Title: Radiocarbon approaches for mapping technological change: the spread of the potter's wheel in the Iberian Peninsula, 1000-0 BCE

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Radiocarbon approaches for mapping technological change: the spread of the potter's wheel in the Iberian Peninsula, 1000-0 BCE

Beatrijs de Groot and Anna Bloxam

Abstract: This paper discusses a quantitative methodology based on the summed probability of radiocarbon dates to reveal complexities and asymmetries in the adoption of technological innovations. By focusing on the spread of the potter's wheel in the Iberian Peninsula during the first millennium BCE, we examine regional variation in the uptake and prevalence of potter's wheel-use and explore long-term dynamics between competing ceramic shaping methods.

The chronology of the spread of wheel-made ceramics in the Iberian Peninsula is analysed in a dataset of 576 radiocarbon dates for 245 pottery-bearing phases of 158 sites from across the Iberian Peninsula, utilising the presence-absence of wheel-made, hand-made and imported ceramics as the basis for a range of spatio-temporal analyses.

The results provide the first systematic long-term overview of the trajectories of technological change in ceramic production in Iron Age Iberia, revealing how areas of technological change correspond to broader socio-economic transformations part of the intensification of (inter)regional trade, surplus production and urban lifeways. Our study demonstrates that a focus on variation in the adoption of complex technologies, revealed through radiocarbon dates, can provide new insights into the drivers behind long-term socio-economic change.

Key-words: Radiocarbon, Summed Probability Distribution, Potter's Wheel, Innovation, Iberian Peninsula, Iron Age

1. Introduction

One of the most important topics in archaeological research concerns explaining the adoption of technological innovations (e.g. Roux, 2010; Roux et al., 2018; Eerkens and Lipo, 2014; Manzo et al., 2018; Amati et al., 2019). Significantly, such studies question the commonplace assumption that 'new' technologies automatically replace 'old' ones as innovation takes place. There can be many reasons why technologies are adopted or 'resisted', such the properties and performance of the innovation itself, environmental, social and personal factors alongside the characteristics of the networks through which information and materials are transmitted (e.g. Amati et al., 2019, 3). Before we can investigate such factors, and the interplay between them, it is first necessary to compare the contexts in which innovations are adopted and to uncover the trajectories of innovation diffusion across space and time.

Mathematical models utilising radiocarbon dates to map the spread of technological innovations demonstrate complexities and asymmetries in the spread of technological innovations (Fort, 2015; Jordan et al., 2016). Such studies demonstrate the utility of quantitative methodologies to understand the pace, direction and timing of technological dispersals across large areas and time-intervals, which are used to address questions surrounding the variable factors that facilitate the spread of innovations in prehistory. In this paper, we investigate the long-term spread of the potter's wheel in the Iberian Peninsula, similarly utilising radiocarbon dates to reveal regional complexities in the uptake of this technology and its relation to socio-economic transformations during the first millennium BCE.

This article provides the first quantitative assessment of the spread of the potter's wheel, in its various forms and uses, across the Iberian Peninsula. Our research provides an initial step in understanding the broader socio-economic conditions underpinning the adoption of the potter's wheel in the Iberian Peninsula, utilising a quantitative methodology to gain insights into comparative differences in the rates of the uptake of this technology in the long-term. Further, we discuss in this article methodologies, which hold potential for analysing the uptake and long-term spread of complex technologies in prehistory more broadly.

1.1 First uses of the potter's wheel

The innovation and spread of the potter's wheel is a subject of enduring academic interest, providing a key example for exploring the complexities of the relationship between technological and socio-economic change in the past (Childe, 1954; Foster, 1959; Roux and Corbetta, 1989; Roux, 2003; Roux and de Miroschedji, 2009; Thér et al., 2017; Berg, 2020; Choleva, 2020; Vidale, 2020). Despite its traditional association with mass-production and the intensification of production, initial uses of the potter's wheel in other contexts of the Mediterranean and Near East have shown that potter's wheels were utilised in ways that do not necessarily increase production speed (Roux, 2003; Roux and de Miroschedji, 2009; Crewe and Knappett, 2012; Roux and Jeffra, 2015; Baldi and Roux, 2016; Thér et al., 2017; Berg, 2020, 7; Choleva, 2020). Such examples show that the motives behind the adoption of the potter's wheel are idiosyncratic and rarely correspond to the emergence of mass production. For example, the first uses of potter's wheels in Mesopotamia and the southern Levant correspond to the production of certain wheel-coiled vessel types, catering for elite demand rather than improving overall productivity (Baldi and Roux, 2016). The initial spread of the potter's wheel cannot, therefore, be directly linked to an economic necessity, though its adoption is likely to affect local craft traditions including the organisation of labour and patterns in the transmission of craft knowledge over an extended time-scale.

In the Iberian Peninsula, however, the uptake and spread of the potter's wheel takes place during a period of long-term socio-economic transformation that culminated in the development of (proto-)urban lifeways (Almagro Gorbea, 2014). It is therefore important to consider the correspondence between technological and socio-economic change is in this particular context. Evidence for the local production of wheel-made pottery is most well-known in the context of Phoenician trade-colonies on the southern Iberian coastline, such as the Bay of Cádiz (Johnston, 2015; Torres Ortiz et al., 2018), Huelva (Delgado Hervás, 2011) and Málaga (Mielke and Torres Ortiz, 2012; Juzgado Navarro et al., 2016). Wheel-made pottery was produced in large quantities as containers for trade goods as well as luxury tableware, circulating locally or regionally around a number of production centres on the southern and western Iberian coast during the period between 800-600 BCE (Behrendt and Mielke, 2011; Mielke, 2015).

The potter's wheel became more fully integrated in economies across central, southern and eastern Iberia after the 7th century BCE, from the Early Iron Age onwards (Ruiz Zapatero, 2014, 214). However, the motivations and transmission processes underpinning the spread of this technology into the wider Peninsula are less well-understood. This is further complicated by suggestions that knowledge of wheel-making must have existed across the Iberian Peninsula prior to the arrival of the Phoenicians (Almagro Gorbea and Fontes, 1997) and through limited evidence for the use of rotary devices for pottery production in central Iberia during the Final Bronze Age (Padilla Fernández, 2019). Furthermore, efforts to reconsider ancient colonial processes in the western Mediterranean have provided new perspectives on the contribution of indigenous communities on the processes of culture change (Tronchetti and Van Dommelen, 2005; Vives-Ferrándiz, 2008; Hodos, 2009). Such studies demonstrate that innovations do not spread automatically from Phoenician to indigenous contexts but that complex negotiations underpin the development of shared material culture. The potter's wheel is an important innovation through which to examine such processes as it provides a fundamentally different technology from shaping pottery by hand, requiring many years of training and observation to perfect. This suggests that the spread of this innovation beyond the Phoenician colonies required extensive interactions between expert individuals and novices from different social groups (e.g. Mielke, 2015).

