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Spatiotemporal modelling of radiocarbon dates using linear regression does not indicate a vector of demic dispersal associated with the earliest Gravettian assemblages in Europe

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Abstract

The causes of major archaeological transitions during the Upper Palaeolithic, such as the Aurignacian-Gravettian transition, remain poorly understood. In an effort to distinguish between demic and cultural diffusionary explanations for such transitions, analyses of radiocarbon and spatial data are sometimes employed. Here, we attempt to replicate a recent spatiotemporal study of the first appearance of Gravettian assemblages in Europe using linear regression analyses of radiocarbon dates and least-costpath measurements of the distances between sites. We find that there are problems with the corpus of radiocarbon dates used and assemble two more appropriate sets of dates. We also find problems with the least-cost-path calculations and repeat these using a more appropriate method. We then repeat the regression analyses and use these as a case study to explore some of the problems with using linear regression analyses of radiocarbon and distance data for hypothesis testing where the total number of sites is very low. We conclude that this method is not capable of distinguishing the geographical origin of Gravettian traditions. We also find that this method frequently obtains false positive results, and that binning of sites may have a significant effect on the ease of obtaining positive results. Finally, we find that there is a negligible difference between the results of linear regression analyses obtained using least-cost-path measurements and those obtained using simple Euclidean distances, suggesting that the former adds little analytical value here despite its computational complexity.

Keywords

Chronology; GIS; cost modelling; least-cost-paths; demography; Upper Palaeolithic; replication

1. Introduction

The chronology of the earliest Gravettian assemblages across Europe (Fig. 1) and their significance for understanding cultural and demographic processes around the beginning of the Mid Upper Palaeolithic have been the subject of numerous studies (e.g. Conard & Moreau 2004; Steguweit 2009; Bolus 2010; Jacobi et al. 2010; Jöris et al. 2010; Moreau 2010; Pesesse 2010; Moreau & Jöris 2013; Münzel et al. 2017). Many differences have been described between Aurignacian and Gravettian archaeological assemblages, including in lithic techno-typology, osseous technology, personal ornaments, funerary practices and raw material use (e.g. Conard & Moreau 2004; Floss & Kieselbach 2004; Henry-Gambier 2008; Steguweit 2009; Bolus 2010; Borgia et al. 2011; Goutas 2016; Goutas & Tejero 2016; Wolf et al. 2016; Touzé 2016; Münzel et al. 2017), suggesting that the Aurignacian-Gravettian transition may have coincided with profound social and cultural changes. Aurignacian and Gravettian assemblages



Figure 1: Locations of sites mentioned in this article. Key: 1: Vale Boi; 2: Antoliñako Koba; 3: Tarté;
4: Arbreda; 5: Abri Pataud; 6: Combe Saunière; 7: Le Sire; 8: Solutré; 9: Maisières-Canal; 10: Huccorgne; 11: Grotta Fumane; 12: Brillenhöhle; 13: Geissenklösterle; 14: Hohle Fels; 15: Sirgenstein; 16: Rio Secco; 17: Grotta Paglicci; 18: Ranis; 19: Willendorf; 20: Krems-Hundssteig;
21: Krems-Wachtberg; 22: Dolní Věstonice IIa; 23: Dolní Věstonice II; 24: Henryków 15; 25: Poiana Cireşului; 26: Mitoc-Malu Galben; 27; Molodova V; 28: Buran-Kaya III; 29: Mira; 30: Kostënki 8;
B1: Lapa do Picareiro; B2: El Castillo; B3: El Palomar; B4: Les Garennes; B5: Arene Candide; B6: Weinberghöhle; B7: Trenčianske Bohuslavice-Pod Tureckom; B8: Komarowa Cave. Codes for sites used following Bicho et al. (2017).

have often been interpreted as being associated with separate populations, and this view remains widespread in the present day (Otte & Keeley 1990; Finlayson & Carrión 2007; Bradtmöller et al. 2012;

Perlès 2013; Reynolds in press). Recent results of palaeogenomic studies also suggest that the spread of Gravettian traditions across Europe was at least partially associated with population movements, although this did not involve a complete population replacement (Fu et al. 2016).

The recent contribution of Bicho et al. (2017) to this debate models a hypothetical wave of advance of an Upper Palaeolithic population associated with the first appearance of Gravettian assemblages across Europe. Their work is based on a corpus of AMS radiocarbon dates obtained from a pre-existing database and least-cost-paths calculated from various sites of suggested origin of Gravettian traditions. It employs linear regression to analyse possible dispersals of a population from a single locus to the rest of Europe. Bicho et al. conclude that Gravettian technology originated in Central Europe, that Gravettian traditions spread very slowly via demic expansion, and that population density in Europe was very low during the period in question. They also model actual routes through Europe that they suggest might have been taken by Upper Palaeolithic people using and spreading Gravettian technology.

Unfortunately, there are a number of shortcomings in the research as presented by Bicho et al. First, the chronological data that they used are inappropriate for their purposes. Many of the radiocarbon dates they used do not, in fact, relate to Gravettian material; moreover, a number of important early Gravettian sites are missing from their dataset. Their analyses also suffer from a number of methodological problems concerning their use of chronological data and the calculation of paths between sites.

In this paper we present the results of a replication study of Bicho et al.'s work as they present it, with a view to strengthening the archaeological community's approach to this and similar research questions. We begin by outlining some shortcomings in Bicho et al.'s selection and use of radiocarbon data, and then discuss the problems with their GIS-based analyses. In order to explore the implications of our critique, we repeated Bicho et al.'s analyses using more appropriate data and methods, and we present and discuss our new results and their implications here. We also repeated their analyses using random chronological data, to explore the effects of geographical structuring and the binning process on the results. Finally, we make some recommendations for future work.

2. A critical review of Bicho et al. (2017)

2.1 Chronological data: problems with the dataset

Bicho et al's dataset is based on the Leuven Radiocarbon Palaeolithic Europe Database (RPED) v20 (Vermeersch 2016). This database, updated annually, collates a very large number of radiocarbon measurements (>14,000) for European Palaeolithic sites, and is an invaluable source of information for researchers. However, as is usual with databases of this size and fully acknowledged on the website where it is published, errors are present within it. To create their dataset, Bicho et al. selected AMS radiocarbon measurements from RPED v20 that were described on the database as Gravettian and older than 27,000 ¹⁴C BP, excluding those with standard errors >500 radiocarbon years. They found 33 sites with dates meeting these criteria, and used the most ancient single result from each site for their analyses.

Unfortunately, in many cases the associations of the dated samples with Gravettian archaeological material are problematic or non-existent (Table 1). These problems presumably derive from errors in RPED v20 but could have been easily rectified by reference to the published literature. Some samples were associated with an archaeological assemblage of unknown attribution, often found underlying a convincing Gravettian layer (Dolní Věstonice IIa, Grotta Arene Candide, Krems-Hundssteig, Krems-Wachtberg, Lapa do Picareiro; see Table 1 for further details and references). In other cases the samples were associated with non-Gravettian assemblages (Ranis) or derive from a layer described as containing both Gravettian and Aurignacian material (El Castillo). Two dates are for carnivore bones that may have no connection whatsoever with human activity (Komarowa Cave, Les Garennes). Other problematic results include those relating to a mammoth ivory sample which may be more ancient than the site where it was found (Maisières-Canal), a sample whose exact origin within the site is unknown (Trenčianske Bohuslavice), and a date on charcoal that is significantly older than all other dates for the layer (Henryków 15).

The corpus of results used by Bicho et al. also excludes a number of important Early Gravettian sites with AMS dates earlier than 27 ¹⁴C kya BP. These include the sites of Molodova V, Kostënki 8 and

Information from B	icho <i>et al</i> . 2017 S1	Table			Comments (this paper)			
Site	Layer	Country	Lab Code	Sample	Date	SD	Archaeological association of sample according to published literature	Further comments
Abri Pataud	5 sublayer H3 back: superior	France	OxA-21586	Bone	28230	290	Gravettian (Higham et al. 2011).	
Antolinako Koba	Lmbk sup	Spain	Beta-230279	Bone	27520	190	Gravettian (Aguirre Ruiz de Gopegui 2012).	
Arbreda	F	Spain	OxA-21782	Bone	28280	290	Gravettian (Wood et al. 2014).	
Brillenhohle	VII	Germany	KIA-19549	Bone	27030	180	Gravettian (Conard & Moreau 2004).	
Buran Kaya III	6-2 and 6-1	Ukraine	GrA-40485	Bone	34050	260	Sample's attribution to Layer 6-2 has been questioned, and it may derive from lower in the sequence (Péan <i>et al.</i> 2013). Layers 6-2, 6-1 and 5-2 described as Gravettian (Yanevich 2014) but cf. Sinitsyn 2013, Hublin 2015.	Oldest date attributed to "Gravettian" layers at site is $33,790 \pm 880$ (Layer 5-2, GifA- 11222/SacA-25139). Oldest date with a standard error <500 years is $32,450 + 250/-230$ (Layer 6-2, GrA-50457) (Péan <i>et al.</i> 2013).
Combe Sauniere	VI	France	OxA-6514	-	27880	440	Gravettian (Drucker <i>et al.</i> 2003).	
Dolni Vestonice II- 05	hearth (5)	Czech Republic	OxA-17813	Charcoal	27080	140	Gravettian (Beresford-Jones <i>et al.</i> 2011).	
Dolni Vestonice IIa	4	Czech Republic	OxA-27333	Charcoal	31650	280	Not associated with a diagnostic lithic assemblage (Svoboda <i>et al.</i> 2015; Novák 2016).	Date for lowest Gravettian layer at site (3c): $28,380 \pm 210$ ¹⁴ C BP (OxA-27331; Svoboda et al. 2015).
El Castillo	14	Spain	Beta-298432	Bone	29740	190	Layer 14 contains both Evolved Aurignacian and Gravettian material (Bernaldo de Quirós <i>et al.</i> 2015).	The overlying Layer 12 also contains Gravettian (and possibly Aurignacian) material but dates are younger than 27,000 ¹⁴ C BP (Bernaldo de Quirós <i>et al.</i> 2015).
Fumane	D1d	Italy	OxA-17571	Charcoal	31590	160	Gravettian (Higham <i>et al.</i> 2009)	as Gravettian in the literature,

