The Neolithic transition in the Iberian Peninsula: data analysis and modeling.

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Abstract
We apply GIS techniques to analyze a carefully selected database of 93 Early Neolithic sites in the Iberian Peninsula. This allows us to study the spatial dynamics of the Neolithic transition in Iberia. We study how the Neolithic was introduced into the peninsula, in order to test the hypothesis that the Neolithic was introduced almost simultaneously from two sources: one at the northeast (via the Mediterranean coast) and another one at the south (possibly from Northern Africa). We also analyze how the expansion of the Neolithic transition took place within the Iberian Peninsula and measure local rates of spread, in order to identify regions with fast and slow rates (such as the slowdown at the Cantabrian coast). In addition, we attempt to reproduce the main results obtained from the GIS analysis by applying reaction-dispersal models to the expansion of the Neolithic transition in the Iberian Peninsula. We conclude that a model with two sources is a reasonable assumption that agrees better with the archaeological data available at present than a model with a single source.

Keywords Neolithic transition, Iberian Peninsula, GIS analysis, Computational modeling, Demic expansion

Introduction

The Neolithic transition in Europe has been often analyzed and modeled at the global, continental scale (Ammerman and Cavalli-Sforza 1984; Pinhasi *et al.* 2005). As more archaeological data are gathered, it is now becoming possible to analyze this transition also at the local level (Bocquet-Appel *et al.* 2009, 2012). Some specific local features of the Neolithic transition previously analyzed have been the role of waterways (Davison *et al.* 2006), the effect of areas with environmental conditions not favoring farming (Patterson *et al.* 2010), the fast spread rate along the Mediterranean (Fort *et al.* 2012) and the slowdown in Northern Europe (Isern and Fort 2010; Isern *et al.* 2012). Here we focus on the Iberian Peninsula. Our main aim is to see what features, if any, the archaeological data imply for the space-time dynamics of the Neolithic expansion in Iberia. We will also analyze their implications for the likely entrance routes of the Neolithic into the Iberian Peninsula.

GIS analysis of the Neolithic transition in the Iberian Peninsula

Early Neolithic database

In this paper we will use a database that aims to provide a scenario of the Neolithic expansion in the Iberian Peninsula that is as comprehensive as possible. For this purpose, the database contains 93 calibrated dates in the peninsula that have been carefully gathered by selecting sites corresponding to the earliest Neolithic evidences. In order to have a reliable database, we have only selected 14C dates on short-lived species (either plants or animals) avoiding determinations both on bulk samples of charcoal or cremated/burnt bones and on shells (due to uncertainties related to the reservoir effect); we have also considered reliable dates those obtained from samples collected inside hearths, on the principle that the firewood used is mostly from bushes and tree branches, rather the trunk (which would cause "old wood" effects on the radiocarbon dating).

The database contains information on the site locations—country and geographic coordinates (longitude and latitude)—and their uncalibrated and calibrated dates. The calibrated dates have been calculated using the Calib 6.0.1 software (Stuiver and Reimer 2010). In the main text we will use mean calibrated dates, but in Appendix A we will also discuss the effect of using the whole range of calibrated dates.

The database in MS Excel format is available as Electronic Supplementary Material (Table S1).

Early Neolithic chronology: interpolation

In order to study the spatial dynamics of the Neolithic expansion in the Iberian Peninsula, Fig. 1 shows the location of the sites in the database (triangles) and the result of performing a kriging interpolation (Oliver and Webster 1990) for the mean calibrated dates using ESRI ArcGIS 10 (Spatial Analyst Tools). Each color in Fig. 1 corresponds to an interval of 100 yr. According to Fig. 1, the earliest Neolithic sites in the peninsula are found at the northeastern and central-eastern Mediterranean coasts, from where there was probably a very fast spread towards the interior (as noted by Fernández and Gómez 2009). Moreover, at the southern and southwestern coasts, some regions display older dates than surrounding areas, so they could be the origin of the Neolithic expansion through the western façade of the Iberian Peninsula[1].

[1] Although not included in the database to avoid uncertainties due to reservoir effect, on the Western Algarve region (south of Portugal) there are some Early Neolithic dates obtained from shells with a calibrated range of 7650–7400 cal BP, corresponding to a mean calibrated age of 7525 cal BP (Carvalho 2010), that would also be in good accord with a Neolithic expansion from the south.

Finally, the latest regions of Neolithic arrival were clearly those on the north and northwestern Cantabrian coast (Fig. 1).

One of the aims of this paper is to test the hypothesis that the Neolithic expansion in the Iberian Peninsula was due to two sources: one from the European continent and another one from the African continent. Fig. 1 clearly shows that an entrance of the Neolithic through the Strait of Gibraltar is a reasonable assumption for the following two reasons. For once, there are some early dates near the strait, which are at the same time consistent with datings from the African shore of the strait and the Chafarinas Islands (for recent synthesis on the possibility of interaction across the Strait of Gibraltar and the Alboran Sea during the Neolithic transition, see Cortés *et al.* 2012, Gibaja *et al.* 2012, Linstäter *et al.* 2012). And second, the isochrones in Fig. 1 seem to display a differentiated behavior of the Neolithic front in the eastern and western areas of the Iberian Peninsula. This issue will be analyzed in more detail below, but in order to introduce our methods it will be useful to discuss another feature first.

