Multiple Sources of the European Neolithic: Mathematical Modelling Constrained by Radiocarbon Dates

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1. Introduction

The transition to the Neolithic was a crucial period in the development of Eurasian societies, defining to a large extent their subsequent evolution. The introduction of agro-pastoral farming, which originated in the Near East about 12,000 years ago and then spread throughout Europe, is usually considered a key feature of this transition (Zvelebil, 1996). Yet the Neolithic was not a simple, single-faceted phenomenon. In his early definition of the Neolithic, Sir John Lubbock (Lubbock, 1865) specified its main characteristics to be the growing of crops, the taming of animals, the use of polished stone and bone tools, and pottery-making.

Ceramic pottery is one of the defining characteristics of the Neolithic. It is true that there are examples of early farming communities apparently not involved in pottery-making. For example, aceramic Neolithic cultures have been identified in the Levant, Upper Mesopotamia and Anatolia (9800–7500 BC), and also in the Peloponnese (7300–6300 BC). (All BC dates supplied are radiocarbon dates calibrated using OxCal v3.10 (Bronk Ramsey, 2001) with calibration curve intcal04.) Wheat, barley and legumes were cultivated at those sites; permanent houses with stone foundations were used, but there is no convincing evidence of pottery (Perles, 2001). In contrast, the Neolithic in North-Eastern boreal Europe is identified with a sedentary (or seasonally sedentary) settlement pattern, social hierarchy and sophisticated symbolic expression, the use of polished stone and bone tools, large-scale manufacture of ceramic ware, but not with agriculture (Oshibkina, 1996): the subsistence apparently remained based on foraging. This combination of attributes is characteristic of the ‘boreal Neolithic’; of these, pottery is in practise the most easily identifiable.

In the present paper we attempt to develop a unified framework describing the spread of both the ‘agro-pastoral’ and ‘boreal’ Neolithic. Our quantitative model of the Neolithization is based on the large amount of relevant radiocarbon dates now available.

2. Selection of Radiocarbon Dates

The compilation of dates used in this study to model the spread of the Neolithic in Europe is available upon request from the authors; unlike all other similar studies known to us it includes dates from the East of Europe. We used data from Gkiasta et al. (2003), Shennan and Steele (2000) and Thissen et al. (2006) for Southern, Central and Western Europe (SCWE), and Dolukhanov et al. (2005) and Timofeev et al. (2004) for Eastern Europe (EE). Our selection and treatment of the dates, described in this section, is motivated by our attempt to understand the spread of agriculture and pottery making throughout Europe.

Many archaeological sites considered have long series of radiocarbon dates: often with 3–10 dates, and occasionally with 30–50. Associated with each radiocarbon measurement is a laboratory error, which after calibration was converted to a calibration error. The laboratory error characterises the accuracy of the measurement of the sample radioactivity rather than the true age of the archaeological site (Dolukhanov et al., 2005); it is thus often unrepresentatively small, suggesting an accuracy of 30 years on occasion. We therefore estimated a minimum error of the radiocarbon determination of archaeological age, and then used it when treating sites with multiple dates. A global minimum error of $\sigma_{\text{min}} = 160$ years is obtained from well explored, archaeologically homogeneous sites with a large number of tightly clustered dates. Such sites are: (1) Ilipinar, 65 dates, with the standard deviation $\sigma = 168$ years (and the mean date 6870 BC); (2) Achilleion, 41 dates, $\sigma = 169$ years (the mean 8682 BC); (3) Asikli Höyük, 47 dates, $\sigma = 156$ years (the mean 7206 BC). Similar estimates are $\sigma_{\text{min}} = 100$ years for LBK sites and $\sigma_{\text{min}} = 130$ years for the Serteya site in North-Western Russia (Dolukhanov et al., 2005); the typical errors vary between different regions and periods. We use the larger of the above values of $\sigma_{\text{min}}$ (i.e., $160$ years) when assessing the quality of the model described below.

For sites with multiple radiocarbon date determinations, the dates are treated and reduced to at most three dates that are representative of the arrival of multiple Neolithic episodes to that location. Examples of sites with multiple measurements.
are Ilipinar and Ivanovskoye-2, where 65 and 21 dates have been published, respectively. Figures 1a and b indicate that for these sites the series of dates form very different distributions; different strategies are used to process these different types of date series as described in the caption to Figure 1 (see Dolukhanov et al., 2005, for more details). If a geographical location provides only one radiocarbon measurement associated with early Neolithic activity, then this is taken to be the most likely date for the arrival of the Neolithic. The uncertainty of this radiocarbon date is taken to be the larger of the calibration error obtained at the 3σ level and the global minimum error discussed above. There are numerous such sites in our collection, including Casabianca, Dachstein and Inchtuthil.