Gaissanklastarla	Le	Germany	0x4 18718	Pone	22280	300	Aurignacian (Moreau 2010; Higham et al. 2013); Croyottion (Higham et al.	only two backed lithics were found in this layer and the association between the dated samples and the lithic artefacts is questionable: see Section 3.1.2 for details. Oldest AMS date for the site with convincing Gravettian
Geisselikiosterie		Germany	OXA-10/10	Bolle	55580	390	2012); see also Jöris <i>et al.</i> 2010.	$28,600 \pm 290 \text{ (OxA-21739)}$ (Higham et al. 2012).
Grotta Arene Candide	P12, hearth VI of Cardini	Italy	LTL3769A	Charcoal	27381	200	Not associated with a diagnostic lithic assemblage (Cardini & Taschini 1994; Rellini <i>et al.</i> 2013).	Next oldest dates for Gravettian layers at the site are younger than 27,000 ¹⁴ C BP (Rellini <i>et</i> <i>al.</i> 2013).
Henrykow 15	9	Poland	Poz-60000	Charcoal	31550	350	Gravettian (Wiśniewski et al. 2015).	Other charcoal dates for layer 9 are much younger: $29,180 \pm 310$ ${}^{14}C BP (Poz-58479) and 28,500 \pm 260$ ${}^{14}C BP (Poz-60001)$ (Wiśniewski et al. 2015).
Hohle Fels, Hohler Fels	II C- 11	Germany	OxA-4599	Bone	28920	440	Gravettian (Conard & Moreau 2004).	There is another date on the same sample as $OxA-4599$, of $29,550 \pm 650$ ($OxA-5007$; Housley <i>et al.</i> 1997), and Jöris et al. (2010) combine the two dates for their analyses. The sample is from a reindeer antler implement rather than a bone. Taller & Conard (2016) write that layer IId of the site contains Gravettian material, but suggest that the bimodal distribution of radiocarbon dates for the layer indicates that there is evidence of both Aurignacian and Gravettian activity within the layer (ibid, p. 120); the oldest

								published date for this layer IId is $30,010 \pm 220$ (KIA-8965).
Huccorgne – Hermitage	4	Belgium	CAMS-5891	Bone	28390	430	Gravettian (Straus 2000).	
Komarowa Cave	С	Poland	GdA-94	Bone	28500	500	None. Sample is on cave bear skull fragment; no archaeological material is described as deriving from Layer C (with the exception of a few possibly cutmarked bones) (Wojtal 2007; Nadachowski <i>et al.</i> 2009; Wojtal <i>et al.</i> 2015).	
Krems-Hundssteig	АН 3	Austria	VERA-2289	Charcoal	32810	450	Date is for a sample from Layer AH 4.21, of unknown archaeological attribution (Wild 2008).	The oldest date for the Gravettian AH 3 layer is 28,780 +270/-260 ¹⁴ C BP (VERA- 2292) (Wild 2008).
Krems-Wachtberg	AH4	Austria	VERA3939	Charcoal	28750	270	Actually from layer AH 5 (Einwögerer <i>et al.</i> 2009, also noted in RPED v 20). Only three (presumably undiagnostic) lithic artefacts are described for this layer (Thomas <i>et al.</i> 2016).	The oldest date for the main Gravettian layer at the site, AH 4, is $28,300 \pm 270$ (VERA- 3932) (Einwögerer <i>et al.</i> 2009).
Lapa do Picareiro	Z	Portugal	Wk-32280	Bone	29054	224	No diagnostic stone tools (Bicho <i>et al.</i> 2015).	Dates for Layer W, the lowermost described Gravettian layer, are all younger than 27,000 ¹⁴ C BP (Bicho <i>et al.</i> 2015).
Le Sire	-	France	Beta-145820	Bone	29350	310	Gravettian (Surmely <i>et al.</i> 2003, 2011).	The lower layer, with radiocarbon dates of ca. 31.5-30 ¹⁴ C kya BP, has also been described as Gravettian, although lithic assemblage is relatively limited and no Gravettian index fossils are described or illustrated for the layer (Surmely <i>et al.</i> 2011).

Les Garennes	-	France	Beta-216143	Bone	28410	230	Hyaena bone from cave; no direct association with any archaeological material (Henry-Gambier <i>et al.</i> 2007).	
Maisieres Canal	unity M H (archaeological layer)	Belgium	OxA-17962	Bone	29060	170	Maisierian/Gravettian (Jacobi et al. 2010; Pesesse & Flas 2011; Touzé et al. 2016). Sample itself is mammoth ivory, is suspected to be older than human occupation of site (Jacobi et al. 2010).	Dates on bone samples are all younger than 29 ¹⁴ C kya BP: the oldest of these is $28,650 \pm 200$ (OxA-18010) (Jacobi <i>et al.</i> 2010).
Mira	Lower, II/2	Ukraine	CURL- 15795	Charcoal	27400	260	Gravettian (preliminary attribution) (Stepanchuk 2005, 2013; Hoffecker <i>et al.</i> 2014).	
Paglicci	23 a	Italy	UtC-1414	-	28100	400	Gravettian (Palma di Cesnola 2006).	There is a slightly older published non-AMS date for the Gravettian layer 22f4, of 28,300 \pm 400 ¹⁴ C BP (Utrecht lab, no code available) (Palma di Cesnola 1993 cited in Mussi 2001, p. 232).
Poiana Ciresului	IV	Romania	Erl-11859	Charcoal	27321	234	Gravettian (Steguweit <i>et al.</i> 2009).	
Palomar	II (3.75-4.15 m)	Spain	Beta-185412	-	28050	230	Date relates to Level VI, possibly attributable to the Middle Palaeolithic (de la Peña Alonso 2012; de la Peña & Vega Toscano 2013).	Dates for Gravettian levels (V- III) are younger than 27,000 ¹⁴ C BP (de la Peña Alonso 2012; de la Peña & Vega Toscano 2013).
Ranis	VI	Germany	OxA-13046	Bone	31780	330	The sample relates to the Lincombian-Ranisian- Jerzmanowician assemblage of Ranis 2 (Grünberg 2006; Flas 2008).	Dates for Ranis 4 (Gravettian/Magdalenian): $28,690 \pm 160$ (OxA-12050) and $14,780 \pm 60$ (OxA-12049) (Grünberg 2006; Higham et al. 2007).
Sirgenstein	II	Germany	KIA-13079	Bone	27250	180	Gravettian (Conard & Bolus 2003): result is properly 27,250 +180/-170 (but see also Jöris <i>et</i>	

							<i>al.</i> 2010 who question dating of	
Solutre	en magma	France	SR- 5595/CAMS- 70703	-	28420	160	Gravettian (Montet-White <i>et al.</i> 2002; Digan <i>et al.</i> 2008).	Listed as SR-5595/CAMS- 71703 in Montet-White <i>et al.</i> 2002. A slightly more ancient non-AMS date has been published for the Gravettian layer in Sondage B: $28,650 \pm$ 1100 (Ly-312; Montet-White <i>et al.</i> 2002).
Tarte	1b-c	France	Ly-2105- OxA	Bone	28410	150	Gravettian (Foucher & San Juan-Foucher 2008; Foucher 2012).	Date relates to layer c1c (Foucher & San Juan-Foucher 2008).
Trencianske Bohuslavice-Pod Tureckom	IV?	Slovakia	GrA-6139	Charcoal	29910	260	Sample of unknown origin (Vlačiky et al. 2013).	Other dates for Gravettian layers are younger than 27,000 ¹⁴ C BP (Vlačiky et al. 2013).
Vale Boi	6 terrace	Portugal	Wk-32146	Shell	28321	422	Gravettian (Marreiros <i>et al.</i> 2015).	
Willendorf II	6 / B4	Germany	GrA-895	-	27620	230	Gravettian (Damblon <i>et al.</i> 1996; Nigst <i>et al.</i> 2008).	The underlying Layer 5 also contains Gravettian material, although its dating is uncertain (Haesaerts <i>et al.</i> 2007; Noiret 2013). The date of $28,560 \pm 520$ BP (GrN-17804) from a stratigraphic unit above Layer 5 (Haesaerts et al. 2007) provides a <i>terminus ante quem</i> for Layer 5 (Jöris et al. 2010) but is not used here because its error exceeds 500 years. The very early date of $30,500 + 900/-800$ (GrN-11193) is no longer held to have a reliable association with Layer 5 (Noiret 2013: 36).

 Table 1: Radiocarbon dates used by Bicho et al. (2017) with comments on their archaeological associations.

Rio Secco (Noiret 2007; Haesaerts et al. 2010; Talamo et al. 2014; Reynolds et al. 2015). A fuller review of the literature would have enabled these dates to be included in the dataset. The focus on AMS dates, which Bicho et al. do not fully justify, also excluded a number of Gravettian assemblages with non-AMS radiocarbon dates older than 27,000 ¹⁴C BP – for example, Mitoc Malu-Galben and the Weinberghöhle caves (Weniger 1990; Noiret 2007; Haesaerts et al. 2010; Jöris et al. 2010; Moreau & Jöris 2013).

