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The chronology of Neolithic dispersal in Central and Eastern Europe

Pavel Dolukhanov [a,*], Anvar Shukurov [b], Detlef Gronenborn [c], Dmitry Sokoloff [d], Vladimir Timofeev [e,1], Ganna Zaitseva [f]

[a] *School of Historical Studies, University of Newcastle upon Tyne, NE1 7RU, UK*
[b] *School of Mathematics and Statistics, University of Newcastle upon Tyne, NE1 7RU, UK*
[c] *Römisch-Germanisches Zentralmuseum, 55116 Mainz, Germany*
[d] *Department of Physics, Moscow University, Vorobyevy Gory, Moscow, 119992, Russia*
[e] *Institute for History of Material Culture, Russian Academy of Sciences, St Petersburg, 191186, Russia*
[f] *Radiocarbon Laboratory, Institute for History of Material Culture, Russian Academy of Sciences, 18 Dvortsovaya nab., St Petersburg, 191186, Russia*

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Abstract

We analyze statistically representative samples of radiocarbon dates from key Early Neolithic sites in Central Europe belonging to the Linear Pottery Ceramic Culture (LBK), and of pottery-bearing cultures on East European Plain (Yelshanian, Rakushechnyi Yar, Buh-Dniestrian, Serteya and boreal East European Plain). The dates from the LBK sites form a statistically homogeneous set with the probability distribution similar to a single-date Gaussian curve. This implies that the duration of the spread of the LBK is shorter than the available temporal resolution of the radiocarbon dating; therefore, the rate of spread must be larger than 4 km/yr, in agreement with earlier estimates. The East European sites exhibit a broad probability distribution of dates. We identify in these data a spatio-temporal sequence from south-east to north-west, which implies the rate of spread of the initial pottery-making of the order of 1.6 km/yr, comparable to the average rate of spread of the Neolithic in Western and Central Europe. We argue that this spatio-temporal sequence is consistent with an idea that the tradition of the initial pottery-making on East European Plain developed under an early impulse from the Eastern Steppe.

Keywords: Neolithic; LBK; Eastern Europe; Propagation rate; Radiocarbon; Statistical analysis

1. Introduction

The transition from the Mesolithic to the Neolithic was the most important landmark in prehistory of mankind. Its character and chronology in various parts of Europe remain controversial. Since Childe [9] had proposed the concept of 'Agricultural revolution', definitions of the Neolithic remained focussed on the introduction of farming. Notwithstanding various modifications of the idea, the shift to *agro-pastoral* farming is deemed to this day to be the most important single signature of the Neolithic [57].

Based on the archaeobotanic evidence relevant to the Neolithic context of Western Europe, Richmond [40] and Hather and Mason [22] question the extent to which the presence of cultigens implied actual cultivation.

* Corresponding author.
E-mail addresses: pavel.dolukhanov@newcastle.ac.uk (P. Dolukhanov), anvar.shukurov@newcastle.ac.uk (A. Shukurov), gronenborn@rgzm.de (D. Gronenborn), sokoloff@dds.srcc.msu.su (D. Sokoloff), ganna@mail.wplus.net (G. Zaitseva).
[1] This is the last paper of V. I. Timofeev who died at the age of 57 as a result of car accident in St Petersburg on 8 August 2004. His friendship and his expertise will be sorely missed by us.

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Although Rowley-Conwy [41] supports the older view that the 'Neolithic people subsided mainly on cultivated plants and domestic animals', a widespread opinion shifts towards viewing the Neolithic revolution as the introduction of domesticates into broad-spectrum economies. As discussed below, recent evidence has changed the traditional perception of the 'sub-Neolithic' communities of Eurasia's boreal forests, who are now considered to be involved, at least partly, in food production, rather than just pottery-making and hunter-gathering. In view of that, the present writers accept Thomas' [46,47] view of the Neolithic as 'a range of various processes, generating considerable variability of subsistence practices'.

A model of the Neolithisation as a result of direct migrations is omnipresent in archaeological discourse since the works of Childe [9]. This concept was developed by Ammerman and Cavalli-Sforza [3] who have suggested that the transition to agriculture in Europe resulted from the expansion of Neolithic farmers from southwest Asia, and was further substantiated with the use of 'genetic markers' [8,32]. Renfrew [38,39] linked up the introduction of farming with the spread of the Indo-European speech.

The advent of radiocarbon dating has provided a new, sensitive instrument for testing models of the Neolithisation. The first series of radiocarbon measurements seemed to confirm the Childean concept of *Ex Oriente lux*, indicating that the 'Neolithic way of life penetrated Europe from the south-east spreading from Greece and the south Balkans…' [11: 67]. More recent, comprehensive radiocarbon data for Neolithic sites suggested a more balanced view. Tringham [52: 216–217] discussed the spread of new techniques, and their adoption (or rejection) by the local groups, resulting from an expansion of population. Dolukhanov and Timofeev [15: 29–30] considered this process as a combination of diffusion and local inventions.

An analysis of a large dataset of Neolithic radiocarbon dates by Gkiasta et al. [19] has confirmed the earlier results of Clark [11] and Ammerman and Cavalli-Sforza [3], showing a correlation of the earliest occurrence of the Neolithic with the distance from an assumed source in the Near East. Gkiasta et al. [19] conclude that both a wave of advance of a cultural trait and a population replacement are consistent with the data.

Our aim here is to assess the chronologies of the Neolithisation in Central Europe and East European Plain as implied by statistical analysis of large datasets of radiocarbon dates. We identify certain spatio-temporal trends in the distribution of the radiocarbon-dated Neolithic sites and their plausible correlation with the spread of the Neolithic in Central and Eastern Europe. Given the temporal resolution of the radiocarbon dating, we do not (and cannot) address the small-scale processes involved in the spread of the Neolithic.

2. The database

This work is based on two major databases of radiocarbon dates recently developed for Neolithic sites in Europe. All dates for the former USSR (Russian Federation, Baltic States, Byelorussia, Ukraine and Moldova) have been included into the database developed at the Institute for History of Material Culture in St Petersburg [51]. The date list for LBK sites in Central Europe was compiled mainly from the *Radon* database [18]. We have also included radiocarbon dates from the sites in Austria and Germany published by Lenneis et al. [28] and Stäuble [44]. The latter dates span rather short time ranges and are relatively homogeneous archaeologically; we use them to estimate a typical empirical uncertainty of the radiocarbon dates. We do not make any distinction between radiocarbon dates obtained by different methods (AMS versus conventional). The reason is that the main source of date uncertainty is *not* the accuracy of the radioactivity measurement in the laboratory, but rather such effects as contamination by young or old carbon, etc. Therefore, the higher instrumental accuracy of the AMS dates does not represent an important advantage from the viewpoint of statistical analysis performed here. Similar arguments apply to the choice of material for radiocarbon dating, e.g., short-life material such as cereal seeds versus the long-life material such as charcoal. Since the plausible lifetime of the latter is still comparable to (or less than) the typical total error of radiocarbon dates, the difference can be ignored. This allows us to use dates based on various materials including charcoal unidentified to species. Any significant improvement in this direction would require field work for sample collection using procedures more stringent than before, as discussed by Christen and Buck [10] and Buck and Christen [6]. Such improved samples would then justify the application of advanced statistical methods, e.g., the Bayesian approach [7].

In all cases, the data marked as 'dubious' in the original publication were omitted. Wherever the total number of dates was too small to admit statistical analysis described in Section 3, only the dates from the lowest strata of multi-stratified sites were included (although we appreciate the limitations of this approach – see Section 3.1). All the dates have been calibrated with the calibration curve of Stuiver et al. [45] using OxCal 3.2. For each date, we used a continuous age interval corresponding to the probability of 95% (2σ) or, occasionally, 99.5% (3σ) as a measure of the calibration error. The calibration errors given in tables below are the 1σ errors thus obtained.

3. Statistical analysis

3.1. The need for statistical analysis

Under favourable conditions, the laboratory analysis of a sample radioactivity can yield very accurate estimates of the *apparent* age of the sample. Radiocarbon dates are often published with the quoted accuracy of a few tens of years (see, e.g., tables below). Nevertheless, it is not unusual that the spread of the dates in a sample confidently known to belong to an archaeologically homogeneous and short-lived object exceeds the published errors and any realistic estimate of the lifetime of the object. For example, the dates from Brunn am Gebirge discussed in Section 4 show a spread of about 400 years, with most of the published errors being about 75 years or less; even the calibration errors are larger than that. Meanwhile, the lifetime of the object was most plausibly about 100 years or even significantly less [43: 197].

The additional scatter of radiocarbon dates can be caused by several factors, e.g., by contamination by young or old carbon (e.g., [1]). For an individual measurement, the radiocarbon age cannot be corrected for this distortion. However, such a correction is feasible if one has a statistically significant set of radiocarbon dates from an archaeologically homogeneous and short-lived object, forming a *coeval set*. In such cases one can reasonably assume that the dates in the set represent a single date contaminated by random noise. The standard deviation of the dates in the coeval set can then be accepted as the *lower* estimate of uncertainty for the whole set of archaeologically related sites. Having thus obtained an estimate of the total uncertainty, we determine whether or not the spread of radiocarbon dates belonging to another archaeological site can be attributed to the random noise alone. If this is the case, all the dates in this set must be treated as a *single date* (that is, all the dates are *coeval* within the accuracy of radiocarbon dating), and the difference between the individual dates is purely random. As many other authors, we assume that the random noise is Gaussian. Otherwise, if the probability distribution of the dates in the set cannot be approximated by a single Gaussian curve, one has to conclude that the set refers to a phenomenon that evolved over a prolonged time, and the whole set cannot be characterized by a single date. A statistical test for a coeval data set is discussed in Section 3.3.