Chronological insights can illuminate the contexts in which wheel-made ceramics first appeared, allowing for an assessment of their relationship with the different forms of settlement and hierarchical structures across the Iberian Peninsula. Furthermore, the long-term perspective of the present study allows for looking beyond the contexts of initial adoption to assess how wheel-making technology changed ceramic production in the long-term. We utilise an absolute chronological framework, making use of a large dataset of radiocarbon dates to analyse spatio-temporal distribution of hand-made and wheel-made ceramics. We discuss methodologies employed to map the spread of wheel-made ceramics as well as examining their long-term prevalence relative to the presence of hand-made pottery using summed probability distributions (SPDs) and kernel density estimations (KDEs) of calibrated radiocarbon dates. Through analysing the dynamics between the prevalence of contemporaneous ceramic shaping methods in an absolute chronological framework we aim to contribute to research into the long-term trajectory of technological change associated with the innovation of the potter's wheel in the ancient western Mediterranean. Furthermore, this article explores the utilisation of the SPD and KDE methods for tracing the long-term spread of innovations and their utility in understanding spatio-temporal dynamics between competing technological traits. The aim of this is to look beyond the questions of 'origins' alone and to compare differences in the regional uptake of innovations after their initial introduction.

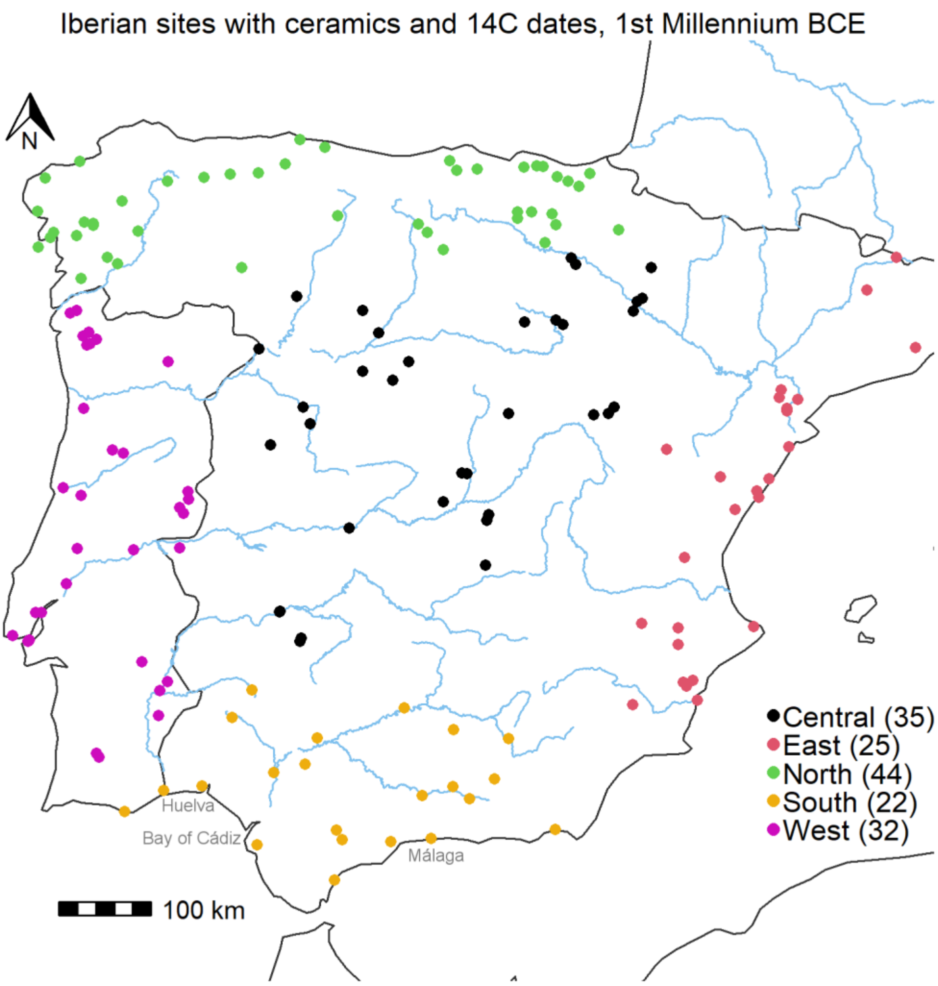

Fig. 1 Location of sites with ceramics and radiocarbon dates, first millennium BCE, arranged by region (North: *n*=44, South: n=22, West: *n*=32, Central: *n*=35, East: *n*=25) and location of sites mentioned in the text. [Single column fitting image COLOUR]

1.2 Mapping the spread of wheel-made ceramics

As in other regions of the Mediterranean, we can expect potter's wheels in the Iberian Peninsula to vary in form, particularly regarding the wheel's mechanism, and to be utilised in several different ways. Little is known about the potter's wheel mechanisms used in the region during the first millennium BCE. Examples of stone pivots thought to be part of low potter's wheels are found in Iron Age contexts from across the Iberian Peninsula, resembling similar mechanisms found in the eastern Mediterranean and Near East (Fernández Maroto, 2013; Jiménez Avila, 2013). Wooden *tournettes* or turntables might also have been used for wheel-throwing or wheel-fashioning but no examples of such mechanisms have been found in Iberia to date. In our study, we use wheel-made pottery as a proxy for the utilisation of potter's wheels in the ceramic shaping process, providing information where available on variability in production methods across the Iberian Peninsula.

Variation in the use of potter's wheels corresponds to variation in the reliance on rotational kinetic energy (RKE), which can be used to 'throw' pottery or finish/shape roughouts made by hand (Roux and Corbetta, 1989; Roux, 2019; Berg, 2020). A seminal paper by Roux and Courty (1998) provides insights into such variations and how these correspond to different skill sets (Roux and Courty, 1998, 750). The process of mastering wheel-throwing, for example, is considered to take several stages covering up to 10 years of observation and practice, much longer than methods that combine hand-shaping and wheel use (Roux, 2019, 261-268). Because different methods of using the potter's wheel in the ceramic shaping process involve different skill-sets and contribute to production speed differently, such variation can be informative for analysing the economic effects of using the potter's wheel.

These different shaping methods are often difficult to distinguish from each other in the finished pot, however. Macro-trace analysis and X-radiography can reveal the specifics of how the wheel was used though few studies provide such detail, recent work by Dorado Alejos (2019) and Padilla Fernández (2019) providing two exceptions. Wheel-made pottery is usually recognised through studying macro-traces of the shaping process on the surface of ceramic vessel walls. The potters' hand-gestures working the clay on the wheel during rotation leave horizontal lines or 'rilling' alongside other marks such as a base spiral and the gradual thinning of vessel walls towards the rim (Berg, 2020, 4). Such traces are sometimes erased, particularly when vessel surfaces are burnished, smoothed or decorated after shaping. The level of detail that can be gained from archaeological publications is therefore limited, allowing only a conservative estimate of the extent of wheel-use in the production of pottery during the first millennium BCE.

