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GENESIS AND GEOGRAPHY OF SOILS

The Development of Chernozems on the Dniester–Prut Interfluve in the Holocene

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Abstract—The development of forest-steppe and steppe chernozems on the Dniester–Prut interfluve in the Holocene was studied on the basis of data on the paleosols buried under archaeological monuments of different ages. The parameters of the mathematic models of the development of the soil humus horizons in different subtypes of chernozems were calculated. They were used to determine the rate of this process and the age of the soils formed on the surface of Trajan's lower rampart. The climate-controlled changes in the character of the soil's development in the Late Holocene were differently pronounced in the different subtypes of chernozems. The suggested differentiation of the trends in the development of the humus horizon in the studied chernozems corresponds to the differences in the soil-forming potential of particular areas (as judged from the energy consumption for pedogenesis).

Keywords: soil and time, rate of pedogenesis, models of soil development, soil chronosequences chernozems, archaeological monuments of the Holocene monuments, the Holocene, soil chronosequences, soil chronofunctions

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INTRODUCTION

As stated by the European Thematic Strategy for Soil Protection [45], the climate changes recorded in many parts of the world during the period of instrumental measurements pose certain risks for soils and the environment and may intensify the processes of soil degradation. The soil–climatic interactions in the ecotone areas, including the transition between the forest-steppe and steppe, are of particular interest.

The Dniester–Prut interfluve is found on the southwestern part of the East European Plain. The genesis and geography of the soils in this vast area have been studied in detail in Moldova [22, 38] and the Trans-Dniester part of Odessa oblast in Ukraine [35, 43]. However, the history of the pedogenesis in the Holocene and the rates of the particular soil processes in this region are insufficiently studied.

The first results of the regional pedochronological investigations were obtained for Trajan's ramparts—a fortification system, some part of which (the rampart and the ditch) is still well preserved. In different years, special pedogenetic studies were conducted on Trajan's lower rampart (LTR) along three segments: near the Prut River (not far from the Kolibash settlement [21]), to the east of the settlement of Vadul-lui-Isak [17], and near the western shore of Lake Sasyk [11]. The LTR's length reaches 126 km, so we can compare the newly formed soils on the top of the rampart with the different background soils, including ordinary [21], calcareous [17], and southern [11] chernozems.

The composition of the microelements in the buried soils in the steppe (under the LTR) and in the forest-steppe (under the Kopach kurgan constructed about 4000 years ago) was examined [9]. The soil buried in the third century BC was studied in the area of the ancient settlement of Kodry [1]. The soil buried 2350 ± 50 yrs ago (cal. 2400 ± 50) was investigated under the LTR in the upper reaches of the Dniester, and the soils formed in the area of the antique town of Nikonii were also studied [27]. In recent years, newly formed and buried soils have been studied on the right bank of the Zbruch River in Ukraine (the rampart under which these soils were buried is also called Trajan's rampart) [12].

The paleogeographic reconstruction of the climate changes on the basis of the spore–pollen diagrams obtained for twelve settlements of the Neolithic and Eneolithic (Copper Age) periods [20] has shown that the phase of the Holocene climatic optimum in in the forest-steppe of the Dniester–Prut interfluve was in the Late Atlantic–Early Subboreal period (6000–4200 yrs ago). The most considerable aridization of the climate occurred 4200–3700 yrs ago, and better climatic conditions were established in the Late Subboreal Period (3300–2800 yrs ago).

In the Holocene, the studied region was subjected to considerable climate fluctuations accompanied by corresponding changes in the character of the pedogenesis. The complicated history of the development of human cultures with specific impacts on soils also has to be taken into account.

We studied the surface soils of different ages developed on the archeological monuments within the Dniester–Prut interfluve in order to reveal the climatic conditions of their development in the Late Holocene.

OBJECTS AND METHODS

Field investigations were performed on the Dniester–Prut interfluve, a part of the Danube–Dniester interfluve in Moldova, and in the southwest of Ukraine. According to the soil-geographical zoning, this region is specified into three provinces: the northern Moldavian forest-steppe province (39% of Moldova), the southwestern province of the northern steppe, and the Danube province of the southern steppe (Fig. 1).

The specific features of the forest-steppe chernozems in Moldova are mainly related to the climatic conditions of this region: this is the most strongly moistened and the coldest part of Moldova. The zonal vegetation is represented by oak forests and rich meadow steppes. Ordinary chernozems of the warm facies (with the mycelial form of carbonate accumulations) are formed in the Trans-Dniester part of Odessa oblast and on the southern branches of the Southern Moldova Upland. The Danube province of the warm southern European facies of chernozems is specified by the very dynamic (pulsating) carbonate accumulations, the strongly varying depth of the effervescence, the high clay content in the upper soil horizons, the high biological activity and intensive mineralization of the organic debris, and by the considerable biological transformation of the soil mass [35].

The modern chernozems of Moldova represent the final (for the present time) thirteenth stage of the pedogenesis in the Quaternary period. The climate of this stage is generally similar to the climate of most of the previous stages. This conclusion is based on the results of the study of loess–paleosol sequences in the Danube reaches in Moldova, where twelve buried paleosols of the Pleistocene are distinguished in the 30-m-high sediment column; all of them are of the chernozemic type [47].

It should be noted that the soils on the Dniester–Prut interfluve have been subjected to anthropogenic influence long ago. The optimum moistening of this territory in the southwestern part of the Russian Plain favors the formation of forest vegetation; however, the economic activity of humans favors the considerable transformation of the forest vegetation.

It is supposed that the earliest agriculture in Europe appeared in the Balkans in the middle of the 7th millennium BC; in the area of modern Romania and Moldova, the first farmers appeared about 8000 yrs ago [33, 37].

Paleobotanical investigations in the Neolithic and Eneolithic settlements on the Dniester–Prut interfluve [44] have shown that the native farmers used cereals, which were transported from their initial source in Middle Asia via the Balkans in the 6th millennium BC. In the southern part of Moldova (in the deposits of the Yalpuh floodplain), the first clear traces of the farming activity date back to the end of the Atlantic period (AT-3): 5550 ± 70 yrs ago (cal. 6400 ± 70 yrs ago) [6].

The historical-cultural individuality of the separate regions on the Dniester–Prut interfluve should be noted. The anthropogenically disturbed surfaces and soils of these regions have different ages. Thus, the monuments of the Linear Pottery culture (6th–5th millennium BC) are found in the forest-steppe zone in the central part of Moldova. The monuments of the Bug–Dniester culture (from the middle of the 6th to the beginning of the 4th millennium BC) are only found in the upper reaches of the Dniester River, whereas the monuments of the Tripolye (Cucuteni–Trypillian) culture (5400–2750 BC) are present to the north of Chisinau (530 and 123 ancient settlements belonging to this culture are known in the forest-steppe areas of Moldova and Odessa oblast, respectively). The distribution patterns of the archeological monuments of different ages in the subzones of ordinary and southern chernozems are generally similar, though some differences should be noted. In the Eneolithic Period (4th–3rd millennia BC), the Gumelnitsy crop farming and stock breeding tribes developed the land in the modern Odessa oblast near the Danube River. There were more than 230 settlements in the Trans-Dniester region of Odessa oblast in the Bronze Period, and 66% of them were in the subzone of southern chernozems. Many antique settlements (from the 6th century BC to the 4th century AD) appeared near the Dniester estuary and in the lower reaches of the Danube River. Younger monuments of the Balkan–Danube culture (the 10th–11th centuries AD) are found in Budzhak oblast (an historical oblast on the Danube–Dniester interfluve near the Black Sea). Monuments of the Golden Horde Period (the 13th–14th centuries AD) are also present in this area.