There is another reason why a collection of dates for a given archaeological object must often be replaced by a single date. In many cases, the frequency of radiocarbon dates is used as a proxy for population density. The spread of the Neolithic discussed here is such an example. It is obvious that the number of radiocarbon age determinations for a site or a certain region is related to the interest and resources of the researchers rather than to the prehistoric population density. Therefore, studies of population dynamics often rely on the earliest radiocarbon date for each site as an estimate of the time when, say, farming was first introduced at the site. However, the earliest date, as any other date, is never known precisely (see above) and, furthermore, this is one of the least probable dates in the set. Therefore, this approach can result in systematic errors, especially in those cases where the probability distribution of individual age measurements for a site can be interpreted as a single date in the sense discussed above. For example, the probability distribution of radiocarbon dates for the LBK site Ulm-Eggingen (Section 4 and Fig. 6) is as similar to a Gaussian as might be expected for a sample of 22 dates. Therefore, one cannot exclude that the spread of the dates in the sample is due to random noise (even if the calibration and instrumental errors alone are taken into account), and then the earliest date in the sample is *not* an acceptable estimate for the arrival of farming to the site. For Ulm-Eggingen, the difference between the most probable and the earliest dates is as large as 544 years. Several other sites where radiocarbon dates exhibit similar behaviour are analyzed in Sections 4 and 5. The method to calculate the likely date for a sample, presented in Section 3.3, is similar to that discussed by, e.g., Aitken [1] (see also [16]).

3.2. Estimates of the date uncertainty

Many statistical techniques require reliable knowledge of the statistical errors of individual data. As argued above, the published errors of radiocarbon dates represent only a relatively small part of the total error. Brunn am Gebirge is a site that can be used to estimate the total uncertainty of radiocarbon date measurements for the LBK. A set of 20 dates from this site was published by Lenneis et al. [28] (see Section 4). Their standard deviation is 99 years, whereas the average instrumental error is $\langle\sigma_i\rangle = 69$ years (after calibration, with individual errors σ_i ranging from 45 to 92 years).

Rosenburg is another site for which a statistically significant set of data has been published by Lenneis et al. [28]. There are seven dates plausibly belonging to the same Phase I of the LBK (see Section 4). The standard deviation of these dates is 127 years, which is significantly larger than their average instrumental error $\langle\sigma_i\rangle = 57$ years.

The difference between the two error estimates, 100–130 years (the standard deviation) and 60–70 years (the mean instrumental error), is significant. Therefore, we accept 100 years as the lower limit for the total error of the LBK radiocarbon dates. Of course, some archaeological objects can have smaller uncertainty (e.g., because of their shorter lifetime), but such cases have to be considered individually, and the corresponding uncertainty has to be estimated from independent evidence.

Similar estimate for the Neolithic of the East European Plain, about 130 years, is obtained in Section 5.

An estimate of the total uncertainty Σ_i for each date in each sample considered below has been chosen as a maximum of the published instrumental error σ_i, as obtained after calibration, and the corresponding lower limit discussed above. The lower limits are 100 and 127 years for the LBK and East European data, respectively, except for the Rosenburg LBK site where 127 years is adopted – see Section 5. These estimates will be important for the statistical test introduced in Section 3.3 which essentially relies on the availability of reliable error estimates.

3.3. The mean age and its confidence interval for a coeval sample

The most probable common date T_0 of the coeval subsample is obtained using the weighted least squares method as (see [16] for detail)

$$T_0 = \frac{\sum_{i=1}^{n} t_i/\Sigma_i^2}{\sum_{i=1}^{n} 1/\Sigma_i^2},$$

where n is the number of age measurements t_i, $i = 1, \ldots, n$, and Σ_i are their errors obtained as described in Section 3.2. The quality of the fit is assessed using the χ^2 test, with the fit being acceptable if

$$\sum_{i=1}^{n} \frac{(t_i - T_0)^2}{\Sigma_i^2} \le \chi^2_{n-1}.$$

This test for the goodness of fit is based on the assumption that the individual dates t_i represent the same average age T_0 contaminated by Gaussian random noise whose amplitude is given by Σ_i. The equality occurs in the above equation if this assumption is true in precise manner. If, however, the left-hand side exceeds χ^2_{n-1}, then the hypothesis must be rejected and t_i cannot be interpreted as a single date contaminated by noise. It is important to note that the left-hand side will be overestimated if the errors are underestimated; this is why it is important to have reliable estimates of the total error Σ_i.

If the χ^2 test is not satisfied, the dates deviating most strongly from the current value of T_0 are discarded one by one until the test is satisfied. This procedure results in a 'coeval subsample'.

The confidence interval Δ of T_0 has been calculated as

$$\Delta = \frac{\sigma}{n}\sqrt{\chi^2_{n-1} - X^2(T_0)},$$

where

$$\frac{1}{\sigma^2} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{\Sigma_i^2},$$

and

$$X^2(T_0) = \sum_{i=1}^{n} X_i^2,$$

with

$$X_i^2 = \frac{(t_i - T_0)^2}{\Sigma_i^2}.$$

The results of our calculations are presented in the form $T = T_0 \pm \Delta$; another important quantity is the standard deviation of the dates in the coeval subsample, σ_c. The quantity T_0 is the most probable age at which the cultural entity studied was at its peak. The confidence interval of T_0, denoted Δ, characterizes the reliability of our knowledge (rather than the object itself). For example, small values of Δ can indicate that a slight improvement of the data can resolve a temporal heterogeneity of the subsample. The standard deviation in the coeval subsample, σ_c, is a measure of the duration of the cultural phenomenon considered. For example, it can reasonably be expected that the early signatures of the cultural entity under consideration might have appeared by (2–3)σ_c earlier than T_0, while the total lifetime of the entity is of order (4–6)σ_c (with the probability 95–99.5%). In many respects, the significance of σ_c is similar to the total error of an individual radiocarbon date.

Our results are based on statistically significant samples; the number of individual dates in such a sample cannot be smaller than, roughly, 5–10. Strictly speaking, 30 or more measurements are needed in order to rely on Gaussian statistics. However, in practice smaller samples are often used with quite satisfactory results. Since random element is present in any data, it is reasonable to expect that the range of the data will grow with the size of the sample (even if the sample has been drawn from statistically homogeneous data). The histogram of a coeval sample will fit a Gaussian shape if our assumptions are correct. The Gaussian distribution admits data that deviate strongly from the mean value, and a pair of dates arbitrarily extracted from the widely separated wings of the Gaussian can be very different. The conclusion that they do belong to a coeval subsample can only be obtained from a simultaneous analysis of all the dates in the sample.

4. The Linear Pottery from Central Europe

Sites of the Linear Pottery Culture (LBK) are spread in a vast area of Central Europe, stretching from the south-western Ukraine and Moldova in the east to the Paris Basin in the west. Since Childe [9], the sites of the LBK or 'Danubian I' culture have been considered as belonging to the first authentic groups of farmers in that area. Van Berg and Hauzeur [54] note a remarkable homogeneity of LBK sites, both in the organisation of space and in the manifestations of the material and spiritual culture.

The sample from *Brunn am Gebirge, Flur Wolfholz, Austria*, contains 20 date measurements given in Table 1. According to Lenneis et al. [28], the inventory of the entire site belongs to the oldest LBK (phase I sensu [48]). The statistical test for contemporaneity introduced in Section 3.3 would be satisfied for the whole subset without discarding any measurements if only the individual date errors were all larger than 80 years. The average instrumental error in the date set is $\langle\sigma_i\rangle \approx 69$ years. Since the difference of $\langle\sigma_i\rangle$ from the value of 80 years is negligible, this date set can be considered coeval, with the average age and its standard deviation given by

$$T_0 = 5252 \pm 99 \text{ cal BC}.$$

Lenneis et al. [28] attest that, although all the dated structures belong to the same LBK phase, difference between the true ages of individual objects can be considerable. These authors distinguish the older structure (*Fundstelle* I) and the younger one (*Fundstelle* II). Nevertheless, the probability distribution of the dates, shown in Fig. 1, fails to reveal any distinction of this kind. The above estimates of the mean age and its uncertainty are consistent with the lifetime of this archaeologically complex settlement of the order of a hundred years (i.e., a few standard deviations). Of course, the different ages of individual, stylistically distinct structures within an archaeologically complex site (e.g., *Fundstellen* I and II) can be discernible with other methods (e.g., the tree ring dating). However, this distinction is not important here as long as the individual structures still exhibit sufficient archaeological and cultural affinity, and as long as the radiocarbon dates contain random errors. This comment applies to all other coeval subsamples discussed below that originate from sites with archaeologically distinct temporal structures.

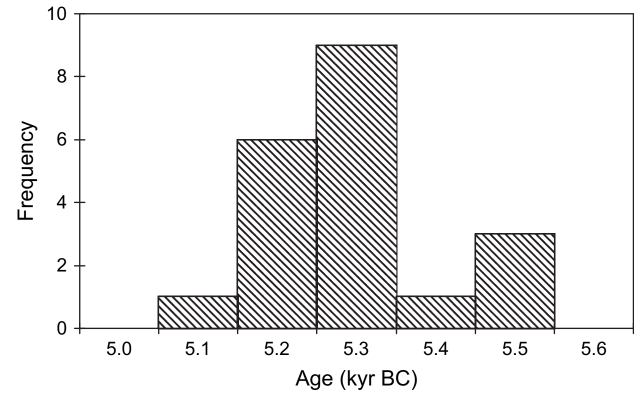

Fig. 1. The frequency of dates (cal BC) in the Brunn am Gebirge sample per 100 yr interval.