Slowdown at the Cantabrian region

An interesting, very clear feature in Fig. 1 is the substantially slower rate of expansion of the Neolithic transition near the Cantabrian coast (i.e. at the northern region, west of the Pyrenees). This can be seen from the fact that the isochrones are closer to each other in that region than elsewhere in the peninsula, which implies a smaller distance advanced by the Neolithic wave every 100 yr.

We can visualize this change in the rate of expansion more clearly by plotting space-time profiles along a given direction, as follows. Figure 2a shows the same interpolation map as in Fig. 1, but we have added three straight lines (directions). Figures 2b, 2c and 2d show the distance to the Mediterranean coast (along each direction) and its interpolated Early Neolithic date, for locations separated 5 km. We have plotted distances versus dates (rather than dates versus distances) because, in this way, the slope provides an estimation of the speed (in km/yr) along each of the three directions (as defined in Fig. 2a). In all three profiles we see that the slope is steeper for older dates, i.e. for locations near the Mediterranean coast (fast spread), and less steep for later dates, i.e. locations nearer to the Cantabrian Sea (slow spread). This change in the slope seems to take place in a smoother way near the Pyrenees (Fig. 2b), whereas we see a more abrupt change in Figs. 2c and 2d, where two clearly differentiated regions are distinguished (in terms of the spread rate). For example, for profile 3 (Fig. 2d), the spread rate is about 2.3 km/yr along the first 500 km from the Mediterranean Sea, but it then abruptly slows down to only about 0.3 km/yr along the next 300 km (i.e., as the upper left corner in Fig. 2a is approached).

This slowdown of the Neolithic expansion, as the Atlantic coast is approached, seems to be a widespread phenomenon elsewhere in Europe (Price 2003). It is worth to mention that some theories (Price 2003; Louwe Kooijmans 2009) and models (Isern and Fort 2010; Isern *et al.* 2012) have proposed that, in Northern Europe, this slowdown of the Neolithic front might have been due to the interaction with Mesolithic populations. In other regions of Iberia, however, Mesolithic-Neolithic interaction may have resulted in rather different outcomes, such as in the case of the Muge shell middens (coastal Portugal) where Mesolithic groups were eventually absorbed by the newcomers after a process of encapsulation of the former for several generations with no archaeologically visible interaction (Carvalho 2010). However, we will not discuss this point further here because it has been already analyzed in detail elsewhere (Isern and Fort 2010, Isern *et al.* 2012, Carvalho 2010) and the main purpose of the present paper is to analyze the possible entrances of the Neolithic transition into the Iberian Peninsula.

Entrances of the Neolithic into the Iberian Peninsula

The relationship between the Neolithic in Iberia and elsewhere in Europe has been reviewed recently (Cruz Berrocal 2012). An interesting open question is the following: Was there only a single entrance route for the Neolithic into the Iberian Peninsula? Besides the visual analysis of the interpolation map (Fig. 1), a more quantitative approach is to search for trends in distance-date profiles under models based on different assumptions regarding the sources. In order to do so, let us define two immediate possible sources for the introduction of the Neolithic into the peninsula: one corresponding to an introduction from the northeast (through the European continent) and defined as location A in Fig. 3a ($42.8^{\circ}\,\mathrm{N}\;\;2.9^{\circ}\,\mathrm{E}$); and another one corresponding to an introduction from the south (through the Strait of Gibraltar) and defined as location B in Fig. 3a ($35.8^{\circ}\,\mathrm{N}\;\;5.36^{\circ}\,\mathrm{W}$). We will calculate the distances between these sources (A and B) and the Neolithic sites using the Haversine equation (de Smith *et al.* 2012, Sec. 4.2.1),

$$d_{ij} = 2R\arcsin\left(\sqrt{\sin^2\left(\frac{\varphi_i-\varphi_j}{2}\right)+\sin^2\left(\frac{\lambda_i-\lambda_j}{2}\right)\cos\varphi_i\cos\varphi_j}\right), \qquad (1)$$

which gives the distance in kilometers between two locations i and j. The pairs (φ,λ) are the latitudes and longitudes of the locations under consideration, and $R = 6371\,\mathrm{km}$ is the average Earth radius.

If we assumed that the Neolithic was introduced into the Iberian Peninsula only from the European continent, then we would expect to find a trend when plotting the distances from every site to point A versus their calibrated dates with earlier dates nearer to the source (point A) and later dates at further away locations. However, what we see in Fig. 3b, where we have plotted the distance to A against the date for all sites, is that both the nearest and the furthest sites to the source A correspond the earliest Neolithic appearances in the peninsula (7600–7400 cal BP), whereas the latest dates (6400–6000 cal BP) are located at intermediate distances. So it is difficult to assign a single trend to the results in Fig. 3b.

On the other hand, if the Neolithic transition took place from two mostly simultaneous sources, we would expect to obtain separate trends for each source. In order to test this scenario, let us assume that northeastern sites (squares in Fig. 3a) are due to a northeastern source (location A) whereas southern and western sites (circles in Fig. 3a) are sites due to a southern source (location B).