We studied six archaeological objects (ancient settlements) in the forest-steppe zone, 25 archaeological monuments in the steppe zone, and several plots at Trajan's and Zmiev ramparts (Fig. 1). The names of the archaeological monuments are given according to manuals [2, 8]. New soils are mainly developed from pedolithic sediments—cultural layers overlying the background natural soils—under grassy steppe vegetation.

The organic carbon content in the soil samples was analyzed by Tyurin's method; the group composition of the humus, by the method of Kononova and Bel'chikova; the total nitrogen (N) content, by Kjeldahl's procedure; the CO_2 of carbonates, by the acidimetric method; the available phosphorus, by Machigin's method; and the soil particle size, by the pipette method.

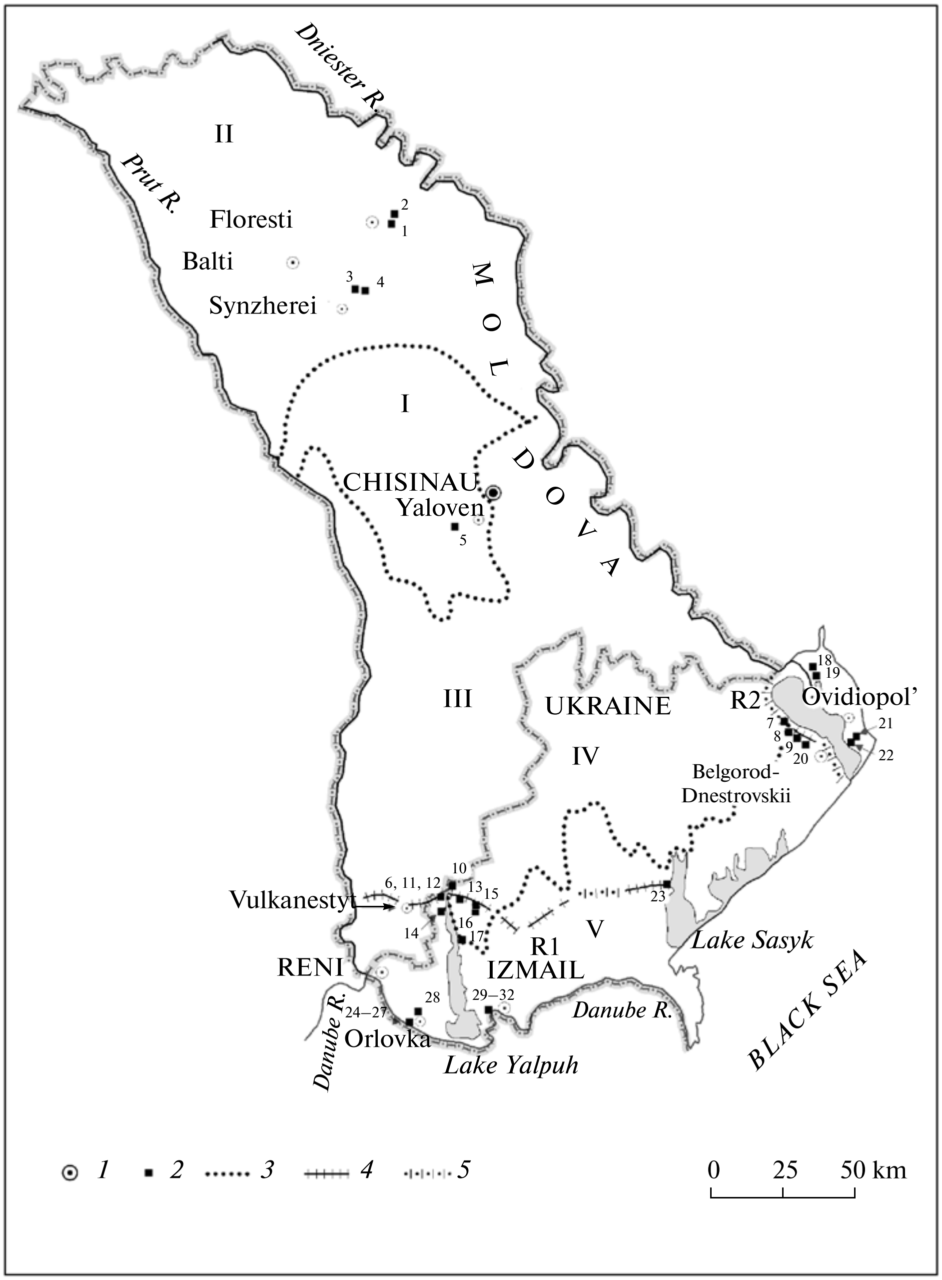

Fig. 1. Localition of the archaeological monuments examined within the Dniester–Prut interfluve: (1) Gura-Kamenchii VI, fifth millennium BC; (2) settlement of the same age (fifth millennium BC); (3) Sakarovka I, last quarter of the third millennium BC; (4) Synzherei XIX, sixth millennium BC; (5) Denchen I, middle part of the 3rd millennium BC; (6) Lower Trajan's rampart, first half of the 2nd century AD; (7) Zmiev rampart, the 4th century AD; (8) Mologa II, the 3rd century AD; (9) Mologa II, since 1385; (10) Yalpug IV, the 10th century BC; (11, 12) Lower Trajan's rampart, the first half of the 2nd century AD; (13) Tabaki I, the second half of the 13th century BC; (14) Bolgrad, Slavonic (the 9th–11th centuries AD), and antique (the 4th–3rd centuries BC) periods; (15) Zhovtnevoe III, first centuries AD; (16) Zhovtnevoe II, middle part of the 2nd millennium BC; (17) Krinichnoe (Karakutsk Gardens), the 7th–8th centuries AD; (18) Nadlimanskoe I, the 3rd century BC; (19) Nadlimanskoe settlement, the 3rd century BC; (20) southern part of the Akkerman fortress (since 1806); (21) Roksolany VII, the 4th–3rd centuries BC; (22) Nikonii settlement, the 5th century BC and the second quarter of the 3rd century AD; (23) Lower Trajan's rampart; the first half of the 2nd century A.D; (24) a settlement on Stony Mount, the 4th–3rd centuries BC; (25) Kartal settlement, bank of the ditch of the Roman period, the 2nd half of the 1st–the beginning of the 3rd centuries AD; (26) settlement of the period of the Medium Hallstatt, the 8th–7th centuries BC; (27) settlement of the Late Bronze Period, the 16th–10th centuries BC; (28) kurgan (1.8–2.0 m in height), the antique period; (29) Izmail, near the wall of the fortress; (30) the same place, the fortress wall was destroyed in 1790; (31) the same place, new earth wall; (32) the same place, St. Nikolai Monastery, the 18th century. Soil-geographic provinces: I—the Central Moldavian forest province; II—the northern Moldavian forest-steppe province; III—the Danube steppe province; IV—northern steppe subzone of ordinary chernozems; V—southern-steppe subzone of southern chernozems (near the Danube province). Conventional signs: (*1*) modern settlements, (*2*) archaeological monuments, (*3*) boundaries of the soil-geographic zoning, (*4*)—preserved earth walls, and (*5*) destroyed parts of the walls (R1—the Lower Trajan's rampart; R2—the Zmiev rampart).

