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Quaternary Science Reviews 287 (2022) 107562

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Assessing anthropogenic influence on fire history during the Holocene in the Iberian Peninsula

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ARTICLE INFO

Article history:
Received 20 December 2021
Received in revised form
22 April 2022
Accepted 8 May 2022
Available online 2 June 2022

Handling Editor: Giovanni Zanchetta

Keywords:
Fire history
Population reconstructions
Human impact
Sedimentary charcoal
Radiocarbon data
Neolithic agriculture
Superposed epoch analysis

ABSTRACT

The relative importance of climate change and human activities in influencing regional fire regimes during the Holocene is still a matter of debate. The introduction of agriculture during the Neolithic provides an opportunity to examine the impact of human activities on fire regimes. Here, we examine changes in fire regimes across Iberia between 10,000 and 3500 cal. BP, reconstructed using sedimentary charcoal records. We compare the regional fire history with estimates of changes in population size, reconstructed based on summed probability distributions of radiocarbon dates on archaeological material. We also compare the fire records and population reconstructions with the timing of the onset of agriculture across the region as indicated by archaeological data. For Iberia as a whole, there are two intervals of rapid population increase centred on ca. 7400 and ca. 5400 cal. BP. Periods of rapid population growth, either for the region as a whole or more locally, do not closely align with changes in charcoal accumulation. Charcoal accumulation had already begun to increase ca. 400 years prior to the onset of the Neolithic and continued to increase for ca. 750 years afterwards, indicating that changes in fire are not directly associated with the introduction of agriculture. Similarly, there is no direct relationship between changes in charcoal accumulation and later intervals of rapid population growth. There is also no significant relationship between population size and charcoal accumulation across the period of analysis. Our analyses show that the introduction of agriculture and subsequent increases in population are not directly linked with changes in fire regimes in Iberia and support the idea that changes in fire are largely driven by other factors such as climate.

1. Introduction

People affect modern fire regimes in various ways, directly by altering the timing and number of ignitions or suppressing fires, and indirectly by altering fuel types, and through changing fuel structure and fuel continuity (Bowman et al., 2011; Archibald, 2016). Land use changes, for example, have been linked to increased frequency of forest fires in the Brazilian Amazon as a result of deforestation (Brando et al., 2020; Cardil et al., 2020), and to an increasing likelihood of larger more intense wildfires in Iberia following agricultural abandonment (Lloret et al., 2002; Pausas and Fernández-Muñoz, 2012). The magnitude of human influence on fire regimes before the recent period is, however, still debated. Several global and regional studies have shown that climate was the dominant driver of changes in fire regimes during the Holocene (e.g. Marlon et al., 2006, 2008, 2013; Power et al., 2008, 2010; Mooney et al., 2011; Daniau et al., 2012). However, human influence has been identified as an important factor in determining Holocene fire history at a local or regional scale (e.g. Scharf, 2010; Vannière et al., 2011; Feurdean et al., 2013; Innes et al., 2013; Zennaro et al., 2015; Dietze et al., 2018; Connor et al., 2019; Gajewski et al., 2019). There are also contrasting conclusions about the influence of people on fire history in Iberia during the early and middle Holocene, with some studies pointing to a limited influence (e.g. Gil-Romera et al., 2010; Burjachs and Expósito, 2015) and others suggesting humans had a major role, particularly through

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https://doi.org/10.1016/j.quascirev.2022.107562

the introduction of agriculture during the Neolithic (e.g. Carracedo et al., 2018; Connor et al., 2019).

Although there are several tools to reconstruct fire history, including historical written records, dendrochronological fire-scar data and chemical markers (Conedera et al., 2009), charcoal preserved in sedimentary sequences is the most widely used approach to investigate fire over millennial timescales and at different spatial scales. However, research that has made use of sedimentary charcoal together with other lines of palaeo-evidence to reconstruct and investigate changes to fire history in Iberia has either focused on individual sites (e.g. Abel-Schaad and López-Sáez, 2013), small regions (e.g. Gil-Romera et al., 2010; García-Alix et al., 2013; Burjachs and Expósito, 2015) or have only used a limited number of records to represent the whole peninsula (e.g. Connor et al., 2019), thus raising the concern that they may not provide a complete picture of the regional fire history.

Human influence on the environment during the Holocene is reflected in changes in land use. These land use changes have been reconstructed in Iberia using pollen data (e.g. Mighall et al., 2006; Revelles et al., 2015; Fyfe et al., 2019), with the appearance of cereal pollen being considered a marker of Neolithic agriculture (e.g. Peña-Chocarro et al., 2005; López-Merino et al., 2010; Cortés Sánchez et al., 2012). However, most pollen records have a limited representation of non-cereal crops and thus may not provide a complete picture of agricultural activities (Trondman et al., 2015). Although fungal spores associated with animal faeces have been used to identify the presence of domesticated animals (e.g. López Sáez and López Merino, 2007; Revelles et al., 2018), land-use transformations as a result of grazing are often identified by the presence of weed plants (e.g. Palmisano et al., 2019; Woodbridge et al., 2019), which can also indicate non-anthropogenic disturbances (Trondman et al., 2015; Roberts et al., 2019). As a result, there can be large uncertainties associated with pollen-based reconstructions of anthropogenic land-use changes.

An alternative approach to reconstruct land-use changes though time involves modelling land use as a function of historical population change and estimates of per capita land use (e.g. Kaplan et al., 2011; Klein Goldewijk et al., 2011; Klein Goldewijk et al., 2017), where increases in population density are assumed to reflect increasing human influence on the environment. However, establishing absolute historical population levels is challenging and estimates before the 1700s are extremely uncertain (Klein Goldewijk et al., 2010). An alternative method is to estimate relative changes in population size based on fluctuations in the quantity of radiocarbon-dated archaeological material (Rick, 1987). This technique has been used extensively to reconstruct changes in population size for Iberia as a whole (e.g. Balsera et al., 2015; Blanco-González et al., 2018; Fernandez-Lopez de Pablo et al., 2019) and for smaller regions of the peninsula (Drake et al., 2017; Fyfe et al., 2019; McLaughlin et al., 2021) for different time periods.

Radiocarbon-dated archaeological material has the additional advantage that the dates are normally associated with particular cultures and can thus be used, for example, to identify the start of Neolithic agriculture at a specific site. This is particularly important because the introduction of agriculture was not a single event. The earliest evidence of Neolithic agriculture in Iberia is dated to ca. 7600 calendar years before 1950 CE (cal. BP) (Zapata et al., 2004; Bernabeu Aubán et al., 2015; Silva and Vander Linden, 2017; Fyfe et al., 2019). Agriculture was established initially in the south and east of the peninsula and spread from there, with the earliest evidence of farming in the northwestern part of the region dated to around 6000 cal. BP (Isern et al., 2012, 2014; Drake et al., 2017). This long and spatially uneven dispersal provides a further means to assess human influence, as the introduction of agriculture has been linked to significant land-use changes in several areas of Europe (e.g. Lechterbeck et al., 2014; Marquer et al., 2014; Woodbridge et al., 2014; Revelles et al., 2018).