Table 1
The date sample for Brunn am Gebirge: (1) sample index, (2) uncalibrated radiocarbon age and (3) its published instrumental error, all according to Lenneis et al. [28], (4) calibrated date and (5) its error resulting from calibration with the above instrumental error; and (6) the sample's material

Index	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	Material
ETH-11127	6520	50	5430	50	charcoal
ETH-11122	6520	55	5425	52	charcoal
ETH-11145	6480	70	5405	58	charcoal
ETH-11124	6470	55	5395	45	charcoal
ETN-11130	6365	55	5290	53	charcoal
ETH-11138	6390	65	5280	70	charcoal
ETH-11147	6365	70	5265	72	charcoal
ETH-11128	6360	60	5260	63	charcoal
ETH-11150	6360	70	5250	67	charcoal
ETH-11149	6335	70	5245	68	charcoal
ETH-11132	6320	65	5240	67	charcoal
ETH-11134	6325	70	5220	77	charcoal
ETH-11146	6315	70	5215	75	charcoal
ETH-11137	6285	70	5200	80	charcoal
ETH-11123	6260	70	5185	82	charcoal
ETH-11129	6265	70	5185	82	charcoal
ETH-11140	6265	70	5185	82	charcoal
ETH-11125	6235	70	5175	92	charcoal
ETH-11121	6265	55	5150	63	charcoal
ETH-11126	6150	75	5045	82	charcoal

The sample from *Rosenburg, Flur Hofmühle, Austria*, contains 10 date measurements presented in Fig. 2 and Table 2. The site occupies the total area of nearly 1 ha and includes seven differently preserved houses and more than 100 pits and 'slot pits' (*Schlitzgruben*). According to Lenneis et al. [28], seven of the dates belong to an 'early phase' of the older LBK, with only one house and one pit (3 measurements) containing younger material. The standard deviation of the seven

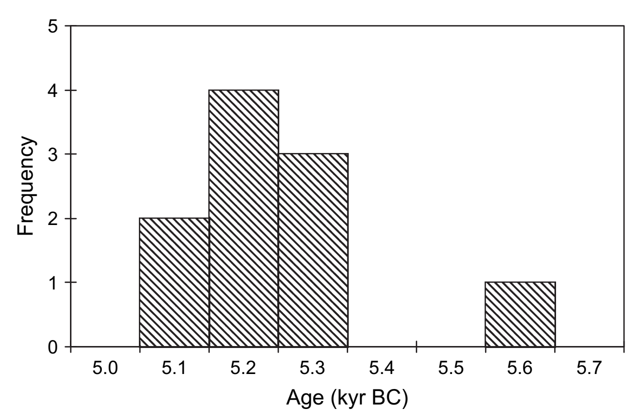

Fig. 2. The frequency of dates (cal BC) in the Rosenburg sample per 100 yr interval.

Table 2
The date sample for Rosenburg, in the format of Table 1, with the structure identifier given in column 2 according to Lenneis et al. [28]

Index	Structure (*Grube*)	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2	Material
GrN-19909	198	6625	130	5525	142	5.70	charcoal
GrN-19914	198	6330	50	5255	62	0.29	charcoal
GrA-452	198	6310	30	5235	35	0.14	charcoal
GrA-449	198	6280	50	5210	57	0.03	charcoal
GrA-458	198	6270	30	5180	37	0.00	charcoal
GrA-456	198	6250	30	5165	35	0.03	charcoal
GrA-454	198	6240	30	5165	35	0.03	charcoal
GrA-422	242	6170	30	5110	40	0.37	charcoal
GrA-423	242	6140	30	5075	48	0.78	charcoal
GrA-649	242	6100	60	5015	75	1.83	charcoal

$X^2(T_0) = 9.2$, $\chi_9^2(0.95) = 16.9$.
All the dates belong to the coeval subsample; X_i^2 is the contribution of the measurement into the total residual $X^2(T_0)$ as defined in Section 3.3. The latter is given at the bottom of the table together with the value of χ^2.

dates belonging to the same Phase I is 127 years. This can be considered as an estimate of the total error of the dates; then all the dates appear to be consistent with each other (in the sense of the above criterion of contemporaneity) and yield the sample age of

$T_0 = 5141 \pm 62$ cal BC,

with the spread

$\sigma_c = 138$ years.

The oldest date, GRN-19909, can be included into the coeval subsample because it has large error.

The sample of *Schwanfeld, Germany*, contains 17 date measurements given in Tables 3 and 4. The dates taken from the list published by Stäuble [44] belong to House 11 (Earliest LBK) and House 14 (Middle Neolithic). Among the eight dates belonging to House 11, seven satisfy the statistical test for contemporaneity (see Fig. 3) with the resulting age of

$T_0 = 5467 \pm 90$ cal BC, $\sigma_c = 514$ years.

The nine dates from House 14 show strong scatter over the time span of 3550–5600 cal BC, and six of them can be deemed to be coeval (Fig. 4) with

$T_0 = 4786 \pm 129$ cal BC, $\sigma_c = 458$ years.

The sample of *Cuiry-les-Chaudardes, France*, contains 15 date measurements presented in Fig. 5 and Table 5. The site belongs to the younger LBK (*Rubané récent*). The statistical test for contemporaneity is satisfied for the whole sample with

$T_0 = 4841 \pm 133$ cal BC, $\sigma_c = 321$ years.

The sample of *Ulm-Eggingen, Germany*, includes 25 date measurements given in Fig. 6 and Table 6. The 22 dates that satisfy the statistical test for contemporaneity are attributed to the stages 4–7 of the Baden-Würtemberg division of the LBK. The resulting age is

$T_0 = 4831 \pm 55$ cal BC, $\sigma_c = 261$ years.

All the discarded dates are older than T_0. The statistical analysis performed here confirms 4800–4900 cal BC as the most probable date of the coeval subsample that includes the younger dates because of their relatively large errors. It has been noted that radiocarbon measurements in south-western Germany favour earlier dates in this range, whereas archaeological evidence [59] suggests the older dates.

Table 3
The date sample for Schwanfeld 11, in the format of Table 2

Index	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2	Material
KN-3044	**7250**	**500**	**6200**	**567**	**1.7**	**wood**
KN-3040	**7100**	**500**	**6000**	**533**	**1.0**	**wood**
KN-3046	**6690**	**140**	**5600**	**133**	**1.0**	**wood**
KN-3041	**6700**	**190**	**5550**	**217**	**0.1**	**wood**
KN-3425	**6520**	**65**	**5425**	**55**	**0.2**	**wood**
KN-3216	**6540**	**260**	**5350**	**283**	**0.2**	**wood**
KN-3192	6060	170	4900	200	8.0	wood
KN-3217	**5800**	**320**	**4600**	**333**	**6.8**	**wood**

$X^2(T_0) = 10.9$, $\chi_6^2(0.95) = 12.6$.
The dates belonging to the coeval subsample are indicated with bold face.

Table 4
The date sample for Schwanfeld 14, in the format of Table 2

Index	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2	Material
KN-3033	**6800**	**370**	**5600**	**400**	**4.14**	**wood**
KN-3034	6660	65	5560	47	59.91	wood
KN-3035	**6065**	**140**	**4950**	**167**	**0.97**	**wood**
KN-3038	**5940**	**300**	**4750**	**317**	**0.01**	**wood**
KN-2966	**5890**	**65**	**4745**	**82**	**0.17**	**wood**
KN-3039	**5810**	**200**	**4650**	**250**	**0.30**	**wood**
KN-3032	5420	140	4250	167	10.34	wood
KN-3037	**5400**	**300**	**4200**	**367**	**2.55**	**wood**
KN-3036	4780	170	3550	250	24.44	wood

$X^2(T_0) = 8.1$, $\chi_5^2(0.95) = 11.1$.
The dates belonging to the coeval subsample are indicated with bold face.

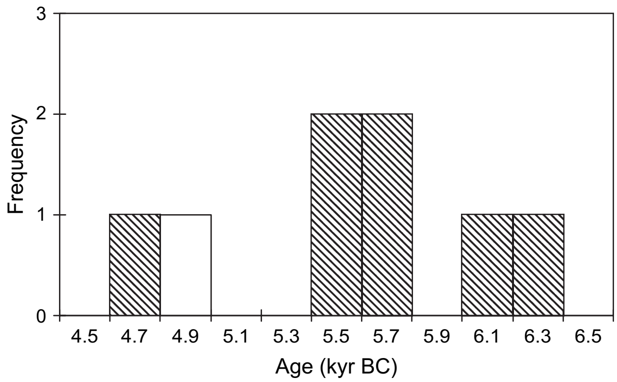

Fig. 3. The frequency of dates (cal BC) in the Schwanfeld 11 sample per 200 yr interval. Dates belonging to the coeval subsample are shown shaded.

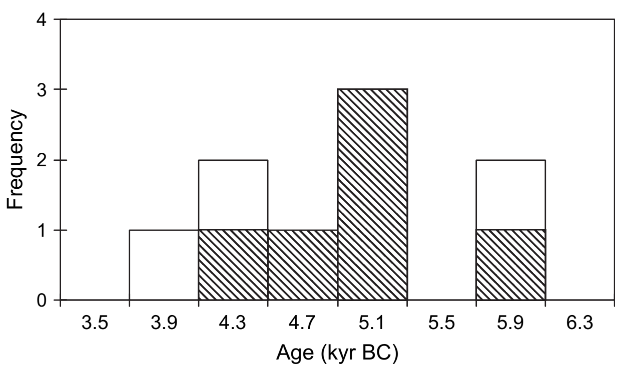

Fig. 4. The frequency of dates (cal BC) in the Schwanfeld 14 sample per 400 yr interval. Dates belonging to the coeval subsample are shown shaded.

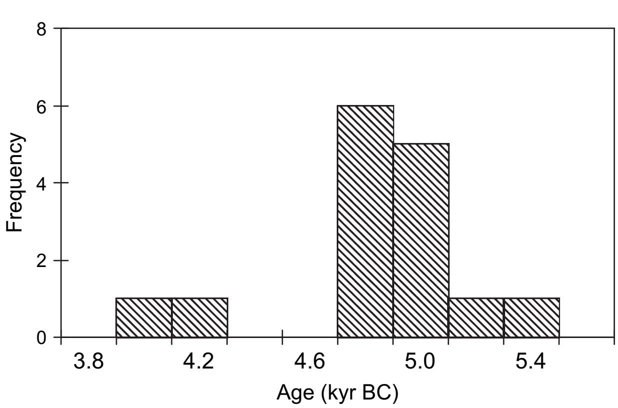

Fig. 5. The frequency of dates (cal BC) in the Cuiry-les-Chaudardes sample per 200 yr interval.

Table 5
The date sample for Cuiry-les-Chaudardes, in the format of Table 2

Index	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2	Material
Ly-1736	6450	160	5300	167	7.56	collagen
Ly-1737	6220	230	5050	250	0.69	collagen
Ly-2321	5960	170	4900	200	0.08	collagen
Ly-2333	5980	110	4875	142	0.05	collagen
Ly-2331	6000	120	4875	142	0.05	collagen
Ly-1829	5930	190	4850	217	0.00	collagen
Ly-2336	5960	150	4850	167	0.00	collagen
Ly-2330	5910	130	4800	150	0.08	collagen
Ly-2335	5840	140	4750	167	0.30	collagen
Ly-2551	5870	170	4750	217	0.18	collagen
Ly-2552	5730	170	4650	217	0.78	collagen
Ly-2332	5800	170	4650	217	0.78	collagen
Ly-1827	5860	300	4650	317	0.37	collagen
Ly-1828	6580	400	4200	350	3.36	collagen
Ly-1826	5360	510	3950	583	2.34	collagen

$X^2(T_0) = 16.6$, $\chi^2_{14}(0.95) = 23.7$.
All the dates are coeval in the sense of the statistical test of Section 3.3.