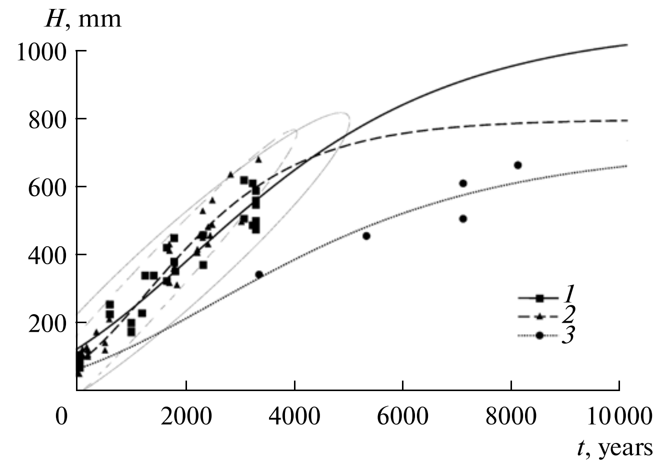

Fig. 2. Changes in the thickness of the humus horizons (*H*) with time (*t*). The zones with 95% probability of the data distribution are marked by ellipses: 1—Northern steppe subzone of ordinary chernozems, 2—Southern steppe subzone of southern chernozems, 3—Northern Moldavian forest-steppe province.

A schematic map of the energy expenses for the pedogenesis (*Q*) within the Dniester–Prut interfluve was developed with the use of ArcGIS software. The energy expenses *Q* were calculated according to the equation suggested by Volobuev [5]; the radiation balance and the annual precipitation are taken into account.

To compile the map, data on the water and temperature regimes (the mean annual temperature, the sum of the active temperatures, the radiation balance, and the precipitation) from 56 meteorological stations (including 20 stations in Romania and Ukraine) were used. The relatively dense network of weather stations in the studied area allowed us to characterize in detail the distribution pattern of the energy expenses (energy potential) of the soil formation. The areas of *Q* were produced using the ArcGIS Spatial Analyst and Geostatistical Analyst program modules. The schematic map was developed using ordinary kriging. A spherical model of the variogram was used; the maximum number of points used for calculating the values in each pixel of the image was 12.

RESULTS AND DISCUSSION

Changes in the soil morphology and properties with time. To understand the soil development with time, we need to determine the direction of the pedogenesis and to reveal the genetic relationships driving it [39]. The state of a soil system can be determined through the input impacts and output signals (the factors of the soil formation—the soil properties) or through the macroparameters of the system (such as the velocity and acceleration). The study of soil chronosequences makes it possible to develop trend models of the formation of the humus horizons [7].

The acquisition of new pedochronological information is particularly important for the development and verification of mathematical models describing the evolution of the soil properties. In particular, the modeling of the soil humus horizons and the humus accumulation is well developed. Earlier [26], it was suggested that the trends of the Holocene evolution of the resource-forming processes in automorphic soils generally agree with the S-shaped curves describing the growth processes in ecosystems. Their approximation by the Gompertz function was shown to be preferable [7]:

$$H = H_{\lim} \exp(-\exp(a + \lambda t)), \quad (1)$$

where H is the thickness of the soil humus horizon, mm; $H_{\lim}$ is its maximum thickness; a is a constant reflecting the initial conditions of the process, λ is a coefficient characterizing the growth rate of H; and t is the time (duration) of the pedogenesis, years.

If we compare the soil chronosequences developing in separate soil-geographical zones (subzones), we may consider incomplete chronosequences differing in the number of particular data (some periods of the soil development may not be preserved within the given territory). However, their mutual analysis with the development of regression equations makes it possible to restore some missing data.

To develop a model describing the growth of the humus horizon in chernozems (forest-steppe, ordinary, and southern chernozems), we used the results of our own field studies (Figs. 1 and 2). The value of $H_{\lim}$ was determined from statistical data on the thickness of the humus horizon in the main subtypes of chernozems [24, 38]. Regional parameters for the models of the development of the humus horizon in chernozems are given in Table 1.

Krupenikov [22] distinguished between two genetic families of chernozems in Moldova: (a) northern (forest-steppe) chernozems (typical, leached, and podzolized chernozems) and (b) southern chernozems with mycelial forms of carbonates (ordinary chernozems, calcareous chernozems, and chernozems under xerophytic forests). This subdivision is related not only to the specific climatic conditions of the pedogenesis in the northern and southern regions of Moldova but also to the differences in the character of the soil's evolution in these regions. For example, the forest-steppe chernozems contain relict features of hydromorphism. This is explained by the forest stage in their formation or by the more humid pedogenic conditions in the past and at present [22]. Calcareous chernozems with a relatively simple morphology and weak differentiation of the carbonates in the profile are considered to be the subtype of chernozems that preceded the formation of other subtypes. The major process in these soils is the process of humus accumulation [22].

Table 1. Parameters of the model of the development of the humus horizons in the chernozems of different provinces

Soil-geographic areas	H_{lim}	a	λ
Northern steppe subzone of ordinary chernozems	1050	0.759	–0.00037
Southern steppe subzone of southern chernozems	780	0.823	–0.00064
Northern Moldavian forest-steppe province	700	0.854	–0.00034

A specific feature of the morphology of the Moldavian chernozems is that the maximum thickness of the humus horizon (45–48 cm) is similar in all the subtypes of the chernozems [24]. The maximum thickness of the layer in which the humus content exceeds 1% is also similar for all the subtypes and reaches 100–110 cm. This points to the monoclimax stage in the Holocene history of the development of the humus profiles in Moldavian chernozems.

Our investigations confirm the similarity of the history of the evolution of the "southern" group of chernozems in Moldavia and Bessarabia: the data sets on the thickness of the humus horizons in the chernozems of different ages developed in two different steppe subzones do not differ statistically (according to the Kolmogorov–Smirnov criterion, $P = 0.95$) (Fig. 2). For the soils in the Balti region of typical chernozems in the northern Moldavian forest-steppe province, the data set is chronologically limited. However, it attests to a different trend in the development of the humus horizon in the typical chernozems of this region. Thus, the studied soils attest to certain differences in the soil-forming potential of the forest-steppe and steppe parts of the Dniester–Prut interfluve.

The analysis of the models of the development of the humus horizon of the chernozems allows us to compare the dynamic characteristics of this process for different eco-climatic soil groups. The chernozems of the southern steppe subzone (the Danube province) are characterized by the low growth rates of the humus horizon in the first 3000 years (0.15–0.18 mm/yr); its equilibrium thickness is reached quicker than that in the other subtypes of chernozems (Fig. 3). This fact confirms the opinion of Krupenikov [22] about calcareous chernozems as the first evolutionary stage of the development of chernozems. Calcareous chernozems reach their equilibrium with the environment relatively quickly. They may be reproduced under the modern conditions of pedogenesis. Note that the rates of the growth of the humus horizon shown in Fig. 3 characterize the stage of the slow growth ($n \times 1000$ yrs). The initial stage of this process ($n \times 10 - n \times 100$ yrs) is characterized by an order of magnitude faster rates of growth of the humus horizon [46].

The similarities and differences between the two genetic groups of chernozems on the Dniester–Prut interfluve are confirmed by the data on the physicochemical properties of the newly formed soils of different ages (Tables 2, 3).