2.2: Least-cost-path data: methodological problems

The GIS analyses used by Bicho et al. are also subject to methodological problems concerning their use of cost modelling using Tobler's hiking function. Modelling of travel cost has been quite widely applied within digital archaeological circles (see Herzog 2014 for extensive discussion of the various methods), in part because of the ready availability of the tools to make calculations and of the required data (primarily Digital Elevation Models [DEMs]). However, there are numerous potential problems associated with cost modelling, particularly for archaeological time periods. These include:

- Failure to model anisotropy in slope-based cost modelling. An 'isotropic' cost surface takes no account of the direction of travel and so is not suited to modelling variables such as slope, where the cost of travel is highly influenced by whether the slope is ascended or descended. By contrast, an 'anisotropic' cost surface does take account of direction of travel (Wheatley & Gillings 2002: 152).
- The need to model land cover. The land surface over which a hypothetical traveller would have travelled will have a very large effect on the cost of movement between the extremes of a paved surface (good for walking) through to extremes such as deep snow, scree, or water bodies (poor or impossible for walking). Naturally this factor would be very hard to model for most archaeological time periods, especially for older time periods where greatest change compared to the modern day has occurred. As such, land cover has not been modelled in the cost calculations undertaken here or by Bicho et al. Li et al (2019) provide a good example of integrating palaeoenvironmental reconstruction into cost modelling for the Palaeolithic.

- The need to model social factors, such as borders, restricted travel zones, or the presence of parties (or animals / environments) hostile to the traveller. This element is largely ignored by archaeological applications of the method and, as with land cover, becomes harder to model as one goes back further into the past. Again, this has not been modelled in the cost calculations undertaken here or by Bicho et al.
- Incorrect application of algorithms.
- Problems with the DEM.

One of several widely used cost modelling algorithms is Tobler's hiking function (Tobler 1993), which Bicho et al. have attempted to apply in their analysis. There are considerable limitations to the hiking function, which is based on rather coarse estimates given by Imhof (1950: 217-220). Imhof's data are not presented as a formulae, but as a series of rather vague estimates of how elevation change effects travel time, including the graph reproduced here (Fig. 2). His data is claimed to represent only travel alone or in small groups (Imhof 1950: 217), for average to good adult walkers taking no breaks and carrying light burdens (Imhof 1950: 219). Tobler's formula is estimated from Imhof's data (Tobler 1993), albeit not very precisely (Herzog 2014: 5.1.4.2), and provides an estimate of either walking velocity (i.e. speed of travel) or pace (i.e. the time taken to cover a specific distance) based upon the slope of the ground surface (signed positively for ascent or negatively for descent). The formula for pace (the time in seconds taken to travel one metre) is what is useful for cost modelling purposes:

 $p = 0.6e^{3.5 |m + 0.05|}$

where:

- p = pace in seconds per metre
- $m = tan \theta$

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\theta = angle of slope
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The primary result of a cost modelling exercise undertaken using this formula will be surfaces showing the time taken to travel from (or alternatively to, although this requires reversing the sign on the slope variable) an origin to any point on the surface, purely according to distance and the slope of the terrain encountered. As such, if implemented correctly, the results of cost modelling using Tobler's hiking function are best discussed in terms of time taken to travel, not distance travelled.



Figure 2: Graph depicting the approximate variation in time taken to travel a particular distance based upon the amount of ascent or descent undertaken (redrawn from Imhof 1950: fig 333).

When applied correctly, Tobler's hiking function has a fairly subtle effect on the paths produced when a cost surface is used to create least cost paths (LCPs) between an origin point and a destination or set of destinations. Essentially, especially when the distances travelled are long, one would expect to see paths that approximate the great circles between the origin and each destination, with local deviations seen to avoid the steepest terrain, especially when travelling uphill. The LCPs presented by Bicho et al. (2017: Fig. 4) do not fit well with this expected outcome. As such, it would appear that Tobler's hiking function has not been calculated correctly (see SI 2 for instructions on implementing Tobler's hiking function in ArcGIS). One possibility is that an isotropic approximation of the hiking function has been implemented: in ArcGIS this would involve generating a slope surface from the DEM and then running that surface through the raster calculator using Tobler's formula. The result of this would be a cost allocation surface that represented both uphill and downhill slopes as if they were uphill slopes. As such, travel across ascending terrain would behave as expected, but travel across descending terrain would be more difficult than expected. The resulting LCPs should thus be different from those calculated correctly, but still relatively similar.



Figure 3: Graphs showing the relationship between pace and degree of slope according to (a) Tobler's hiking function (solid black line), (b) an isotropic approximation of Tobler's hiking function (dotted black line), and (c) using degree of slope as a direct multiplier for travel cost (solid grey line). Only (a) takes account of the difference between positive (ascent) and negative (descent) degrees of slope; (b) and (c) ignore the sign for calculations on negative slopes. These all assume a fastest pace of 0.6 seconds per metre.

However, the LCPs presented by Bicho et al. appear to be much more sensitive to variation in slope than either the anisotropic or isotropic approximations of the hiking function should produce. Another possibility is that unmodified slope was used as a cost allocation surface in the cost modelling exercise. The results produced would be very sensitive to variation in terrain slope, as even a mild slope of $\pm 2^{\circ}$ would effectively double the cost of travel across that DEM cell when compared to a slope of $\pm 1^{\circ}$ (Fig. 3). Although extreme slopes (c. $\pm 50^{\circ}$) would be quicker to traverse than when using the hiking function, these would very rarely be reached by travellers due to the much higher cost of intermediate gradual slopes. This would produce cost surfaces resulting in LCPs that stay very close to river valleys and follow flat coastlines wherever possible. It would also produce results that would be very sensitive to changes in the DEM extent, as inclusion (or removal) of new river valleys or coast would open up (or remove) routes that the hypothetical traveller would quickly gravitate towards due to their low cost.

When compared on a map (Fig. 4), LCPs calculated from Buran-Kaya III to the other sites in the dataset using the three methods discussed above show considerable variation, but along the lines predicted. The anisotropic paths calculated using the hiking function approximate to great circles, except where oceans or high mountain ranges get in the way. The paths calculated using the isotropic approximation of the hiking function are similar to the anisotropic paths, but are more terrain sensitive, avoiding hills which would even out the increased cost of ascent through the decreased cost of (relatively gentle) descent. The paths calculated using slope as a cost allocation surface follow river valleys and coastlines and avoid elevated ground wherever possible. The latter case is the closest approximation of the LCPs presented by Bicho et al., although there is a fairly large degree of variation, which is at least in part due to the different extent of DEM used (notably the availability of the northern European coastline in the models here which was clipped away in the Bicho et al. DEM). Therefore, it does not appear that Tobler's hiking function was implemented correctly by Bicho et al., as the results appear too sensitive to changes in the slope of the terrain.



Figure 4: Map showing least cost paths from Buran-Kaya III (BK) calculated using (a) the anisotropic Tobler's hiking function, (b) an isotropic approximation of Tobler's hiking function, and (c) using unmodified slope as the cost allocation surface.

3. Replication study

Although the problems with Bicho et al.'s data and methods described above are, in our view, comprehensive enough to cast serious doubt on their results and conclusions, we attempted to replicate their analyses in order to further explore the significance of our observations. Numerous researchers have, like Bicho et al., presented arguments that Gravettian assemblages appeared earliest in Central Europe (e.g. Otte & Keeley 1990; Conard & Bolus 2003; Moreau & Jöris 2013), and the possibility of identifying a demographic wave-of-advance across Europe associated with the earliest Gravettian assemblages is worth investigating.

3.1 Materials: Chronological data

To carry out the replication study we constructed two sets of chronological data. The first (Chronological Dataset 1) is based on a face-value assessment of the literature, assuming that all claims for radiocarbon dates associated with Gravettian assemblages are accurate. The second (Chronological Dataset 2) is based on a more critical assessment of the literature, and excludes some early dates where we have doubts over their association with Gravettian material.

3.1.1 Chronological Dataset 1

Chronological Dataset 1 was assembled using the same criteria for selection as Bicho et al. (i.e. AMS dates older than 27,000 ¹⁴C BP, excluding those with standard errors >500 years) but with the additional criterion that the dated samples had to be described in the literature as having associations with Gravettian assemblages (Table 2; SI 3). This dataset is not necessarily exhaustive but provides a more accurate reflection of published claims for the dating of Gravettian assemblages than that of Bicho et al.

We carried out our date calibrations and median calculations in OxCal 4.3 using IntCal13 (Bronk Ramsey 2009; Reimer et al. 2013). For our chronological point values, we decided not to use what Bicho et al. call the "mean calibrated age". Inspection of their data indicates that this represents the midpoint between the upper and lower boundaries of the 95.4% probability range of the calibrated radiocarbon dates. However, it is incorrect to describe this as the "mean calibrated age". Calibrated radiocarbon dates do not generally have symmetrical distributions and therefore the midpoint of the 95.4% probability range is not equivalent to the "mean" of a result. We instead chose to use the median value of the probability distribution for each calibrated date. The use of the median as a point estimate is itself not unproblematic, particularly where distributions are unimodal (Telford et al. 2004; Michczyński 2007; Blaauw 2010). However, where distributions are unimodal (as they are here: see SI 4) it is arguably a more statistically meaningful value than the midpoint between the upper and lower boundaries of the 95.4% probability range. In any case, we performed some exploratory analyses using