If only a few (less than 8) date measurements are available for a site and those dates all agree within the calibration error, we use their mean value and characterise its uncertainty with an error equal to the maximum of the calibrated measurement errors \( \sigma_i \), the standard deviation of the dates involved \( \sigma(t_i) \), and the global minimum error introduced above:

\[
\sigma = \max \{ \sigma_i, \sigma(t_i), \sigma_{\min} \} \quad (1)
\]

where \( i=1, 2, ..., n \), with \( n \) the total number of dates in the cluster. An example of such a site is Bademagaçi, where we have 4 dates, all within 60 years of one another; Figure 1c shows the histogram of radiocarbon dates of this site. The typical error of these dates is approximately 30 years, thus Equation (1) yields \( \sigma_{\min} \) as an uncertainty estimate. However, we apply slightly different procedures for clusters of dates that do not quite agree within the calibration error.

For a series of dates that cluster in time but do not agree within the calibration error, we use different approaches depending on the number of dates available and their errors. Should the cluster contain less than 8 dates, we take the mean of the dates (as in the previous case), as any more sophisticated statistical technique would be inappropriate for such a small sample; the error is taken as Equation (1). An example of such a site is Okrana Bolnica–Stara Zagora with 7 measurements, and Figure 1f shows that the dates are tightly clustered around the mean value.
If the cluster has more than 8 dates (e.g. Ilipinar, shown in Figure 1a), the $\chi^2$ statistical test can be used to calculate the most likely date $T$ of a coeval subsample as described in detail by Dolukhanov et al. (2005):

$$\frac{\sum t_i - T}{\sum 1/\sigma_i^2},$$

where $\tilde{\sigma}_i = \max(\sigma_i, \sigma_{\text{min}})$. The coeval subsample is obtained by calculating the statistic $\chi^2 = \sum (t_i - T)^2/\tilde{\sigma}_i^2$ and comparing it with $\chi^2$. If $\chi^2 \leq \chi^2_{n-1}$, the sample is coeval and the date $T$ is the best representative of the sample. If $\chi^2 > \chi^2_{n-1}$, the sample is not coeval, and the strongest outliers in the sample are discarded one by one until the criterion for a coeval sample is satisfied.

If a site has many radiocarbon determinations that do not cluster around a single date, a histogram of the dates is analyzed. If the data have a wide range and have no discernible peaks (i.e., are approximately uniformly distributed in time), this may suggest prolonged Neolithic activity at the site, and we choose, as do many other authors, the oldest date (or one of the oldest, if there are reasons to reject outliers) as representing the first appearance of the Neolithic. Examples of such sites are Mersin and Halula where there are 6 and 9 dates with a range of 550 and 1900 years, respectively, and no significant peaks (see Figures 1d and 1e); here the oldest dates are 6950 and 8800 years BC and the associated errors are 217 and 167 years.

Apart from sites with either no significant peak or only one peak, there are sites whose radiocarbon dates have a multimodal structure which may indicate multiple waves of advance passing through this location. Ivanovskoye-2 (with 21 dates) is a typical site in this category, and Figure 1b depicts two distinct peaks. In such cases multiple dates were attributed to the site, with the above methods applied to each peak. After this selection and processing, the total number of dates in our compilation is 478.

3. Modelling

The mechanisms of the spread of the Neolithic in Europe remain controversial. Gordon Childe (1925) advocated direct migration of the farming population from the Near East. This idea was developed in the form of the demic expansion (wave of advance) model (Ammerman and Cavalli-Sforza, 1973). The Neolithization was viewed as the spread of colonist farmers who overwhelmed the indigenous hunter-gatherers or converted them to the cultivation of domesticated cereals and the rearing of animal stock (Price, 2000). An alternative approach views the Neolithization as an adoption of agriculture (or other attributes) by indigenous hunter-gatherers through the diffusion of cultural novelties by means of intermarriages, assimilation and borrowing (Tilley, 1994, Thomas, 1996, Whittle, 1996). Recent genetic evidence favours cultural transmission (Haak et al., 2005).