We have similarly analyzed ten dates from the *Blicquy, Belgium*, where the result is

$$T_0 = 5302 \pm 112 \text{ cal BC}, \; \sigma_c = 255 \text{ years}.$$

The whole LBK date list presented in Table 7 is taken from the *Radon* database, with the addition of the dates obtained here. It includes 47 measurements; 40 of them can be combined into a coeval subsample, with the most probable age of

$$T_0 = 5154 \pm 62 \text{ cal BC},$$

and the standard deviation

$$\sigma_c = 183 \text{ years}.$$

Both the general sample and its coeval part are further illustrated in Fig. 7 in the form of the date probability distributions. The significance and implications of these

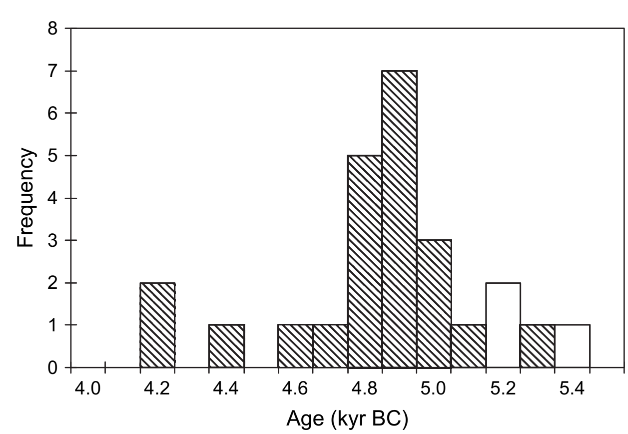

Fig. 6. The frequency of dates (cal BC) in the Ulm-Eggingen sample per 100 yr interval. Dates belonging to the coeval subsample are shown shaded.

Table 6
The date sample for Ulm-Eggingen, in the format of Table 2

Index	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2	Material
Hv-14732	6500	100	5375	108	25.3	charcoal
Hv-14727	**6390**	**170**	**5225**	**175**	**5.1**	**charcoal**
Hv-13596	6245	120	5150	133	5.7	charcoal
Hv-13600	6205	60	5120	67	8.4	charcoal
Hv-14725	**6135**	**105**	**5075**	**125**	**3.8**	**charcoal**
Hv-14730	**6120**	**150**	**4975**	**158**	**0.8**	**charcoal**
Hv-13601	**5995**	**60**	**4950**	**100**	**1.4**	**charcoal**
Hv-14731	**6125**	**235**	**4950**	**250**	**0.2**	**charcoal**
Hv-14724	**6035**	**105**	**4900**	**133**	**0.3**	**charcoal**
Hv-14722	**6100**	**270**	**4900**	**300**	**0.1**	**charcoal**
Hv-14734	**6010**	**60**	**4885**	**58**	**0.3**	**charcoal**
Hv-12982	**5960**	**90**	**4875**	**125**	**0.1**	**charcoal**
Hv-13599	**5960**	**60**	**4865**	**68**	**0.1**	**charcoal**
Hv-14729	**5980**	**200**	**4850**	**217**	**0.0**	**charcoal**
Hv-14735	**5935**	**115**	**4825**	**142**	**0.0**	**charcoal**
Hv-14728	**5965**	**200**	**4800**	**233**	**0.0**	**charcoal**
Hv-13595	**5855**	**80**	**4750**	**100**	**0.6**	**charcoal**
Hv-13597	**5840**	**145**	**4750**	**167**	**0.2**	**charcoal**
Hv-14726	**5870**	**225**	**4750**	**250**	**0.1**	**charcoal**
Hv-14733	**5875**	**60**	**4735**	**72**	**0.9**	**charcoal**
Hv-13598	**5810**	**80**	**4650**	**100**	**3.3**	**charcoal**
Hv-13594	**5740**	**195**	**4600**	**233**	**1.0**	**charcoal**
Hv-14721	**5590**	**160**	**4400**	**200**	**4.6**	**charcoal**
Hv-14736	**5295**	**295**	**4150**	**383**	**3.2**	**charcoal**
Hv-14737	**5410**	**320**	**4150**	**383**	**3.2**	**charcoal**

$X^2(T_0) = 29.4$, $\chi^2_{21}(0.95) = 32.7$.
The dates belonging to the coeval subsample are indicated with bold face.

results in the broader context of the European Neolithic are discussed in Section 6. Four of the discarded dates are younger than 4700 cal BC. This agrees with archaeological evidence that LBK sites younger than 4800 cal BC in the Paris basin are unlikely. Further to the east, the LBK had ended around or before 5000 cal BC.

5. The Neolithic of East European Plain

The sites on East European Plain, described as Neolithic, feature large-scale production of pottery, with no or limited evidence of either agriculture or stockbreeding [34]. These sites are found in all parts of East European Plain in environments invariably rich in wildlife resources. Some sites are of a considerable size and apparently were of a permanent character. Considerable progress was attained in tool making, architecture and symbolism with evidence of social hierarchy. There is evidence of trade contacts between hunter-gathering and agricultural communities, which involved flint, amber, mollusc shells. Based on the styles of pottery and the typology of stone, bone and antler tools, a number of local ‘archaeological cultures’ are identified, some of which had several chronological stages. In this section we consider radiocarbon dates from several archaeological cultures belonging to the early Neolithic: the Yelshanian sites in the Lower Volga–Ural Interfluve; Rakushechnyi Yar and related sites in the Lower Don area; Buh-Dniestrian in South-Western Ukraine; Upper Volga and other Early Neolithic cultures in Central and Northern Russia.

Prior to investigating the dates from the early Neolithic sites, we have analyzed a series of recently obtained dates for pile structures of the site of *Serteya 2*, a clearly stratified Late Neolithic lake settlement in the upper stretches of the Western Dvina river at 55°30′N, 31°30′E. This settlement belongs to a large cluster of sites which were in existence through the early and middle Holocene [14,33]. Analysis of archaeological and pollen data has revealed cereal pollen and evidence for forest clearance, suggesting swidden-type agriculture [17].

The excavated area is below the water level in the drainage canal and consists of rows of piles forming six distinct clusters. Each of these clusters allegedly formed a foundation for a platform on which a house was erected. The platform is well preserved in the case of Structure 1. Thus, wood samples from each structure apparently belong to a single house constructed during a single season. All the piles are made of spruce, which could not sustain prolonged stocking. Hence, the dates from each structure characterise a momentary event in the sense of radiocarbon dating. Several samples were taken from different sets of year-rings of a single pile. We have calculated the empirical error for four sets from Structures 1, 2, 3 and 6. In the case of Structure 1, all dates form a Gaussian-type distribution with one date obviously falling out (Fig. 8). The mean age of the remaining dates is 2304 cal BC with a standard deviation of 113 years. The corresponding values for the other structures are 2372 ± 83 cal BC for Structure 2; 2295 ± 129 cal BC for Structure 3 (with one outlier), and 2219 ± 184 cal BC for Structure 6 (with one outlier). The average age of all four structures is 2298 ± 127 cal BC. The latter standard deviation, 127 years, is adopted as the minimum error in the statistical analysis of the dates for the entire East European Plain.

The sites of the *Yelshanian Culture* [30] have been identified in a vast area of the steppe stretching between the Lower Volga and the Ural Rivers. The subsistence was based on the hunting of a wide range of animals (wild horse, aurochs, elk, brown bear, red deer, fallow deer, saiga antelope, marten, beaver), food collecting (tortoise, edible molluscs, mostly *Unio*), and fishing. Remains of domestic animals (horse, cattle, sheep and goat) were found at several sites, yet the penetration from the later levels cannot be excluded. The archaic-looking pottery is made from the silty clay tempered with organic matter, fish scales and bone. The sample contains eight dates presented in Table 8, and five of them can be assumed to be coeval since they group

Table 7
Radiocarbon dates for the Linear Pottery (LBK) sites in Central Europe: the site name, laboratory index, the uncalibrated age and its instrumental error, the calibrated age and an estimate of its total error