In the current study, the adoption of wheel-based shaping is analysed through studying the presence-absence of wheel-made pottery in a sample of radiocarbon-dated archaeological site-phases. Information is gathered from site reports and specialist analyses (supplementary table). Most publications provide a detailed description of the ceramic assemblages excavated, either for chrono-typological purposes or for discussing ceramic technologies in their own right. However, information regarding the specific mode by which the potter's wheel was used is rare. Here, we focus on the distinction between hand-made and wheel-made pottery, where wheel-made pottery is a broad category that includes pottery classified as such by previous researchers.

2. Materials and Methods

2.1 The dataset

The dataset is composed of radiocarbon dated site-phases from Late Bronze Age and Iron Age sites in the Iberian Peninsula, gathered from the IDEArq-C14 online database (IDEArq; Del Bosque González and Vicent García, 2016; Uriarte González et al., 2017). Using articles, site-reports, monographs and unpublished 'grey literature', the presence of wheel-made, hand-made, and imported wheel-made ceramics associated with each site-phase was recorded in a relational database. The resulting dataset contains 576 radiocarbon dates on organic material from 245 pottery-bearing phases of 158 sites (supplementary table). In order to examine regional variation in the prevalence of wheel-made ceramics through time we divide these site-phases into five geographical regions (Figure 1).

In line with the biases described in the previous section, there are several important points that need to be taken into account when observing the outcomes of our research:

1. Late Bronze Age ceramics are generally labelled as hand-made in the literature, even though isolated cases of wheel-use in Late Bronze Age contexts are known (Padilla Fernández, 2019, 231-232). The dataset cannot account for variation in the interpretations of past studies.
2. Without archaeometric analyses it is rarely possible to identify where ceramics were produced; such methods have not been used in most cases. When the literature described the presence of imported wheel-made ceramics we recorded this as such, even when the basis for such

interpretations were typological rather than archaeometric. The dataset therefore demonstrates the growing use of potter's wheels across the Iberian Peninsula rather than pinpointing ceramic production centres necessarily.

3. In the absence of a complete array of quantitative information, we cannot examine inter-site variation in the frequency of potter's wheel use, except for in a subset of site-phases (explored in section 3.2).
4. In most of the Iberian Peninsula the utilisation of typological methods for dating archaeological sites remains of great importance, particularly for sites dating to the latest part of the period; as a consequence the proportion of radiocarbon-dated site-phases with pottery declines from 200 BCE onwards. This bias will be explored using the SPD method.
5. Wheel-made pottery is more often used for typological dating than hand-made pottery. Therefore, it can be expected that sites with hand-made pottery only are more frequently dated with radiocarbon dates and are therefore overrepresented in the dataset (particularly after 200 BCE).
6. The included site-phases represent a sample of the available published information, providing a preliminary overview of the spread of the potter's wheel. This study is designed to facilitate the addition of new information, increasing the spatio-temporal coverage of the dataset, through providing access to the dataset and R-codes.

2.2 Timing of the spread of wheel-thrown ceramics

The dataset of radiocarbon-dated site-phases is used to map the spread of wheel-made ceramics over time (Figure 2). Radiocarbon dates were calibrated and their probability of falling into each of a series of 200-year 'bins' was calculated. Following Collard et al. (2010), the resulting probability was used as a weighting mechanism for mapping the spatial density of site-phases with ceramics using kernel density estimation. The spatio-temporal density of different ceramic types encountered at the site-phases with associated radiocarbon dates is plotted across the series of binned 'time slices' spanning the Late Bronze Age and Iron Age of Iberia (1000-0 BCE). This period includes the 'Hallstatt plateau' in the calibration curve, dating to c. 780-405 BCE (Taylor et al., 1996, 663), which limits the precision of calibrated radiocarbon dates in this period. The impact of this plateau on the results is discussed further in sections 3 and 4. Section 3.2 provides a further study of the plateau on a sample of our dataset.

In order to reduce the risk of highly-sampled sites skewing the results, the dataset was thinned so that no more than three radiocarbon dates per ceramic type within each site-phase were included in the weighting; dates with low associated errors and the lowest risk of marine carbon sources were prioritised. Radiocarbon dates were calibrated in R 4.0.0 (R Core Team, 2020) using the IntCal20 calibration curve (Reimer et al., 2020) and the 'rcarbon' package (Bevan and Crema, 2020). Density maps were created using the 'spatstat' package (Baddeley et al., 2015).