Irrespective of the particular mechanism of the spread of the Neolithic (or of its various signatures), the underlying process can be considered some sort of 'random walk', of either humans or ideas. Therefore, mathematical modelling of the spread (at suitably large scales in space and time) can arguably be based on a 'universal' equation (known as reaction-diffusion equation) with parameters chosen appropriately (Cavalli-Sforza and Feldman, 1981). A salient feature of this equation is the development of a propagation front (where the population density, or any other relevant variable, is equal to a given constant value) which advances at a constant speed (Murray, 1993) (in the approximation of a homogeneous habitat). This type of spread of incipient agriculture has been confirmed by radiocarbon dates (Ammerman and Biagi, 2003, Ammerman and Cavalli-Sforza, 1971, Ammerman and Cavalli-Sforza, 1973, Ammerman and Cavalli-Sforza, 1984, Gkiasta et al., 2003, Pinhasi et al., 2005). In Figure 2a we plot the distance from a putative source in the Near East versus the $^14$C dates for early Neolithic sites in SCWE; the linear correlation is consistent with a constant propagation speed. Due to the inhomogeneous nature of the landscape of Europe we would not expect to see a precise correlation between distance from source and time of first arrival; there are many geographical features that naturally cause barriers to travel (e.g. the Mediterranean sea). It was also suggested in a previous work (Davison et al., 2006) that there are variations in the propagation speed in the region of major rivers; this again detracts from the linear nature of the spread. In spite of this the correlation coefficient is found to be -0.80. This is surprisingly high, given the above caveats.

In contrast to earlier models, we include the 'boreal', East-European (EE) Neolithic sites, which we present in the same format in Fig. 2b. It is clear that the Eastern data are not all consistent with the idea of spread from a single source in the Near East. A correlation coefficient of -0.52 is sufficient evidence to conclude that the dates do not cluster around a line of best fit; thus any conclusion drawn from straight line fitting would be questionable at best. There is also a tail of older dates that vary little in space; this suggests an area of prolonged occupation by Neolithic peoples. This may be indicative of an area where a Neolithic tradition began but halted until it had saturated the area, before subsequently expanding across the landscape. Our modelling indicates that another wave of advance swept westward through Eastern Europe about 1500 years earlier than the conventional Near-Eastern one; we speculate that it may even have spread further to produce early ceramic sites in Western Europe (e.g. the La Hoguette and Roucadour groups).
Our population dynamics model, described in detail in Davison et al. (2006), was refined for our present simulations. The model is based on the random walk of individuals first considered in a similar context by Fisher (1937). At any point in space each individual will take a step in any given direction with the same probability; i.e. they are as likely to step left as right. This assumption of equal probabilities gives rise to an isotropic random walk (i.e. classical diffusion). If however the probability of moving in one direction is altered by a desire for a particular environment, then the equal probabilities assumption of the isotropic random walk is violated; this gives rise to an anisotropic random walk. We thus solve the reaction–diffusion equation supplemented with an advection of speed $\mathbf{V}$, arising from this anisotropic component of the random walk of individuals that underlies the large-scale diffusion (Davison et al., 2006, Murray, 1993):

$$\frac{\partial N}{\partial t} + (\nabla \cdot \mathbf{V}) N = \rho N \left( 1 - \frac{N}{K} \right) + \nabla \cdot (\nu \nabla N), \quad (2)$$

where $N$ is the population density, $\gamma$ is the intrinsic growth rate of the population, $K$ is the carrying capacity, and $\nu$ is the diffusivity (mobility) of the population. We solve Equation (2) numerically in two dimensions on a spherical surface with a grid spacing of $1/12$ degree ($2\pi$ km, depending on latitude). All the variables in Equation (2) can be functions of position and time, as described below and by Davison et al. (2006).

We consider two non-interacting populations, each modelled with Equation (2), but with different values of the parameters; the difference is intended to represent differences between subsistence strategies (farmers versus hunter-gatherers) and/or between demic and cultural diffusion. We
use non-interacting populations as it is thought that farmers and hunter-gatherers rarely moved through a region simultaneously. In addition to this, the two populations scarcely compete for resources due to their distinct subsistence strategies; their interactions would therefore have been weak, and a non-interacting model is acceptable as a first approximation.

We therefore numerically solve two versions of Equation (2), one for each of two non-interacting populations, with different origins of dispersal. The numerical scheme adopted has centered differences in space

\[ f^n(x_i) = \frac{f(x_i + h) - 2f(x_i) + f(x_i - h)}{h^2} - \frac{h^2}{12} f''(\xi), \quad x_i \leq \xi \leq x_i + h, \]

and evolves with explicit Euler time stepping using forward differences in time. The step size is controlled using the Courant–Friedrichs–Lewy (CFL) condition; thus the population front is prevented from advancing more than one grid cell in one time step:

\[ \Delta t \leq \min \frac{A_1 \Delta \phi \Delta \theta^2}{2v \Delta \phi^2 + A_1 \Delta \phi + A_2 \Delta \theta} \quad \text{where} \quad 0 < A < 1. \]

The boundaries of the computational domain are at 75°N and 25°N, and 60°E and 15°W, as shown in Figure 4; these were chosen to comfortably incorporate the pan-European area of interest. We use zero-flux conditions at the domain boundaries, i.e. dN/dn = 0, where n is the normal to the boundary; at most points this condition is academic, as the boundary is in the (unpopulated) sea. The environmental factors included in the model are the altitude, latitude, coastlines and the Danube-Rhine river system. The equation describing the farming population includes the advection velocity V along the major waterways (the Danube, the Rhine and the sea coastlines; V ≠ 0 within corridors 10 km wide on each side of a river or 10 km inshore near the sea), resulting from the anisotropic diffusion in those areas. The components of the advective velocity are given in Davison et al. (2006), but will be briefly discussed here. There are two considerations when prescribing V, the direction and the magnitude. The direction is taken to be parallel to the shoreline/river and away from the maximum of the population. The magnitude is prescribed to diminish with distance from shoreline/river, from a maximum value described below.