Before discussing the results, let us just point out that the only intent of this division is to identify the sites most probably due to a Neolithic expansion from the south (or the north), but in any case the intent is to assign a single cultural identity at all levels to all the sites represented by circles (or squares).

Figures 3c and 3d show the results of plotting the distance from each site to their presumed source. For northeastern sites (Fig. 3c) we see that taking into account just this fraction of the sites has improved the visualization of a possible trend (although there are still several early Neolithic sites at distant locations). More importantly, for southern and western sites we see a clear trend when computing their distances to B (Fig. 3d), with later dates at more distant locations. Moreover, by comparing Figs. 3b, 3c and 3d we can see that southern and western sites (that show a clear trend in Fig. 3d) correspond to distances larger than 700 km in Fig. 3b, where they do not display any trend between dates and distances to location A.

Therefore, this analysis shows that (i) the nearest and furthest sites to location A are mostly coetaneous (Fig. 3b), so that it is possible that the furthest sites are due to a Neolithic expansion form a different source; (ii) at the western half of the peninsula, the data are consistent with a Neolithic expansion from the south (Fig. 3d) rather than from the northeast (Fig. 3b, sites with distances above 700 km).

A southerly entrance into the peninsula, as evidenced in conclusion (ii), deserves a further comment. It should be mentioned that there is the possibility of a southern entry point even without a spread from the Near East via North Africa. Alternatively, i.e. assuming that the Saharan Neolithic never reached the coastal regions of Mediterranean Africa (for an opposite view, see Daugas and El Idrissi 2008), there are currently three different understandings of the transition to farming in the region: the first proposes that the full “Neolithic package” (i.e., farming economy, pottery, polished stone tools, sedentary ways of life) arrived initially to northeast Iberia and only subsequently spread to northern Morocco (Zilhão 2001); the second suggests that the Neolithic arrived simultaneously both to Morocco and Iberia, whether via an African route from Sicily to Tunisia and Algeria (Bernabeu *et al.* 2003) or through the northern rim of Western Mediterranean (Linstädter *et al.* 2012); finally, the third envisages a rather complex interaction process according to which some material culture items transferred between both shores of the Strait of Gibraltar resulting in a somewhat mixed model including acculturation and migration processes (Manen *et al.* 2007, Cortés *et al.* 2012).

The fact, however, is that the available data are still very scarce and, for the most part, outdated. Only more recently the resumption of fieldwork and systematic reanalysis of materials from old excavations, namely in Morocco, have been providing new insights and hard data regarding the transition to farming (e.g., Daugas and El Idrissi 2008, El Idrissi 2012, Linstädter *et al.* 2012, Ramos *et al.* 2010, Rojo and Garrido 2010). All authors agree that at some point in time a farming economic system was established in the region, but disagree not only on its weight in the overall subsistence strategies but also on chronology. If one applies to the northern regions of Morocco the same criteria of sample selection used in this paper, only two sites bear reliable radiocarbon dates related to the earliest stages of the Neolithic: Kaf That el Ghar and Ifri Oudadane. At the former site, a seed of barley was dated to ca. 7300 cal BP (LyOxA-971: 6350 ± 85 BP; see Ballouche and Marinval 2003); at the latter a batch of nine samples of domestic plant species indicated the time interval of ca. 7650 to 7100 cal BP for the earliest Neolithic occupation at the site (the so-called “Early Neolithic A”; radiocarbon determinations Beta-295779: 6740 ± 50 BP and Beta-318608: 6140 ± 30 BP on lentil and wheat, respectively). The oldest result—ca. 100 years older than the dates known for Iberia—is relativized by the authors, according to whom the available “[...] radiocarbon dates overlap on the calibration curve and can be considered roughly contemporaneous” (Morales *et al.* 2013: 2666).

In sum, an entry of the farming economy in Iberia from North Africa remains elusive due to severe limitations of the archaeological record, in spite of the recent promising developments pointed out above, but cannot be excluded *a priori* from any reasoning. Besides, it is interesting to note that those first evidences of agriculture in Morocco have several archaeological elements similar to the technical manifestations of the Neolithic in south Iberia, which in turn differ to those observed at the north of the peninsula (e.g., heat treatment of flint, pottery style, etc.) (Gibaja *et al.* 2012, Gibaja and Carvalho 2010). This fact suggests, therefore, the consideration of a two way entrance for the Neolithic in Iberia.

Computational model

Finally we will attempt to simulate the Neolithic expansion in the Iberian Peninsula by using a computational model. Ancient genetics supports demic (rather than cultural) diffusion for the Neolithic transition in Iberia (Gamba *et al.* 2011). Accordingly, we will use a demic model. Particularly, we will use the software developed by Toni Pujol to simulate front propagation in real geographies (see Fort *et al.* 2012) and adapt it to properly describe the Neolithic transition in the Iberian Peninsula.

The demic computational model assumes that the origin of the Neolithic expansion in Europe took place in a region at the Near East corresponding to the PPNB/C culture about 9000 cal BP (assuming older initial conditions for the front spread would yield earlier arrival dates than observed, as shown in detail by Fort *et al.* 2012). The Neolithic range expansion is computed on a grid of 180×102 nodes, with a distance of $50\,\text{km}$ between nearest neighbors (ethnographic data show that 50 km is the characteristic distance[2] moved by pre-industrial farmers per generation, see Fort *et al.* 2007). The demic model uses a reproduction-dispersal scheme that calculates the population density at every node after every iteration (which corresponds to one generation) by taking into account two processes: (i) population growth due to net reproduction, and (ii) population dispersal (which includes sea travel, as necessary to properly describe the fast spread along the Mediterranean Sea with realistic parameter values, see Fort *et al.* 2012). Below we summarize this computational scheme and give the parameter values used in the model.