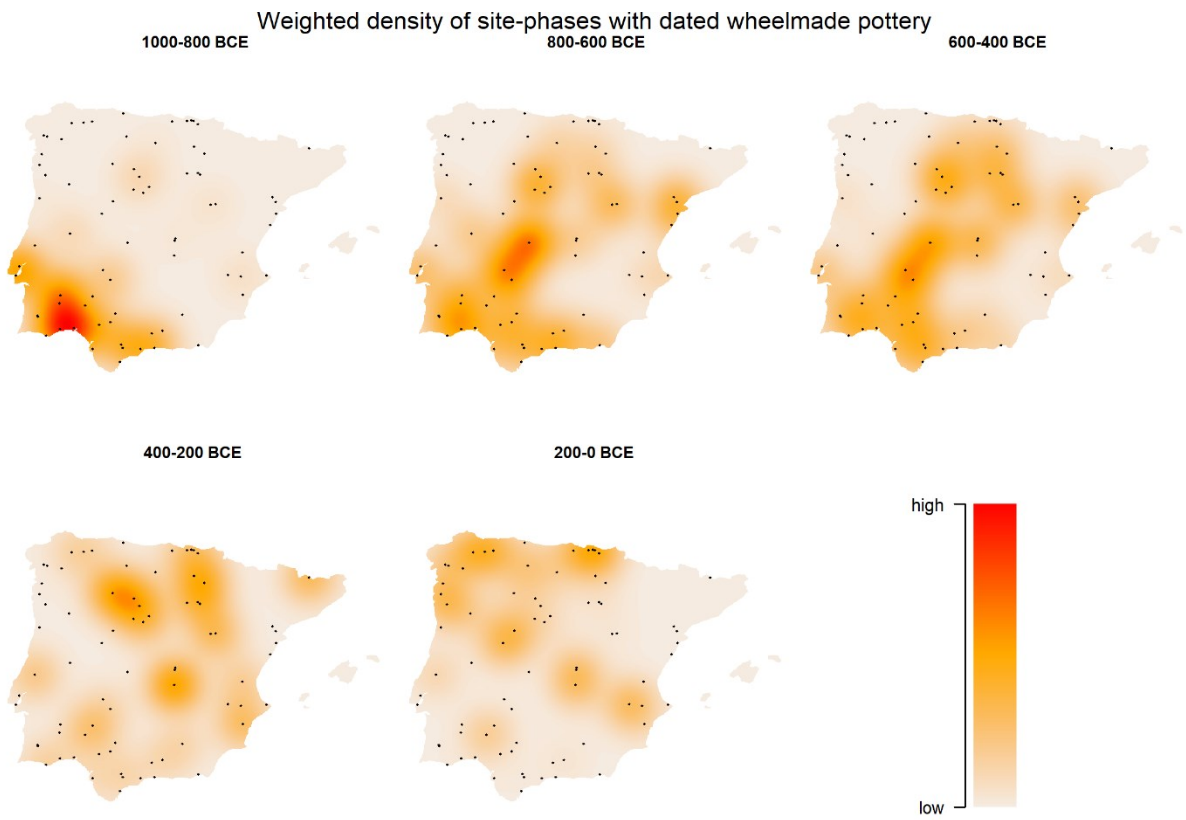

Fig. 2 Maps showing the probabilistic spatial density of calibrated radiocarbon dates associated with site-phases with wheel-made pottery in the Iberian Peninsula, divided by 200-year time-slices. Thinned dataset, bandwidth = 40km. UTM zone 30N projection. [2-column fitting image COLOUR]

2.3 SPD and KDE of calibrated radiocarbon dates

The dynamics of continuity and change in ceramic shaping methods were explored using summed probability distribution (SPD) and kernel density estimation (KDE) of radiocarbon dates. Each provides a means of combining and analysing the probability distributions generated by the calibration of multiple radiocarbon determinations. The former method has predominantly been developed and utilised within archaeology as a means of establishing a proxy for the reconstruction of past population dynamics and the chronology of archaeological cultures (Shennan et al., 2013; Timpson et al., 2014). More recently, the methods involved have been used to explore continuity and change in archaeological practices and technologies more directly, for example funerary diversity in Bronze Age Britain (Bloxam, 2020; Bloxam and Parker Pearson, forthcoming) and continuity and change in Neolithic toolkits (Mazzucco et al., 2020). We use SPD in a similar manner to these latter examples, examining the dated evidence for the archaeological entity under study directly; in this case ceramic vessels and the technologies they represent. We employ KDE as a complementary approach to exploring and presenting the data, and as a means of assessing the impact of the Hallstatt plateau on our interpretations (Bronk Ramsey, 2017). To this end, we utilise McLaughlin's *rowcal* method (McLaughlin, 2019) which estimates the uncertainty surrounding each result using Monte Carlo simulation.

We analyse the evidence for regional differences in the changing prevalence of wheel-made ceramics revealed by these methods through permutation testing of the SPD results. Permutation testing was carried out in *rcarbon* following Crema, et al. (2016). In this approach, Monte Carlo sampling is used to create a null model with a 95% confidence envelope, reflecting the shape of an SPD curve in which the ‘region’ labels for dates are randomly assigned. The empirical SPD for each region is then compared to the null model to test for any significant deviation that could reflect archaeologically meaningful regional variations in the adoption and development of wheel-throwing technologies.

3. Results

3.1 Chronology of the spread of wheel-thrown ceramics

The timing of the spread of wheel-made pottery corresponds to a range of transformative processes in the first millennium BCE. Figure 2 shows that the earliest locally produced wheel-made pottery in our dataset can be found in the coastal fringe of the south west, from site-phases dating to the period between 1000-800 BCE. These site-phases correspond to Phoenician and ‘indigenous’ sites in southern Spain and Portugal, where workshops utilising the potter’s wheel and double-chambered updraught kilns are first established.

In the centuries that follow, we find that wheel-made pottery then appears in central Iberia, with high probability densities in the interior and the northern extent of the Iberian Central Plateau as well as in eastern Iberia. The northerly spread of wheel-made pottery in this period corresponds to the uptake of wheel-throwing in pottery workshops relating to Celtiberian oppida and settlements (Lorrio, 2014). From this point onwards, however, a plateau in the calibration curve prevents a more precise understanding of the spread of wheel-made pottery between 800-400 BCE. The spread of wheel-made pottery into the northern regions of the Iberian Peninsula seems to emerge and spread from the central region, as can be observed in the final maps (400-200 BCE and 200-0 BCE).

Figure 3 plots the changing spatial intensity of wheel-made imported vessels following the same method as Figure 2. This analysis only allows for examining the presence of imported wheel-made pottery after 1000 BCE, while wheel-made imports or local imitations of wheel-made Mycenaean pottery already appear in southern Iberia prior to this period (Almagro Gorbea and Fontes, 1997). However, the plots show that wheel-made pottery classified as ‘imported’ is also found at early dates in both the south-west and the north-east of Iberia. In north-western Iberia, the substantial delay in the adoption of the potter’s wheel contrasts with an earlier use of imported wheel-made pottery, indicating a lower impetus for local recreation and imitation of novel ceramic production methods found in the imported wheel-made wares than was the case in the Iberian South.