The focus of our model is the speed of the front propagation \( U \), since this quantity can be most readily linked to the radiocarbon age used to date the ‘first arrival’ of the wave of advance. This feature of the solution depends only on the linear terms in Equation (2) and, in particular, is independent of the carrying capacity \( K \). Moreover, to a first approximation \( U \) only depends on the product \( \gamma \nu \):

\[ U = 2\sqrt{\gamma \nu}. \]
altered shoreline. In ongoing work we include paleotopography in our model, and aim to investigate the spread across seas further, with particular focus on Scandinavia and the UK.

The inclusion of advection along the Danube–Rhine corridor and the sea coastlines is required to reproduce the rapid spread of the Linear Pottery and Impressed Ware cultures apparent from the radiocarbon and archaeological evidence (see Davison et al. (2006) for details). The spread of farming in the Danube–Rhine corridor was as rapid as 4 km/year (Ammerman and Cavalli-Sforza, 1971), and that in the Mediterranean coastal areas reached 20 km/year (Zilhão, 2001); we set our maximum advective velocity in these regions accordingly. There are no indications that similar acceleration occurred for the hunter-gatherers spreading from the East. We therefore adopt \( V = 0 \) in the corresponding equation.

The starting positions and times for the two waves of advance — i.e., the initial conditions for Equation (2) — were selected as follows. For the population of farmers, we position the origin and adjust the starting time so as to minimize the root mean square difference between the SCWE \(^{14}\)C dates and the arrival time of the modelled population at the corresponding locations. This places the centre at 35ºN, 39ºE, with the propagation starting at 6,700 BC. For the source in the East of Europe, we have tentatively selected a region centered at 71ºN, 56ºE in the Ural mountains (to the east of the Neolithic sites used here), so that the propagation front reaches the sites in a well developed form. We do not suggest that pottery-making originated independently in this region. More reasonably, this technology spread, through the bottleneck between the Ural Mountains and the Caspian Sea, from a location further to the east. The starting time for this wave of advance was fixed by trial and error at 8200 BC; this reasonably fits most of the dates in Eastern Europe attributable to this centre. For both populations, the initial distribution of \( N \) is a truncated Gaussian of a radius 300 km.

4. Previous Population Dynamics Models

There have been many earlier attempts to explain the pattern of the spread through Europe of the Neolithic (usually considered as synonymous with land farming in these studies). These have almost exclusively used radiocarbon dating evidence for Neolithic first arrivals.

Edmonson (1961) conducted a pioneering study of Neolithic diffusion rates. He suggested that an invention will travel radially from its origin, spreading in all directions with the same speed. He worked under the assumption of ergodicity; that the population is homogeneous and individuals behave identically. This is mathematically analogous to isotropic diffusion, with inventions diffusing with constant speed through the available space. Edmonson suggests that this extremely simplified model explains the real observations well; this was the birth of the idea of the Neolithic as a diffusive phenomenon.

His estimation of the apparent mean propagation speed of Neolithic traits, such as copper or pottery, was approximately 1.9 km/year (1.2 miles/year). (This estimate refers to a far larger geographical area than Europe.) It is clear from the tables he compiled that the scatter in speeds about this value is significant; values are as large as 4.3 km/yr in Kenya, and as low as 0.18 km/yr in China. Edmonson assumed that he was measuring cultural transmission.

The earliest representation of the spatio-temporal trends of the Neolithic transition in Europe were the maps presented by Clark (1965a). Clarke produced one of the pioneering analyses (also presented in Clark, 1965b) of radiocarbon dates (see Figure 4). The data were binned into three broad
age ranges (2,800-4,000 BC; 4,000-5,200 BC; and earlier than 5,200 BC). The information gained from such a schematic representation can only be as detailed as the binning process allows however there are still some discernable trends.

Clark (1965a) verified what had been long advocated by archaeologists such as Gordon Childe (discussed above in section 3), that the Neolithic revolution penetrated Europe from the South-East, spreading through Greece and the south Balkans and then, with side branches northwards towards the lower Danube and into Bessarabia, and westwards across the Adriatic to middle Italy, pushing into the middle Danube and so into central Europe. Clark claimed (based on Figure 4) that the agricultural revolution was confined to an area of about 10 degrees of latitude between Greece and Iran until around 5,200 BC. This analysis is admittedly crude — with little content beyond the ‘ideogram’ of Figure 4 — but Clark concludes that such a crude message is better than no message at all. And indeed, the pattern found remains identifiable in the extensive radiocarbon record now available.