Site	Index	Age bp (yr)	σ_i (yr)	Age cal BC (yr)	Σ_i (yr)
Les Longrais	Ly-150	5290	150	4100	167
Montbelliard	Gif-5165	5320	120	4125	142
Chichery	Gif-3354	5600	120	4450	150
Frankenau	VRI-207	5660	100	4525	125
Horné Lefantovce	**Bln-304**	**5775**	**140**	**4700**	**200**
Kaster	KN-2130	5840	55	4700	100
Schwanfeld 14				**4786**	**458**
Guttenbrunn	Bln-2227	5935	50	4830	100
Ulm-Eggingen				**4831**	**261**
Cuiry-les-Chaudardes				**4841**	**321**
Dresden-Nickern	**Bln-73/73A**	**5945**	**100**	**4850**	**133**
Hallertau	**HAM-197**	**5990**	**90**	**4875**	**125**
Menneville	**Ly-2322**	**6030**	**130**	**4900**	**225**
Mold	**Bln-58**	**5990**	**160**	**4900**	**300**
Chabarovice	**Bln-437**	**6070**	**200**	**4950**	**217**
Kirschnaumen-Evendorff	**Ly-1181**	**6050**	**200**	**4975**	**263**
Kecovo	**GrN-2435**	**6080**	**75**	**5000**	**100**
Dachstein	**Ly-1295**	**6280**	**320**	**5050**	**350**
Hienheim	**GrN-5870**	**6125**	**35**	**5065**	**100**
Friedberg	**Bln-56**	**6120**	**100**	**5075**	**125**
Niedermerz 3	**KN-2286**	**6180**	**120**	**5075**	**188**
Niedermerz 1	**KN-I.594**	**6180**	**50**	**5100**	**100**
Eilsleben	**OxA-1627**	**6190**	**90**	**5100**	**117**
Langweiler 2	**KN-I.885**	**6210**	**125**	**5100**	**133**
Lautereck	**GrN-4750**	**6140**	**45**	**5100**	**200**
Northeim-Imbshausen	**H-1573/1126**	**6192**	**140**	**5100**	**250**
Müddersheim	**KN-I.6**	**6210**	**50**	**5110**	**100**
Mohelnice	**MOC-70**	**6220**	**80**	**5125**	**163**
Niemcza	**Bln-1319**	**6210**	**80**	**5125**	**163**
Dnoboh-Hrada	**LJ-2040**	**6300**	**300**	**5150**	**317**
Bylany Stage II a-c	**GrN-4754**	**6270**	**65**	**5190**	**100**
Rosenburg				**5187**	**138**
Langweiler 9	**KN-2697**	**6370**	**210**	**5200**	**233**
Elsloo	**GrN-5733**	**6300**	**65**	**5215**	**100**
Köln-Mengenich	**KN-I.369**	**6320**	**70**	**5220**	**100**
Gerlingen	**KN-2295**	**6390**	**160**	**5225**	**158**
Langweiler 1	**KN-2301**	**6340**	**70**	**5245**	**100**
Brunn am Gebirge				**5252**	**99**
Geleen	**GrN-995**	**6370**	**60**	**5260**	**100**
Duderstadt	**H-919/889**	**6422**	**100**	**5300**	**100**
Blicquy				**5302**	**255**
Lamersdorf	**KN-I.367**	**6410**	**45**	**5340**	**100**
Langweiler 8	**KN-2989**	**6540**	**155**	**5375**	**158**
Eitzum	**Bln-51**	**6530**	**100**	**5400**	**100**
Göttingen	**H-1534/1027**	**6530**	**180**	**5400**	**200**
Schwanfeld 11				**5467**	**514**
Bylany Stage IV	BM-569	6754	96	5625	108

$X^2(T_0) = 46.3$, $\chi^2_{39}(0.95) = 54.6$.
The dates shown with no entries in columns 2–4 are those obtained in Section 4, where we adopt $\Sigma_i = \sigma_c$. Dates belonging to the coeval subsample are shown in bold face.

within a narrow age interval, with the mean age and standard deviation of

$$T_0 = 6910 \pm 58 \text{ cal BC}.$$

The remaining dates are older than that (8025–7475 cal BC).

Rakushechnyi Yar is a clearly stratified Neolithic settlement located on a small island in the lower stretches of the River Don, ca 100 km upstream of the city of Rostov. Belanovskaya [5], who excavated the site, has identified 23 archaeological levels. The deepest levels (23–6) belong to the Early Neolithic. Animal remains consist of both the wild (red deer, roe deer, fox, hare,

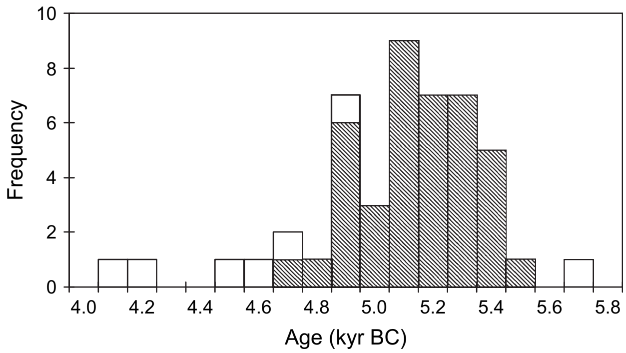

Fig. 7. The rate of occurrence of radiocarbon dated sites for the LBK sites in Central Europe, according to Table 7 (radiocarbon age in cal BC, binned into 100 yr intervals). The coeval subsample is shown shaded, and the remaining dates, unshaded.

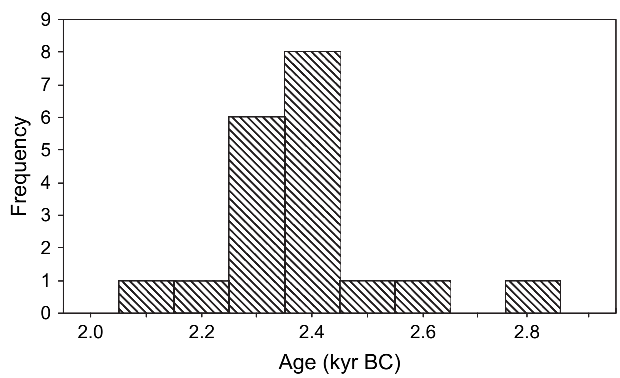

Fig. 8. The frequency of dates (cal BC) per 100 yr in the Serteya 2, Structure 1.

and numerous birds) and domesticated species (sheep, goat, cattle, dog, and horse, either wild or domestic). Numerous shells of edible molluscs (mostly, *Viviparus*) indicate the importance of food gathering. The pottery is often tempered with organic matter and includes both the flat- and pointed-bottom varieties.

Two Early Neolithic sites of *Matveyev Kurgan 1 and 2* are in the valley of the Miuss River, on the littoral of the Azov Sea [26]. The animal remains of both sites are

Table 8
The date sample for Yelshanian in the format of Table 1

Site	Index	Material	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)
Chekalino 1	Le-4781	shell	8990	100	8025	163
Chekalino 1	GIN-7085	shell	8680	120	7725	118
Lebyazhinka 4	GIN-7088	shell	8470	140	7475	213
Chekalino 1	**Le-4783**	**shell**	**8050**	**120**	**7000**	**225**
Ivanovskaya	**Le-2343**	**bone**	**8020**	**90**	**6925**	**163**
Chekalino 1	**Le-4782**	**shell**	**8000**	**120**	**6900**	**200**
Chekalino 1	**Le-4784**	**shell**	**7940**	**140**	**6875**	**213**
Chekalino 1	**GIN-7086**	**shell**	**7950**	**130**	**6850**	**200**

The dates accepted as coeval are highlighted with bold face.

dominated by wild species: aurochs, red deer, roe deer, beaver, wolf, wild boar, kulan and wild ass (the latter two were more typical of the Mesolithic age). The domesticates, which form 18–20% of the total assemblage, include horse, cattle, sheep/goat, pig and dog. Both sites contain rich stone industries, and a few potsherds. The 10 radiocarbon dates from the lower layers (the Early Neolithic) are presented in Table 9, of which six dates satisfy the criterion for contemporaneity, yielding

$T_0 = 5863 \pm 130$ cal BC, $\sigma_c = 247$ years.

The remaining dates include one younger date (5000 cal BC) and three older ones (6550–6850 cal BC).

About 40 sites belonging to the *Buh-Dniestrian Culture* are located on the lower terraces of the River Dniester (Nistru) and its tributaries, and on the River Pyvdenyi Buh [12,31]. At earlier sites, about 80% of animal remains belong to wild species, mostly roe deer and red deer. Among the domestic animals, pig, cattle and sheep/goat have been identified. Archaeological deposits contain huge amounts of *Unio* molluscs and tortoise shells. The pottery includes deep bowls with S-shaped profile and hemispherical flat-bottomed beakers made of clay tempered with organic matter and crushed shells. Ornamental patterns consist of the rows of shell-rim impressions, finger impressions, and incised lines forming

Table 9
The date sample for Rakushechnyi Yar and Matveev Kurgan (two dates labelled MK1) in the format of Table 2

Site	Index	Material	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2
Layer 20	Ki-6476	organic crust	930	140	6850	200	24.4
Layer 20	Ki-6477	organic crust	7860	130	6725	163	28.1
Layer 20	Ki-6475	organic crust	7690	110	6550	175	15.4
MK 1	**GrN 7193**	**unknown**	**7505**	**210**	**6400**	**300**	**3.2**
Layer 9	**Le-5344**	**shell**	**7180**	**250**	**6000**	**250**	**0.3**
MK 1	**Le-1217**	**charcoal**	**7180**	**70**	**5980**	**70**	**0.9**
Layer 15	**Ki-6480**	**organic crust**	**7040**	**100**	**5860**	**95**	**0.0**
Layers 14-15	**Ki-6478**	**organic crust**	**6930**	**100**	**5780**	**90**	**0.4**
Layer 15	**Ki-6479**	**organic crust**	**6825**	**100**	**5700**	**100**	**1.6**
Layer 8	Bln-704	charcoal	6070	100	5000	115	46.2

$X^2(T_0) = 6.4$, $\chi^2_5(0.95) = 11.1$.
The coeval dates are highlighted with bold face.

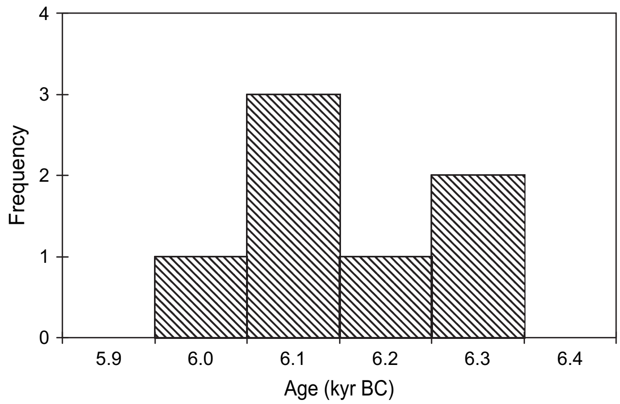

Fig. 9. The frequency of dates (cal BC) for the Buh-Dniestrian per 100 yr interval.

zigzags; several patterns find direct analogies in the 'monochrome' pottery of the Balkan Early Neolithic (Starčevo-Criş Culture). Imported potsherds of Linear Pottery (with 'music-note' patterns) were found at several sites belonging to the Culture's latest phase. The radiocarbon date sample contains the total of 7 date measurements from the sites on the Pyvdenyi Buh presented in Fig. 9 and Table 10. All the seven dates satisfy the statistical test for contemporaneity, with

$T_0 = 6121 \pm 143$ cal BC, $\sigma_c = 101$ years.

The *early Neolithic in the boreal East European Plain* exhibits several stylistic varieties of the 'notch-and-comb decorated pottery'. The *Upper Volga Culture* consists of small-size sites usually found along the rivers of the Upper Volga basin, on lake shores, and in bogs and mires [25]. The subsistence of the Upper Volga groups was based on hunting (elk, red deer, roe deer, aurochs, wild boar, and other wild forest animals), supplemented by fishing and food-collecting. The early types of pottery consist of small vessels (15–30 cm in diameter) that are either conic or flat bottomed, and made of chamotte-tempered clay.

