with changes in the depth of soil carbonates. Within a larger part of the considered territory, the thickness of the soil humus profiles in the Subboreal period varied within 10% and reached 60–70 or 70–80% of the modern thickness of soil humus profiles in the corresponding regions. However, our schematic maps provide valuable information on the final stage of the evolution of soil humus profiles that took place after 3600–3200 BP. Most of the researchers studying soil evolution in steppe regions of the south of eastern Europe argue that the transformation of soil humus profiles was most pronounced at the beginning of the Subatlantic period [2, 9, 25]. Schematic maps clearly display the area with minimal values of the thickness of soil humus profiles extending from the northern Crimea and the Sea of Azov in the northeastern direction towards the forest-steppe zone of the Middle Volga region through the middle reaches of the Don River. The genesis of this area is not quite clear. It can be supposed that its development was related to the transformation of atmospheric circulation upon the transition from the Subboreal to the Subatlantic period, which resulted in sharper changes in the soil humus profiles along the "great climatic axis of Eurasia" discovered by Voeikov [8] and later named after him [35]. This axis separates the areas with high air pressure and anticyclonic weather conditions to the south from the areas of predominant lows and frequent cyclones moving from the southwest and west and bringing precipitation to the north of the axis. Thus, we suggest that the transformation of the climatic system that shaped the modern landscapes and soils in the southern part of eastern Europe upon the transition from the Subboreal to the Subatlantic period led to the evolution of the humus profiles of chernozems, which was most pronounced in the zone of the boundary between different air masses with a width of 200–300 km.

The developed schematic maps of soil characteristics for different chronological intervals seem to be promising for a better understanding of the factors and mechanisms of the evolution of the environment and soils and, at the same time, for verification and refinement of the existing paleoclimatic models. At the same time, we realize that the density of key points with special studies of the Holocene evolution of soils is not quite representative for reliable judgment of the regularities of the soil cover evolution. With the acquisition of new data, the suggested patterns of soil evolution can be refined.

Our study has confirmed the great theoretical and practical meaning of the method of soil chronosequences for the paleosol and paleogeographic reconstructions. A modification of this method as applied for the compilation and analysis of the schematic maps of soil properties in different chronointervals of the Holocene can be referred to as the method of chronoareas of soil properties, or, simply, as the method of soil chronoareas.

## CONCLUSIONS

(1) During the second half of the Holocene, the soil cover of treeless landscapes in the southern part of eastern Europe was characterized by the metachronous development. The regions with differently directed trends of changes in the soil properties and the regions with enhanced and retarded transformation of the soil properties can be separated. For example, in the chronointerval from 5000 to 4500 BP, a large area of soils with enhanced leaching of carbonates extended from the Lower Don region to the forest-steppe zone of the Middle Volga region; the depths of effervescence in the soils of that time were analogous to or deeper than in the modern soils. This fact attests to the increased atmospheric moistening of the area of the Don basin and Middle Volga reaches at the beginning of the Subboreal period.

(2) The depth of effervescence in the soil profiles was subjected to more pronounced changes under the impact of climatic fluctuations in comparison with changes in the thickness of soil humus profiles. In the Subboreal period, the following regional sequences of events related to the evolution of soil carbonate profiles were established: intensive leaching → calcification → less intensive leaching (Middle and Lower Don basin and Middle Volga basin), slight calcification → intensive calcification → intensive leaching (Lower Volga basin) → slight calcification → intensive calcification → slight leaching (southwestern part of the forest-steppe zone in the Central Russian Upland), and low-contrasting alternations of the slight leaching and slight calcification processes within the Poltava Plain and the Prichernomorskaya Lowland.

(3) In the Subboreal period, the thickness of soil humus profiles in the southern part of eastern Europe was characterized by the low-contrasting variations within 60–70 and 70–80% of its modern values. At the end of the Subboreal–the beginning of the Subatlantic period, the maximum increase in the thickness of soil humus profiles took place in the chernozemic zone, within the 200- to 300-km-wide stretch of land extending from the northern Crimea and the Sea of Azov in the northeastern direction towards the forest-steppe Middle Volga region through the steppe areas of the Middle Don basin. This area approximately corresponds to the contact zone between the cyclonic and anticyclonic weather regimes along the Voeikov axis. An increase in the amount of precipitation in the considered region at the end of the Subboreal–the beginning of the Subatlantic period favored more active growth of the thickness of humus horizons of local chernozems in comparison with their analogues on neighboring territories.

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