Ammerman and Cavalli-Sforza (1971) focused on measuring the rate of spread of early farming in Europe. They suggested that the terms ‘early farming’ and ‘Neolithic’ are synonymous, but we argue that there are examples of Neolithic sites hosting no evidence of farming, so that the terms should not be used interchangeably. They did not consider pottery as a Neolithic signature, and in contrast to Edmonson, their measurement is based on a single trait (cereal). The geographical domain of study was significantly narrower than that of previous works, focusing primarily on Western Europe, where the radiocarbon evidence for cereals was at the time most abundant. Ammerman and Cavalli-Sforza focused their attention on the radiocarbon evidence of early farming first arrivals. They provided a regression analysis of distance from a source and age in years BP. They located the source by placing a grid over Europe and calculating the correlation coefficient between distance from each grid point and age BP for all data; the grid point with largest correlation coefficient magnitude was accepted as the source. The linear regression techniques adopted gave a rate of spread of $U \approx 1$ km/year on average in Europe; this estimate has remained widely accepted since then. They also noted very significant regional variations in the rate of spread. For example, unfavourable ecological and geographical factors caused a retardation of spread to the Alps; similarly retarded spread occurs at latitudes above 54° N. The Danube and Rhine valleys, the propagation path of the LBK culture, had an increased propagation speed (perhaps as high as 4-6 km/year), as did the Mediterranean coast. Ammerman and Cavalli-Sforza (1971) gave the speed of front propagation in the Mediterranean as 1.5 km/year, and in the West Mediterranean as 2.1 km/year.

Figure 4. Early representation of radiocarbon dates for the Neolithic of Europe, presented by Clark (1965). Dates are binned into the three broad age ranges shown in the inset.
An updated estimate of the propagation speed in the Mediterranean coastal area was derived more recently by Zilhão (2001), and is significantly higher than that estimated by Ammerman and Cavalli-Sforza (1971) from more limited data. Zilhão considered various radiocarbon measurements, and concluded that the spread of the Cardial and related Neolithic cultures in Iberia, over the 2000 km from the gulf of Genoa to the estuary of the Mondego, took no more than 100-200 years; this gives an average speed of 10-20 km/year. The major contribution of this work was to reassess the problem of reservoir effects in the dating of bulk shell samples. By comparing the radiocarbon dates of archaeologically and stratigraphically contiguous samples of both shell and charcoal, an estimate of the reservoir effect on the shells can be obtained; together with the advent of AMS dating, this enabled the re-evaluation of the spread of the Neolithic in the Mediterranean coastal area.

Thus the speeds of propagation, \( U \), of the wave front of invading Neolithic farmers in Europe can be summarised as follows:

\[
U \approx 1 \text{ km/yr} \quad \text{on average in Europe},
\]

\[
U \approx 4-6 \text{ km/yr} \quad \text{for the Danube–Rhine valleys (LBK culture)},
\]

\[
U \approx 10-20 \text{ km/yr} \quad \text{in Mediterranean coast regions (Impressed ware culture)}.
\]

Interpretations of these observations are usually based on the reaction-diffusion equation of population dynamics known as the Fisher–Kolmogorov–Petrovskii–Piskuniov equation; FKPP hereafter (Fisher, 1937, Kolmogorov et al., 1937). The constant propagation speed of the population front is a salient feature of solutions to this equation in one dimension (Murray, 1993).

There have been a number of applications of this equation to biological processes and population dynamics; in particular, efforts have been made to apply it to the Neolithic process. The specific applications of this approach to the spread of the Neolithic in Europe, however, have hardly advanced beyond simple one-dimensional models in a homogeneous environment.

The simplest and first model of this type was Ammerman and Cavalli-Sforza (1973). Following their 1971 paper on estimates of the rate of spread of the Neolithic (as discussed above), Ammerman and Cavalli-Sforza (1973) presented a ‘wave-of-advance’ model. This used the FKPP equation,

\[
\frac{\partial N}{\partial t} = \gamma N \left(1 - \frac{N}{K}\right) + \nu \nabla^2 N ,
\]

with logistic growth and homogeneous isotropic diffusion, as an approximation for the process. They considered various approximations of the parameter values, treating the Neolithic as a ‘demic’ diffusion process. This model neglected any heterogeneity of the environment; even coastlines were neglected at this level of approximation. A simulation was carried out in one dimension.