Site	Code	Latitud	Longitud	Layer	Lab code	Date	SD	Calibrated	Calibrated	Median	Difference from	References
		e	e					from	to		Bicho et al. (2017)	
Buran-Kaya III	BK	45.017	34.3833	6-2	GrA-50457	32450	+250/ -230	37053	35747	36360	Different date used	Péan et al. 2013
Grotta Fumane	FUMA N	45.5062	10.9666	D1d	OxA-17571	31590	160	35916	35041	35470	No change	Higham et al. 2009
Henryków 15	HENRY	50.6432	16.996	9	Poz-60000	31550	350	36181	34772	35450	No change	Wiśniewski et al. 2015
Rio Secco	RS	46.2809	12.9714	6	MAMS-15907	29390	135	33915	33310	33627	Not included by Bicho et al. (2017)	Talamo et al. 2014
Molodova V	MOLO	48.5669	27.1832	10–9	GrA-23198	29370	280	34059	32921	33563	Not included by Bicho et al. (2017)	Haesaerts et al. 2010
Le Sire	SIRE	45.7	3.2333	Upper	Beta-145820	29350	310	34095	32834	33534	No change	Surmely et al. 2011
Hohle Fels	HOHLE	48.3792	9.7541	IIc	OxA-4599†	28920	440	33912	31781	33012	Different date	Housley et al. 1997;
					OxA-5007†	29550	650				(combined calibrated result) used	Conard & Moreau 2004; Jöris et al. 2010
Krems- Hundssteig	KRE-H	48.4148	15.6016	AH 3	VERA-2292	28780	+270/ -260	33617	31995	32913	Different date used	Wild 2008
Ranis 4	RANIS	50.6613	11.5632		OxA-12050	28690	160	33389	32146	32811	Different date used	Grünberg 2006; Higham et al. 2007
Maisières- Canal	MAISI	50.4804	3.9803	M 10	OxA-18010	28650	200	33388	31935	32731	Different date used	Jacobi et al. 2010
Geissenklösterle	GEISSE	48.3934	9.7804	Ia	OxA-21739	28600	290	33460	31708	32624	Different date used	Higham et al. 2012
Huccorgne – Hermitage	HUCCO R	50.5625	5.1806	4	CAMS-5891	28390	430	33464	31395	32364	No change	Straus 2000
Solutré	SOLUT	46.2976	4.726	magm a	SR-5595/ CAMS-70703	28420	160	32918	31719	32349	No change	Montet-White et al. 2002
Tarté	TARTE	43.1072	0.9828	clc	Ly-2105-OxA	28410	150	32887	31729	32334	No change	Foucher & San Juan- Foucher 2008
Dolní Věstonice IIa	DVI	48.8828	16.6361	3с	OxA-27331	28380	210	32964	31594	32292	Different date used	Svoboda et al. 2015
Vale Boi	VB	37.0944	-8.815	6 terrac e	Wk-32146	28321	422	33389	31354	32288	No change	Marreiros et al. 2015
Krems- Wachtberg	KRE-W	48.4149	15.5993	4	VERA-3932	28300	270	33003	31459	32206	Different date used	Einwögerer et al. 2009
Arbreda	ARBRE	42.1611	2.747	F	OxA-21782	28280	290	33030	31424	32190	No change	Wood et al. 2014
Abri Pataud	PATAU D	44.9379	1.0121	5 rear upper	OxA-21586	28230	290	32966	31393	32132	No change	Higham et al. 2011
Grotta Paglicci	PAGLI	41.654	15.6152	23a	UtC-1414	28100	400	33103	31210	32051	No change	Palma di Cesnola 2006
Combe Saunière	COMB E	45.2307	0.8836	VI	OxA-6514	27880	440	32971	31060	31849	No change	Drucker et al. 2003
Kostënki 8	KOST8	39.0717	51.3747	Π	OxA-30198	27670	270	32245	31050	31474	Not included by Bicho et al. (2017)	Reynolds et al. 2015
Willendorf II	WILEN D	48.323	15.399	6	GrA-895	27620	230	31929	31053	31409	No change	Damblon et al. 1996, Nigst et al. 2008

Antoliñako	AK	43.371	-2.6519	Lmbk	Beta-230279	27520	190	31643	31052	31328	No change	Aguirre Ruiz de
Koba				sup								Gopegui 2012
Mira	MIRA	47.675	35.1024	II/2	CURL-15795	27400	260	31706	30924	31275	No change	Stepanchuk 2005,
												2013; Hoffecker et al.
												2014
Poiana Cireșului	POIAN	46.9306	26.3277	IV	Erl-11859	27321	234	31551	30921	31224	No change	Steguweit et al. 2009
Sirgenstein	SIRG	48.3853	9.7617	II	KIA-13079	27250	+180/	31421	30946	31179	Date error corrected	Conard & Bolus 2003
							-170					
Dolní Věstonice	DVI5	48.8828	16.6361	DVII-	OxA-17813	27080	140	31294	30880	31093	No change	Beresford-Jones et al.
II				05							Ũ	2011
Brillenhöhle	BRILL	48.406	9.7782	VII	KIA-19549	27030	180	31300	30825	31069	No change	Conard & Moreau
											-	2004

Table 2: Dates included in Chronological Dataset 1. Bold: sites that were not included by Bicho et al. (2017); italics: sites with different dates from those used by Bicho et al. (2017). See Table 1 and main text for explanations of changes and exclusions of dates. See main text for explanation of new inclusions of dates. Excluded from this dataset are: Grotta Arene Candide, El Castillo, Les Garennes, Komarowa Cave, Lapa do Picareiro, El Palomar and Trenčianske Bohuslavice-Pod Tureckom as well as Mitoc Malu-Galben. †Dates combined in OxCal 4.3 using the R_Combine command.

both midpoint values and median values, and it appears that the choice of one or another value has very little effect on the final results of the regression analyses performed here.

3.1.2 Chronological Dataset 2

Although the construction of Chronological Dataset 1 was based on an extensive literature review, we had doubts over some of the extremely early dates for Gravettian assemblages. As can be seen in Figure 5, the oldest dates for Buran-Kaya III, Henryków 15 and Grotta Fumane are markedly older than the rest of the dates included in the dataset. Being the oldest dates in the dataset, these results had the most potential to skew our analyses. In fact, there are good archaeological reasons to doubt the published dating of each of these sites.

For Buran-Kaya III (Crimea), although the assemblages from Layers 6.2, 6.1 and 5.2 have been described in print as Gravettian and there are numerous backed lithics described for the layers (Prat et al. 2011; Péan et al. 2013; Yanevich 2014), the description of these layers as Gravettian has previously been questioned (Sinitsyn 2013; Hublin 2015). Here, we note the apparent large temporal gap that exists between this assemblage and the next youngest Gravettian assemblages (especially if we exclude the very early dates for Henryków 15 and Grotta Fumane, as suggested below). The oldest available AMS radiocarbon date for Layers 6.2-5.2 is 32,450 +250/-230 (GrA-50457), and numerous other dates for the same layers are older than 30,000 ¹⁴C BP (Péan et al. 2013). As recently discussed in detail with relation to Early Upper Palaeolithic industries (Teyssandier & Zilhão 2018), the definition of a technocomplex must include a consideration of the underlying social and environmental factors that led to the creation of an archaeologically recognisable group of assemblages. The description of a group of assemblages as "Gravettian" rests on an assumption that there was some kind of cultural connection between them, and we should expect both temporal and geographical coherence in site distribution. This condition is not met for Buran-Kaya III: it is not temporally (or geographically) coherent with other Gravettian sites. If the dating and description of the lithic assemblage are correct, their similarity to Gravettian assemblages may be an example of convergent evolution. It can also be noted that there



Figure 5: Curve plot figure of calibrated radiocarbon dates included in Chronological Dataset 1: note the markedly early dates for Buran-Kaya III, Grotta Fumane and Henryków 15.

is a date for the Aurignacian Layer F of Siuren I, also in Crimea, of $29,950 \pm 700$ ¹⁴C BP (OxA-5155) (Chabai 2001; Demidenko & Otte 2001–2002). If accurate, this implies that any early appearance of Gravettian assemblages in Crimea was not the result of a simple unidirectional cultural transition.

The same arguments regarding temporal and geographical coherence could also be applied to the sites of Henryków 15 and Grotta Fumane. At Henryków 15 (Poland), a lithic assemblage from Layers 8 and 9 has been described as Gravettian; 1284 artefacts were discovered in these layers, including 87 retouched tools, of which 6 were described as backed pieces (Wiśniewski et al. 2015). There are three

radiocarbon dates on charcoal samples from Layer 9; the oldest result ($31,550 \pm 350^{14}$ C BP; Poz-60000) is much more ancient than the other two dates $(29,180 \pm 310^{-14}\text{C BP}; \text{Poz-}58479 \text{ and } 28,500 \pm 260^{-14}\text{C}$ BP; Poz-60001). Although it was suggested in the publication of the dates that the younger dates could have been affected by contamination, the association between the charcoal samples and the lithic artefacts found at the site can also be questioned: the layer was subject to significant periglacial and slope processes and the oldest dated sample apparently comes from a square 5 m away from the other two samples (Wiśniewski et al. 2015: Table 3). It is not clear that all three samples derive from the same event, or that they are all securely associated with the Gravettian lithic artefacts found in Layer 9. In the absence of further work on the taphonomy and chronology of the site, the very early date for Henryków 15 is best treated with caution. The younger two results conceivably date a single event and arguably provide a better indication of the age of the human activity represented in Layer 9 (if combined in OxCal 4.2 using the Combine function they yield acceptable agreement indices; this is not the case if the oldest date is included). We can also note that, although we did not identify any dated late Aurignacian assemblages in the immediate vicinity of Henryków 15, there are numerous Aurignacian assemblages dated to the period 32,000-29,000 ¹⁴C BP in Moravia, a few hundred kilometres away. These include assemblages from the sites of Napajedla III, Stránská Skála IIIa, Stránská Skála IIIf and probably Líšeň I (Svoboda 2003; Škrdla 2017; Demidenko et al. 2017).