(i) Population growth process: At each node (x,y), we compute the new population number due to the reproduction process $N'(x,y,t)$ in terms of the initial population $N(x,y,t)$ as follows (Fort *et al.* 2007)

$$\begin{aligned} N'(x,y,t) &= R_0 N(x,y,t) \quad \text{if} \quad N(x,y,t) < N_{\max}/R_0, \\ N'(x,y,t) &= N_{\max}(x,y,t) \quad \text{if} \quad N(x,y,t) \geq N_{\max}/R_0, \end{aligned} \tag{2}$$

where R_0 is the net reproductive rate per generation, and $N_{\max}$ is the carrying capacity of farmers. The condition in the equation above ensures that the population number is never higher than $N_{\max}$. In the model we apply the value $R_0 = 2.45$, as obtained from the relation $R_0 = \exp(aT)$ (see Fort *et al.* 2007, note 26), the observed mean growth rate $a = 0.028\ \text{yr}^{-1}$ for pre-industrial farming populations that settled into empty space (Isern *et al.* 2008) and the observed mean generation time $T = 32\,\text{yr}$ for pre-industrial farmers (Fort *et al.* 2004). We will also apply $N_{\max} \approx 3200\,\text{farmers/node}$, as calculated from $N_{\max} = l^2 n_{\max}$, where $l \approx 50\,\text{km}$ is the distance between nodes and $n_{\max} = 1.28\,\text{farmers/km}^2$ is the maximum density of farmers (Currat and Excoffier 2005). It is worth mentioning that using logistic reproduction and/or other values for $N_{\max}$ would yield the same results for the front propagation dynamics (i.e., for the spread rates and isochrone maps).

(ii) Dispersal process: The model we are using (Fort *et al.* 2012) takes into account the presence of sea and allows sea travel up to a certain distance,[3] so the dispersal process will differ between inland and coastal nodes. For inland nodes, the dispersal is assumed to take place homogeneously, so at the end of one iteration $p_e N'(x,y,t)$ individuals will stay at the same node (x,y) with probability p_e (this parameter is called the persistence) and the rest

[2] The characteristic distance corresponds to the distance that individuals would move each generation in a very simple, but useful, approximation to the real dispersion process that divides the population in "dispersers" and "non-dispersers", with a probability p_e (persistence) to be a non-disperser (i.e., to stay at the same location after a generation). The characteristic distance can be calculated from real mobility data m as $\sqrt{m/(1-p_e)}$ (Fort *et al*. 2007).

[3] The model can also take mountains into account as barriers, but we will not do so because their effect is small (see Fort *et al*. 2012, Appendix B).

will move to the four nearest neighbors ($(1-p_e)N'(x,y,t)/4$ individuals to each node). For coastal nodes, the individuals whose destination point would be in the sea are distributed among all coastal nodes within the sea travel range considered (details can be found in Fort *et al.* 2012, Appendix A). The persistence value used is $p_e = 0.38$ (this is the mean of the observed values for pre-industrial farmers, see Fort *et al.* 2007). We will consider sea travels ranging up to 200 km (so that the front arrives at realistic dates to the Iberian Peninsula from the Near East).

The program repeats these two steps for about 200 iterations (200 generations) in order to model the Neolithic transition in the whole European continent. For every node, the arrival time of the Neolithic is recorded when the number of individuals is 90% of $N_{\max}$. Finally, the results from the model can be represented graphically with a GIS software to generate a chronology of the simulated Neolithic expansion in cal BP (Fig. 4).

Fig. 4 shows the arrival times of the Neolithic in the Iberian Peninsula predicted by the model for two scenarios: (i) a scenario where the Neolithic farmers can spread through the African continent in addition to Europe (Fig. 4a) and (ii) a second scenario where the expansion through Africa has been forbidden (Fig. 4b). The results have been plotted by following the same color scheme as in the interpolation map (Fig. 1) for the sake of comparison.

Obviously, this model assumes that inland dispersal is homogeneous, so it cannot simulate the slowdown near the Cantabrian Sea. But in spite of its simplicity, this model will be useful to analyze the possible entrances of the Neolithic into the peninsula.

For both scenarios, the model predicts an introduction of the Neolithic from the European continent between 7300–7200 cal BP (Figs. 4a and b), which is fairly consistent with the interpolation of the archeological data in Fig. 1. Other attempts run with sea travels ranging up to 150 km or 250 km yielded much poorer fits, with predicted times for introduction of the Neolithic within the periods 6800–6700 cal BP and 7700–7600 cal BP respectively.