The humus reserves in the soils at different stages of their development can be compared after calculating the specific humus reserves per 10 cm of the humus horizon. These data can be interpreted as the concentration of the organic matter (OM) in the soil humus profile. The generalized data on the humus distribution and the bulk density values in the full-profile chernozems of Moldova [38, 40] indicate that the humus pools in the major subtypes of chernozems change from 280 t/ha (ordinary chernozems) to 300 t/ha (calcareous and typical chernozems) and 335 t/ha (leached chernozems). The specific humus reserves (per each 10 cm of the profile) are less variable and decrease from 42.9 to 38.6 t/ha in the following soil sequence: deep typical chernozems → leached chernozems → ordinary chernozems → calcareous chernozems.

With respect to the relative humus content, the difference between the separate subtypes of chernozems is statistically unreliable. There is a tendency for a

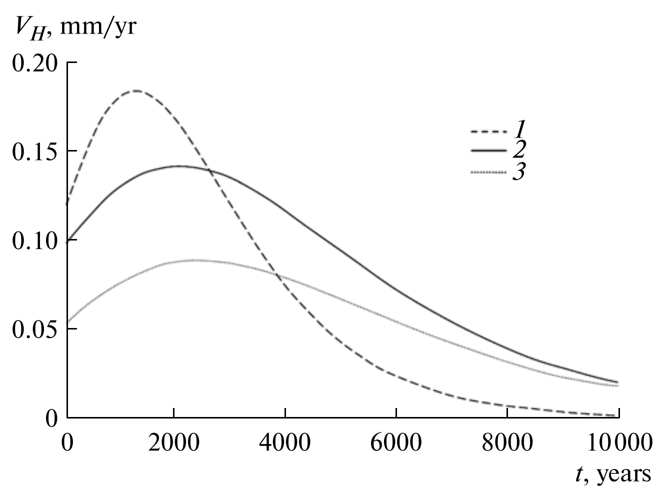

Fig. 3. Changes in the rates of growth of the humus horizons (V_H, mm/yr) with time (t): *1*—Northern steppe subzone of ordinary chernozems, *2*—Southern steppe subzone of southern chernozems, *3*—Northern Moldavian forest-steppe province.

Table 2. Physicochemical properties of the forest-steppe soils (Moldova)

Object number*	Soil age, yrs	Horizon	Depth, cm	Humus	N	$CaCO_3$	pH H_2O	Exchangeable cations Ca^{2+}	Exchangeable cations Mg^{2+}	Phosphorus available, mg/100g	Phosphorus total, %	Particle content, %; particle size, mm >0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	Σ<0.01
				%	%	%		mmol/100 g	mmol/100 g									
5	3300	A	0–21	2.18	0.182	0	7.65	20.58	2.90	2.90	0.206	0.93	40.19	22.89	4.48	11.01	20.5	35.99
		AB	21–34	1.76	0.113	2.8	7.90	19.54	4.25	4.25	0.224	0.88	40.71	23.11	4.84	10.90	19.56	35.30
		BC	34–48	1.24	0.090	3.0	7.85	19.92	4.96	4.96	0.258	0.69	42.96	23.43	5.48	11.45	15.99	32.92
		C	48–78	1.22	Not det.	3.2	8.10	Not det.	4.12	4.12	0.327	0.90	41.63	23.13	4.60	8.50	21.24	34.34
		C	78–88	1.08	″	4.4	8.30	″	3.09	3.09	0.258	1.07	40.49	23.79	4.46	9.54	20.65	34.65
1	7000	Ar	0–6	5.00	0.301	3.4	7.60	32.35	1.74	1.74	0.226	0.37	15.23	30.88	7.13	13.98	32.41	53.52
		A	6–23	3.76	0.206	3.8	7.75	30.14	0.68	0.68	0.278	0.51	9.90	29.75	14.87	17.07	27.96	59.84
		AB	23–33	3.17	0.154	4.7	7.85	29.48	0.68	0.68	0.294	0.30	21.59	30.19	5.68	14.89	27.35	47.92
		Ban	33–49	2.58	0.178	5.5	7.95	28.81	0.68	0.68	0.226	0.23	21.86	29.86	6.69	14.20	27.16	48.05
		B	49–79	2.94	0.164	2.8	7.80	29.08	0.52	0.52	0.208	0.38	28.92	29.97	7.41	8.30	25.02	40.73
		B	79–89	1.66	0.101	9.5	7.90	26.81	Not det.			0.09	11.19	41.89	6.09	14.67	26.07	46.83
2	7000	Aa	0–29	3.90	0.188	1.9	7.90	33.47	1.90	1.90	0.208	0.07	5.55	38.16	8.76	15.09	32.37	56.22
		A	29–40	3.94	0.215	1.9	7.85	32.36	2.72	2.72	0.174	0.11	5.33	40.50	6.74	16.86	30.46	54.06
		AB	40–60	2.85	0.141	4.9	7.95	31.70	1.04	1.04	0.208	0.02	2.50	37.67	10.16	15.76	33.89	59.81
		B	60–83	2.52	0.186	7.9	8.15	31.18	1.74	1.74	0.199	0.01	5.07	36.14	7.77	18.23	32.78	58.78
		B	83–106	1.78	0.155	7.5	8.20	30.12	1.38	1.38	0.190	0.02	4.42	35.70	8.70	17.71	33.45	59.86
		BC	106–116	1.25	Not det.	9.0	8.30	Not det.				0.01	5.37	37.05	8.64	16.74	32.19	57.57
3	5250	A	0–27	2.83	0.218	0	7.70	25.10	0.87	0.87	0.278	0.07	5.26	26.86	8.88	17.56	41.37	67.81
		AB	27–39	3.33	0.204	0.9	7.80	24.71	0.53	0.53	0.140	0.07	7.45	23.84	8.73	18.56	41.35	68.64
		B	39–65	1.66	0.139	8.5	8.05	23.92	0.52	0.52	0.190	0.04	2.74	26.90	10.75	20.13	39.44	70.32
		B	65–85	0.95	Not det.	12.4	8.25	Not det.				0.05	3.38	25.48	11.76	23.89	35.44	71.09
		B	85–95	0.82	″	11.5	8.40	″				0.05	3.95	24.66	11.38	22.93	37.03	71.34
4	8000	Aa	0–34	3.76	0.252	0.9	7.95	24.98	2.08	2.08	0.260	0.15	9.44	33.35	11.82	15.43	29.61	56.86
		Aa	34–52	3.57	0.204	1.5	7.95	28.73	1.38	1.38	0.346	0.04	7.20	39.07	7.49	15.4	30.80	53.69
		AB	52–70	2.41	0.149	7.7	8.05	26.78	1.04	1.04	0.326	0.07	7.73	37.38	8.39	16.42	31.01	55.82
		B	70–85	1.75	0.090	9.9	8.25	25.24	1.21	1.21	0.240	0.06	5.74	37.06	9.63	16.00	31.51	57.14
		B	85–109	1.71	0.083	9.3	8.25	26.90	1.55	1.55	0.224	0.09	6.90	35.65	10.45	15.69	31.18	57.36
		BC	109–132	1.30	0.069	8.4	8.25		1.88	1.88	0.206	0.15	8.93	34.92	9.96	15.57	30.47	56.00

* Here and in Table 3, the numbers of the studied objects correspond to those shown in Fig. 1.