In this paper, we investigate the relationship between humans and fire during the Holocene period, using a dataset of 32 sedimentary charcoal sites from the Iberian Peninsula and a reconstruction of changes in human population based on more than 6300 published radiocarbon samples. We focus on the early to middle Holocene, between 10,000 and 3500 cal. BP, because of constraints in the amount of radiocarbon data after this time. We focus on relationships at a regional scale, accounting for the fact that the start of the Neolithic was asynchronous, in order to evaluate relationships statistically and reduce the noise associated with site-level differences in registration. We do not assume that the relationship between human population changes and fire is necessarily the same everywhere or consistent through time, only that some impact will be apparent in the fire records if there is a causal link between the two. Through comparison of the sedimentary charcoal and archaeological radiocarbon date records, we address the following questions: 1) Are rapid changes in population reflected in changes in fire? 2) Is there a relationship between fire and the onset of agriculture in Iberia? 3) Is there a relationship between population size and changes in fire?

2. Materials and method

2.1. Fire history

We used sedimentary charcoal extracted from the Reading Palaeofire Database (Harrison et al., 2022) to reconstruct the fire history of Iberia. The RPD provides Bayesian age-depth models for each of the records using the INTCAL20 Northern Hemisphere (Reimer et al., 2020) and Marine20 (Heaton et al., 2020) calibration curves as appropriate (see Harrison et al., 2022). There are 54 records from 39 sites across Iberia with charcoal data covering some part of the period between 10,000 and 3500 cal. BP. Multiple records are available from some sites, either because different charcoal size factions were counted to distinguish local from regional fires or, for one site, because multiple sedimentary cores were taken. We selected a single record to represent each site. For the single site with multiple sedimentary cores, we selected the record with the greatest number of sampled radiocarbon ages for age-depth modelling purposes. For the other sites with multiple records, we gave preference firstly to records with the greatest number of charcoal samples and secondly to macro-charcoal records, which are believed to be more likely to indicate local fires (Clark and Patterson, 1997). However, analysis of charcoal composites for sites with multiple records shows no substantial differences when including either micro- or macro-charcoal sites (see Supplementary Information, S1). We subsequently excluded four sites at elevations above 2000m because there are relatively few archaeological sites above this elevation and the amount of both charcoal and radiocarbon data is thus insufficient to draw conclusions about the relationship between fire and human influence. For data quality control purposes, we additionally excluded a further three sites that contained less than five charcoal samples within the time range of analysis, as they provide a limited record of fire history. Thus, the final analyses were based on 32 records (Fig. 1; Table 1). We imposed no limit on the minimum length or sampling resolution of each record since we use binned data in our subsequent analysis, but every record provided information for a minimum of six 100-year bins and the average number of 100-year bins per record was 28. Each record had at least one dating tie-point per 3000 years for the construction of the age model, with 70% having a dating tie-point every 1500 years on average.

We constructed a regional composite curve from the individual

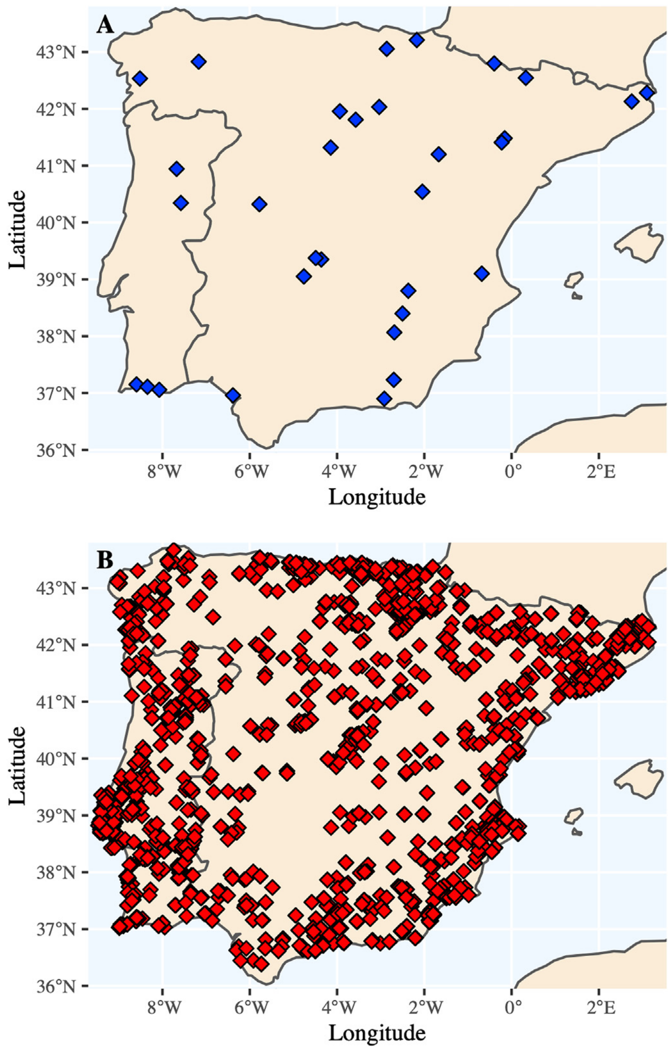

Fig. 1. Maps of Iberia showing the locations of the charcoal (A) and archaeological (B) sites.

sedimentary charcoal records. This curve was constructed in three steps, following a modified version of the protocol described by Power et al. (2008). Firstly, individual samples were converted into influx (i.e. particles/cm^2/year), re-scaled by site using a max transformation, Box-Cox transformed to homogenise inter-site variance, and then converted to z-scores using a base period of 200−8200 cal. BP, to ensure that each site has a common mean and variance. We used a max transformation rather than the minimax transformation used by Power et al. (2008) to take account of zero values of charcoal accumulation; the impact of this difference on the composite charcoal curve is almost imperceptible (see S2). The base period was chosen to maximise the number of cores used for analysis; previous research has shown that the length of the base period does not significantly affect the composite curve (Power et al., 2010). Secondly, data from individual records were binned into 100-year bins. This reduces the potential impact of high-resolution sampling at individual sites on the composite curve (Marlon et al., 2008). The 100-year bin width was chosen as a compromise between maximising the temporal resolution of the composite curve and ensuring sufficient data coverage. Since choice of bin width could affect the final composite curve, we investigated the impact of using different bin widths (see S3). Finally, a locally fitted regression ("LOCFIT": Loader, 2020) with a 500-year smoothing (half) window was fitted to the data. This step reduces the potential impact of outliers on the shape of the composite curve (e.g. Daniau et al., 2012). The 500-year smoothing window was chosen to emphasise the millennial trends in the data; the influence of using a shorter 250-year (half) window and a longer 1000-year (half) window width was investigated. Bootstrap resampling (with replacement) of individual records 1000 times was performed to generate 95% confidence intervals for the composite curve (Marlon et al., 2008; Mooney et al., 2011).

The code and general approach used in this data treatment was based on amendments of R scripts developed by Bartlein (n.d.) (see https://pjbartlein.github.io/GCDv3Analysis/index.html) for analysis of the Global Charcoal Database v3 (Marlon et al., 2016), available for the R statistical language (R Core Team, 2021) (see section Data availability).