However, the dual and single-entrance models differ significantly at the lower half of the peninsula. Indeed, we see in Fig. 4a that if we allow the expansion of the Neolithic front along the African coast, a northwards Neolithic wave appears at the southwestern region, similarly to the archaeological observations (Figs. 1 and 3d). From Fig. 4a alone it may not be clear that this northwards expansion is due to a Neolithic expansion coming from Africa (rather than a fast expansion along the southern coasts), but the lack of such behavior in Fig. 4b makes it clear that this feature of the model is indeed due to the entrance from Northern Africa.

On the other hand, it would also be possible to tune the model in order predict a fast maritime expansion that would yield to multiple entrance points along the Mediterranean coast (which would be in agreement with a demic expansion with seafaring, as predicted by Zilhão 2001, 2003) and an upward Neolithic expansion in west Iberia (such as in Fig. 4a). However, to obtain these results we need to establish sea travels of up to 400 km, much faster than the mean value of 150 km providing the best fit for the study of the whole continent (Fort *et al.* 2012), yielding a much earlier estimated arrival time in the Iberian Peninsula at about 8000–7900 cal BP.

Therefore, to obtain reasonable predictions of both the arrival times of the Neolithic at the north of the Iberian Peninsula—and all the eastern Mediterranean coast—and the short time span between the earliest dates at the north and the south of the Peninsula, without considering an African influence, we would have to define a more complex model. A possibility would be to assume that the maritime technology may have evolved as the Neolithic expanded, allowing faster and further sea travels. Such behavior has been observed in Austronesia (Fort 2003). And, whereas there is not enough evidence to support or reject such an assumption for the Mediterranean, a possible argument against a more evolved maritime technology for the Early Neolithic in the Iberian Peninsula could be the lack of Early Neolithic evidences in the Balearic Islands. However, data seem to indicate that the maritime expansion was faster in Western Mediterranean than in Central Mediterranean (Ammerman 2010), so the use of varying sea travel ranges might be a prospective worth considering in the future.

To sum up, with the simple model used in this paper, we have been able to obtain a better description of the Neolithic expansion in the Iberian Peninsula when allowing the spread of the Neolithic from the Near East across both Europe and Africa. This leads to an entrance of the Neolithic into the Iberian peninsula from the south (in addition to the northeastern entrance), and yields more consistent results than a single-entrance European model (Fig. 4b) for the northwards expansion that is observed along the western side of the Iberian Peninsula (according to the archaeological data available at present). However, we cannot exclude the option that a more complex model could yield similarly consistent results also for a scenario where a Neolithic expansion along North Africa, and its interaction with Iberia, were prevented.

Conclusions

In this paper we have gathered a new Early Neolithic database for the Iberian Peninsula, in which we have favored samples on short-lived species as far as possible, since they provide the best quality dates. We have used this database to perform interpolation maps whose analysis shows the following features. First, there was a substantial slowdown as the Neolithic front approached the Cantabrian Sea (Fig. 2). Second, the earliest Neolithic sites are located at the northeastern and eastern coasts, but there are also early sites in the southern and southwestern coasts (Fig. 1). The space-time trends are clearer if assuming two entrances of the Neolithic into Iberia (one from Europe and another one from Africa) than if assuming a single European entrance (Fig. 3). A simulation using a demic model, based on realistic parameter values, is also more consistent with the archaeological data available at present if it allows for two entrances (one from Europe and another one from Africa) than if it only allows for a single entrance from Europe (Fig. 4). Therefore, the results show that it is reasonable to assume the possibility of an African origin for the southern Neolithic, although we cannot discard either the possibility of a fast maritime colonization from the north. Consequently, further study and data gathering from North Africa will be necessary in order to reach a sound conclusion on whether there was an entrance of the Neolithic into Iberia via the Strait of Gibraltar or not. On the other hand, as more data become available in the future, it could be interesting to apply additional criteria and thereby select only the most reliable dates (for an interesting proposal on sample quality ranking, see e.g. Zilhão 2011). Of course, requiring more strict criteria always implies to work with less data, and some details can be lost. Given the current context, we think that the database used here is a reasonable compromise between dating accuracy and geographical detail.

Before closing we would like to stress that the present paper does not attempt to provide final answers but should be regarded as a modeling exercise, which now moves from the continental down to the regional level. For example, the cluster of early dates on the east coast of the Peninsula (Fig. 1) essentially coevals with dates near the two entry points discussed (the northeast and the Strait of Gibraltar). Less land-based models could be developed in the future to describe those multiple points of entry. For example, perhaps maritime technologies improved during the more than 3000 years that elapsed since the PPNA in Cyprus and the start of the Neolithic in the Iberian Peninsula, leading to a comparatively rapid western spread (and multiple points of entry into the Iberian Peninsula). In any case, the more details we want to describe, the more refinement (and assumptions) will be necessary in the models. In spite of this, the present paper is useful both as a first step and as a tool to discuss some specific questions (e.g., whether two entry points or a single one provide a more realistic description of the data available at present).

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Appendix A: Dating uncertainties

In this paper we have performed analyses and reached conclusions by using mean calibrated dates. However, radiocarbon dating and calibration yield a probability range (not an exact value) for each date. Thus here we discuss the effect of such date uncertainties.

Fig. 5 shows Neolithic transition isochrones obtained from the interpolation of the upper (Fig. 5a) and lower (Fig. 5b) bounds for the 68.3% (1 sigma) confidence interval of each calibrated date BP (find the calibrated ranges in supporting Table S1). Obviously this yields an early scenario (Fig. 5a) and a late scenario (Fig. 5b) for the Neolithic transition. The maps in Fig. 5 have been prepared by following the same color scheme as in previous figures, for the sake of comparison.