Table 3. Chemical properties of the soils in the Black Sea province (Odessa oblast, Ukraine)

Object number/object description	Soil age, yrs	Horizon	Depth, cm	pH_{KCl}	$CaCO_3$	humus	N	C : N
					%			
Kartal settlement, 0.15 km to the east; excavation	43	An	0–8	8.55	8.49	3.19	0.145	12.7
29	62	A	0–7	8.60	7.60	4.88	0.275	10.3
		AB	7–13	8.85	10.28	1.78	0.095	10.8
East side of the wall near the Izmail fortress; soil developed on a breastwork	62	A	0–4	8.55	9.61	2.88	0.160	10.4
		AB	4–7	8.70	8.47	1.73	0.088	11.4
Izmail, flowerbed at the gates of Michael the King	80	A+AB	0–10	8.50	5.65	4.19	0.180	13.5
		B	10–18	8.50	2.02	3.45	0.190	10.5
31	216	A	0–6	8.55	10.08	4.12	0.275	8.7
		AB	6–12	8.75	11.07	2.09	0.140	8.6
		BC	12–33	9.00	5.35	0.73	0.090	4.7
32	360	A	0–7	8.75	7.41	4.27	0.210	11.8
		AB	7–17	9.00	9.26	1.88	0.130	8.4
25	1800	A	0–21	8.75	8.14	2.45	0.130	10.9
		AB	21–36	8.90	8.76	1.52	0.145	6.1
		Bh	36–42	8.95	12.67	1.05	0.090	6.8
		BC	42–50	9.05	11.53	Not det.		
26	2750	A	0–29	8.85	2.91	2.46	0.105	13.6
		AB	29–62	8.70	11.62	2.65	0.120	12.8
		B	62–84	8.75	11.16	2.15	0.120	10.4
27	3000	A	0–26	8.85	9.18	2.46	0.115	12.4
		AB	26–49	8.60	6.96	3.04	0.130	13.5
		B	49–79	8.65	5.38	3.14	0.120	15.2
13	3250	Ap	0–24	8.60	3.56	2.62	0.150	10.1
		A	24–33	8.70	5.79	2.09	0.130	9.3
		AB	33–51	8.70	6.68	2.04	0.110	10.7
		Bh	51–73	8.65	13.32	1.41	0.130	6.3
0.3 km to the east from the Zaliznychnoe settlement. Lower Trajan's rampart	*	A	0–31	8.00	1.59	3.24	0.150	12.5
		AB	31–42	7.85	2.26	1.94	0.140	8.0
Kartal settlement; soil developed from the Neolithic cultural layer and buried in the Roman period	3300	[A]	0–28	9.50	8.68	1.57	0.090	10.1
		[AB]	28–67	9.30	10.02	1.46	0.055	15.4
		BC	67–88	8.95	13.82	1.26	Not det.	

*Dating of the authors; see in text.

decrease in the humus content in the A horizon with an increase in the age of the studied soils. The newly formed (regenerated) humus horizons are richer in humus than the underlying disturbed soil layers. The specific reserves of humus increase with time up to the soil age of 2000 years. In the older soils, the specific reserves of humus are lower. This may be related to two reasons. First, the soils with the age of more than 2000 years have passed through the period with a low soil-forming potential of the environment (this period was less favorable for pedogenesis than the modern period). It is probable that the “memory” of these soils keeps the record of this less favorable period. Second, in the course of the soil development, the stage of active accumulation of the organic matter is replaced by the stage of a gradual increment in the thickness of the soil humus profile; the organomineral soil complex is stabilized at the quasi-climax stage. These regularities of the soil development were established for forest-steppe chernozems of central Russia [46].

With respect to their acidity (pH) and the content of carbonates, the chernozems of the studied area can be arranged into the following sequence: forest-steppe chernozems (typical and leached)—ordinary chernozems—calcareous and southern chernozems. In this sequence, the soil pH and the carbonate content increase, and the differentiation of the soil profiles with respect to these properties decreases; it corresponds to the rise in the heat supply and the drop in the atmospheric precipitation.

Unique features of the investigated soils are related to the long-term anthropogenic impacts affecting the morphology and properties of the soils. The soil profiles are complicated and reflect different stages of pedogenesis and anthropogenic influence. They include the agrogenic features, the newly formed features developed within the archaeological layers, and the residual (relict) features inherited from the previous stages of the soil development (objects 1–4, Table 2). The soil development on cultural layers of ancient settlements followed the pattern of transforming or superposed evolution [42]. After the abandoning of these settlements, a series of the A, AB, and B horizons is formed within the cultural layer. The thickness and morphology of these horizons correspond to the age of the soils. Partially, these horizons inherit the properties of the former soils. For example, a relatively high humus content in the B horizon (Table 2) may be inherited from the previous stage of the soil development in this area. The lower horizons (B and BC) of the modern soils already existed by the beginning of the formation of the cultural layer. The horizons developed within the cultural layer are marked by the increased content of total phosphorus (Table 2).

Modern agrogenic impacts favor the vertical differentiation of the soil profile with a decrease in the humus content in the plow layer, the leaching of carbonates, and the accumulation of clay matter under the plow layer.

The method of pedogenetic chronology and its approbation. The obtained models (Eq. 1) and their parameters (Table 1) can be used for dating of some archeological monuments (ancient settlements, tops of ramparts, etc.). In essence, this method is based on the dependence of the genetic soil properties (the thickness of the soil horizons, the soil humus pool, etc.) on the time (duration) of the soil development. This dependence is specific for each particular region with its own set of the environmental factors of the soil formation. It was tested on the Taman Peninsula, where the Cimmerian rampart was dated [29]. The age of this rampart is disputable (as well as the age of Trajan’s rampart).

Equation (1) describes the process under the conditions of the minimum disturbance of the pedogenesis, i.e., for automorphic soils with the absence of the input or removal of solid matter. The age of the surface of the archaeological monuments (the age of the soils developed on them) can be calculated according to the following equation derived from Eq. (1):

$$t = -\frac{a - \ln(-\ln(H/H_{\lim}))}{\lambda}. \quad (2)$$

The empirical coefficients required for determining the age of the newly formed soils according to Eq. (2) are given in Table 1. Let us consider the application of this method for dating two prominent archaeological monuments in the region—Trajan’s and Zmiev ramparts.

The construction of Trajan’s ramparts is often attributed to the epoch of the Roman Emperor Trajan. Thus, their approximate age is about 1900 years. In the 19th century, earthy walls (ramparts) stretching along the Prut and Dniester rivers were subdivided by Brun [4] into the upper (from the settlement of Kaushan to the settlement of Leov) and lower (from the settlement of Vodolui–Isaki (Vadul–Lui–Isak at present) on the Prut River to the settlement of Akkerman (Belgorod-Dnestrovskii) on the Dniester River. In the period of the Roman Empire, the Lower rampart was included into the defense system of the Lower Mesia province [3, p. 153]. It is generally believed that Trajan’s rampart was constructed by the Romans in the period from the end of the first century AD to the fourth century AD. However, there are certain archaeological arguments in favor of the later period of the rampart’s construction (in the seventh or even in the ninth centuries AD). It can be also supposed that Trajan’s ramparts were in use many times, both in the antique period and in the medieval epoch [36]. This interpretation explains the existence of two ditches on both sides of the rampart in some places. It is possible that the initial ditch at the northern side of the rampart was filled and the new ditch at the southern side of the rampart was cut. The problem may be solved on the basis of data on the soils developed on the ramparts and buried under them.