Despite its apparent simplicity, the ‘wave-of-advance’ model is remarkably successful in explaining the constant rate of spread of farming over the vast area from the Near East to Western Europe. Further developments of this model, and comments by Ammerman and Cavalli-Sforza themselves, make clear the need to include heterogeneity of the geographical domain. Regional variations in the spread of the Neolithic — most notably the rapid advances of the Linear Pottery (LBK) and Impressed Ware traditions, along the Danube–Rhine corridor and the Mediterranean coastline, respectively — are key phenomena already discussed above.

The results of Ammerman and Cavalli-Sforza have more recently been confirmed by Gkiasta et al. (2003), using a significantly more comprehensive radiocarbon database. The latter authors suggested that the regional variations in the spread may be due to variations in the importance of demic versus cultural transmission, with the former leading to a more abrupt transition. However, the radiocarbon data alone do not appear sufficient to clarify and quantify this distinction.

In reaction to the work of Ammerman and Cavalli-Sforza, Zilhão (2001) considered the likely applicability of such a model to the Neolithic Cardial culture in the Mediterranean coast area. The conclusion was that, in order to achieve the speeds observed in these areas via a ‘wave of advance’ model, the diffusivity would have to be 30 times greater than that observed ethnographically. On these grounds, Zilhão concluded that the spread in this region took place via maritime pioneer colonization, rather than the direct random (land) migration inherent to the ‘wave of advance’ model.

While much work has been carried out into the measurement of the Neolithic dispersal, work on modelling this phenomenon remains sparse. Fort and Méndez (1999a,b) discussed the front propagation speed resulting from various generalizations of the FKPP equation, but their results were restricted to one dimension and to homogeneous systems. The model introduced in the preceding section, and discussed further below, attempts to take into account the effect of heterogeneous, two-dimensional environments on the process.

Steele et al. (1998) took steps towards addressing the influence of the environment on a wave of advance, when they developed a model of Paleo-Indian dispersal into North America. This hunter-gatherer population was described by a two-dimensional reaction-diffusion equation (i.e. the FKPP equation), which was solved numerically on a grid. The advance of this model was the introduction of environmental
heterogeneities into the parameters; they allowed for spatial variation in the carrying capacity, and used their extensive paleo-environmental reconstructions as input data. The carrying capacity varied across the grid according to the median observed hunter-gatherer population densities in different habitats. The diffusion constant was held globally constant throughout the simulations. Various simulations were carried out for both constant and varying carrying capacity, and a number of final population densities presented; a patchy population distribution was achieved by varying the value of carrying capacity in space. These authors used comparison with the United States fluted point data as their measure of model success, and concluded that in the absence of environmental variation, these data cannot be accurately reproduced by a model of this type. By varying carrying capacity however, the model could accurately reproduce the greatest density of occupation in the eastern woodland habitats. They noted that the diffusivity (mobility) of people must also be a function of position and time, and suggested that the spread might have followed major river valleys (Anderson, 1990), but did not include these effects into their model.

In addition to the work described above, some preliminary studies have also been carried out into multi-population models of human dispersal, in the context of Neolithic populations. The space into which the Neolithic penetrated was at the time inhabited by Mesolithic hunter-gatherer groups. Many authors believe that, rather than a ‘demic’ process in which the hunters simply became extinct, the Neolithic revolution occurred as a result of a combination of human migration and technological (cultural) transmission. If this were the case, then the models described above would not be sufficient to capture this more complex process. A model which includes three populations was first proposed by Aoki et al. (1996), who examined the travelling wave solutions for the spread of farmers into a region occupied by hunter-gatherers in one dimension. The model has three interacting populations: farmers (F), hunters (H), and converts (C) from hunting to farming. There are thus three coupled reaction-diffusion equations

\[
\frac{\partial F}{\partial t} = r_F [1 - (F + C)/K] + D \frac{\partial^2 F}{\partial x^2},
\]

\[
\frac{\partial C}{\partial t} = r_C [1 - (F + C)/K] + D \frac{\partial^2 C}{\partial x^2} + e(F + C)H,
\]

\[
\frac{\partial H}{\partial t} = r_H [1 - H/L] + D \frac{\partial^2 H}{\partial x^2} - e(F + C)H.
\]

Here D is the (universal) diffusion coefficient, K and L are the carrying capacities of total farmers and hunters respectively, and the r parameters are the growth rates for the
three populations. In this model there is also the parameter \( \epsilon \) which represents the ‘conversion rate’ of hunters to farmers. Aoki et al. (1996) discuss the different wave front combinations that can be formed by different combinations of parameters.