The sites of the *Sperrings Culture* (or the I:1 Style of the Finnish writers) are located on ancient sea and lake shore-lines in a vast territory encompassing southern and central Finland and Ladoga and Onega Lake basins in Russian Karelia [35]. The pottery corpus consists of large conic vessels with straight rims decorated with impressions of cord, incised lines and pits forming a simple zoned ornament.

Early pottery-bearing sites occur in the *extreme north-east of European Russia*, on the Pechora and Northern Dvina rivers [29,55]. The pottery reflects Upper Volga influences.

We have also analyzed dates for Zedmar, Kaliningrad Oblast [49], where we have isolated two coeval subsets whose dates are presented in Table 12.

The total sample for *early pottery-bearing sites of the boreal East European Plain* contains 55 radiocarbon date measurements presented in Table 11 and Fig. 10. They include a series of dates from the stratified wetland sites of the Upper Volga Culture: Ivanovskoe 2, 2a, 3 and 7, Berendeevo 1 and 2a, and Yazykovo. The sample also includes dates for the sites of Valdai Culture which several writers consider to be related to the Upper Volga Culture [25]. We also include several dates from Sperrings sites (located in Karelia), as well as two dates from Chernoborskaya-type sites in the Russian North-East. Thirty-two dates satisfy the statistical test for contemporaneity and yield

$T_0 = 5417 \pm 30$ cal BC, $\sigma_c = 160$ years.

The probability distribution for the coeval subsample is shown with hatched boxes in Fig. 10. The remaining dates include those which are older (5800–6200 cal BC) and younger (4200–5200 cal BC) than the coeval sample. The number of dates that do not belong to the coeval subsample is large; this indicates that this collection of dates belongs to a heterogeneous and/or long-lived cultural entity. These data deserve careful study based on a more extensive selection of age determinations and other evidence.

Our selection of Neolithic dates for *East European Plain as a whole* contains 129 measurements presented in Table 12 and Fig. 11. This selection suggests a much older age of the initial pottery-making than earlier

Table 10
The date sample for the Buh-Dniestrian in the format of Table 2

Site	Index	Material	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2
Sokol'tsy 2	Ki-6697	bone	7470	60	6295	63	1.9
Sokol'tsy 2	Ki-6698	bone	7405	55	6210	67	0.5
Baz'kov Ostrov	Ki-6651	horn	7325	60	6115	63	0.0
Pechora	Ki-6693	horn	7305	50	6095	48	0.0
Pechora	Ki-6692	bone	7260	65	6075	58	0.1
Baz'kov Ostrov	Ki-6696	boar tusk	7215	55	6060	55	0.2
Baz'kov Ostrov	Ki-6652	boar tusk	7160	55	5995	62	1.0

$X^2(T_0) = 3.8$, $\chi_6^2(0.95) = 12.6$.
All the dates belong to the coeval subsample.

Table 11
The date sample for the Upper Volga and related Early Neolithic sites presented in the format of Table 2

Site	Index	Material	Age bp (yr)	Instrumental error (yr)	Age cal BC (yr)	Calibration error (yr)	X_i^2
Berendeevo 2a	Le-1585	wood	7270	80	6095	73	28.5
Berendeevo 2a	Le-1561	wood	7240	80	6100	100	28.9
Ivanovskoe 7	IGAN-95	lake mud	7170	40	6030	50	23.3
Ivanovskoe 3	Le-1972	peat	7110	80	5940	80	17.0
Ivanovskoe 2	Le-1950	wood	7080	80	5885	83	13.6
Berendeevo 2a	Le-1560	wood	7080	80	5885	83	13.6
Berendeevo 1	Le-1576	wood	7050	80	5860	80	12.2
Ivanovskoe 3	Le-1250	peat	7010	70	5835	68	10.8
Ivanovskoe 7	IGAN-96	humic acids from soil	6970	70	5820	70	10.1
Ivanovskoe 3	Le-1947	wood	6980	80	5820	75	10.1
Yazykovo	Le-2051	charcoal	6950	70	5810	75	9.6
Ivanovskoe 3	Le-1904	wood	6930	80	5785	83	8.4
Berendeevo 2a	Le-1585	wood	6930	70	5780	63	8.2
Ivanovskoe 3	Le-1948	wood	6900	70	5770	63	7.7
Ivanovskoe 3	Le-1911	wood	6860	70	5715	68	5.5
Nizhnie Kotitsy 2	**Le-1333**	**charcoal**	**6860**	**100**	**5700**	**100**	**5.0**
Zhabki 3	GIN-2767	charcoal	6870	100	5700	100	5.0
Okaemovo-5	**GIN-6193**	**lake mud**	**6800**	**140**	**5675**	**138**	**3.5**
Vashutinskaja	**Le-2607**	**charcoal**	**6820**	**80**	**5665**	**75**	**3.8**
Okaemovo-18	**GIN-6416**	**elk bone**	**6800**	**60**	**5655**	**58**	**3.5**
Berendeevo 2a	**Le-1586**	**charcoal**	**6780**	**70**	**5640**	**60**	**3.1**
Yazykovo	**Le-2053**	**charcoal**	**6730**	**80**	**5575**	**68**	**1.5**
Ivanovskoe 3	**Le-1913**	**charcoal**	**6690**	**70**	**5555**	**58**	**1.2**
Prilukskaya	**Le-4813**	**charcoal**	**6680**	**70**	**5555**	**58**	**1.2**
Ivanovskoe 7	**IGAN-92**	**burned wood**	**6670**	**70**	**5535**	**53**	**0.9**
Ivanovskoe 3	**Le-1970**	**wood**	**6570**	**80**	**5460**	**70**	**0.1**
Ivanovskoe 3	**Le-1935**	**charcoal**	**6540**	**70**	**5445**	**68**	**0.0**
Zales'e 1	**Le-1144**	**charcoal**	**6530**	**50**	**5430**	**50**	**0.0**
Ivanovskoe 3	**IGAN-71**	**lake mud**	**6500**	**50**	**5420**	**55**	**0.0**
Pegerma 9	**TA-1161**	**charcoal**	**6510**	**90**	**5420**	**70**	**0.0**
Yerpin Pudas	**TA-344**	**charcoal**	**6510**	**120**	**5415**	**98**	**0.0**
Hepo-jarvi	**Le-1412**	**charcoal**	**6480**	**60**	**5400**	**65**	**0.0**
Sheltozero-9	**TA-1312**	**charcoal**	**6480**	**70**	**5400**	**65**	**0.0**
Nikolskaya Pravaya	**Le-2055**	**wood**	**6470**	**70**	**5395**	**68**	**0.0**
Zhabki 3	**GIN-3214**	**charcoal**	**6460**	**160**	**5350**	**175**	**0.1**
Hepo-jarvi	**Le-1411**	**charcoal**	**6380**	**60**	**5335**	**53**	**0.4**
Ivanovskoe 3	**Le-1978**	**wood**	**6360**	**80**	**5300**	**100**	**0.8**
Yazykovo	**Le-1189**	**wood**	**6370**	**80**	**5300**	**100**	**0.8**
Sheltozero 10	**TA-1308**	**charcoal**	**6400**	**80**	**5295**	**78**	**0.9**
Shettima 1	**TA-1152**	**charcoal**	**6400**	**150**	**5275**	**163**	**0.8**
Ivanovskoe 3	**Le-1973**	**wood**	**6370**	**70**	**5270**	**70**	**1.3**
Prilukskaya	**Le-4814**	**charcoal**	**6350**	**60**	**5255**	**62**	**1.6**
Lanino 2	**Le-4347**	**charcoal**	**6440**	**370**	**5250**	**375**	**0.2**
Ivanovskoe 3	**Le-3097**	**wood**	**6350**	**70**	**5245**	**68**	**1.8**
Ivanovskoe 3	**IGAN-160**	**lake mud**	**6300**	**40**	**5205**	**45**	**2.8**
Ivanovskoe 2	**Le-1974**	**wood**	**6270**	**80**	**5185**	**85**	**3.3**
Yazykovo	**Le-1080**	**peat**	**6250**	**60**	**5180**	**70**	**3.5**
Lanino 2	**Le-3298**	**charcoal**	**6296**	**260**	**5150**	**275**	**0.9**
Ivanovskoe 3	Le-3094	wood	6210	60	5125	73	5.3
Ivanovskoe 7	IGAN-94	wood	6100	40	5030	63	9.3
Yerpin Pudas	TA-799	charcoal	5990	100	4925	163	9.2
Yerpin Pudas	TA-472	charcoal	5860	100	4705	118	31.4
Yerpin Pudas	TA-413	charcoal	5825	80	4650	100	36.5
Lanino 2	Le-3485	charcoal	5570	80	4410	85	62.9
Lanino 2	Le-3490	charcoal	5440	140	4275	163	49.4
Chernaya Rechka 1	Le-1223	charcoal	5440	140	4275	163	49.4

$X^2(T_0) = 43.4$, $\chi^2_{31}(0.95) = 45.0$.
Dates belonging to the coeval subsample are indicated with boldface.

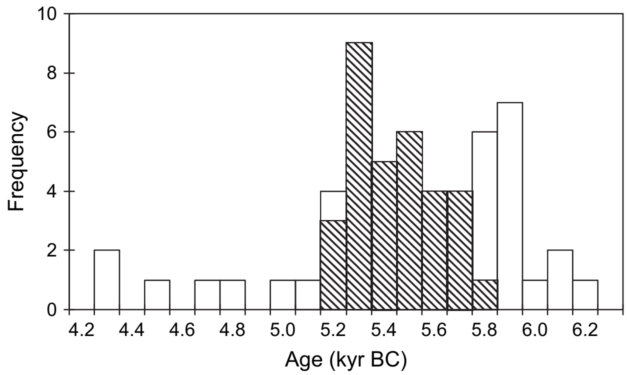

Fig. 10. The frequency of dates (cal BC) for the Upper Volga and related Early Neolithic sites per 100 yr interval. The coeval subsample is shown shaded.

estimates from radiocarbon dates [15] or geological evidence [42]. Importantly, we have now identified an earlier cluster of dates belonging mainly to Yelshanian.