Measurements made at the beginning of the 19th century showed that the maximum height of the ramparts was 1.2–1.5 m [13]. According to [21] and [11], the total thickness of the buried soil and filled earth wall is similar on both plots (2.0–2.3 m). A description of the rampart made in the period of the land measuring works of 1822–1828 showed that the ditch near Trajan’s rampart was 4.3–5.3 m deep and up to 17 m wide [41]. Measurements to the west from Bolgrad (where the rampart crosses the Burlacheny ravine) showed that the northern ditch is filled with colluvial deposits 2.95 m in thickness; the humus-accumulative layer formed in these deposits is 1.92 m in thickness.

In addition to the upper and lower Trajan ramparts, the Zmiev rampart was studied. It stretches along the Dniester River [41]. On the map of the 1870s, the Zmiev rampart is shown along the western bank of the Dniester Estuary (12 km to the north from Akkerman). This rampart is up to 1.25 m in height and is composed of the material from the humus soil horizons; the humus content in it is 1.2%, and the content of carbonates is 4.1%. This rampart was obviously constructed after the end of the 4th century AD, because a settlement of the 2nd–3rd centuries AD is found under the rampart. The age of this rampart in the subzone of ordinary chernozems was determined according to Eq. (2). The total thickness of the humus layer (368 ± 48 mm; $n = 14$) suggests that the rampart could not have been constructed later than in the second half of the 4th century AD. Near the village of Tabaki, the thickness of the humus layer reaches 390 ± 10 mm ($n = 7$), and the calculated age of the rampart is within the range from the second century BC to the beginning of the 1st century AD. Near the Bol'shoi Yalpuh River, the thickness of the humus layer is 370 mm ($n = 14$), and the calculated age corresponds to the second half of the first century AD. The degree of the morphological development of the newly formed soil on the ramparts can be estimated via its comparison with the background full-profile soils; with respect to the thickness of the A1 horizon, it reaches 97%; with respect to the total thickness of the humus layer, it is about 64%.

Upon the dating of the soils developed on the earthy ramparts (walls), we should take into account the possible influence of various disturbing factors: the erosion of the upper horizons, the trampling of the vegetation, the soil compaction, etc. Thus, the long-term use of Trajan's rampart as a road favored considerable soil compaction (up to 1.55 g/cm^3 in the A horizon and 1.39 g/cm^3 in the AB horizon). If this increased bulk density is taken into account, certain corrections to the thickness of the humus horizons should be made. For a plot 0.6 km to the east from the Tabaki settlement, the thickness has to be increased by at least 27 cm. This makes the age of the soil (and the rampart) older by 150–200 yrs.

A part of Trajan's lower rampart in the subzone of southern chernozems (to the west of Lake Sasyk) is 9.6 km long, and a road disturbs the rampart‘s surface. An undisturbed plot was found near Lake Sasyk, where the rampart (in 1981) was dissected by a quarry of the local brickworks (plot no. 23, Fig. 1). The thickness of the humus layer on the undisturbed part of the rampart is 428 mm ($n = 5$), and the age of this soil corresponds to the end of the second century AD. It is probable that no reconstructions of the rampart in this place were performed later.

In the work of Krupenikov [21], the thickness of the soil developed on the rampart is not indicated directly. As judged from the given plots, it is about 40 cm. The background soil—an ordinary heavy loamy chernozem—is 78 cm thick (with respect to the thickness of the humus layer) and, hence, much older. The relatively young age of the soil on Trajan's lower rampart is also confirmed by other data: the clay (<0.001 mm) content in the upper 40-cm-thick layer of the newly formed soil is 11% lower that that in the buried soil and 7.4% lower than that in the background plowed ordinary chernozem [21].

The model of the development of the soil humus horizons with time in the southern steppe subzone (the Danube province) was applied to this soil; its age was determined to be 1917 years; i.e., it corresponds to the first half of the first century AD.

Thus, the most ancient dates of Trajan's lower rampart obtained with the use of the pedochronological method correspond to the second–first centuries BC. As a result of numerous reconstruction in the first two centuries of its functioning, the rampart was "rejuvenated." Possible denudation of the surface also makes the dates calculated from the data on the thickness of the humus horizons somewhat younger. The age of the rampart may correspond to the third–fourth centuries AD.

Reconstruction of the paleoclimate. Though the soil's evolution is closely related to the climate fluctuations, not all the changes in the soil's properties may be fixed in the solid-phase products of the soil's functioning, because many soil properties and processes are inert, reversible, and cyclic. Changes in the humus profile, the qualitative composition of the humus, the content and distribution pattern of the carbonates and clay particles, and many other soil properties require much longer periods than those of the temperature and moisture regimes [25].

The composition of the humus in the Moldavian chernozems [38] is characterized by the dominance of humic acids (50% of the organic matter on the average). Their content is lower (by 5–10%) in the calcareous chernozems, and the C_{ha}-to-C_{fa} ratio varies greatly (1.5–3.2) with the lowest values in the calcareous chernozems.

Pedogenetic studies provided evidence of a dryer climatic period before the construction of Trajan's lower rampart. The analysis of the soil water extracts indicates that the distribution patterns of the salts in the buried and modern soils in the subzone of ordinary chernozems are different [21]. In the subzone of calcareous chernozems [17], the leaching of salts from the modern soil during the period of the rampart's existence reaches 3.3 t/ha. The exchangeable sodium content in the buried soil is 2% of the cation exchange capacity; in the modern soils, exchangeable sodium is absent. Thus, the data on the migration of soluble salts and carbonates and on the composition of the adsorbed bases in the buried soil and the modern plowed soils allowed us to conclude that the climate before the rampart‘s construction was dryer than that in the later period [17]. However, it should be taken

Table 4. Group composition of the humus in the surface and buried soils in different parts of the Lower Trajan's rampart (LTR)

Studied area	Object	Horizon	Duration of the pedogenesis (duration of the buried soil's state), yrs	Depth, cm	C_{org}, %	% of C_{org}		100 C_{ha}/C_{org}	C_{ha}/C_{fa}
						HA	FA		
Ordinary chernozems [22]									
Kolibash settlement, Vulkaneshty district, Moldova	LTR; soil on the rampart	A	2000	0–9	2.18	23.4	15.0	61	1.5
		AB		30–40	0.85	32.8	16.8	66	1.9
	The same place, buried soil	[A]	2000	200–210	1.58	53.4	15.8	77	3.3
		[AB]		230–240	1.11	41.8	19.4	68	2.2
	Cropland (50 m from the rampart)	A	Holocene	0–20	2.18	50.1	15.2	77	3.2
		AB		40–50	1.17	49.0	20.8	70	2.3
Ordinary and calcareous chernozems									
Valul-Roman station, Bolgrad district, Odessa oblast, Ukraine	LTR	A	2000	0–30	0.96	16.7	12.5	57	1.3
		[A+AB]	The same	30–37*	1.26	25.4	12.7	67	2.0
	Virgin plot	A+AB	Holocene	0–56	1.23	18.7	16.3	53	1.2
Southern chernozems									
Glubokoe settlement, Tatarbunari district, Odessa oblast	LTR, soil on the rampart	A	2000	0–20	1.60	28.7	11.3	72	2.5
		AB	The same	20–42	1.72	28.5	12.7	69	2.2
	The same place, buried soil	[A+AB]	The same	63–73	2.21	26.2	9.0	74	2.9
				113–123	1.78	27.5	8.4	77	3.3
				143–153	1.35	29.6	10.4	74	2.9
	Cropland	A	Holocene	0–20	1.80	32.2	11.1	74	2.9
		AB		32–50	1.47	31.9	11.6	73	2.7

* A fragment of the humus horizon.

into consideration that the soil buried under the rampart was obviously virgin, while the properties of the modern plowed soils that are attributed to a more humid climate might also be specified by the agrogenesis. It was found [28] that the 150-year-long agricultural impact lead to changes in the structural organization of the entire soil profile resulting in the deeper (by 4 cm) humus profile, the loss of some solonetzic features, and the deeper (by 22 cm) upper boundary of the carbonate-bearing horizon.