At Grotta Fumane (Italy), the strength of the association between the charcoal dated to $31,590 \pm 160$ ¹⁴C BP (OxA-17571; Higham et al. 2009) and Gravettian artefacts found in layer D1d can also be questioned. Only two plausibly diagnostic Gravettian artefacts were found in D1d: a fragment of a backed bladelet (Bartolomei et al. 1992) and a fragment of a possible Gravette point (Broglio 1996–1997; Broglio et al. 2009). Other radiocarbon dates for the site do not help to support the possibility that the extremely early charcoal date is indicative of the age of these two artefacts. A terrestrial shell sample from the overlying layer D1e has been dated to $26,890 \pm 530$ ¹⁴C BP (R-2784), around 5,000 years younger than the very old date for layer D1d. There are also two dates for charcoal samples from the "base" of D1d, of $29,828 \pm 390$ ¹⁴C BP (LTL374A) and $30,700 \pm 400$ ¹⁴C BP (UtC-2050) (Higham et al. 2009). It may well be the case that the samples and assemblage attributed to Layer D1d includes

Site	Code	Latitude	Longitud e	Layer	Lab code	Date	SD	Calibrated from	Calibrated to	Median	Difference from Bicho et al. (2017)	References
Rio Secco	RS	46.2809	12.9714	6	MAMS- 15907	29390	135	33915	33310	33627	Not included by Bicho et al. (2017)	Talamo et al. 2014
Molodova V	MOLO	48.5669	27.1832	10–9	GrA-23198	29370	280	34059	32921	33563	Not included by Bicho et al. (2017)	Haesaerts et al. 2010
Le Sire	SIRE	45.7	3.2333	Upper	Beta-145820	29350	310	34095	32834	33534	No change	Surmely et al. 2011
Henryków 15	HENRY	50.6432	16.996	9	Poz-58479	29180	310	33977	32609	33361	Different date used	Wiśniewski et al. 2015
Hohle Fels	HOHLE	48.3792	9.7541	IIc	OxA-4599†	28920	440	33912	31781	33012	Different date (combined	Housley et al. 1997;
					OxA-5007†	29550	650				calibrated result) used	Conard & Moreau 2004; Jöris et al. 2010
Krems- Hundssteig	KRE-H	48.4148	15.6016	AH 3	VERA-2292	28780	+270/ -260	33617	31995	32913	Different date used	Wild 2008
Ranis 4	RANIS	50.6613	11.5632		OxA-12050	28690	160	33389	32146	32811	Different date used	Grünberg 2006; Higham et al. 2007
Maisières- Canal	MAISI	50.4804	3.9803	M 10	OxA-18010	28650	200	33388	31935	32731	Different date used	Jacobi et al. 2010
Geissenklösterle	GEISSE	48.3934	9.7804	Ia	OxA-21739	28600	290	33460	31708	32624	Different date used	Higham et al. 2012
Huccorgne – Hermitage	HUCCO R	50.5625	5.1806	4	CAMS-5891	28390	430	33464	31395	32364	No change	Straus 2000
Solutré	SOLUT	46.2976	4.726	magma	SR-5595/ CAMS- 70703	28420	160	32918	31719	32349	No change	Montet-White et al. 2002
Tarté	TARTE	43.1072	0.9828	clc	Ly-2105- OxA	28410	150	32887	31729	32334	No change	Foucher & San Juan- Foucher 2008
Dolní Věstonice Iia	DVI	48.8828	16.6361	3с	OxA-27331	28380	210	32964	31594	32292	Different date used	Svoboda et al. 2015
Vale Boi	VB	37.0944	-8.815	6 terrace	Wk-32146	28321	422	33389	31354	32288	No change	Marreiros et al. 2015
Krems- Wachtberg	KRE-W	48.4149	15.5993	4	VERA-3932	28300	270	33003	31459	32206	Different date used	Einwögerer et al. 2009
Arbreda	ARBRE	42.1611	2.747	F	OxA-21782	28280	290	33030	31424	32190	No change	Wood et al. 2014
Abri Pataud	PATAU D	44.9379	1.0121	5 rear upper	OxA-21586	28230	290	32966	31393	32132	No change	Higham et al. 2011
Grotta Paglicci	PAGLI	41.654	15.6152	23a	UtC-1414	28100	400	33103	31210	32051	No change	Palma di Cesnola 2006
Combe Saunière	COMB E	45.2307	0.8836	VI	OxA-6514	27880	440	32971	31060	31849	No change	Drucker et al. 2003
Kostënki 8	KOST8	39.0717	51.3747	П	OxA-30198	27670	270	32245	31050	31474	Not included by Bicho et al. (2017)	Reynolds et al. 2015
Willendorf II	WILEN D	48.323	15.399	6	GrA-895	27620	230	31929	31053	31409	No change	Damblon et al. 1996, Nigst et al. 2008
Antoliñako Koba	AK	43.371	-2.6519	Lmbk sup	Beta-230279	27520	190	31643	31052	31328	No change	Aguirre Ruiz de Gopegui 2012
Mitoc-Malu Galben	MITOC	48.111	27.036	Gr 1	OxA-1778	27500	600	33129	30655	31584	Not included by Bicho et al. (2017)	Damblon & Haesaerts 2007
Mira	MIRA	47.675	35.1024	II/2	CURL-15795	27400	260	31706	30924	31275	No change	Stepanchuk 2005, 2013; Hoffecker et al. 2014

Poiana Cireșului	POIAN	46.9306	26.3277	IV	Erl-11859	27321	234	31551	30921	31224	No change	Steguweit et al. 2009
Sirgenstein	SIRG	48.3853	9.7617	II	KIA-13079	27250	180	31426	30941	31179	No change	Conard & Bolus 2003
Dolní Věstonice	DVI5	48.8828	16.6361	DVII-	OxA-17813	27080	140	31294	30880	31093	No change	Beresford-Jones et al.
II				05								2011
Brillenhöhle	BRILL	48.406	9.7782	VII	KIA-19549	27030	180	31300	30825	31069	No change	Conard & Moreau 2004

Table 3: Dates included in Chronological Dataset 2. This dataset differs from Chronological Dataset 1 in the absence of Buran-Kaya III and Grotta Fumane, the inclusion of Mitoc-Malu Galben, and the use of a different date for Henryków 15. Bold: sites that were not included by Bicho et al. (2017); italics: sites with different dates from those used by Bicho et al. (2017). See Table 1 and main text for explanations of changes and exclusions of dates. See main text for explanation of new inclusions of dates. Excluded from this dataset are: Buran-Kaya III, Grotta Fumane, Grotta Arene Candide, El Castillo, Les Garennes, Komarowa Cave, Lapa do Picareiro, El Palomar and Trenčianske Bohuslavice-Pod Tureckom. †Dates combined in OxCal 4.3 using the R_Combine command.

material deposited over a period of several thousand years, and the dated charcoal sample may therefore be considerably older than the two artefacts described as Gravettian.

Due to the problems with the dating of these three sites, we constructed Chronological Dataset 2 (Table 3, SI 3), which takes into account our judgements regarding these three sites. Buran-Kaya III and Grotta Fumane are not included in this dataset because of the absence of dates meeting the criteria for inclusion, while the date of $29,180 \pm 310^{-14}$ C BP (Poz-58479) is used for Henryków 15.

Since the analyses carried out here are highly dependent on the oldest dates in the dataset, it is worth reviewing the three sites with the oldest dates that remain in our dataset, which we go on to use as potential origin sites in our replication of Bicho et al.'s analyses. These sites are Molodova V, Rio Secco and Le Sire.

At Molodova V (Ukraine), a long sequence of archaeological layers includes several that have been described as Gravettian, of which the lowermost is Layer 10 (Noiret 2007). The Layer 10 assemblage contains several backed lithics, although it also includes a carinated scraper (Otte 1981; Noiret 2007) that could be considered diagnostically Aurignacian. The overlying Layer 9, which also yielded a small number of backed lithics, appears to be more securely described as (unmixed) Gravettian. A charcoal sample from between the two layers was dated to $29,370 \pm 280$ ¹⁴C BP (GrA-23198; Haesaerts et al. 2010). The position of this sample above Layer 10 means that it can be used as a *terminus ante quem* for the earliest Gravettian artefacts at the site even if potentially Aurignacian artefacts were also found in Layer 10.

At Rio Secco (Italy), Layer 6 has been described as a thin layer sandwiched between archaeologically sterile levels and containing a small collection of Gravettian lithics (Peresani et al. 2014; Talamo et al. 2014). The two radiocarbon dates on charcoal from this layer recently produced at MPI-EVA/Mannheim are in very good agreement with each other: $29,390 \pm 135$ ¹⁴C BP (MAMS-15907) and $28,995 \pm 135$ ¹⁴C BP (MAMS-15906) (Talamo et al. 2014). There are also two slightly younger dates for the same layer, obtained at a different laboratory.

At Le Sire (France), two levels of finds have been described as Gravettian (Surmely et al. 2011). However, only the upper level has yielded significant numbers of backed lithics, and there are no diagnostic Gravettian lithic artefacts illustrated or described in detail for the lower level. A horse bone from the site has been dated to $29,350 \pm 310$ ¹⁴C BP (Beta-145820). This result was originally presented for the principal level with Gravettian lithics, before the lower level was described (Surmely et al. 2003), and although in a later publication some doubt is mentioned over the exact sample association, it is denoted as probably being from the upper layer (Surmely et al. 2011). The other dates for the upper level are somewhat younger, falling between ca. 27.5 and 28.5 ¹⁴C kya BP. There are several significantly older dates for the lower level, of ca. 31.5-30 ¹⁴C kBP, but although this level is described in the literature as Gravettian, we do not find this attribution entirely convincing due to the absence of illustrated diagnostic index fossils. In any case, the high statistical errors on these reasons, we use the result of 29,350 \pm 310 ¹⁴C BP (Beta-145820) in our analyses, although we do not exclude the possibility that the layer is better dated to 28.5 ¹⁴C kya BP or later.