By comparing the results from Fig. 5 with the interpolation map in Fig. 1, we see that in all three maps the behavior is fundamentally the same, but shifted in time. All maps display an early Neolithic transition at the northeastern coast to the center, a slightly later Neolithic expansion from the south, a slowdown near the Cantabrian coast, and the latest arrival of the Neolithic front at the northwestern extreme of the peninsula.

Therefore, the conclusions drawn in the present paper remain valid even when considering date uncertainties.

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Figure Captions

Fig. 1 Observed chronology of the Neolithic transition in the Iberian Peninsula. Map obtained by kriging interpolation of 93 Early Neolithic dates (triangles)

Fig. 2 Neolithic expansion profiles. The profiles in (b), (c) and (d) represent the relation between the distance to the Mediterranean coast and first Neolithic date of the points along the straight lines (directions) defined in (a). The local slope of the profile provides an estimate of the rate of expansion of the Neolithic wave along each profiling direction

Fig. 3 Exploration of source distance trends. (a) Crosses labeled A and B are two immediate presumed sources for the Neolithic expansion in the Iberian Peninsula. The symbols represent the Neolithic sites, with squares corresponding to sites presumably due to a Neolithic expansion from A, and circles to sites presumably due to a Neolithic expansion from B. (b) Distances from source A to all sites in relation to their dates, which display no trend. (c) Distances from source A to northeastern sites (squares in (a)) in relation to their dates, which display a slight trend-like behavior. (d) Distances from source B to southern and western sites (circles in (a)) in relation to their dates, which display a clear trend

Fig. 4 Modeled chronology of the Neolithic wave in the Iberian Peninsula. (a) Modeled Neolithic arrival times when allowing a Neolithic range expansion through both the European and African continents. (b) Modeled Neolithic arrival times when allowing the Neolithic range expansion only through the European continent, but not through Africa

Fig. 5 Date uncertainties in the Neolithic wave. Interpolation maps of upper and lower bounds for the 68.3% (1 sigma) confidence intervals of calibrated dates, yielding respectively (a) an early Neolithic transition scenario and (b) a late Neolithic transition scenario, relative to the interpolation scenario using mean calibrated dates (Fig. 1)

Electronic Supplementary Material

Table S1 Early Neolithic database. Information about 93 Early Neolithic sites in the Iberian Peninsula: site name, country, latitude/longitude, radiocarbon date and SD, mean calibrated age and calibrated date range