More recently, Ackland et al. (2007) have significantly extended the multi-population approach of Aoki et al. (1996), and combined this with ideas first put forward by Cohen (1992). Here, in addition to logistic growth and demic diffusion, two further interactions are introduced. Hunters may convert to farming upon contact with original farmers (Aoki et al., 1996) or converted farmers, and there is direct competition for resources between the two farming populations (original farmers and converts). Modified logistic and diffusive terms (first proposed by Cohen, 1992) are employed. A number of scenarios are simulated in which competing populations are appropriate, one being the Neolithic revolution in Europe (here, as in many other cases, this is considered synonymous with the introduction of arable farming). The model results in an internal boundary, at which the dominant invading population becomes the converts rather than the original farmers, occurring close to the observed boundary of the LBK culture. However, the LBK boundary does not extend as far east as the boundary in their model, and also extends further west along the Rhine- Danube valley. This disparity is attributed to the probability that the LBK culture spread faster along these rivers than elsewhere, a feature they did not try to model. This is consistent with the radiocarbon record examined by Ammerman and Cavalli-Sforza among others, as discussed above.

In any model of interacting populations, however, there is the inherent difficulty of estimating the ‘conversion rate’ between populations. There exists little archaeological evidence for the initial spread of farming, with regard to the quantification of interactions with the in situ hunter-gatherers. In the current work, we adopt an approach which neglects any population interaction. This is based on the assumption that there is no competition for resources between the two populations; i.e., we assume a hunter-gatherer population can live side by side with a farming population (at the typically low Neolithic population densities) and not deplete the same resources.

5. Comparison of the model with radiocarbon dates

The quality of the model was assessed by considering the time lag \( \Delta T = T - T_m \) between the modelled arrival time(s) of the wave(s) of advance to a site, \( T_m \), and the actual 14C date(s) of this site, \( T \), obtained as described in Sect. 2. The sites were attributed to that centre (Near East or Urals) which provided the smallest magnitude of \( \Delta T \). This procedure admittedly favours the model, and the attributions have to be carefully compared with the archaeological and typological characteristics of each site. Such evidence is incomplete or insufficient in a great number of cases; we leave the laborious task of incorporating independent evidence in a systematic and detailed manner for future work. Our formulaic method of attribution has inevitably failed in some cases, but our preliminary checks have confirmed that the results are still broadly consistent with the evidence available.

First, we considered a model with a single source in the Near East. The resulting time lags are presented in Figure 6a–c. In Figure 6a the sites shown are those at which the one-source model date and the radiocarbon date agree within 500 years (55% of the pan-European dates); Figure 6d gives a similar figure for the two source model (now 70% of the pan-European dates). The points in the EE area are significantly more abundant in Figure 6d than in 6a, while the difference in the SCWE area is less striking; this suggests that while the SCWE sites are fitted reasonably well with the one source model, with \( |\Delta T| < 500 \) years for 68% of data points, the fit is unacceptably poor for EE, where only 38% of the radiocarbon dates can be fit to within 500 years. The standard deviation of the pan-European time lags here is \( s = 800 \) years. Outliers are numerous (illustrated by the abundance of points in Figure 6c) when all of the European sites are included, and they make the distribution skewed, and offset from \( \Delta T = 0 \). The outliers are mainly located in the east; for the SCWE sites, the distribution is more tightly clustered (\( s = 540 \) years), has negligible mean value, and is quite symmetric. In contrast, the time lags for sites in Eastern Europe (EE), with respect to the centre in the Near East, have a rather flat distribution (\( s = 1040 \) years), which is strongly skewed and has a significant mean value (310 years). The failure of the single-source model to accommodate the 14C dates from Eastern Europe justifies our use of the more complicated model with two sources of propagation. (Attempts were also made to locate a single source in various other locations, such as the Urals, but this did not improve the agreement.)

Adding another source in the East makes the model much more successful; the values of the time lag, shown in Figure 6d–f, are systematically smaller (i.e. there are significantly fewer points in Figure 6f (5%) compared to Figure 6c (17%)). The resulting \( \Delta T \) distribution for all the sites is quite narrow (\( s = 520 \) years) and almost perfectly symmetric, with a negligible mean value (40 years). The distributions remain similarly acceptable when calculated separately for each source (with \( s = 490 \) and 570 years, respectively). The improvement is especially striking in EE, where the sites are split almost equally between the two sources.

We tentatively consider a model acceptable if the standard deviation \( s \) of the time lag \( \Delta T \), is not larger than 3 standard dating errors \( \sigma \); i.e., about 500 years, given our estimate of \( \sigma \) close to 160 years over the pan-European domain. This criterion cannot be satisfied with any single-source model, but is satisfied comfortably with two sources. While we
would never expect a large-scale model of the sort proposed here to accurately describe the complex process of the Neolithization in fine detail (and so the resulting values of $\Delta T$ cannot be uniformly small), the degree of improvement in terms of the standard deviation of $\Delta T$ clearly favours the two-source model. The reduction in $s$ is statistically significant, and cannot be explained by the increase in the complexity of the model alone. The confidence intervals of the sample standard deviations $s$ for one-source and two-source models do not overlap ($740 < \sigma_{\text{One Source}} < 840$ vs $480 < \sigma_{\text{Two Source}} < 550$); moreover, the F-test confirms this at a 99% significance level.