The probability distribution of the dates shown in Fig. 11 is rather broad, and one might identify at least two maxima at about 5100 cal BC and 3300 cal BC. A straightforward application of the procedure of Section 3.2, as in the case of the LBK dates, would split the sample into a set of 'coeval subsamples', but this is not justified in this case since the probability distribution is very different from a single Gaussian. Instead, we have applied the Kolmogorov–Smirnov test to find out if the histogram in Fig. 11 shows any statistically significant deviations from the uniform distribution. Except for the earliest dates, younger than 2600 cal BC, the hypothesis that the probability distribution of the dates for the East European Plain is uniform cannot be rejected at the significance level of 80% (in other words, the probability that the maxima are real does not exceed 20%). This implies that the dates of the East European Plain represent a phenomenon prolonged in time, and so cannot be described as a single date. The maxima in the histogram of Fig. 11 are not statistically reliable.

6. Discussion

Since Childe [9], the spread of LBK settlements in Central Europe was viewed as a classical example of prehistoric migration. More recent studies [37,56] attach much greater significance to indigenous adoption and to contacts between invading farmers and local foragers [20,21]. These views were strengthened by the discovery of a distinct cultural tradition in the north-western part of the LBK area, La Hoguette. This was viewed as belonging to local Mesolithic groups that started practising horticulture and herding before the arrival of the LBK [37].

Gronenborn [20: 156] suggests that the earliest LBK sites appeared in Transdanubia at around 5700–5660 cal BC, and reached Franconia at about 5500 cal BC. Price et al. [37] argue that the 'initial' LBK appeared in Hungary at around 5700 cal BC and spread further west. Our analysis does not reveal any temporal structure in the entire sample of the radiocarbon LBK dates for Central Europe. Forty out of 47 LBK dates in our sample satisfy the criterion of contemporaneity, forming a nearly Gaussian distribution with the 2σ-range of 5600–4800 cal BC, with the most probable age of 5154 ± 62 cal BC, and without any apparent temporal substructure. Our analysis indicates the spread of the LBK was so fast that it cannot be subdivided into distinct events using radiocarbon dating alone. This is why most of the LBK date sample can be characterized in terms of a single date (presumably corresponding to the culture peak or rather the peak of activities at the individual sites) with a relatively small error.

The resulting lower estimate of the rate of spread can be obtained from the width of the above probability distribution. With the largest dimension of the LBK region of about 1500 km (from Transdanubia to the Paris Basin) and the time taken to spread over that area of about 360 years (twice the standard deviation of the dates in the coeval LBK subsample), the average propagation rate of the LBK could not be less than 4 km/yr. The rate of the LBK expansion can be best estimated for the earliest LBK which spread from Transdanubia to the Rhine valley within less than 150 years [20]. Settlers thus covered an average distance of about 850 km at the rate of at least 5.6 km/yr. The actual propagation speed could be even larger, as only the loess regions were settled. This value is consistent with the earlier estimates of about 6 km/yr obtained by Ammerman and Cavalli-Sforza [3] and Gkiasta et al. [19] from data for a significantly larger region. The LBK propagation rate is in a striking contrast to the average rate of spread of the European Neolithic, 1 km/s [3].

The probability distribution of radiocarbon dates for individual pottery-bearing cultures on East European Plain (Section 5, Table 12, Fig. 11) reveals a different spatio-temporal structure extended over a long time interval. Our statistical age estimates indicate a clear temporal sequence from Yelshanian (6910 ± 58 cal BC), through Buh-Dniestrian (6121 ± 101 cal BC) and Rakushechnyi Yar (5846 ± 128 cal BC), to Upper Volga (5317 ± 30 cal BC). The rate of spread of the early pottery-bearing cultures in East European Plain, estimated from the extent of the region involved (ca 2500 km) and the time of spread (ca 1600 years), is about 1.6 km/yr. This is significantly smaller than the rate of spread of the LBK but somewhat larger than the average European Neolithic rate of spread. The comparable magnitudes of the rates of spread of farming in Western Europe and early pottery-making in Eastern

Table 12
Radiocarbon dates for the Neolithic sites on East European Plain: the site name, laboratory index, the uncalibrated age and its instrumental error, the calibrated age and an estimate of its total error

Site	Index	Material	Age bp (yr)	σ_i (yr)	Age cal BC (yr)	Σ_i (yr)
Kladovets 4	TA-1410	charcoal	3400	60	1710	127
Villa	TA-20	bone	3570	240	1950	317
Muchkas	Le-5162	charcoal	3610	20	1955	127
Shakes	Le-3709	charcoal	3680	350	2100	333
Vladychinskaya	Le-1341	charcoal	3820	60	2225	127
Zalavruga 4	TA-994	charcoal	3810	50	2250	127
Serteya 2					2298	127
Lakshozero 2	TA-1520	charcoal	3920	60	2350	127
Sjaberskoe 3	Le-3427	charcoal	3910	100	2425	158
Kudomguba 7	TA-1893	charcoal	4010	80	2500	133
Usvyat Stage i	TA-203	wood	4100	70	2650	127
Nida	Bln-2592	charcoal	4070	50	2665	127
Krivun	Le-2364	wood	4090	50	2670	127
Mayak 2	Le-1491	charcoal	4160	70	2695	127
Zolotets 4	TA-793	charcoal	4150	80	2700	127
Tugunda 14	TA-2018	charcoal	4210	60	2750	127
Usvyat Stage g/i	TA-202	wood	4210	70	2750	127
Zedmar 2					2770	179
Voinavolok 24	TA-820	charcoal	4250	70	2775	127
Chernaya Maza	Le-941	charcoal	4250	45	2775	127
Povenchanka 15	TA-1519	charcoal	4270	60	2825	127
Dubokrai 1	Le-2838	wood	3660	40	2870	127
Voinavolok 27	TA-1748	charcoal	4280	80	2900	150
Maieri 2	TA-1518	charcoal	4300	100	2925	158
Yumizh 1	Le-2599	charcoal	4320	40	2930	127
Rakushechnyi Yar	Bln-704	charcoal	4360	100	2950	150
Vladychinskaya	Le-1220	charcoal	4300	60	2950	127
Šventoji	Bln-4385	wood	4360	50	3025	127
Voinavolok 27	TA-1448	charcoal	4410	50	3110	127
Dubokrai 5	Le-3891	wood	4430	60	3115	127
Žemajtiške	Bln-2593	unknown	4420	60	3115	127
Severnaja Salma	Le-4509	charcoal	4550	570	3150	717
Oskchoi 2	Le-1730	charcoal	4530	40	3150	127
Borovskoe 3	Le-4612	charcoal	4480	70	3175	127
Vodysh	Le-1228	charcoal	4590	140	3200	200
Nerpich'ya Guba	Le-1329	charcoal	4630	100	3300	133
Krivun	Le-1331	charcoal	4650	90	3300	133
Sarnate	Bln-769	wood	4639	100	3300	133
Zolotets 4	TA-391	charcoal	4620	60	3325	127
Šventoji	L7-2528	wood	4640	60	3350	127
Choinovty	Le-5164	charcoal	4640	25	3425	127
Šventoji	L7-2523	wood	4730	100	3475	158
Maslovo Boloto 4	Le-1234	charcoal	4780	120	3500	167
Kudrukula	CAMS-6265	bone	4770	60	3535	127
Modlona	Le-994	charcoal	4850	120	3550	167
Utinoe Boloto	Le-1237	charcoal	4870	230	3550	317
Zalavruga 1	TA-393	charcoal	4775	70	3560	127
Sukhaja Vodla 2	NA-1553	unknown	4810	60	3570	127
Chernaja Guba 9	TA-2023	charcoal	4840	80	3650	127
Usvyat Stage g	Le-256	unknown	4870	40	3650	127
Kudrukula	CAMS-6266	bone	4860	60	3650	127
Chernaja Guba 3	TA-1890	charcoal	4950	100	3700	127
Spiginas	GIN-5569	bone	5020	200	3750	250
Tsaga 1	Le-4292	charcoal	5020	250	3750	317
Lugovski Torfjanik	Le-950	wood	5000	100	3800	150
Besovy Sledki	TA-431	wood	5000	60	3805	127
Imerka 5	Le-2160	charcoal	5050	40	3835	127
Ivanovskoe 2	Le-1977	wood	5060	40	3840	127
Gundorovka	GIN-9040	bone	5080	40	3850	127
Zedmar 1					3870	192
Zvejnieki	OxA-5986	bone	5110	45	3900	127
Serteya 10	Le-5258	wood	5100	80	3925	127

Table 12 (*continued*)