In the 19 centuries after its burial, the soil under Trajan's lower rampart lost about 19–22% of the organic matter as a result of the diagenesis (Table 4). A comparison of the degree of the organic matter's humification ($100 \times C_{ha}/C_{org}$) in the buried soils under the rampart and in the full-Holocene background soils in the subzones of modern ordinary and southern chernozems shows that the degree of humification is higher in the buried soils. However, in the zone of calcareous chernozems, the degree of humification is higher in the modern soils. It should be taken into consideration that the relative increase in the degree of humification may be related not only to the more favorable climatic conditions but also to the effect of the diagenesis in the buried soils [15]. According to I.V. Ivanov (personal communication), one of the main factors of the changes in the ratios between the organic matter fractions in the buried soils is the transformation of the fractions with a general decrease in the content of the unstable fractions and the residual accumulation of the more stable fractions.

The composition of water extracts from the soils buried under Trajan's rampart is approximately the same as that in the modern southern chernozems (however, the content of magnesium and chlorine is lower in the buried soil). The contents of C_{ha} and C_{fa} in the buried paleosol do not differ from those in the modern plowed soils. In the soil developed on the ramparts, the C_{ha}/C_{fa} ratio varies from 2.0 to 3.3, thus pointing to the predominance of humic acids; an increased content (58–64%) of the nonhydrolyzable residue (the humin fraction) is also typical of this soil.

By the present time, vast data on the climatic fluctuations during the Subatlantic period have been obtained. In the northern Black Sea region, the climate became warmer and dryer at the end of the 3rd century BC; the maximum aridity was observed for two centuries up to the beginning of the 1st century BC. The accumulation of salts took place in the lakes of the Crimea in that period [10], and the drop in the Black Sea level gained its maximum in the last 2500 yrs. This period is referred to as the Ol'viisk regression [14]. It began at the end of the fourth–the beginning of the third century BC. By the middle of the 1st century, the Black Sea's level was as low as –8 to –10 m (below sea level). The period of the climate's aridization (2400–1800 years ago) was the period of the active accumulation of carbonates in the steppe soils [1]. The slowing down of the pedogenesis because of the unfavorable climatic conditions was due to the Roman maximum in the solar activity [16]. This was 1975 years ago according to the number of sunspots and 2050 years ago according to the intensity of the pedogenesis in the steppe zone.

The environmental conditions that existed in the modern subzone of ordinary chernozems 19 centuries ago were recorded in the soil properties, such as the intensive effervescence with HCl, the clearly pronounced maximum of the carbonates, and the narrower Ca-to-Mg ratio [22]. These characteristics allow us to conclude that the climate in the period preceding the construction of Trajan's rampart was dryer than the modern climate. In the southern regions, in the subzone of modern southern chernozems, the climatic conditions were more stable within the last 20 centuries, and more arid soil variants were not formed. In the area with more arid conditions (60 km to the east of the Dniester River), where dark chestnut soils are formed, the values of the coefficient of moistening do not exceed 0.45–0.48, and the energy expenses for the pedogenesis (Q) are no more than 890 MJ/m^2 per year.

Relationships between the soil patterns and the modern climate patterns. Cyclic patterns of climatic changes with peaks of the maximum precipitation (and the minimum temperatures) occurring once in 35 years were established at the beginning of the 20th century (Bruckner's cycles) [31]. The data of the meteorological stations in Moldova [19] for 1888–2006 show that the annual precipitation increased by 100 mm/year (from 470 to 570 mm), and the mean yearly air temperature increased by 0.9°C in that period. However, the recent decades have been characterized by repeated abnormally cold years, which may attest to the recent cooling of the climate in Moldova [18].

The regional differentiation of the climatic conditions during the period of the instrumental measurements can be seen from the map of the energy expenses for the pedogenesis (Q) (Fig. 4).

On the Dniester–Prut interfluve, Q varies from 915 to 1158 MJ/m^2 per year (1076 MJ/m^2 per year on the average); on 86.7% of the area, it is within 1000–1150 MJ/m^2 per year. The complicated topography of the area (the alternation of plains and uplands) causes the uneven distribution of the atmospheric precipitation, which results in the considerable spatial differentiation of the energy expenses for the pedogenesis. A general decrease in the values of Q is observed from the northwest to the southeast.

Two main areas with minimum Q are well pronounced in Moldova. The area of Balti (Drochia–Floresti–Balti) is the area of typical chernozems forming under relatively low Q (1075–1100 MJ/m^2 per year). At a distance of 30–40 km to the south, the annual precipitation increases by 150 mm, and the energy potential of the pedogenesis increases by 50 MJ/m^2 per year and more. The second area with relatively small Q values is found in the forest-steppe zone of the southern Moldavian Plain; it is also characterized by a low moisture supply. The highest Q values are typical on the well-moistened western slopes of the Central Moldavian and Podolsk uplands. In Bessarabia, the deficit of moisture is the main limiting factor.

A comparison of the soil map with the map of the Q values shows that the areas of leached and typical chernozems correspond to the areas with the highest Q, and ordinary and calcareous chernozems are mainly found in the areas with low Q. A statistical analysis of the distribution pattern of Q (interpolated values calculated for cells of 3 × 3.5 km) has shown that these values in the zones of ordinary ($n = 422$) and calcareous ($n = 905$) chernozems are within 970–1150 MJ/m^2 per year; the average values calculated for these zones are also very close (1095 and 1088 MJ/m^2 per year, respectively).

The relatively small changes in the energy potential of the pedogenesis in the zone of steppe chernozems are in agreement with our data on the results of modeling of the development of the soil humus horizons. Thus, the monoclimax type of the development of the humus horizon may be caused by the climatic conditions.