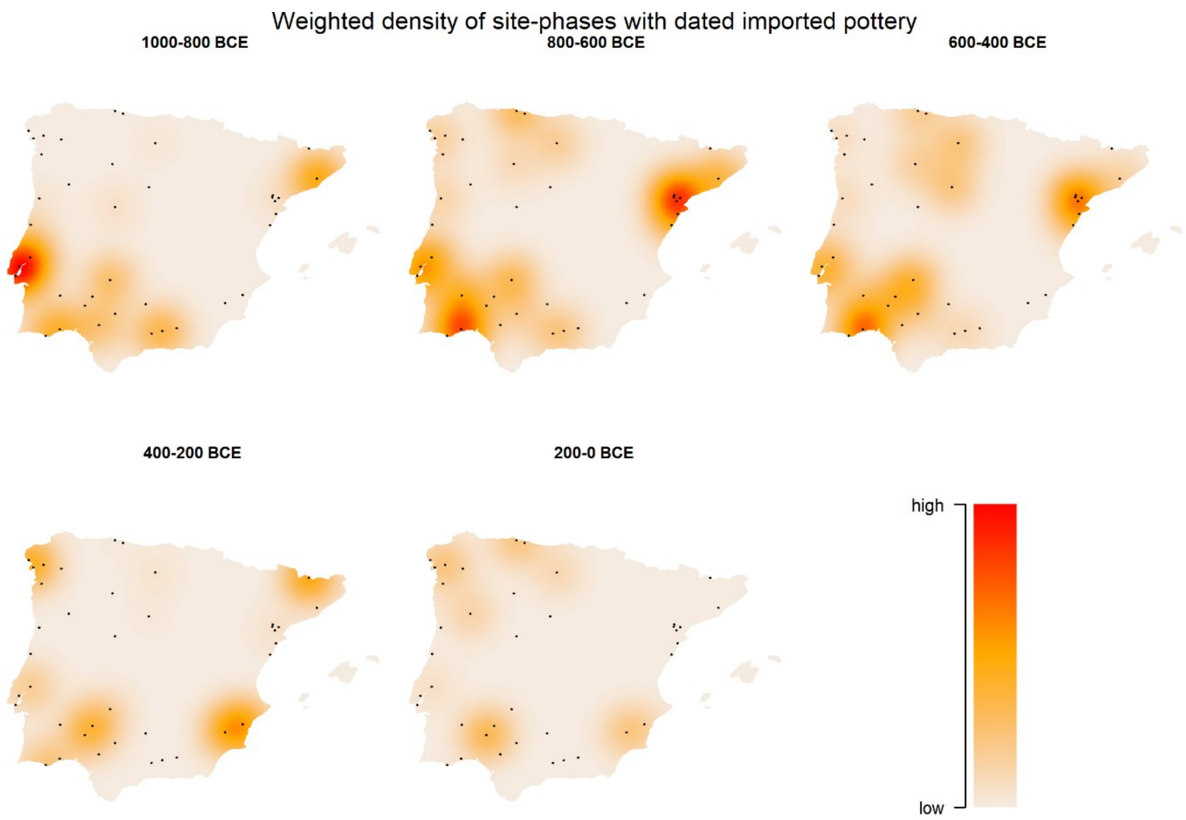

Fig. 3 Probabilistic spatial density of calibrated radiocarbon dates associated with site-phases with imported wheel-made ceramics in the Iberian Peninsula in the period 1000 - 0 BCE. Thinned dataset, bandwidth = 40km. UTM zone 30N projection. [2-column fitting image COLOUR]

3.2 Co-existing ceramic shaping methods

Information regarding temporal fluctuations in the proportion of wheel-made and hand-made ceramics can inform research into the varied levels of dependence on wheel-thrown ceramics in each region. In absence of a fully quantified dataset of ceramic shaping types for each site-phase, we analyse the proportional variation of hand-made and wheel-made pottery in a subset of site-phases and analyse trends in their intra-site prevalence. It needs to be reiterated here that we can expect ambiguity in the dataset deriving from unidentified shaping methods such as wheel-coiling, which is difficult to recognise, and therefore might have been recorded as either handmade or wheel-made in the literature.

Figure 4 presents the proportion of handmade versus wheel-made ceramics fragments by count for each of the site-phases with quantified ceramic assemblages, with the region indicated alongside the site code. All calibrated dates associated with the assemblage from each site phase were summed, and the summed dates were probabilistically binned into ‘early’ (1000-800 BCE), ‘middle’ (800-400 BCE) or ‘late’ (400-0 BCE) groups. The combined dates for site-phases were then ordered from earliest to latest using the Order function in OxCal 4.4 (Bronk Ramsey, 2009). This enables an inspection of temporality taking into account the difficulty of chronologically ordering sites, particularly those which fall within the ‘middle’ (Hallstatt plateau) range.

The results reveal that the majority of the early site phases for which ceramic quantifications are available contain handmade pottery only. After 800 BCE, the majority of site phases contain both pottery types. The proportion of the assemblage represented by wheel-made wares varies greatly between site phases and within regions during this middle period. Although at a general level, there seems to be a growing prevalence of wheel-made pottery, further interpretation of the quantified dataset is hampered by the low spatio-temporal coverage of the sample. Notably, however, throughout all three time periods all quantified site-phases continue to contain handmade pottery; even in the late period, after 400 BCE, site phases containing exclusively handmade assemblages can be identified. The continued reliance on hand-made pottery suggests that wheel-made pottery might not have completely replaced pre-existing technological knowledge and skills relating to hand-shaping, although a more detailed technological assessment is needed to confirm such continuity.

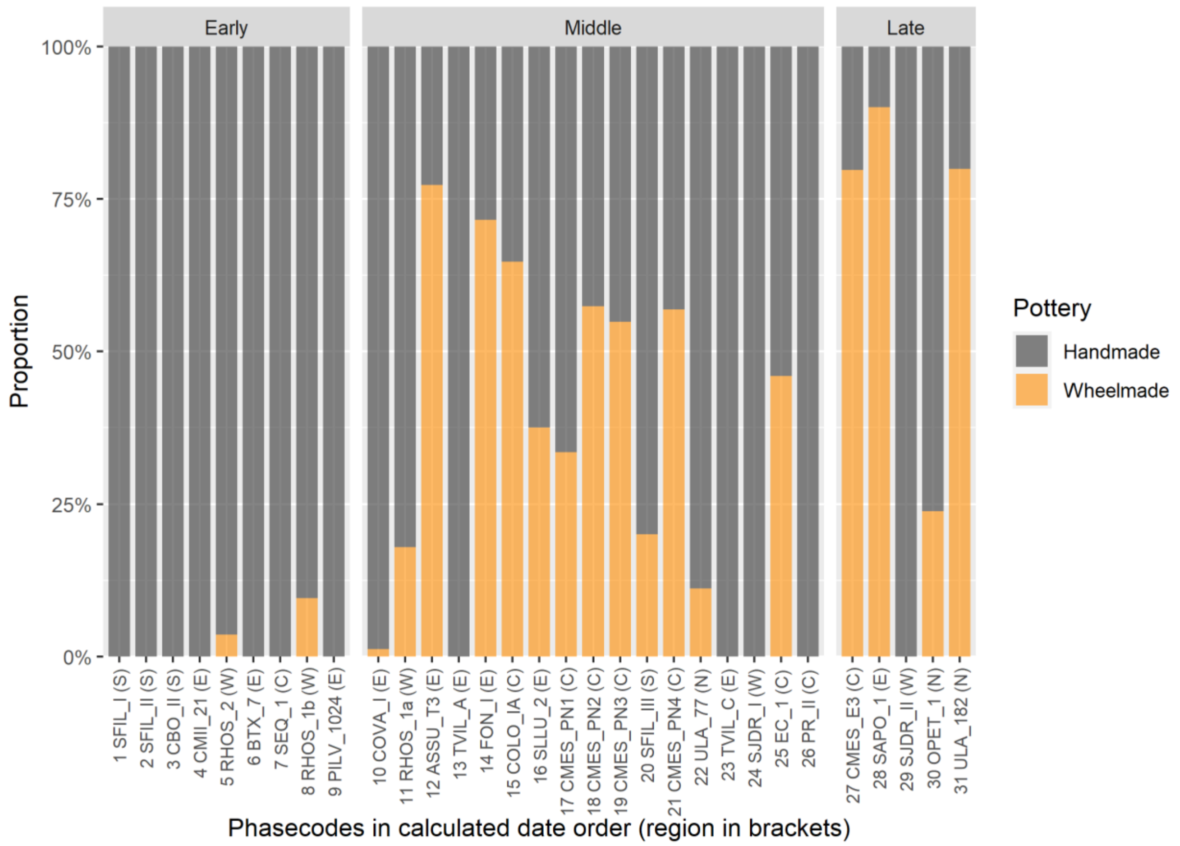

Fig. 4. Proportions of handmade and wheel-made ceramics at 31 site-phases from across Iberia, in order of calculated 14C age cal BCE from old (left) to young (right). Regions for each are indicated in brackets.