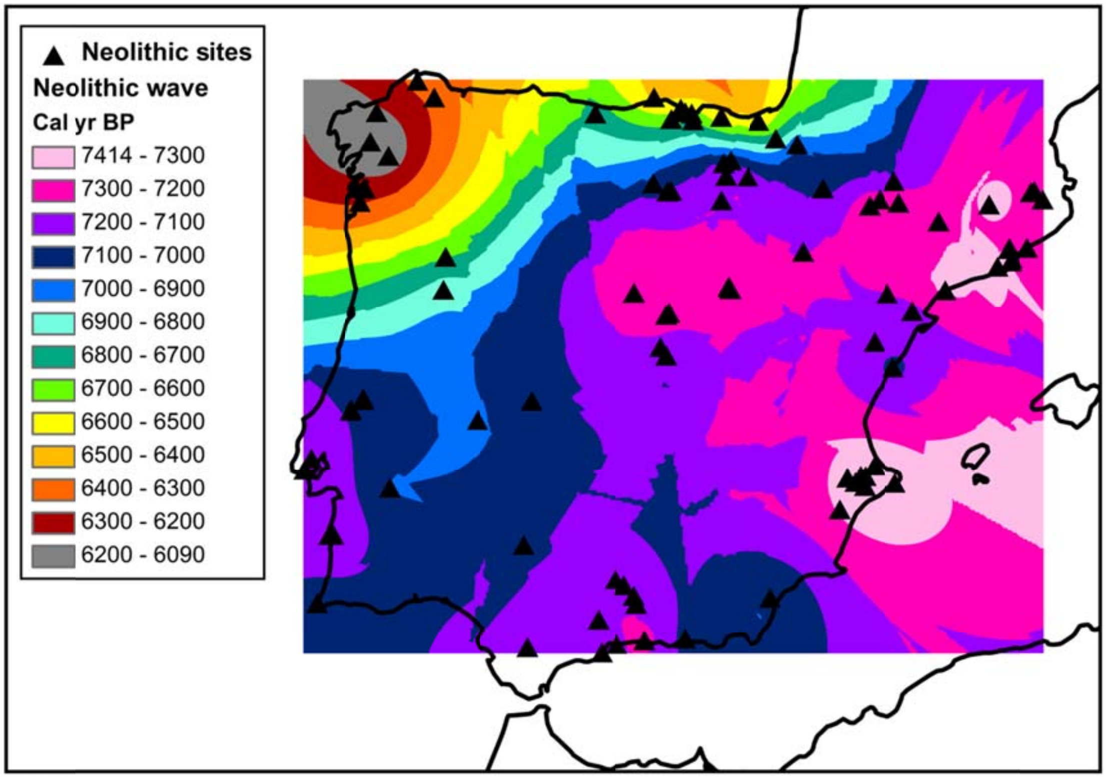
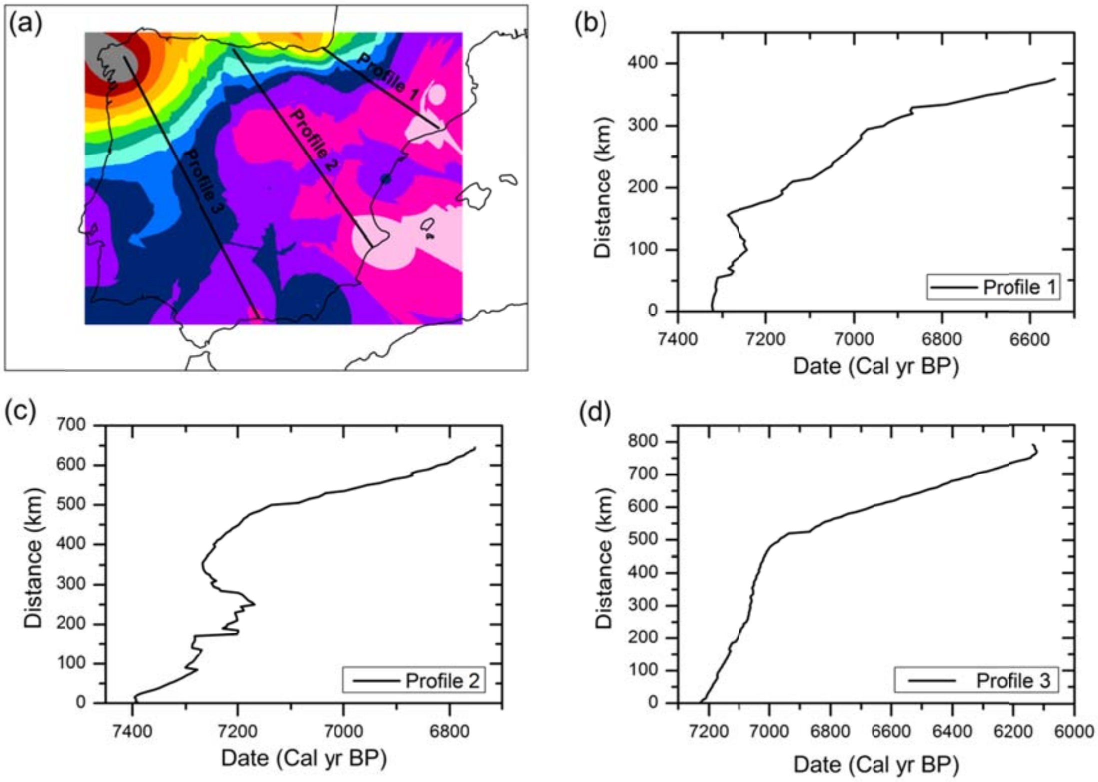
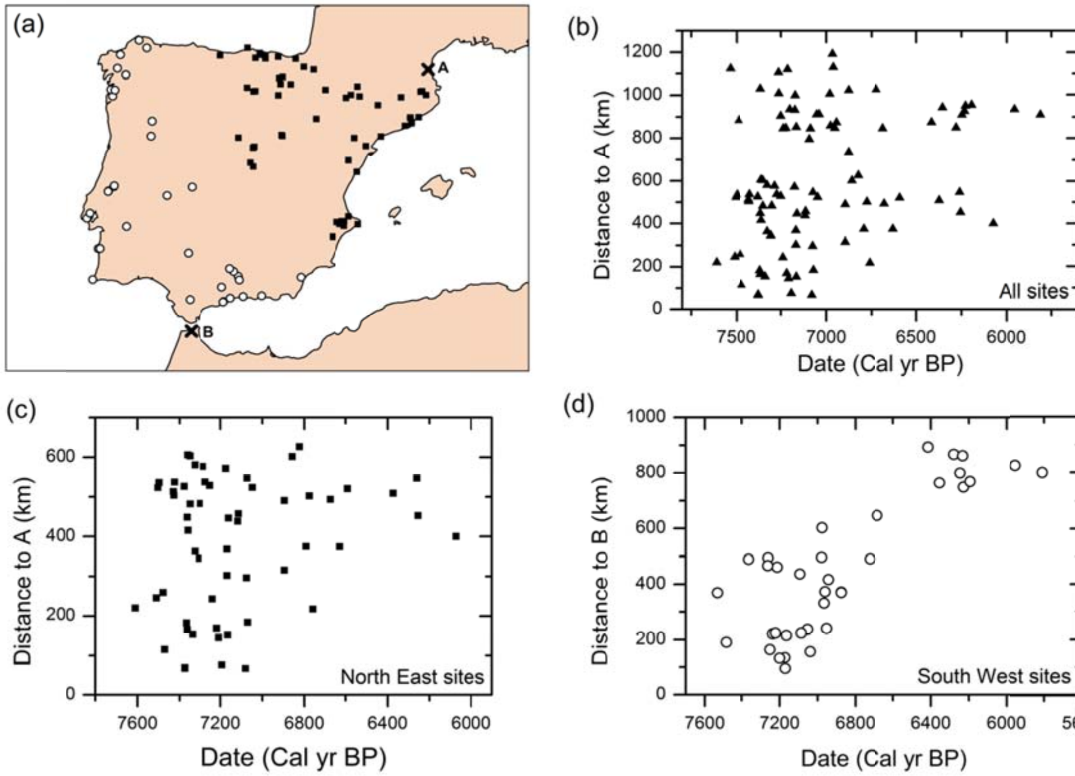