2.2. Population change and the spread of neolithic agriculture

We used the quantity of radiocarbon dated material to reconstruct changes in population size. The use of radiocarbon dated material in this way is based on a chain of inference whereby 1) a larger population would leave a larger amount of radiocarbon datable material; 2) a larger amount of material would lead to a greater amount of that material being preserved; and 3) the greater amount of material would lead to a greater chance that this would be discovered through archaeological study and then processed for radiocarbon dating (Rick, 1987). Relative changes in population size are then estimated through the creation of a summed probability distribution (SPD) of the aggregated calibrated radiocarbon dates through time.

The robustness of this "dates as data" approach is largely dependent on using the maximum amount of data available for a region (Williams, 2012). We assembled data from recently published sources (Table 2) to create a dataset for analysis. The dataset was cleaned to remove duplicates, to correct errors e.g. in geographic location, to remove dates with standard errors >200 years (following e.g. Fernandez-Lopez de Pablo et al., 2019; McLaughlin et al., 2021) and to remove dates on marine shells where no local marine reservoir correction was provided. To align with the charcoal data, any dates from sites above 2000m were removed. Where discrepancies between the datasets were apparent, we tried as far possible to use the most recently published dataset. The final consolidated dataset consisted of 6343 radiocarbon samples from 1615 sites (Fig. 1, see section Data availability). Analyses were not performed for the period after 3500 cal. BP because of the limited number of radiocarbon dates available after this time from Iberia, as site chronologies for the late Holocene are generally established using cultural dating techniques such as typo-chronology (Fyfe et al., 2019) (see S4 for details of the quantity of radiocarbon material available through time).

An SPD was constructed using the radiocarbon data and the R package *rcarbon* (v1.4.2: Crema and Bevan, 2021). Radiocarbon date calibration was performed using the calibration curve IntCal2020 (Reimer et al., 2020) and the Marine20 curve (Heaton et al., 2020) for marine shell samples with the associated local marine offset value adjustment. The site data were binned using 100-year bins to create a single probability value to prevent site oversampling (Shennan et al., 2013). Dates were not normalised; this avoids spurious spikes in the data linked to the shape of the calibration curve (Weninger et al., 2015). The SPD was smoothed using a 200-year running mean, to limit both the potential for sampling error and for the calibration process to create spurious spikes (Shennan et al., 2013), whilst at the same time proving sufficient detail to identify key trends. The *rcarbon* package was used to construct a fitted exponential model of population growth based on a Monte

Table 1
Information about the charcoal sites used for analyses. Latitude and longitude are given in decimal degrees where N and E are positive, and W is negative. Note that site names reflect site data within the Reading Palaeofire Database, which does not include diacritics.

Site name	Lat. (°)	Lon. (°)	Elevation (m a.s.l.)	Depositional context	Charcoal methods	Record length between 10–3.5k (age ka)	Resolution (samples/age ka)	No. of 100-year bins represented between 10–3.5k (age ka)	Citation
Alvor Estuary Ribeira do Farelo Ribeira da Torre	37.15	−8.59	1	estuarine sediment	macro, pollen slide	4.36	7.57	29	Schneider et al. (2016, 2010)
Arbarrain Mire	43.21	−2.17	1004	bog sediment	macro, sieved	3.35	11.34	31	Pérez-Díaz et al. (2018)
Armacao de Pera Ribeira de Alcantarilha	37.11	−8.34	2	estuarine sediment	macro, pollen slide	4.16	1.68	7	Schneider et al. (2016, 2010)
Basa de la Mora	42.55	0.33	1906	lake sediment	micro, pollen slide	6.36	15.72	54	Pérez-Sanz et al. (2013)
Campo Lameiro	42.53	−8.52	295	soil	micro, sieved	6.37	3.45	22	Kaal et al. (2008)
Canada de la Cruz	38.07	−2.69	1595	lake sediment	micro, pollen slide	5.88	2.72	14	Carrión et al. (2001b)
Canada del Gitano_Sierra de Baza	37.23	−2.7	1900	bog sediment	micro, pollen slide	4.98	12.65	48	Carrión et al. (2007)
Castello Lagoon	42.28	3.1	2	other	macro, sieved	1.29	12.40	9	Ejarque et al. (2016)
Cha das Lameiras	40.94	−7.68	950	soil	macro, other	5.28	2.84	15	López-Sáez et al. (2017)
Charco da Candieira	40.34	−7.58	1409	lake sediment	micro, pollen slide	6.57	17.81	65	Connor et al. (2012); van der Knaap and van Leeuwen (1997, 1995)
Cubelles	41.2	−1.67	2	other	macro, not known	2.46	5.28	12	Riera-Mora and Esteban-Amat (1994)
El Brezosa	39.35	−4.36	733	bog sediment	macro, sieved	0.52	125.00	6	Morales-Molino et al. (2018)
El Carrizal	41.32	−4.14	860	lake sediment	micro, pollen slide	4.57	3.50	16	Franco-Múgica et al. (2005)
El Perro mire	39.05	−4.76	690	bog sediment	macro, sieved	1.17	15.38	13	Luelmo-Lautenschlaeger et al. (2019a, 2019b)
El Portalet	42.8	−0.4	1802	bog sediment	macro, sieved	2.64	70.08	27	González-Sampériz et al. (2006)
Espinosa de Cerrato	41.96	−3.94	885	other	micro, pollen slide	6.55	12.82	65	Morales-Molino et al. (2017)
Hinojos Marsh	36.96	−6.39	2	bog sediment	macro, pollen slide	1.28	22.66	13	López-Sáez et al. (2018a)
Hoya del Castillo	41.48	−0.16	258	lake sediment	micro, other	4.37	18.08	41	Davis and Stevenson (2007)
Laguna Guallar	41.41	−0.23	336	lake sediment	macro, sieved	1.97	24.87	20	Davis and Stevenson (2007); (Davis, unpublished data)
Lake Banyoles	42.13	2.75	174	lake sediment	macro, sieved	5.34	18.54	53	Revelles et al. (2015)
Las Pardillas	42.03	−3.03	1850	lake sediment	macro, sieved	6.40	5.62	35	Sánchez Goñi and Hannon (1999)
Las Vinuelas	39.37	−4.49	761	bog sediment	macro, sieved	0.71	11.27	8	Morales-Molino et al. (2019)
Navamuno	40.32	−5.78	1505	bog sediment	macro, sieved	3.38	8.28	20	López-Sáez et al. (2020)
Navarres	39.1	−0.68	225	bog sediment	micro, sieved	6.48	8.95	53	Carrión and Van Geel (1999)
Ojos del Tremendal	40.54	−2.04	1650	bog sediment	micro, pollen slide	6.41	5.15	32	Stevenson (2000)
Pena da Cadela	42.83	−7.17	970	bog sediment	micro, pollen slide	1.76	11.26	18	Martinez Cortizas et al. (2002)
Sierra de Gador	36.9	−2.92	1530	bog sediment	micro, pollen slide	2.75	13.82	28	Carrion et al. (2003)
Siles Lake	38.4	−2.5	1320	lake sediment	micro, pollen slide	6.42	5.61	33	Carrion (2002)
Tubilla del Lago	41.81	−3.57	900			3.93	11.20	36	Morales-Molino et al. (2017)