3.3 SPD and KDE of co-existing ceramic shaping methods

The spatial intensity plots reveal the changing prevalence of ceramic technologies across a series of broad ‘time slices’. Figure 5 presents these processes in further detail, comparing the trajectory of hand-made, wheel-made, and (wheel-made) imported ceramics within each Iberian region over the first millennium BCE using the SPD and KDE methods. The results demonstrate that the two methods provide different solutions (or in the case of KDE, ranges of solutions) to the aggregation of the radiocarbon data. We consider that neither result is the ‘correct’ one; rather they provide two alternative means of investigating the evidence. The two approaches indicate broadly similar trajectories outside the Hallstatt plateau but vary more markedly within this range; for this reason, our assessment of the data takes into consideration both sets of results and avoids over-interpretation of the SPD shape, particularly within the plateau period.

These SPD and KDE plots suggest that a low prevalence of site-phases with wheel-made ceramics was already present in the South and West regions of Iberia at 1000 BCE. Some of this early signal may result from the summing of the distribution 'tails' of determinations with relatively large associated errors but it largely reflects the early onset of wheel-made pottery production at sites such as Huelva, in our South region.

Following a low level of early presence in the South and West regions, the local LBA-IA boundary is then associated with either an increase in prevalence or the first appearance of wheel-made pottery in each region. The subsequent 400-year period is affected to some extent by the Hallstatt plateau, though it is possible to suggest general trends for each region: levels of wheel-made pottery are highest in the Central and South regions during this period, with the Central area seeing the clearest increase in prevalence between 800 and 400 BCE, in both the KDE and SPD plots. The North has lower overall levels, but wheel-making appears to be first introduced towards the start of the plateau and shows a trend of increasing prevalence throughout the rest of the first millennium BCE. The remaining regions, West and East, show a pattern of stagnation or even decline in prevalence between 800 and 400 BCE. The KDE and SPD results correspond well across periods and regions, with differences between the two occurring predominantly at the start of the calibration plateau; reaffirming our approach to consider only broad trends over this period.

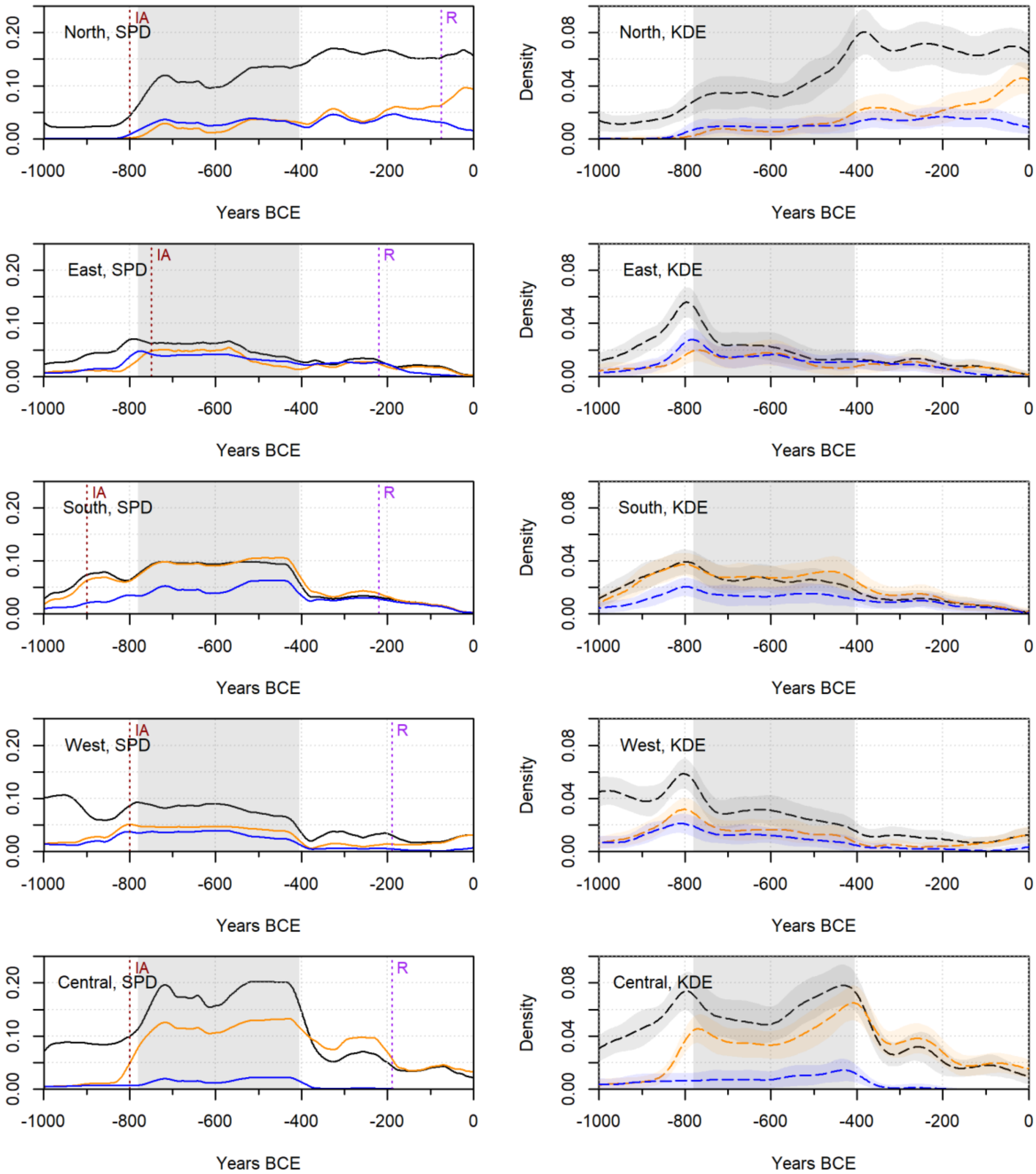

Fig. 5 Plots showing non-normalised SPD and KDE results for ceramic assemblages in first Millennium BCE Iberia. Black = handmade (N=372), orange = wheel-made (N=177), blue = imported wheel-made (N=90). Boundaries mark the approximate start of the Iron Age (IA) and Roman (R) periods in each region as indicated by various authors in Almagro-Gorbea (2014). Grey window marks the 'Hallstatt plateau' in the radiocarbon curve. 50-year smoothing used SPDs. [2-column fitting image COLOUR]