There is a close correlation between Q and the length of the period of the biological activity (PBA) [34] ($r = 0.87$). Therefore, the earlier found dependence of the degree of humification ($H = C_{ha}/C_{fa}$) and the PBA ($H = a \cdot \mathrm{PBA}^m$ (at $m = 3$) [32]) may be used to explain the differences in the types of humus upon the changes in Q. The calcareous chernozems of Moldova are similar to southern chernozems and are characterized by a relatively large thickness of the humus layer against the background of the low humus content, alkaline reaction, and the presence of carbonates in the topsoil [38]. However, despite the similarity of the morphological features, the calcareous and ordinary chernozems differ in the group composition ($C_{ha} : C_{fa}$) of humus in the upper 40 cm: 1.6–2.1 and 2.9–3.1, respectively. As shown earlier [30], in dependence on the thickness of the humus layer on the energy potential of the pedogenesis (Q), there is a limiting value of Q equal to about 1040–1080 MJ/m^2 per year. The further rise in Q is not accompanied by a corresponding increase in the thickness of the humus

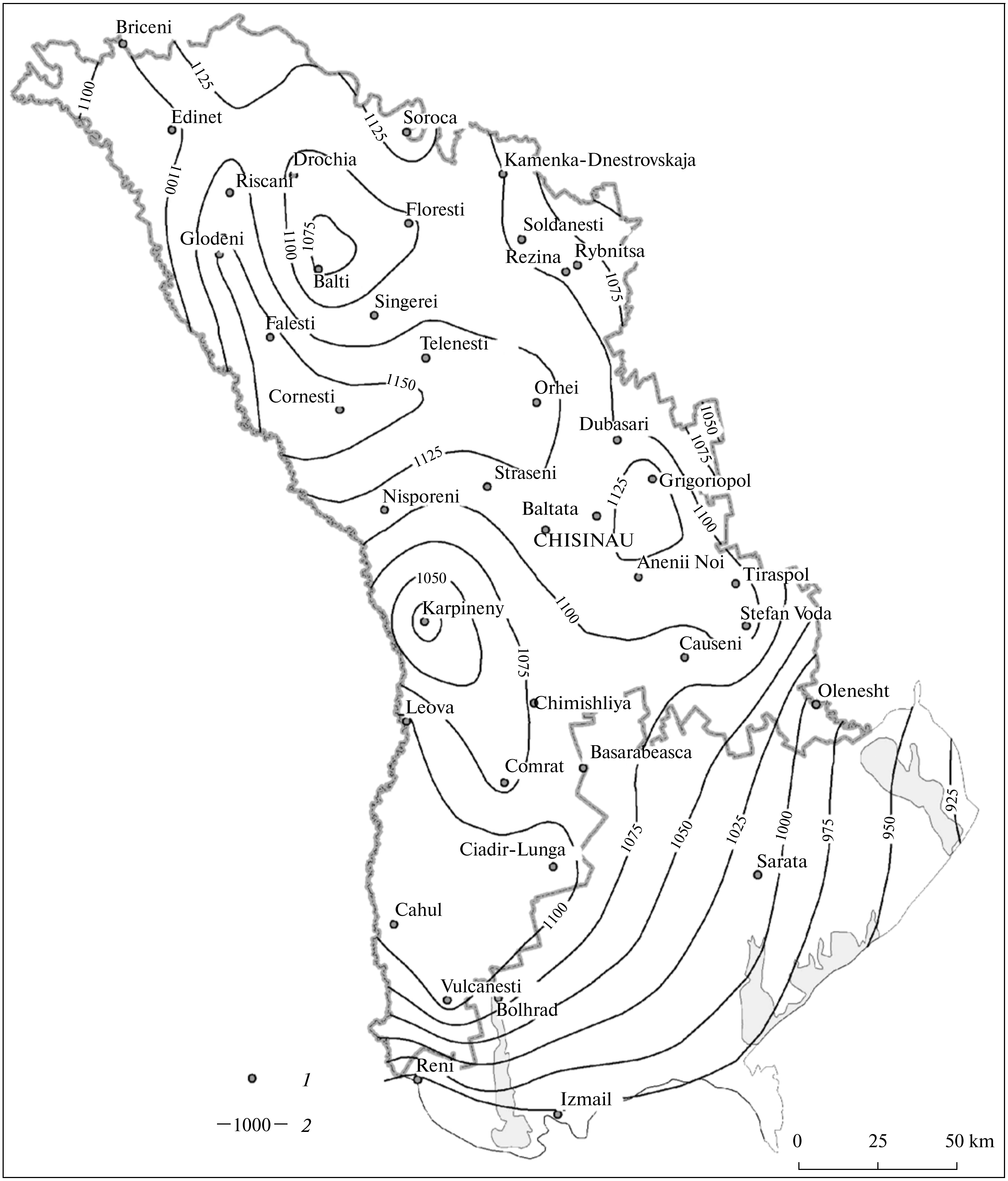

Fig. 4. Distribution of the energy expenses for the pedogenesis (Q, MJ/m^2 per year) on the Dniester–Prut interfluve: (*1*) weather stations and (*2*) Q values (MJ/m^2 per year).

horizon. Instead, the latter asymptotically approaches some limiting value. Therefore, the PBA duration also has some limiting value; when it is reached, the type of humus remains relatively stable in the humate range ($C_{ha} : C_{fa} > 2$), and it is in an equilibrium state with the morphological "maturity" of the soils.

CONCLUSIONS

The parameters of the models characterizing the development of the humus horizons of the chernozems on the Dniester–Prut interfluve have been calculated on the basis of the chronofunctions provided by the empirical data on the soils of different ages formed on dated surfaces of archaeological monuments. The insignificant differences between these parameters for the soils of the northern and southern steppe subzones allow us to conclude that the soil-forming potentials in these regions during the last 3000 years have been approximately similar. The soil-forming potential for a longer period (8000 years) in the Bel'tsy area of the northern Moldavian forest-steppe province with typical chernozems has been lower. The model calculations make it possible to determine the rates of the development of the humus horizon in the Moldavian chernozems during the first 3000 years of its most active growth. According to the rates of this process, the studied soils can be arranged into the following sequence: chernozems of the southern steppe subzone (up to 0.18 mm/year) > chernozems of the northern steppe subzone (0.14 mm/year) > chernozems of the northern Moldavian forest-steppe province (0.09 mm/year).

The regional chronofunctions that take into account the environmental conditions in the particular subzones of the chernozemic zone can be used for the pedogenetic chronology, i.e., for dating autonomous soils developed on the surface of earthy or stony archaeological monuments. This approach is based on the correlation between the irreversible genetic soil properties (the thickness of the soil horizons) and the time. In particular, it was used for dating the soils developed on Trajan's ramparts in different parts. It was found that the construction of this fortification wall began in the second–first centuries BC. The method of the pedogenetic dating of archaeological monuments with uncertain times of construction opens new possibilities for the paleogeographic reconstructions of the environment for separate periods of the Holocene on the basis of the analysis of the paleosols buried under the archaeological monuments and the new soils developed on them.

The state of the soil system can be described by the macroparameters of this system; in particular, the direction, velocity, and acceleration of the processes transforming the system are important. The characteristic time of the development of the humus horizon in the southern steppe chernozems is about 3000 years; in the northern steppe chernozems, 5000 years; and, in the forest-steppe chernozems (the northern Moldavian province), 6000 years.

The humus content in the chernozems increases during the first 2000 years of their development. In the older chernozems, it is somewhat lower. This may be related to the fact that the soils with the age of more than 2000 years preserve some properties inherited from the previous less favorable period of their development. In particular, these properties were described in the paleosols buried under Trajan's rampart in the area of the modern subzone of ordinary chernozems. To the south of this area, the climatic conditions have been more stable; we can also assume that the southern chernozems are less responsive to changes in the climate.

The modern pedogenetic potential of the climate specifies the spatial differentiation of the soil cover by the soil-climatic zones and subzones. The high energy potential of the pedogenesis in the area of the Dniester–Prut interfluve area results in the lower effect of the climate on the soil's morphology (its major features are preserved); however, the soils developing under somewhat different climatic conditions differ in their functional characteristics.

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