Table 1 (*continued*)

Site name	Lat. (°)	Lon. (°)	Elevation (m a.s.l.)	Depositional context	Charcoal methods	Record length between 10–3.5k (age ka)	Resolution (samples/age ka)	No. of 100-year bins represented between 10–3.5k (age ka)	Citation
				bog sediment	micro, pollen slide				
Valle do Lobo Ribeira de Carcavai	37.06	−8.07	2	estuarine sediment	macro, pollen slide	4.85	9.90	26	Schneider et al. (2016, 2010)
Verdeospesoa	43.06	−2.86	1015	bog sediment	macro, sieved	5.97	1.01	6	Pérez-Díaz and López-Sáez (2017; 2019)
Villaverde	38.8	−2.37	870	bog sediment	micro, pollen slide	5.72	12.06	45	Carrión et al. (2001a)
High elevation sites									
Laguna de la Mosca	37.06	−3.32	2889	lake sediment	macro, sieved	4.86	27.16	34	Manzano et al. (2019)
Laguna de la Mula	37.06	−3.42	2497	lake sediment	macro, sieved	1.13	22.12	11	Jiménez-Moreno et al. (2013)
Laguna de Rio Seco	37.05	−3.35	3020	lake sediment	macro, sieved	6.56	25.04	66	Anderson et al. (2011)
Marbore	42.7	0.04	2612	lake sediment	micro, pollen slide	6.45	8.68	47	Leunda et al. (2017)

Table 2
Details of published archaeological radiocarbon data used for population analysis. Focus period refers to actual radiocarbon years BP.

Reference	Title	Dataset region	Approx. focus period (uncal. BP)
Balsera et al. (2015)	Approaching the demography of late prehistoric Iberia through summed calibrated date probability distributions (7000-2000 cal. BC)	Iberia	7k – 2k
Capuzzo et al. (2014) [a]	EUBAR: a database of ^{14}C measurements for the European Bronze Age. A Bayesian analysis of ^{14}C-dated archaeological contexts from northern Italy and southern France	Western Europe	4k – 2k
d'Errico et al. (2011) [a]	PACEA geo-referenced radiocarbon database	Europe	40k – 8k
Drake et al. (2017)	Regional demographic dynamics in the Neolithic transition in Iberia: results from summed calibrated date analysis	Iberia	9k – 6k
Hinz et al. (2012) [a]	RADON - Radiocarbon dates online 2012. Central European database of ^{14}C dates for the Neolithic and the Early Bronze Age	Europe	40k – 0k
Kniesel et al. (2014) [a]	Radon-B	Europe	4.5k – 2.5k
Manning et al. (2016) [a]	The cultural evolution of Neolithic Europe. EUROEVOL Dataset 1: sites, phases and radiocarbon data	Western Europe	8k – 4k
McLaughlin et al. (2021)	Late Glacial and Early Holocene human demographic responses to climatic and environmental change in Atlantic Iberia	West/Southwest Coast Portugal	20k – 5k
Pardo-Gordó et al. (2019)	Timing the Mesolithic-Neolithic transition in the Iberian Peninsula: the radiocarbon dataset	Iberia	8k – 5.5k
Vermeersch (2020) [a]	Radiocarbon Palaeolithic Europe database: A regularly updated dataset of the radiometric data regarding the Palaeolithic of Europe, Siberia included	Europe	From palaeolithic to modern

[a] Datasets accessed via R package *c14bazAAR* (Schmid et al., 2019).

Carlo conditional simulation. This was used to identify periods of growth (and decline) within the SPD significantly different from the fitted model (Timpson et al., 2014). The rate of change of the SPD was constructed using *rcarbon* based on change over a 50-year period, with statistical testing of the observed growth rates against fitted null model growth rates. Both exponential and logistic growth curves have been used as null models in previous work on Iberia (e.g. Balsera et al., 2015; Drake et al., 2017; Fernandez-Lopez de Pablo et al., 2019; Fyfe et al., 2019; McLaughlin et al., 2021). As the focus of our analysis is on deviations from longer-term population growth rather than testing variations in growth associated with the density dependent maximum or carrying capacity threshold, we used an exponential model. Furthermore, this specific model also takes into account, from a theoretical point of view, constant homogeneous taphonomic loss of archaeological sites, without having to resort to any other correction bias (Timpson et al., 2014).

Some 1343 radiocarbon samples from 430 sites that were explicitly tagged as associated with Neolithic material were used to identify the spatial pattern of the onset of agriculture across Iberia, on the assumption that evidence of the Neolithic represents the start of agriculture in an area, using kriging interpolation. This kriged Neolithic surface was then used to assign the first date of agriculture at each charcoal site. The kriging interpolation was necessary because (a) there are some charcoal sites that are not close to archaeological sites with Neolithic dates, and (b) the incomplete nature of the sampled archaeological record means the earliest Neolithic date at a particular site may not be coherent with that of other sites in the area. For example, the oldest Neolithic date from one site may be several thousands of years younger than for a neighbouring site. We pre-processed the data as follows. Where several dates from an archaeological site were identified as Neolithic, the oldest calibrated date was used except when a tagged sample had an age earlier than 7600 cal. BP, which is the generally accepted earliest date for the Neolithic in Iberia (Zapata et al., 2004; Bernabeu Aubán et al., 2015; Silva and Vander Linden, 2017; Fyfe et al., 2019). The site ages were compared to all sites within a 50 km radius, and only retained if they were the oldest date within this buffer zone. This approach filters out spatially unrealistic Neolithic dates, which is necessary to produce a non-singular fitted variogram model. The choice of a buffer size was based on balancing data inclusivity against spatial coherence: 50 km was the smallest buffer, and hence the largest number of surface points, that could produce a fitted model. The degree of spatial autocorrelation between the remaining 59 Neolithic surface points was then described using a variogram, using the R package *gstat* (v2.0-7) (Pebesma, 2004; Gräler et al., 2016) and a variogram model fitted based on the (weighted) mean squared difference between the model and variogram using the *gstat* default. The choice of model was however constrained by the accepted earliest start of the Neolithic in Iberia of 7600 cal. BP; there were several better fitting models that were excluded because of this constraint. An *Exponential* – type model was fitted to the variogram and used in the ordinary kriging interpolation. Although the general interpolation shape remains relatively coherent despite the choice of variogram model, there are small differences in the interpolated surface (see S5).

2.3. Analysis of fire, population and the onset of agriculture

2.3.1. General approach

To assesses the potential influence of people on fire regimes, we performed three statistical tests: Superposed Epoch Analysis (SEA) of the regional charcoal z-score composite focusing on times of rapid population change (Section 2.3.2) and associated with the time-transgressive start of the Neolithic (Section 2.3.3), and correlation analysis on segmented data (Section 2.3.4). In each case, we used appropriate tools to assess the impact of uncertainty in the data sources and to determine whether a signal emerged from the noise inherent in the records. These methods were designed to investigate relationships in a more robust manner than possible through simple visual comparison of the records. Our approach is to determine whether a relationship between fire and either rapid population growth, the spread of agriculture or population levels can be detected at a regional level to avoid possible differences between individual sites. Although we assume that a strong enough signal would be detectable at the regional scale, no assumptions have been made about the nature of any relationship.