Alongside the adoption and changing prevalence of wheel-thrown ceramics, in all regions site-phases with hand-made pottery persist throughout the period considered in this study, with the SPD indicating a greater prevalence of hand-made than wheel-made ceramics throughout the first millennium BCE in most regions. This suggests that hand-shaping methods remained an important part of the technological repertoire of groups inhabiting the Iberian Peninsula throughout the Iron Age, even as they encountered and adopted new ceramic technologies. Even with a possible bias relating to the reliance on radiocarbon dating where typologies are insufficient (pertaining more strongly to sites where wheel-made pottery is absent), the continued prevalence of hand-made pottery raises questions, explored below, as to how widely the potter's wheel was utilised and how broadly it sparked socio-economic changes across the Iberian Peninsula.

Figure 5 also demonstrates, however, that the relative importance of the two traditions varies between regions. The North region displays a gradual growth in the prevalence of site-phases with wheel-made pottery over the course of the first millennium BCE, throughout which time hand-made pottery is substantially more widespread. In the Central region, hand-made ceramics are similarly dominant until a sharp decrease in their prevalence seen at the end of the radiocarbon plateau (although this could reflect gradual decrease during the plateau, not seen until its end). From this point, wheel-made pottery is the most common form for around 200 years until the start of the Roman horizon in this region. In the southern region, wheel-made pottery is roughly as common as hand-made wares from its introduction and during the Hallstatt plateau. In East and West Iberia, the summed probability of site-phases with hand-made pottery remains around the same, or possibly slightly higher, as that of wheel-made pottery throughout the Iron Age. Nevertheless, we do find a steady presence of wheel-made pottery in both regions, with the prevalence being highest at the start of the Iron Age, before a decline in the overall summed probability after 400 BCE, which affects all regions except for the North.

The general decline in summed probability seen in most regions in the later parts of the period reflects a difference in archaeological research practices rather than a decline of pottery-using settlements. Historical sources and well-established pottery typologies are widely used to date these more recent archaeological deposits, and consequently we have relatively few radiocarbon dates for material from this period. Pottery typologies in the North region are less well-established, however, leading to a greater reliance on radiocarbon dating here even in the period after 400 BCE.

The statistical significance of fluctuations in the regional SPDs of wheel-made pottery is tested by comparing the empirical data against the null model. Figure 6 demonstrates that each regional SPD for wheel-made pottery seen above [Figure 5] deviates significantly from the null model at several points over the first millennium BCE. The global p-values provide an overall goodness-of-fit test for each curve, taking into account the frequency and magnitude of deviations across iterations. These indicate that the North, South, and West regions deviate significantly from the null model at $p < 0.05$, while the overall level of deviation seen in the East and Central regions is non-significant.

In Central and North Iberia the summed probability of wheel-made ceramics is significantly lower than expected in the earlier part of the period, before 800 and 550 BCE respectively. This fits with the observation that the potter's wheel was adopted later in these regions than elsewhere in Iberia. In contrast, in South Iberia – and more briefly in West Iberia – the prevalence of site-phases with wheel-made ceramics is significantly higher than expected in the Late Bronze Age, corresponding to the early onset of Phoenician pottery production in these regions.

4. Discussion

4.1 Chronologies of the spread of the potter's wheel

The trajectory of the spread of wheel-made ceramics through the Iberian Peninsula is marked by regional diversity, both in the chronology of its first introduction and the prevalence of its use. Our study has demonstrated such regional asymmetries, which allow for exploring the correlation between technological and socio-economic transformations. For example, chronological mapping of the first appearance of wheel-made pottery reflects the systematic use of potter's wheels on the southern Iberian coastline for the production of Phoenician amphorae and table-ware. The potter's wheel, here, played an important role in the intensification of ceramic production for trade and to support novel consumption practices of local populations. Also beyond the Phoenician colonies, the growing prevalence of wheel-made pottery serves as a proxy for a shift in the mode of ceramic production, now organised in workshops with updraught kilns. This shift reflects changes in the scale of production, the organisation of labour and complexity of supply and demand systems (Rice, 2015, 350-362). Our study demonstrates that the spread of the wheel-made pottery broadly corresponds to areas of proto-urban and nucleated settlement where we can expect a necessity for a more complex system of supply and demand than at smaller scale and largely self-sufficient sites. In contrast, the slow uptake of wheel-made pottery in north-west Iberia reflects the more dispersed and smaller scale forms of settlement, such as the castros (hillforts) that prevail in much of this region during the Iron Age.

Variation in the probability density (Figure 5) of site-phases with hand-made or wheel-made pottery further highlight how such asymmetries develop in the long-term, after initial adoption. The continued reliance on hand-made pottery in all regions of the Iberian Peninsula, demonstrated by the SPD and proportional analyses, suggests that the potter's wheel supplements rather than replaces hand-shaping. This poses interesting questions surrounding the way this innovation was adopted, perhaps appearing alongside 'old' ceramic forms instead of being integrated into existing potting traditions. A detailed analysis of the long-term development of production sequences, or *chaînes opératoires*, of hand-made pottery alongside the adoption of the potter's wheel can provide deeper insights into the impact the appearance of pottery workshops might have had on the transmission of technological knowledge, passed on through the Late Bronze Age.

A reason for the continuity of hand-shaping relates to the use of potter's wheels for the production of a restricted repertoire of ceramics. The potter's wheel initially catered for the production of transport amphorae and luxury table-ware. For example, at the Iberian oppida, wheel-made ceramics played an important role in the trade and consumption of wine, which may have in turn underpinned the emergence of the Celtiberian aristocracies after 550 BCE (e.g. Burillo-Mozota and Burillo-Cuadrado, 2019, 328). The first adoption of wheel-made pottery in association with 'feasting' assemblages (including vessels for the consumption of wine) has also been observed in Late Bronze Age Anatolia (Glatz, 2016), the Aegean (Berg, 2007; Choleva, 2020), Italy (Borgna and Levi, 2015) and Southern France (Dietler, 1990; 1995). The continued reliance on hand-shaping for the production of cooking ware, for example, could reflect a preference for older ceramic forms. Furthermore, like in the 4th millennium BCE Levant (Roux, 2003), pottery workshops might have been attached to segments of society that controlled only specific prestigious and economic activities rather than more widespread day-to-day activities such as cooking. This is also suggested by evidence from north-east Iberia, which showed that craft activities including pottery production remained largely domestic, with isolated work-places utilising the potter's wheel operating on a seasonal basis (Gorgues, 2017).