Neolithic sites
Neolithic wave
Cal yr BP
7414 - 7300
7300 - 7200
7200 - 7100
7100 - 7000
7000 - 6900
6900 - 6800
6800 - 6700
6700 - 6600
6600 - 6500
6500 - 6400
6400 - 6300
6300 - 6200
6200 - 6090

Fig. 1



(a)
Profile 1
Profile 2
Profile 3
(b)
Distance (km)
Date (Cal yr BP)
Profile 1
(c)
Distance (km)
Date (Cal yr BP)
Profile 2
(d)
Distance (km)
Date (Cal yr BP)
Profile 3

Fig. 2



(a)
A
B
(b)
Distance to A (km)
Date (Cal yr BP)
All sites
(c)
Distance to A (km)
Date (Cal yr BP)
North East sites
(d)
Distance to B (km)
Date (Cal yr BP)
South West sites

Fig. 3

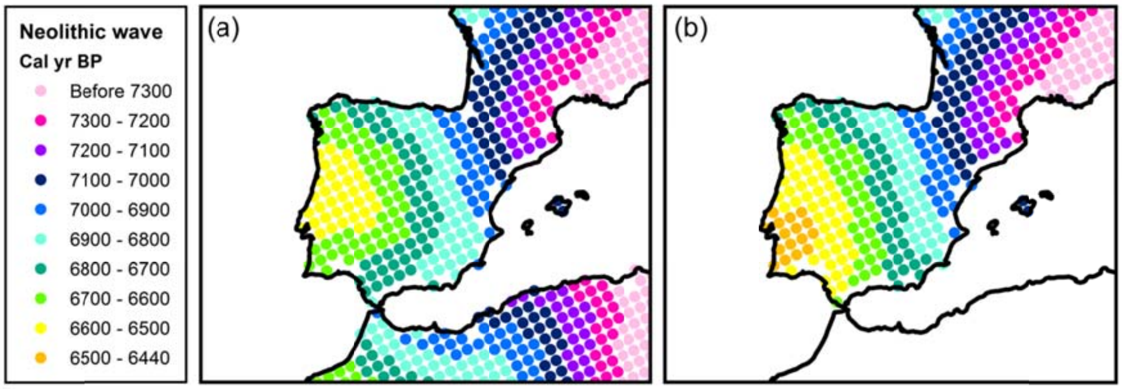

Neolithic wave
Cal yr BP
Before 7300
7300 - 7200
7200 - 7100
7100 - 7000
7000 - 6900
6900 - 6800
6800 - 6700
6700 - 6600
6600 - 6500
6500 - 6440
(a)
(b)

Fig. 4

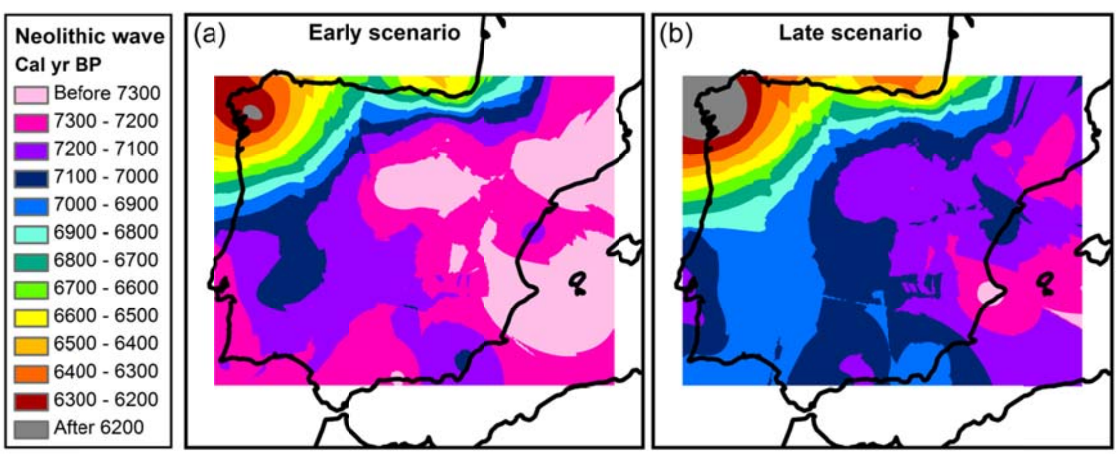

Neolithic wave
Cal yr BP
Before 7300
7300 - 7200
7200 - 7100
7100 - 7000
7000 - 6900
6900 - 6800
6800 - 6700
6700 - 6600
6600 - 6500
6500 - 6400
6400 - 6300
6300 - 6200
After 6200
(a)
Early scenario
(b)
Late scenario

Fig. 5