2.3.2. Concurrent changes in rapid population growth and fire

Periods of rapid growth in population were identified as times when either the SPD was greater than the fitted null model, or the rate of change of the SPD was substantially different from the null model. These periods were compared with the timings of significant changes in mean values for the SPD, based on changepoint analysis. Changepoint analysis was performed using the R package *changepoint* (v2.2.2: Killick and Eckley, 2014), with the binary segmentation approach (Edwards and Cavalli-Sforza, 1965) used to identify the mean values of the SPD where changes occurred. We used Superposed Epoch Analysis (SEA) to examine the charcoal z-score time series in a 750-year time window before and after each key date. This approach identifies whether there are consistent relationships between the fire history and specific events (see e.g. Arneth et al., 2010; Daniau et al., 2010). To test whether a longer-term trend in the resulting composite curve could influence the results, we also detrended the z-score composite by fitting a simple linear regression to the composite curve and extracting the residuals. We generated a 95% confidence interval by making 1000 runs where the time point was randomly selected within a ±200-year window around each key date. This window was chosen to align with that used for the Neolithic analysis, which was itself determined by the maximum permitted dating error for radiocarbon samples within the archaeological radiocarbon dataset.

We ran an intervention analysis using autoregressive integrated moving average (ARIMA) modelling (Box and Tiao, 1975) to test whether there was an association between the key population dates and z-scores of charcoal accumulation, with post-epoch model forecasting compared to actual z-score values. ARIMA model forecasting was performed with R package *fable* (v0.3.1: O'Hara-Wild et al., 2021), with 750 years of annualised z-score composite values informing the auto generated model. Annualising the z-score composite was performed using cubic spline interpolation, with R package *zoo* (v1.8-9: Zeileis and Grothendieck, 2005).

2.3.3. Assessing the impact of the Neolithic

The interpolated surface of the timing of the start of the Neolithic was used to assign a date for the onset of agriculture at each charcoal site. For each site, the sample dates were then aligned to the associated Neolithic date. Z-score composites were then constructed based on these centred dates using the binning and smoothing procedures discussed above. Detrended composites were also constructed from simple linear regression of the composite, to test whether a longer-term trend in the curves affected the results. We tested the influence of the Neolithic surface on the shape of this curve by running the kriging interpolation 1000 times, with random ±200-year adjustments to the median calibrated dates of archaeological samples with Neolithic cultural tags. This 200-year adjustment was chosen because it was the maximum permitted error for the radiocarbon dates in the dataset. A Neolithic z-score charcoal composite was then re-calculated, and 95% confidence intervals assessed. Intervention analysis was performed on this Neolithic z-score charcoal composite curve using ARIMA forecasting, comparing the forecasted post-Neolithic curve to the actual z-score curve to assess whether an immediate significant change in the time series followed the spread of agriculture, using 750 years pre-epoch annualised data to inform the ARIMA model.

2.3.4. Changes in population size and fire

The SPD reconstructions provide an approximate measure of changes in population size through time. We assessed the relationship between population size and fire by comparing the SPD and the z-score of charcoal influx, both through visual inspection of the smoothed curves and through correlation analysis using unsmoothed data. Correlations were made by binning both the charcoal and the SPD data using 100-year bins. We then examined the correlations when values of the SPD and charcoal composite were above the 75% value, between the 75% and 25% value and below the 25% value, and also for the intervals identified by changepoint analysis as corresponding to significant changes in the mean values of the SPD.

3. Results

3.1. Fire and population change through time

3.1.1. Fire

The z-score composite of charcoal influx for the whole of Iberia (Fig. 2, 500-year smoothing window) shows an initial increase in fire between 10,000 and 9500 cal. BP, a decline in fire until 8800 cal. BP, followed by an increase and peak in fire around 8200 cal. BP. Fire then declines until 7600 cal. BP, after which it increases until 7000 cal. BP. Fire then declines once more until around 6500 cal. BP, after which there is a period of stability in fire until around 6100 cal. BP. Fire then declines further to a minimum around 5800 cal. BP. There is an increase in fire up to 4700 cal. BP, with a more rapid increase from 5800 cal. BP to 5200 cal. BP followed by a more gradual increase. Fire declines to a minimum around 3800 cal. BP, and the last part of the record is characterised by an increase in fire. This broad pattern is not affected by the choice of charcoal site bin width (see S3) or smoothing window (half) width (Fig. 2). However,

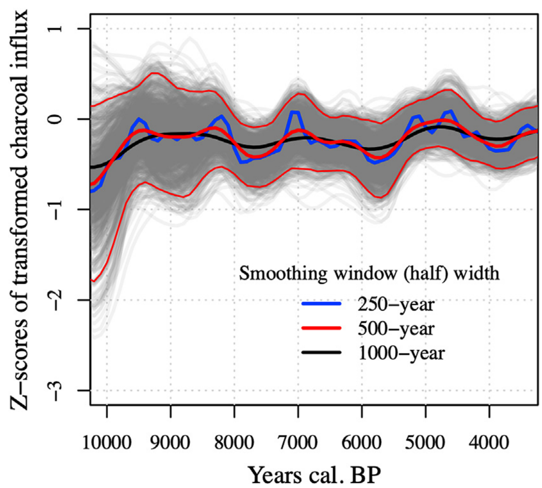

Fig. 2. Z-score composite of charcoal influx for Iberia, 10,000 to 3500 cal. BP. The solid lines show the median value, with smoothing windows of 500 (red), 250 (blue) and 1000 (black) years, the thin red lines show the 95% confidence intervals of 1000 bootstrap resample runs.

the inclusion of high elevation sites has a small but visible impact on the shape of the curve, suggesting these high-elevation sites had a different trend in charcoal accumulation (see S6). Changepoint analysis detected no differences in mean values across the period covered by the composite curve. However, the 95% confidence intervals generated by bootstrap re-sampling become slightly narrower through time, as a result of the increasing number of records included (see S7 for details of the number of records contributing to the composite curve through time). Across the period of analysis there is a marginal upwards trend in fire (see S8).

3.1.2. Population change

The SPD for Iberia between in 10,000 and 3500 cal. BP (Fig. 3) shows a general trend of increasing population through time, with changepoint analysis of the mean of the SPD identifying changes at ca. 7490 cal. BP and ca. 5320 cal. BP. The first episode of high growth occurs between ca. 7400 cal. BP and ca. 6880 cal. BP. This change broadly corresponds to the start of the Neolithic period in Iberia. Two periods of population decline in comparison to the exponential model occur from ca. 6400 to ca. 6220 cal. BP and from ca. 5560 to ca. 5370 cal. BP. Another period of higher growth occurs between ca. 4750 and ca. 4460 cal. BP, followed by a period of significant population decline between ca. 3720 cal. BP and the end of the record at 3500 cal. BP. The rate of change of the SPD likewise identified periods of high growth and population decline, the most important of which is the high rate of change between ca. 5370 to ca. 5160 cal. BP. This is the fastest rate of change in the record, but is not reflected in the SPD because it follows the decline in population that occurred between ca. 5370 to ca. 5170 cal. BP. The interval of growth at ca. 4730 cal. BP in the SPD is in part a reflection of this interval of high rate of change in population.