There are also several sites where there are early non-AMS dates for samples from Gravettian levels. This includes the site of Mitoc-Malu Galben in Romania (Haesaerts et al. 2010). Although there is no date for the most ancient Gravettian layer (Gravettian I) from this site that meets all the criteria of Bicho et al., we did include the date of $27,500 \pm 600^{-14}$ C BP (OxA-1778; Haesaerts et al. 2010) in Chronological Dataset 2, in order to augment the relatively sparse corpus of dates for this part of Europe. This is not the oldest date with an apparent association with the Gravettian I layer, but a previous study of its chronology found this to be the oldest date that is consistent with the site's overall chronostratigraphy (Damblon & Haesaerts 2007).

In summary, we used two sets of chronological data for our analyses, as follows:

a) Chronological Dataset 1, described above: based on a review of the literature where we took claims for the dating of Gravettian assemblages at face value (see Table 2 and SI 3; coded "CHRONO DATA 1" in SI).

 b) Chronological Dataset 2, described above: based on a more critical analysis of claims for the dating of Gravettian assemblages (see Table 3 and SI 3; coded "CHRONO_DATA_2" in SI).

3.2 Materials: Distance data

For the purposes of the replication study, we produced least-cost-paths using Tobler's hiking function based on the same DEM data used by Bicho et al. (see SI 2 for details of method). These are a vast oversimplification of the travel costs involved in walking from each origin to each destination, as they only take account of the slope of the ground surface and not any other inhibiting factors (such as land cover), and they assume travel by lightly burdened individuals or small groups of adults. We calculated the least-cost-paths as travel time values between all sites included in our chronological datasets, given in seconds and coded "PD" in SI 3. During our analyses these results were converted to hour values (coded "PD HR" in SI 6).

For the six potential origin sites considered in the analyses here (the three oldest sites in each of Chronological Datasets 1 and 2) we also, like Bicho et al., converted the paths into distance measures. These represent the physical lengths of the paths that were modelled to take the least time to walk (coded "PD DIST" in the SI).

Finally, we calculated simple Euclidean distances between all sites in our datasets (coded "ED" in the SI).

To summarize, the data used is as follows:

 a) Our least-cost path travel time values calculated using the anisotropic Tobler's hiking function (calculated from and to all sites in our dataset) (values in seconds are coded "PD" in SI; values in hours are coded "PD HR");

- b) Our least-cost path distance values for the paths calculated in (a) (calculated from Buran-Kaya III, Henryków 15, Fumane, Rio Secco, Molodova V and Le Sire to all sites in our dataset) (coded "PD DIST" in SI);
- c) Euclidean distance values (calculated from and to all sites in our dataset) (coded "ED" in SI).

3.3 Methods

The analyses carried out by Bicho et al. (2017) are simple linear regression analyses to calculate the Pearson correlation coefficient (r). The data analysed are the distance of a site from a possible source site and the age difference between the site and the possible source site. They did not use all sites in their regression analyses: rather, they binned the sites according to travel time from the source site and selected only the oldest site from each bin for analysis.

We repeated these analyses using our datasets, as follows. All analyses were carried out in R 3.5.0 and all scripts used for analysis are available in SI 5.

We constructed an initial datasheet (SI 3; metadata provided in SI 1) containing the chronological and geographical data to be used in the analyses. We converted the time values for the paths from seconds to hours and rounded to the nearest hour, and coded these results as "PD_HR". (code: SI 5.1). We then calculated the differences between the age values used for all sites, for each of the three sets of chronological data used in our analyses, producing positive integer results where a site was younger than the potential source site and negative integer results where a site was older than the potential source site and negative integer results where a site was older than the potential source site. (code: SI 5.2).

For each of the six potential origin sites (Buran-Kaya III, Henryków 15, Grotta Fumane, Molodova V, Rio Secco and Le Sire), we allocated all other sites to 150 km isopleth bins based on our PD_DIST data (distance values for calculated LCPs), similarly to Bicho et al. We also allocated sites to 100 km and 250 km bins to test the robustness of the analyses with respect to bin size. Using the "PD" values (i.e. time values for calculated LCPs), we also allocated sites to 120 kilosecond (ks) bins (this value was

chosen as it gave approximately the same number of bins as the 150 km divisions). We also allocated sites to 90 ks and 150 ks bins, again to test for robustness (code: SI 5.3).

With this data (provided as SI 6), we were ready to carry out regression analyses.

Following Bicho et al., for each source site we selected the sites with the oldest age value within each isopleth of travel from the source site, and excluded other sites from analysis (code: SI 5.4 and SI 5.5).

We first carried out regression analyses using our Chronological Dataset 1 (coded "CHRONO_DATA_1" in the SI), using the sites of Buran-Kaya III, Henryków 15 and Grotta Fumane as potential origin sites. For this set of analyses we, like Bicho et al., excluded sites with *older* age values than the potential source site and did not include Mitoc-Malu Galben. We ran regression analyses between the three sets of path values (coded "PD_DIST", "PD_HR" and "ED") and age differences between each site (code: SI 5.6; results: Table 4 and SI 7.1–7.3.

Next, we carried out regression analyses using Chronological Dataset 2 (coded "CHRONO_DATA_2" in the SI), using Molodova V, Rio Secco and Le Sire as potential origin sites. For this set of analyses we did not exclude sites with older age values than the potential source site – as the dates used for the three potential source sites are extremely close, it is not possible to say that one date is older than the other, and therefore we judged it inappropriate to exclude them. We ran regression analyses between the three sets of path values (coded "PD_DIST", "PD_HR" and "ED") and age differences between each site (code: SI 5.7; results: Table 5 and SI 7.4-7.6).

Finally, we produced scatterplots of all the data used for regression analyses, and included regression lines where $r \ge 0.5$ and $p \le 0.05$ (code: SI 5.8; results: SI 8).

3.4 Results

The results for Chronological Dataset 1 (Table 4) show that there is a moderate positive correlation between radiocarbon values and the calculated path values from the origin site when using the sites of Henryków 15 and Grotta Fumane as origin sites (r > 0.6 and p < 0.05 in almost all instances). No

significant correlations are found when using the site of Buran-Kaya III as the origin. The results are fairly robust with respect to the size of the isopleth bins used. The results are extremely similar for each set of path values.

		Bins:		Bins:		Bins:		D	1001	D	0.0.1	D	1 5 0 1
		150 kı	n	100 ki	n	250 ki	n	Bins:	120 ks	Bins:	90 ks	Bins:	150 ks
Origin site Path values			ICT		ICT		ICT	PD		PD		PD	
		PD_DIST		PD_DIST		PD_D	151						
		r	Р	r	p	r	Р	R	Р	r	p	r	Р
Buran-	PD_DIST	0.349	0.221	0.348	0.204	0.313	0.322	0.453	0.139	0.357	0.21	0.466	0.149
Kaya III	PD_HR	0.349	0.222	0.347	0.205	0.313	0.323	0.454	0.138	0.357	0.21	0.466	0.148
(BK)	ED	0.358	0.209	0.354	0.195	0.32	0.311	0.458	0.134	0.365	0.199	0.47	0.145
Henryków	PD_DIST	0.679	0.015	0.527	0.044	0.61	0.061	0.669	0.017	0.606	0.022	0.707	0.033
15	PD_HR	0.676	0.016	0.525	0.045	0.609	0.062	0.665	0.018	0.602	0.023	0.704	0.034
(HENRY)	ED	0.676	0.016	0.514	0.05	0.608	0.062	0.667	0.018	0.605	0.022	0.705	0.034
Grotta	PD_DIST	0.627	0.029	0.67	0.009	0.728	0.017	0.647	0.043	0.681	0.01	0.728	0.017
Fumane	PD_HR	0.628	0.029	0.67	0.009	0.727	0.017	0.65	0.042	0.682	0.01	0.727	0.017
(FUMAN)	ED	0.625	0.03	0.667	0.009	0.727	0.017	0.644	0.044	0.678	0.011	0.727	0.017

Table 4: Results of regression analyses using Chronological Dataset 1 and our least-cost path distance values. We excluded sites older than the origin site from the regression analyses, as well as excluding Mitoc Malu-Galben (i.e. we took the literature on Gravettian sites at face value, and replicated the approach of Bicho et al. as closely as possible).

The results for Chronological Dataset 2 (Table 5) show a moderate positive correlation between radiocarbon values and the calculated path values from the origin site when Rio Secco is used as the origin site (r > 0.65 and p < 0.05 in almost all instances). These correlations are robust with respect to isopleth bin size. Weaker correlations are seen when using Le Sire as an origin site, while for Molodova V, no correlations are found. Again, the results for each set of path values are very similar.

		Bins:		Bins:		Bins:							
		150 kr	n	100 kr	n	250 kr	n	Bins: 1	120 ks	Bins: 9	90 ks	Bins: 1	150 ks
Origin site	rigin site Path values			100 111		200 11		PD		PD		PD	
		PD_D	IST	PD_DIST		PD_D	IST						
		r	р	r	р	r	Р	r	р	r	Р	r	Р
Molodova	PD_DIST	0.025	0.929	0.03	0.913	0.174	0.588	0.02	0.945	0.026	0.928	0.182	0.551
V	PD_HR	0.025	0.931	0.028	0.917	0.172	0.593	0.02	0.947	0.024	0.932	0.181	0.554
(MOLO)	ED	0.025	0.929	0.031	0.909	0.176	0.584	0.02	0.946	0.027	0.924	0.183	0.55
Rio Secco	PD_DIST	0.656	0.039	0.652	0.016	0.681	0.063	0.726	0.011	0.695	0.012	0.728	0.017
(RS)	PD_HR	0.652	0.041	0.648	0.017	0.676	0.066	0.721	0.012	0.692	0.013	0.723	0.018
	ED	0.659	0.038	0.653	0.015	0.685	0.061	0.731	0.011	0.695	0.012	0.731	0.016
Le Sire	PD_DIST	0.449	0.093	0.401	0.139	0.544	0.104	0.448	0.144	0.472	0.089	0.536	0.072
(SIRE)	PD_HR	0.445	0.097	0.396	0.144	0.538	0.109	0.442	0.15	0.467	0.092	0.531	0.076
	ED	0.455	0.088	0.408	0.131	0.551	0.099	0.455	0.137	0.479	0.083	0.544	0.068

Table 5: Results of regression analyses using Chronological Dataset 2 and our least-cost path distance values. We included sites older than the origin site from the regression analyses, and included Mitoc Malu-Galben (i.e. we took a critical approach to the literature on Gravettian sites, and made some changes to the approach of Bicho et al.).