Site	Index	Material	Age bp (yr)	σ_i (yr)	Age cal BC (yr)	Σ_i (yr)
Universitetskaja 3	Le-1013	wood	5080	125	3925	142
Ivanovskoe 4	Le-2900	wood	5160	40	3940	127
Suna 12	TA-1310	charcoal	5160	70	3975	127
Tekhonovo Sarskoe	Le-1735	charcoal	5260	60	4075	127
Krasnoe Selo	Le-637	charcoal	5300	300	4100	400
Staroryazanskaja 1a	Le-1803	wood	5280	60	4125	127
Lipetskoe Ozero	Le-3743	bone	5310	110	4125	127
Krivina 3	Le-1658	peat	5290	60	4145	127
Choinovty 1	Le-1729	charcoal	5320	60	4155	127
Chernushka 1	Le-1874	unknown	5350	60	4165	127
Rudnja Serteiskaya	Le-3020	wood	5390	40	4195	127
Matveev Kurgan 2	Le-882	charcoal	5400	200	4250	250
Lanino 2	Le-3490	charcoal	5440	140	4275	175
Ust'-Drozdovka	Le-1332	charcoal	5510	100	4325	127
Žemajtiške	Bln-2594	no	5510	60	4340	127
Chavan'ga	Le-1222	charcoal	5560	80	4400	127
Ivanovskoe 5	Le-1109	peat	5560	100	4400	133
Kolupaevskaya	Le-1194	charcoal	5600	150	4450	167
Zatsen'e	Ki-6214	bone	5625	40	4465	127
Zarech'e Torfyanik	Le-969	peat	5670	50	4530	127
Rudnya Stage d/e	Le-2570	wood	5770	60	4645	127
Chernaja Rechka 1	TA-1550	charcoal	5800	100	4650	127
Osovets 4	Ki-6213	bone	5860	50	4720	127
Yerpin Pudas	TA-472	charcoal	5860	100	4725	127
Kladovets 5a	TA-1450	charcoal	5850	80	4725	127
Mjangora 1	TA-1079	charcoal	5880	80	4750	127
Khvalynsk 1	UPI-120	bone	5880	79	4750	127
Sakhtysh 1	Le-1258	wood	5900	70	4775	127
Lebjazhinka 3	GIN-7087	shell	5960	180	4850	217
Vyun	Le-561	wood	5980	100	4875	127
Yerpin Pudas	TA-799	charcoal	5990	100	4875	127
Podol 3	Le-5172	charcoal	6010	50	4900	127
Zvejnieki	OxA-5970	bone	6005	75	4925	127
Varfolomeyevskaya	Lu-2620	unknown	6090	160	4950	167
Ruhnu 2	Le-5627	charcoal	6150	60	5055	127
Rudnya d	Le-2569	wood	6180	70	5080	127
Chernaja Rechka 1	TA-1634	charcoal	6200	100	5100	127
Khvalynsk	AA-12571	bone	6200	85	5125	127
Yasinovatka	Ki-6605	bone	6255	70	5180	127
Berendeevo 2a	Le-1557	charcoal	6310	70	5210	127
Ust' Rybezhna	Le-405	charcoal	6380	220	5250	250
Glukhaja	Le-4200	charcoal	6460	300	5250	317
Shettima 1	TA-1152	charcoal	6400	150	5250	150
Hepo Jarvi	Le-1411	charcoal	6380	60	5290	127
Sheltozero 10	TA-1308	charcoal	6400	80	5295	127
Zhabki 3	GIN-3214	charcoal	6460	150	5300	150
Ivanovskoe 3b	Le-1978	wood	6360	80	5300	127
Nikol'skaya Pravaya	Le-2055	wood	6470	70	5400	127
Pegrema 9	TA-1161	charcoal	6510	90	5420	127
Zales'ye	Le-1144	charcoal	6530	50	5430	127
Chernaya Guba 9	TA-1315	charcoal	6530	80	5435	127
Ivanovskoe 7	IGAN-92	wood	6670	70	5570	127
Yazykovo 1	Le-2053	charcoal	6730	80	5620	127
Brikuli	Le-1770	charcoal	6770	80	5645	127
Okaemovo 18	GIN-6416	bone	6800	60	5655	127
Kurovo 2	Le-1736	charcoal	6770	70	5665	127
Vashutinskaya	Le-2607	charcoal	6820	80	5665	127
Nizhnie Kotitsy 5	Le-1333	charcoal	6860	100	5700	127
Grad 3	Ki-6650	bone	6865	50	5725	127
Savran'	Ki-6654	bone	6985	60	5810	127
Lukovo Ozero 3	Le-2054	charcoal	7010	80	5830	127
Ivanovskoe 3a	Le-1250	peat	7010	70	5835	127
Rakushechnyi Yar	Ki-6480	food remains	7040	100	5900	127

(*continued on next page*)

Table 12 (*continued*)

Site	Index	Material	Age bp (yr)	σ_i (yr)	Age cal BC (yr)	Σ_i (yr)
Matveev Kurgan 1	Le-1217	charcoal	7180	70	5980	127
Baz'kov Ostrov	Ki-6652	tusk	7160	55	5995	127
Surskoi Ostrov	Ki-6691	bone	7245	60	6085	127
Pechora	Ki-6692	bone	7260	65	6095	127
Berendeevo 2a	Le-1561	wood	7240	80	6100	127

The dates shown with no entries in columns 2–4 are those obtained in Section 5, where we adopt $\Sigma_i = \sigma_c$.

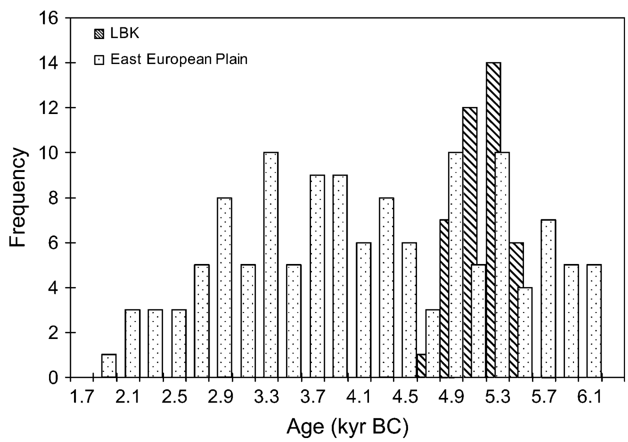

Fig. 11. The rate of occurrence of Neolithic radiocarbon dated sites on East European Plain (light grey) and the coeval subsample of the LBK dates (dark grey), both in cal BC per 200 yr interval.

Europe are highly significant as they may imply different aspects of the same process.

A spatio-temporal trend directed from the south-east to the north-west, clearly visible in Fig. 12, apparently suggests that the tradition of pottery-making in the East European Plain developed under an impulse from the Eastern Steppe (cf. [50]). Recent evidence shows a very early appearance of pottery-making in an area further east, stretching along the southern edge of the boreal forest in Eurasia [53]. This includes Jomon Culture in Japan, with the earliest 'incipient' stage at ca 11,000 cal BC [2]. An early centre of pottery-making has been identified in the Russian Far East on the lower stretches of the Amur River: Gasya (14,200–10,690 cal BC), Khummi (14,600–9700 cal BC) and Goncharka (13,400–9700 cal BC), as well as Gromatukha on the Zeya River (13,500–9230 cal BC; [13,23,27]). Early dates have been obtained for pottery-bearing sites in the Trans-Baikal province in southern Siberia: Ust-Karenga (11,600–10,450 cal BC), Ust-Kyakhta (11,900–11,150 cal BC)

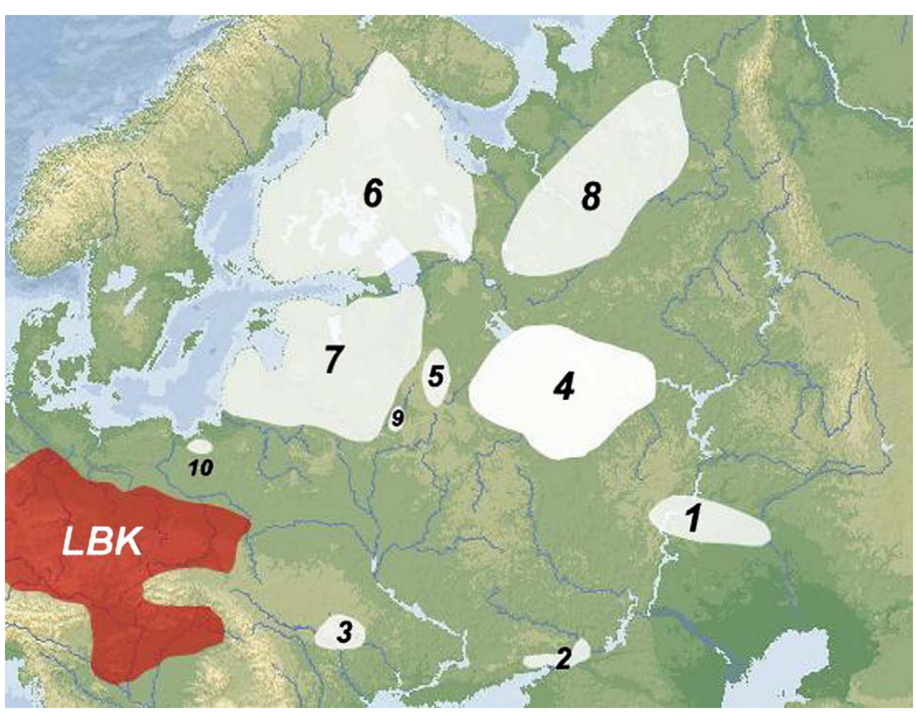

Fig. 12. Neolithic cultures in the central and eastern Europe, with the dates obtained here: Linear Pottery Culture (LBK); Yelshanian (1); Rakushechnyi Yar (2); Buh-Dniestrian (3); Upper Volga (4); Valdai (5); Sperrings (6); Narva (7); Chernoborskaya (8); Serteya (9); and Zedmar (10). The sequence from (1) to (10) is ordered both in time (see Section 5) and in space.

and Studenoye (11,250–10,350 cal BC) [27]. At these sites, the subsistence was based on hunting–gathering and intense procurement of aquatic resources. Their pottery assemblages are stylistically unrelated to each other and are believed to be local inventions [24]. One may only speculate that pottery-making independently developed in the context of broad-spectrum hunter-gathering economies. This technical novelty initially emerged in the forest-steppe belt of northern Eurasia starting at about 14,500 cal BC, and spread to the west to reach the south-eastern confines of East European Plain by 7000 cal BC.

The group of dates at 5300–4900 cal BC that form the statistically insignificant maximum in Fig. 11 largely belongs to Upper Volga and other early pottery-bearing cultures in the boreal central and northern Russia. This time span is close to the assessed age of the LBK in Europe. Significantly, this period corresponds to the Holocene climatic optimum, characterized by the maximum rise of temperature and biological productivity of landscapes in both Central and Eastern Europe [36].

The model advanced by Aoki et al. [4] can be relevant in explaining these phenomena. These writers model the advance of expanding farmers accompanied by partial conversion of the indigenous population into farming. The intruding farmers can spread either as a wave front or as an isolated, solitary wave. However, either intruding or converted farmers remain behind the propagating wave (front) in both cases. There are no definite signs of widespread farming in the East European Neolithic sites, even though there is clear evidence of the interaction of those cultures with farming [58]. This suggests yet another scenario where an advancing wave of farming is not accepted by the local hunter–gatherers, but still results in considerable demographic and cultural modifications. The approach of Aoki et al. [4] can be further developed to incorporate the advantages of the wave of advance, adoption and other models in a single mathematical framework. Reliable assessment of these possibilities requires further analysis, including detailed numerical simulations.

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