Given the broad consistency of the dates at ca. 7400 and ca. 5370 cal. BP with those identified by the changepoint analysis, these dates were used in the SEA analysis. The impact of using an exponential growth model rather than a logistic growth model had little impact on the identification on periods of rapid growth (see S9).

3.1.3. Relationship between changes in population and fire

While there is no obvious relationship between the SPD and the z-score composite curve of charcoal influx across the entire period

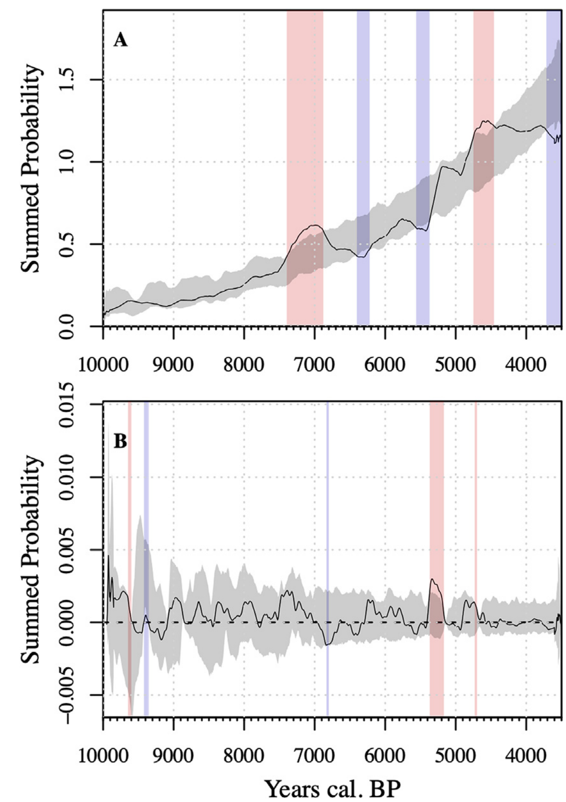

Fig. 3. (A) Summed probability distribution (black line) and exponential null model for Iberia (grey envelope) (10,000–3500 cal. BP) (B) Summed probability distribution rate of change and exponential null model for Iberia (10,000–3500k cal. BP), both constructed from radiocarbon data from archaeological sites; Deviations from simulated growth models are shown in red (positive deviation) and blue (negative deviation).

of analysis (Fig. 4), there are some time periods when peaks in the two records appear to align, most noticeably the peaks at ca. 7000 cal. BP. There are no significant correlations between population and fire activity across the whole record, or when the population data are segmented, either by quartiles or by time intervals between periods of rapid change (Table 3), and the sign of the relationship is inconsistent. Similarly, segmenting the dataset by charcoal quartiles generates no significant relationships (Table 3).

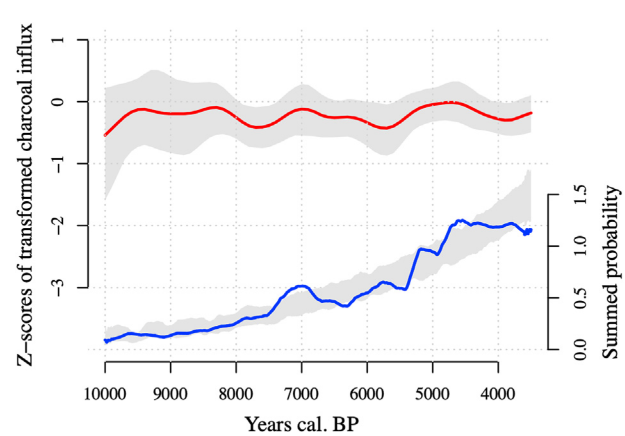

Fig. 4. Temporal comparison between z-scores of transformed charcoal influx and summed probability distribution for Iberia (10–3.5k cal. BP). Grey shading on the z-score composite curve shows the 95% confidence intervals of 1000 bootstrap resample runs; grey shading on the summed probability curve shows the exponential null model.

Table 3
Correlations between the SPD and z-score composite of charcoal influx for different segments of SPD and charcoal data.

Segmentation		Correlation (R)	P-value (sig ≤0.05)
All data		0.16	0.21
SPD	Below 25% value	0.33	0.20
	Between 25% and 75% value	−0.01	0.94
	Above 75% value	−0.28	0.28
	Prior to first changepoint at 7469 BP	−0.20	0.32
	Between first changepoint and second changepoint at 5324 BP	−0.01	0.95
	After second changepoint at 5324 BP	−0.08	0.74
Charcoal z-scores	Below 25% value	0.31	0.22
	Between 25% and 75% value	−0.08	0.67
	Above 75% value	0.14	0.58

3.1.4. Relationship between changes in population and fire during key growth periods

The SEA analysis shows that fire was increasing ca. 275 years before the intervals of rapid growth at 7400 and 5370 cal. BP (Fig. 5) following a period of earlier decline. Fire reaches a maximum ca. 275 years after these periods of rapid population growth and then remains relatively stable thereafter. Detrending the charcoal z-score composite does not affect these overall findings (see S10).

The precise specification of the timings of these rapid population growth periods does not substantially alter this pattern (see S11) and intervention analysis through ARIMA modelling (see S12) confirms that the influence of population growth on charcoal influx is negligible.

3.2. The impact of the Neolithic on fire history

The start of the Neolithic was time-transgressive (Fig. 6), with the earliest dates registered in the east and in coastal regions. The latest start of the Neolithic was registered in the northwest of the peninsula, in southern Portugal and in relatively mountainous inland regions of eastern Spain.

The analysis of regional fire history with respect to the site-specific dating of the Neolithic transition (Fig. 7) shows that fire is generally declining prior to the local onset of agriculture, starting from ca. 750 years to ca. 450 years before. However, as in the previous analysis, fire starts to increase before the site-specific onset of the Neolithic. As with the SEA analysis, detrending the resulting z-score composite curve does not affect these overall findings (see S13). The increase in fire begins ca. 450 years prior to the onset of the Neolithic and continues after the onset of agriculture. This pre-Neolithic trend is robust to minor adjustments in underlying radiocarbon cultural data (see S14). ARIMA modelling forecasts (see S15) also indicate no obvious change in the charcoal composite for the following 200 years after the site-specific Neolithic start date.

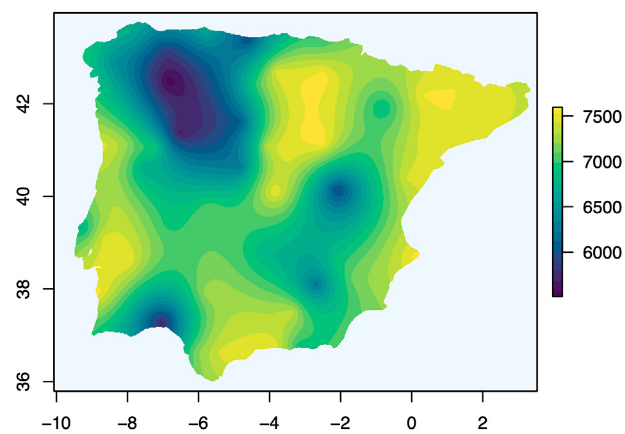

Fig. 6. Ordinary kriging interpolated spread of the Neolithic across Iberia in cal. BP.