4. Replication study using random data

4.1 Materials and methods

The results of the first replication study described above and exploratory analyses caused us some concerns regarding the influence of the geographical structuring of the data on the results. Hence, we also carried out replication studies using random chronological data. To do this, for each potential origin site we generated 1000 sets of random chronological data, assigning the oldest generated date in each set to the potential origin site (SI 9). We then binned the sites according to the real PD_HR distance

Origin site code	Site name	Percentage of results where r ≥ 0.5 and p < 0.05	Percentage of results where $r \ge 0.6$ and $p < 0.05$
AK	Antoliñako Koba	3.8%	1.5%
ARBRE	L'Arbreda	11.8%	10.0%
BK	Buran Kaya III	15.7%	13.3%
BRILL	Brillenhöhle	18.0%	14.7%
COMBE	Combe Saunière	22.3%	15.7%
DVI	Dolní Věstonice IIa	14.5%	10.4%
DVI5	Dolní Věstonice II-05	12.2%	8.0%
FUMAN	Grotta di Fumane	12.4%	12.4%
GEISSE	Geissenklösterle	17.2%	11.5%
HENRY	Henryków 15	18.0%	15.2%
HOHLE	Hohle Fels	16.1%	11.3%
HUCCOR	Huccorgne - Hermitage	10.7%	9.7%
KOST8	Kostënki 8	4.4%	0.8%
KRE_H	Krems-Hundssteig	15.0%	12.8%
KRE W	Krems-Wachtberg	16.3%	13.0%
MAISI	Maisières Canal	16.1%	12.1%
MIRA	Mira	10.6%	3.0%
MITOC	Mitoc-Malu Galben	13.4%	11.4%
MOLO	Molodova V	7.6%	4.7%
PAGLI	Grotta Paglicci	9.3%	9.3%
PATAUD	Abri Pataud	21.2%	12.2%
POIAN	Poiana Ciresului	9.9%	7.3%
RANIS	Ranis	35.8%	28.8%
RS	Rio Secco	15.2%	12.4%
SIRE	Le Sire	6.0%	3.7%
SIRG	Sirgenstein	17.6%	12.9%
SOLUT	Solutré	28.8%	18.5%
TARTE	Tarte	7.6%	5.4%
VB	Vale Boi	19.7%	14.0%
WILEND	Willendorf II	16.4%	13.8%

Table 6: Percentages of positive results obtained in regression analyses when using 1000 sets of random chronological data and real PD_HR values between all sites. Note the large differences between results for e.g. AK/KOST8 and RANIS.

data and ran regression analyses using each set of random chronological data and the PD_HR path distance data used above (PD_HR data was used rather than PD_DIST because it was available for all site pairs). We repeated these analyses using *all* sites as potential origin sites. We then summarized the results by counting the number of instances where $r \ge 0.5$ and p < 0.05, and where $r \ge 0.6$ and p < 0.05. All code is provided in SI 5.10.

4.2 Results

The results were very surprising. Rather than the percentage of positive results being approximately the same regardless of which site was used as the origin, there was in fact an extremely large range of variation (Table 6; SI 10). Taking a "positive" result as one where $r \ge 0.5$ and p < 0.05, such results were obtained 3.8% of the time when using Antoliñako Koba as the origin, and 35.8% of the time when using Ranis as the origin, i.e. almost ten times as often. This is obviously a troubling observation, as it suggests that it is far easier to obtain positive results when using certain sites as the origin than others.

The reason for this must lie somewhere in the geographical structuring of the sites. Figure 6 depicts the summary results. We can note that all the origin sites with very high rates of positive results are found in France and Germany; on the other hand, origin sites in Eastern Europe tend to give lower rates of positive results. However, the geographical clustering is not perfect. We suspected that the binning process was affecting the outcomes of the regressions, and creating the wide disparities we see between origin sites in their results. We postulated that in cases where there were more sites closer to the origin site than distant from it, the likelihood of obtaining positive results in the regression analyses would be increased. This is because the binning process excludes younger sites from analysis in bins where more than one site is found. All else being equal, there is a positive correlation between the number of sites found in a bin and the average age of the site retained for analysis from that bin. If there are more sites in the bins closer to the origin site will, on average, be older than those distant from the origin site, and hence it will be more likely that a positive result be obtained in the regression analyses.



Figure 6: Summary of results of regression analyses using random chronological data. The circles for each site indicate the percentages of results where $r \ge 0.5$ and p < 0.05 when using that site as the origin.

We examined histograms of the number of sites in each 120 ks bin for each origin site (all histograms provided in SI 11), which appeared to support our conjecture. We calculated the ratio between the number of sites in the first quarter of non-empty bins and the number of sites in the last quarter of non-empty bins, for each origin site. For example, for Huccorgne (Fig. 7), where there are 7 sites in the first quarter of the non-empty bins and 4 sites in the last quarter, the ratio is 1.75. We then carried out linear regressions to study the relationship between these values and the percentage of positive results obtained in the simulations.

The results (Fig. 8 and SI 12) demonstrate a clear correlation between bin structure and the ease of obtaining positive results. Where there are many sites in the bins closest to the origin site and few sites

HUCCOR: sites per 120ks bin



Figure 7: *Histogram showing numbers of sites per bin when using Huccorgne as the origin site, with first and last quarters of bins coloured grey.*

in the bins distant from the origin site, the rate of obtaining "positive" results in the regression analyses tends to be high. The inverse is also true.

This observation has major ramifications. It suggests that, where sites are distributed non-randomly and there are a small number of sites per bin (as is usually the case for Palaeolithic studies) linear regression results may be strongly affected by the filtering effects of any binning process, and the effects will vary between origin sites. This casts serious doubt on the appropriateness of this method for such studies.

A full investigation of the effects of differing bin sizes, geographical structuring, etc., in the general case is beyond the scope of the current paper. In principle it should be possible to fully quantify the effects of bin structure on linear regression studies of this type, and to establish thresholds for bin size, data quantities, etc. beyond which these effects become negligible. The effects of differing levels of precision in radiocarbon dates and calibration curves could also be modelled to help establish minimum



Ratio between numbers of sites in first and last quarters of 120ks bins

Figure 8: Comparison of the ratios between numbers of sites in first and last quarters of the 120ks bins again the percentage of "positive" results obtained when using random chronological data, for each origin site.

standards for the use of such data. In the present study, however, our observations suggest that linear regression approaches are not appropriate to test hypothesised dispersals associated with the earliest Gravettian assemblages.

5. Discussion

The data and methods reviews and replication studies described above provide interesting counterpoints to the results presented by Bicho et al. (2017). Our approach to interpreting our results is also rather different from theirs.

There is a substantial existing literature on the use of linear regressions to model demic and cultural dispersal dynamics in archaeology, including for the beginning of the Neolithic across Europe, the Late Glacial recolonization of Northern Europe, and the spread of Clovis traditions in North America (e.g. Gkiasta et al. 2003; Fort et al. 2004; Pinhasi et al. 2005; Hamilton & Buchanan 2007; Collard et al. 2010; Jerardino et al. 2014). The methods used in such analyses are well-described in numerous publications (e.g. Hazelwood & Steele 2004; Steele 2009, 2010; Fort et al. 2015). To summarize, this approach involves linear regression analysis of the relative ages of a series of sites and their distances from a putative origin. Studies vary in which precise type of regression analysis they use, in whether they select the oldest sites according to spatial bins, in the assigning of chronological values to sites (especially in how point values are chosen) and in the calculation of distances from the origin. However, the usual aim of such analyses is to calculate an average speed of advance associated with the spread of a particular type of assemblage. The results are typically used to discern the likely mechanism of spread (e.g. demic dispersal or cultural diffusion) and, often, the most likely geographic origin of the tradition. High r-values and low p-values are often also taken as indications that the general model of spread is accurate.

Turning to the present study and looking at the results obtained when using Chronological Dataset 1, we can see that the values obtained using Grotta Fumane and Henryków 15 as origins are superficially satisfactory, with high correlation coefficients and p-values <0.05, which are robust with respect to bin size (Table 4). However, these results were produced using chronological data that is, as argued above, likely incorrect: we do not believe that the very old dates for these sites really reflect the age of Gravettian activity there. We would suggest that these results show the ease of obtaining spurious

positive results using this method, not that the very old dates for Grotta Fumane and/or Henryków 15 are in fact correct.

For Chronological Dataset 2, we obtained high correlation coefficient values and low p-values when using the site of Rio Secco as an origin, which appear robust with respect to bin size (Table 5). However, we are not convinced either that these results demonstrate that Rio Secco represents the geographical origin of Gravettian traditions. Our basis for doubt can be found in examination of the regression plots themselves (Figures 9–11). Here we present the plots produced when using the PD_HR (travel time) distance values and 120 ks bins; all other plots are provided in SI 8.