The uneven spread of this technology to the Iberian interior might have created economic inequalities at a local level. Nevertheless, the reluctance towards adopting the potter's wheel seen in North-West Iberia (whether this was a conscious choice or because such groups were isolated from appropriate learning networks) might have allowed some groups to maintain a degree of autonomy over production, rather than contributing to forms of elite control seen in other regions. Although some studies have shown that rotary devices were used for finishing ceramic vessels in some areas in North-West Iberia (Corral, 2008), there is no evidence yet for surplus production and trade in ceramics in the same forms as seen in southern and Central Iberia. The absence of surplus production can be considered as an active strategy to counter the processes of hierarchisation seen in other parts of the Iberian Peninsula (Currás and Sastre, 2019). Nevertheless, given the internal variability of socio-economic structures existing in this region (González Ruibal, 2011), the rejection of wheel-throwing might also correspond to other factors, such as the preference for containers made of wood rather than pottery (Torres-Martínez et al., 2018).

The slow uptake of the potter's wheel in northern Iberia might also relate to variable access to networks through which technological knowledge is transmitted. Although contact with potter's wheel-using groups is evidenced by the presence of Phoenician imports in northern Iberia from the Early Iron Age onwards (Figure 3 and González Ruibal, 2004, 295), such contacts did not lead to the local production of wheel-made ceramics. Factors that caused friction in the adoption of the potter's wheel in northern Iberia may have been any combination of unconscious continuity of learned knowledge and skills, deliberate conformity to traditional technological knowledge, power relations, political and economic strategies, and the availability of appropriate learning/interaction networks. Technological studies into the development of Iron Age ceramic technologies in northern Iberia can provide deeper insights into these processes.

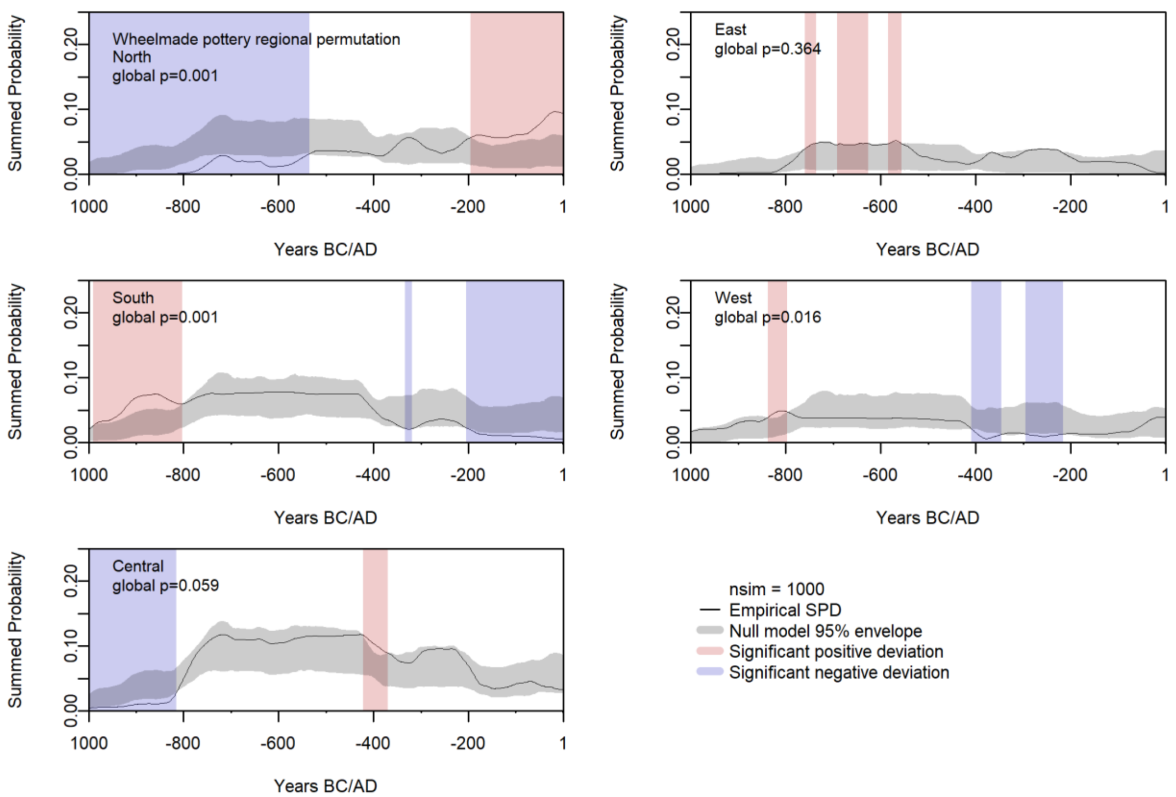

Fig. 6 Permutation test showing the variation in summed probability of wheel-made pottery in Central, North, South, East and West Iberia. The empirical SPD is represented by a solid black line. The grey areas represent a simulated 95% confidence envelope for the null model. Red and blue bands indicate areas where the SPD deviates from the null model (red where the summed probability of site-phases with wheel-made ceramics exceed expectations and blue where it is beneath expectations). Non-normalised SPDs and 50-year smoothing used throughout. [2-column fitting image COLOUR]

4.2 *Long-term trajectories of technological change*

The methodology employed in this study clarify the chronology of the diffusion of new ceramic technologies in the Iberian Peninsula during the Iron Age. This has revealed dynamics of continuity and change that support broader interpretations about the correlation between transformations in ceramic technology, urbanism and surplus production. We have demonstrated that the timing of the uptake and prevalence of wheel-made ceramics corresponds to regional idiosyncrasies in production and demand, although detailed interpretations are limited by biases relating to typological dating and the Hallstatt plateau in the calibration curve.

The methodology employed exposes the spread of ceramic technologies using a dataset and method that can be expanded, adapted and reproduced using the supplementary data. We are confident that the patterns we obtained are meaningful, as we have analysed incremental subsets, which all produced similar results (see also Timpson, et al., 2014) and compared different approaches to analysis of the data. The particular strength of the method is that it allows for analysing dynamics of technological continuity and change in a long-term and comparative framework. As such, we have been able to demonstrate that complex technologies like the potter's wheel do not automatically spread and outcompete other modes of ceramic production because of their economic efficiency, but that its adoption and long-term use corresponds to spatio-temporal idiosyncrasies relating to factors such as settlement type, hierarchical structures and consumption practices.

By analysing this topic utilising a quantitative framework, our research allows for exploring the dynamics between technological change and other long-term historical and environmental processes at similar spatio-temporal scales in the future. Further, by providing a detailed overview of the utilised methodology, this paper proposes novel ways for exploring the dynamics of long-term technological change in prehistory more broadly.

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Code availability: R codes are enclosed in the digital supplement.

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