It is instructive to represent the data in the same format as in Figure 2a, b, but now with each date attributed to one of the sources, as suggested by our model. This has been done in Figure 2c, d, where the close correlation of Figure 2a is restored for the pan-European data. The dates are consistent with constant rates of spread from one of the two sources. Using straight-line fitting, we obtain the average speed of front propagation of $1.1 \pm 0.1$ km/year for the wave originating in the Near East (Figure 2c), and $1.7 \pm 0.3$ km/year for the source in the East (Figure 2d); $2\sigma$ values are given as uncertainties here and below. The spread from the Near East is slowed in Eastern Europe to $0.7 \pm 0.1$ km/year; excluding the dates from the East (as in Figure 2a) gives a higher speed of $1.2 \pm 0.1$ km/year. The estimates for the data in both western and eastern Europe are compatible with earlier results (Dolukhanov et al., 2005, Gkiasta et al., 2003, Pinhasi et al., 2005). Care must be taken when using such estimates, however, since the spread occurs in a strongly heterogeneous space, and so cannot be fully characterised by a single constant speed. The rate of spread varies on both pan-European scale and on smaller scales, e.g., near major waterways (Davison et al., 2006).
Our allocation of sites to sources is discussed above, and must be critically evaluated as typological archaeological evidence becomes available. Provisionally, however, we consider a few sites here, and analyse how they fit into the two source model. Taking Ivanovskoye-2 as an example, the data form two peaks (Figure 1b). The times at which each of the waves arrive at this location are 4349BC (for the Near-Eastern wave) and 5400BC (for the Eastern Wave); it can be seen that these each correspond to one peak. As a second example, we accept two dates for the Mayak site; one from the younger cluster (2601 ± 192 BC), and one from the older date (4590 ± 47 BC) which is an outlier to the younger peak. When the allocation of sites to sources is then performed, one of the sites is consistent with the Near-eastern wave (arriving at 2506 BC), and the other with the eastern wave (arriving at 4718 BC). Thus in these two representative test cases, it is shown that where there are two discernible peaks, they generally correspond one to each of our proposed waves of advance. This is indicative of the Neolithic process being at least dual faceted.

Conclusions

Our model has significant implications for the understanding of the Neolithization of Europe. It substantiates our suggestion that the spread of the Neolithic involved at least two waves propagating from distinct centres, starting at about 8200 BC in Eastern Europe and 6700 BC in the Near East. The earlier wave, spreading from the east via the 'steppe corridor', resulted in the spread of pottery-making and the establishment of the 'eastern version' of the Neolithic in Europe. A later wave, originating in the Fertile Crescent of the Near East, is the well-studied process that brought farming to Europe.

It is conceivable that the westernmost extension of the earlier (eastern) wave of advance produced the pre-agricultural ceramic sites of La Hogue type in north-eastern France and western Germany, and of Roucadour-type (also known as Epicardial) in western Mediterranean and Atlantic France (Berg and Hauzer, 2001, Jeunesse, 1987). The available dates for the earlier Roucadour sites (7500–6500 BC) (Roussault-Laroque, 1990) are not inconsistent with this idea, but a definitive conclusion needs additional work.

The nature of the eastern source needs to be further explored. The early-pottery sites of the Yelshanian Culture (Mamonov, 2000) have been identified in a vast steppe area stretching between the Lower Volga and the Ural Rivers. The oldest dates from that area are about 8000 BC (although the peak of the culture occurred 1000 years later) (Dolukhanov et al., 2005). Even earlier dates have been obtained for pottery-bearing sites in Southern Siberia and the Russian Far East (Kuzmin and Orlova, 2000, Timofeev et al., 2004). This empirical relation between our hypothetical eastern source and the earlier pottery-bearing sites further east may indicate some causal relationship.

According to our model, the early Neolithic sites in Eastern Europe belong to both waves, in roughly equal numbers. Unlike elsewhere in Europe, the wave attributable to the Near East does not seem to have introduced farming in the East. The reason for this is not clear, but may involve the local environment: low fertility of soils and prolonged winters combined with the richness of aquatic and terrestrial wildlife resources (Dolukhanov, 1996).

Regardless of the precise nature of the eastern source, the current work suggests the existence of a wave which spread into Europe from the east carrying the tradition of early Neolithic pottery-making. If confirmed by further evidence (in particular, archaeological, typological, and genetic evidence), this suggestion will require some serious re-evaluation of the origins of the Neolithic in Europe.

References

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