Travel time from origin site (hrs)

Figure 9: Plot of inter-site LCP travel time against age differences (using Chronological Dataset 2 values) with Molodova V as origin.

If we look first at Figure 9, using Molodova V as the origin, we can see that the correlation coefficient is extremely low: r = 0.02. However, this low value is largely caused by the Poiana Cireșului, Mira and Mitoc-Malu Galben datapoints, which are geographically very close to Molodova but far younger. If we exclude these three sites from the analysis, we get very different results, with r values > 0.65 and p values < 0.05 (code: SI 5.9; results: SI 7.7). The fact that these three sites (which are some of the latest in the entire dataset and arguably say nothing about the spread of the earliest Gravettian traditions) can affect the results so strongly illustrates one of the weaknesses of this type of analysis. The extremely sparse distribution of sites in this case means that relatively young sites are not necessarily excluded during the binning process.





Figure 10: Plot of inter-site LCP travel time against age differences (using Chronological Dataset 2 values) with Rio Secco as origin. Linear regression line shown in light grey.

We turn now to Figure 10, using Rio Secco as the origin. In this case we obtained a fairly high correlation coefficient: r = 0.692 (p < 0.05). However, the regression line does not fully describe the relationships between site age and distance from Rio Secco in this plot. In particular, if we look at the oldest three sites plotted (Rio Secco, Le Sire and Molodova V) then we can see that their distribution diverges strongly from the regression line obtained for the dataset as a whole. The linear regression results obtained here reflect the trend that sites that are distant from Rio Secco tend to be younger than those that are closer. However, the most important sites for understanding the earliest distribution of Gravettian sites must be the oldest ones, and here we can see that these sites do not adhere to the general



Origin: SIRE; path data: PD_HR_SIRE; chronological data: REL_AGE_CHRONO_DATA_2_SIRE; bins: BIN_120ks_SIRE; r = 0.442; p = 0.15

Travel time from origin site (hrs)

Figure 11: Plot of inter-site LCP travel time against age differences (using Chronological Dataset 2 values) with Le Sire as origin.

trend followed by the rest of the data: rather, they are extremely close in age but distant in space. The same argument can also be made when using Molodova V (Fig. 9) or Le Sire (Fig. 11) as the origin.

Essentially, we argue that the results of these regression analyses do not accurately describe the spread of Gravettian traditions in Europe, beyond perhaps showing that the oldest sites in the periphery of Europe are mostly younger than the oldest sites in other regions. In all cases the oldest sites in the dataset, which must be the most important for understanding the processes of interest, appear to follow a different trend than the overall linear regression.

Problems with linear regressions as reflections of the spread of traditions have previously been recognised for other cases, such as the spread of farming in Europe, where it is now well-understood that the speed of advance of these traditions was not uniform across Europe and thus that the results obtained from linear regressions can only represent averages for the entire continent, not reflecting regional or local processes (Zilhão 2001; Fiedel & Anthony 2003). As a result, researchers have turned to other methods to model and represent waves of advance, such as simulations, vector maps and interpolation of data (e.g. Bocquet-Appel et al. 2009; Fort et al. 2012; Isern et al. 2017).

There are other criticisms that could be raised concerning the approach used by Bicho et al. and replicated here. One key problem concerns the validity of using a single integer value, derived from a single calibrated radiocarbon date, to represent the age of an assemblage. This practice prevents proper expression of the inherent uncertainty of these dates, and hence of spatiotemporal models based on them. The use of single dates rather than multiple dates also means that our chronological evaluation of archaeological layers is inappropriately limited. To solve the latter problem, the combination of dates for a single layer using Bayesian or other approaches may help. However, this needs to be carried out with careful attention to the particular taphonomic circumstances at each site, and critical evaluation of the available dates. Finally, the rather arbitrary decisions to exclude non-AMS dates and those with standard errors of >500 years means that certain datapoints are excluded despite their possible importance (e.g. the dates for Weinberghöhle and the older date for Willendorf; Jöris et al. 2010; see also Table 1). Although the AMS method offers a significant advantage over non-AMS methods in

terms of sample size, it is not correct to assume that non-AMS results are systematically less accurate than AMS results (Scott et al. 2010a, 2010b).

6. Conclusions

First, we reject the conclusions of Bicho et al. (2017) that Gravettian traditions originated in Central Europe, that they spread very slowly, and that population density was very low at the beginning of the Mid Upper Palaeolithic. Rather, our results suggest that Gravettian traditions may have spread very quickly in Europe from an unknown origin, but these inferences remain speculative due to the sparseness of our dataset and our doubts concerning the robusticity of the methods used.

There are several assemblages with dates of 29,500–29,000 ¹⁴C BP (34,000–33,000 cal BP) included in this study: Rio Secco, Le Sire, Molodova V, Henryków 15, and Hohle Fels (Figure 12). These sites are distant in space, from France to Ukraine and Germany to Italy. Their distribution strongly suggests that the spread of Gravettian traditions could have taken place very rapidly – possibly within a few hundred years – across most of Europe. This should perhaps not be surprising: subject to the substantial caveats discussed above, the longest journey time calculated in this study between any two sites (from Kostënki 8/II to Vale Boi) was only around 109 days, assuming eight hours of walking per day. The date that we suggest for the first appearance of Gravettian assemblages, of ca. 29,500 ¹⁴C BP, is in line with the conclusions of previous studies that examined Gravettian chronology within the relatively well-studied region of Central Europe, using a somewhat different corpus of dates, including non-AMS measurements (Jöris et al. 2010; Moreau & Jöris 2013).

At the periphery of the Gravettian distribution (northwestern Europe, Russia and Iberia) there are no Gravettian sites in our dataset pre-dating 29,000 ¹⁴C BP. This does not necessarily reflect a real lag in the appearance of Gravettian traditions in these regions, and may be the result of the incompleteness of this study, or of research history, geology, or other factors. Only one early Gravettian site is known in Russia and the chronology of this extremely sparse record should not be over-interpreted (Reynolds et



Figure 12: Calibrated radiocarbon ages for older dates from Chronological Dataset 2. Brackets below probability distributions show 68.2% and 95.4% probability ranges. Dates calibrated against IntCal13 using OxCal 4.3 (Bronk Ramsey 2009; Reimer et al. 2013).

al. 2015). The thick LGM loess deposits found in much of Eastern Europe (Haase et al. 2007; Romanowska 2012) may have hampered the discovery of sites of early Gravettian age. In northwestern Europe, where interpretation of the earliest Gravettian assemblages is complicated by their techno-typological peculiarities, the record is also relatively sparse, but other authors have also concluded that there appear to be no Gravettian assemblages dating to before ca. 29,000 ¹⁴C BP (e.g. Jacobi et al. 2010; Pesesse & Flas 2011; Touzé 2016; Touzé et al. 2016). In Iberia, on the other hand, we can note that very early dates have now been published for Gravettian layers at several sites in the Basque country (Marín-Arroyo et al. 2018) although these appeared too late for consideration in this study.

More generally, we have several conclusions and recommendations regarding the methods and approach used by Bicho et al.

First, it should be clear from this study that the uncritical use of radiocarbon date information from large databases should be avoided unless the risks of doing so are well understood and controlled for. There is no substitute for a detailed understanding of individual sites, particularly with respect to sample association and taphonomy.

Second, the use of cost modelling in studies such as this needs careful consideration. As discussed above, there are numerous theoretical shortcomings in the use of simple anisotropic least-cost-path modelling to model the relative costs of various paths for real past landscapes. However, the extremely similar values obtained for the regression analyses whether modelled travel time, modelled path length or Euclidean distance was used (Tables 4, 5) suggests that the former two datasets in fact add little value to the study. The use of such techniques may in some cases add to the complexity of a research study without in fact being analytically useful. This is perhaps especially the case where data is ultimately intended for use in linear regression analyses, which may tend to average out the differences between LCP and Euclidean values. We recommend that future studies using cost modelling include a comparison with results obtained using Euclidean values, so that the appropriateness of LCP techniques can be better weighed in the future.

Third, the use of regression approaches to modelling the spread of traditions in the archaeological record perhaps requires more critical attention than it has previously received. Despite the long history of this sort of analysis, and its apparent success in certain cases, it remains a rather blunt instrument for understanding complex processes of demic dispersal and cultural diffusion. In particular, we remain sceptical that the obtention of high r-values and low p-values necessarily indicates that a linear regression is a faithful representation of a vector of advance. The ease of obtaining probably spurious positive results in this study suggests that the method has definite limitations for hypothesis testing. We recommend that, at a minimum, positive results obtained using this approach are supported by publication of actual plots, not just r and p-values, and that residuals analyses are performed where appropriate.

Regarding the application of these approaches to Upper Palaeolithic case studies, in our view it remains to be demonstrated that the details of Upper Palaeolithic demic and diffusion processes can be confidently identified in the archaeological record given the sparseness of the record and our current level of chronological resolution (Zilhão & d'Errico 2003: 344–345; Teyssandier & Zilhão 2018). The archaeologically recent example of the rapid replacement of the Dorset culture by the Thule in Arctic North America – which took place over at most a few hundred years – shows that demic and cultural replacement among hunter-gatherers can take place very quickly over very large areas (McGhee 1984; Fitzhugh 1997; Raghavan et al. 2014). The task of describing a process like this for the beginning of the Mid Upper Palaeolithic – where our chronological resolution remains limited and our corpus of sites is relatively small – needs to be approached with ample recognition of our epistemological limits. The study of these processes during the Late Pleistocene may require the development of new methods tailored to sparse datasets that, unlike the methods discussed here, can take into account chronological uncertainty, and provide a firm focus on the precise relationships between the oldest sites under study.

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Data availability statement

All data and code used in this research is available in the SI and at doi.org/10.17605/OSF.IO/6XRTS.

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