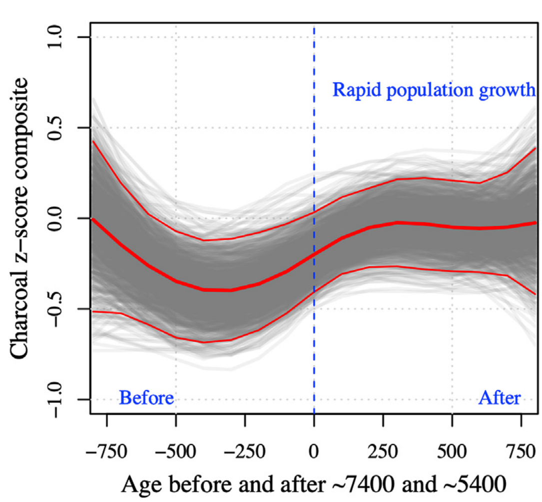

Fig. 5. Superposed epoch analysis of z-score composite of charcoal influx for Iberia, with dates aligned before and after SPD key growth periods at 7400 and 5370 cal. BP. Grey lines indicate 1000 bootstrap re-samples of records, with replacement. The solid red line shows the median z-score values, and the fine red lines are the 95% confidence intervals.

4. Discussion

Our results show that the population of Iberia grew at an exponential rate between 10,000 and 3500 cal. BP, punctuated by periods of rapid population growth and decline. This general increase in population is consistent with the other reconstructions for Iberia covering overlapping time periods (Balsera et al., 2015; Fernández-López de Pablo et al., 2019) and with different spatial foci (Lillios et al., 2016; Drake et al., 2017; Fyfe et al., 2019; Pardo-Gordó and Carvalho, 2020). This similarity between our results and prior studies is not surprising since they are based on the same or similar datasets. The first period of rapid growth identified between ca. 7400 and ca. 6880 cal. BP coincides with a period of population growth identified between 7250 and 7100 cal. BP by Balsera et al. (2015) for Iberia as a whole, and broadly aligns with periods of rapid growth identified by Drake et al. (2017) for their “southwest” and “inner Mediterranean” regions of Iberia between 7250 and 6750 cal. BP and 7400 and 6900 cal. BP respectively. However, this period of rapid growth is not present in the “northwestern” region analysed by Drake et al. (2017) or in Portugal (Pardo-Gordó and Carvalho, 2020). The second period of rapid growth between ca. 5370 to ca. 5170 cal. BP coincides with an increase at ca. 5350 cal. BP in the SPD curve developed by

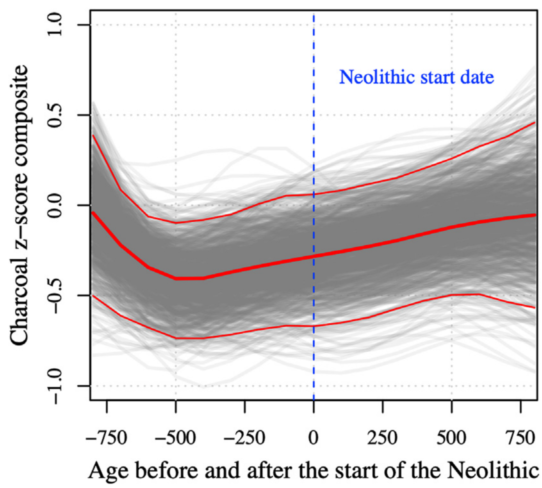

Fig. 7. Superposed epoch analysis of z-score composite of charcoal influx for Iberia, based on spatially heterogenous dates relative to the start of the Neolithic across Iberia. Grey lines indicate 1000 bootstrap re-samples of core sites, with replacement. The solid red line shows the median z-score values, and the fine red lines are the 95% confidence intervals.

Balsera et al. (2015) for Iberia as a whole, and has also been identified for Portugal (5351–4934 cal. BP; Pardo-Gordó and Carvalho, 2020) and for southwestern Iberia (ca. 5300 to ca. 4500 cal. BP; Lillios et al., 2016). However, it has not been recognised in analyses of population changes in northwestern or southeastern Iberia (Lillios et al., 2016). These differences suggest regional variation in population growth, with implications for local landuse change.

Our reconstruction of regional fire shows periods of increase and decline throughout the composite record. There are two other comparable regional-scale reconstructions of fire history that largely focus on Iberia and these show limited similarity with our z-score composite curve. Connor et al. (2019), for example, shows a steady increase in fire for Iberia as a whole from ca. 6700 to ca. 4700 cal. BP, whereas our composite curve shows a decrease in fire from ca. 6100 to ca. 5,800, followed by a subsequent increase until ca. 4700 cal. BP. However, the reconstructed decrease in fire between ca. 5000 and ca. 3800 cal. BP is seen in the composite curve of Connor et al. (2019). Iberia is included in the z-score curves for the “Mediterranean West” and “Mediterranean West South” regions produced by Vannière et al. (2011), but again there is limited similarity with our reconstructions. However, the reconstructed increase in fire from ca. 5800 to ca. 4700 cal. BP is seen in the “Mediterranean West South” region. Shen et al. (2021) have reconstructed the fire history of the Iberian Peninsula over the Holocene using pollen data and a calibration that relates charcoal abundance directly to burnt area. Although the burnt area reconstruction is not strictly comparable to the z-score composite curve of fire activity, and indeed the two records differ in several respects, nevertheless there are some common features including a peak in fire before 7000 cal. BP and an interval of lower fire after 7000 cal. BP (Shen et al., 2021).

Both Connor et al. (2019) and Vannière et al. (2011) use fewer individual records to reconstruct their regional curves: Connor et al. (2019) uses 13 records and Vannière et al. (2011) uses 11 records for the Mediterranean West region (including 7 non-Iberian records) and 9 records for the Mediterranean West South region (including 3 non-Iberian records). Our analysis includes all of the Iberian sites from Vannière et al. (2011) and 11 of the sites from Connor et al. (2019). The differences in site numbers, the different regions used by Vannière et al. (2011) and our application of the updated INTCAL20 calibration curves, likely underpin the differences with our reconstructions. Differences in the criteria used for site selection could also contribute to differences in the regional curves. Connor et al. (2019), for example, only used records with greater than 5000 cal. years of data, an average sampling resolution <100 cal. years, with an average interval of <1500 cal. years between dating samples, and excluded records with sedimentary hiatuses. The absolute length of the record is not important for our analyses since we used binned data to minimise the impact of different sampling frequencies on the composite curve and all of the records provide information for at least six of the 100-year bins between 10,000 and 3500 cal. BP. Although we include three records with an hiatus, we constructed separate age models before and after the hiatus. The sampling resolution of each record was always >1 sample per 1000 years and 55% of the records had an average sampling resolution of <100 years for the 10,000 to 3500 cal. BP interval. Furthermore, all of the records had age models constructed with at least one dating tie-point per 3000 cal. years on average, with most (>70%) having at least one dating tie-point per 1500 cal. years on average. Thus, it seems unlikely that the inclusion of a greater number of sites in our analyses has significantly compromised the data quality, and this is confirmed by the confidence intervals generated by bootstrap resampling, but the better spatial coverage provides a more robust region-wide assessment of changes in fire regimes.

Although increases (or decreases) in anthropogenic burning to either create or maintain open landscapes as populations grow more rapidly (or decline) have been considered important during the Holocene (e.g. Gobet et al., 2003; Kaal et al., 2011; Vannière et al., 2016; Dietze et al., 2018), there is no consistent correlation between rapid changes in the rate of population growth and the occurrence of fire in Iberia. Both the correlation analysis and the SEA analysis show no relationship between fire and periods of high population growth, or, in the case of the correlation analysis, for periods of rapid population decline. Furthermore, we detected no significant relationship between population size, as indexed by SPD values, and fire activity. These analyses suggest that the influence of human activities on Iberian fire regimes during the period between 10,000 and 3500 cal. BP was limited.

Although there are differences in methodology and data used, our reconstructions of the spread of the Neolithic show similar patterns to previous research, particularly that the earliest Neolithic locations are found in the south, east and northeast of Iberia suggesting multiple start locations as shown by Bernabeu Aubán et al. (2015) and the later spread of the Neolithic to the northwest of Iberia indicated by Isern et al. (2014). Our analyses do not identify a clear relationship between the timing of the Neolithic transition and the fire record, in contrast with other studies that suggest that fires in Iberia at this time were closely linked to land cover burning associated with Neolithic agriculture (Carracedo et al., 2018; Connor et al., 2019). However, other regional and site-level studies indicate that the widespread use of fire to create open spaces for agriculture often occurred much later than the first introduction of Neolithic culture (e.g. Morales-Molino and García-Antón, 2014; Iglesias et al., 2019). Whilst the spread of agriculture may have had an impact on fire regimes in the longer term or a site-specific level, our results suggest that the initial spread of the Neolithic had limited direct implications for region-wide fire regimes.

Our research conclusions are based on several assumptions. These include: 1) the ability to reconstruct fire, population change and the spread of the Neolithic; 2) the use of estimated population and the spread of agriculture to approximate human influence on fire; 3) the temporal correspondence of changes in fire with population changes as evidence of a causal link between them; and 4) the ability to detect this relationship at a regional scale.

We assume that our estimates of fire, population change and the spread of agriculture through time are sufficiently robust, despite uncertainties inherent to each reconstruction approach. The use of sedimentary charcoal records to reconstruct fire is widespread in palaeofire research, but it is recognised that uncertainties in the accuracy of the age depth model (e.g. Trachsel and Telford, 2016; Blaauw et al., 2018; Zimmerman and Wahl, 2020) or the stability of site characteristics through time (e.g. Whitlock and Anderson, 2003; Allen et al., 2008; Iglesias et al., 2015) could influence reconstructed fire at individual sites. These uncertainties underpin our focus on broad-scale, rather than site-based, patterns in fire, which are less likely to be affected by individual site uncertainty. Composite charcoal accumulation curves rarely reflect individual charcoal records (e.g. Marlon et al., 2009; Daniau et al., 2010), but are designed to minimise the impact of local conditions and to draw attention to broadscale patterns in the data. Composite charcoal records provide an indication of fire activity but may not reflect other aspects of the fire regime (Conedera et al., 2009), such as fire intensity or duration, which could be influenced by human actions.

Despite their widespread use, there are acknowledged limitations associated with the SPD approach to estimating population including biases in sampling of identified archaeological sites (e.g. Torfing, 2015), variation in the sampling intensity of radiocarbon dates through time (Crema and Bevan, 2021), and the creation of artificial peaks or smooth periods in the SPD produced by radiocarbon calibration (Crema and Bevan, 2021). Furthermore, SPDs do not provide information about variations in settlement sizes, which could affect the picture of population growth. Methodological developments designed to reduce potential bias, including the use of model fitting and hypothesis testing (e.g. Shennan et al., 2013; Timpson et al., 2014) underlie our approach to detecting periods of rapid population change. Our focus on regional rather than local change, which would rely on fewer radiocarbon dates and thus potentially produce less reliable SPDs, is also a way of reducing potential bias. The ability to assess the spread of the Neolithic across Iberia using radiocarbon dates relies on the availability of items from this cultural period. Assessing the degree to which missing dates affect the interpolated surface, and the use of composite charcoal curves rather than site-level information, mitigates the degree to which these inaccuracies affect our conclusions.

Our second assumption is that population changes and the start of agriculture can be used as a measure of human influence on fire regimes via changes in land use. Other sources of evidence of human impacts on land use, such as the presence of taxa indicative of farming such as cereals (e.g. Zapata et al., 2004; Peña-Chocarro et al., 2005; López-Merino et al., 2010; Cortés Sánchez et al., 2012), the presence of species indicating open landscapes and disturbance such as *Plantago* (e.g. López-Merino et al., 2010; Kaal et al., 2011), or the presence of fungi found in the faeces of grazing animals (e.g. López Sáez and López Merino, 2007; Abel-Schaad and López-Sáez, 2013; Morales-Molino and García-Antón, 2014; Revelles et al., 2018), could potentially be compared with charcoal records to determine whether the inferred changes in land use correlate with changes in fire regimes. However, these alternatives also have inherent uncertainties and do not provide a direct measure of human impact on fire regimes.

Thirdly, we assume that changes in population and fire would occur at the same time and focus on periods of rapid population growth and the start of agriculture as periods when landscape change might be expected to be large and hence changes in fire most visible. There could be lags between population changes and changes in fire, such that an increase in fire may occur sometime after population has started to increase. However, our analysis shows that increases in fire precede periods of rapid population growth by several centuries, which is more difficult to explain. There may be non-linear population dynamics that could explain the absence of rapid population growth following land clearance and increases human-induced burning, but we are unable to plausibly explain this result based on the data available.

Finally, we assume that a human influence on fire is detectable at regional scale and is not obscured by local variation. Other studies of the relationships between people and fire in Iberia using multiple records (e.g. López-Sáez et al., 2018b; Connor et al., 2019), have only used sites where the fire record could be compared directly with evidence of human impact based on other types of palaeo-records. However, the geographic distribution of the charcoal sites aligns well with the archaeological site data. Our SEA analysis focuses on changes in fire at two time periods, and any potential human impact may be obscured if the signal is not consistent between these time periods. However, the analysis of the impact of the Neolithic on fire regimes is spatially and temporally precise. Given that neither analysis shows an immediate effect on fire regimes, this suggests that the conclusion that there is no obvious relationship between humans and fire is robust.

At the region-wide scale, the temporal consistency of the changes in fire with respect to population changes in different time intervals, and in relationship to the asynchronous Neolithisation of the Iberian Peninsula, suggests that neither rapid changes in population nor the introduction of agriculture had a noticeable impact on fire in Iberia during the early and middle Holocene. This suggests that other drivers of fire, such as climate and climate-induced environmental changes, may have been a more important influence during this period. Climate influences fire directly through controlling fire weather and fuel moisture and indirectly through influencing vegetation type and productivity and hence fuel availability (Bowman et al., 2009; Bradstock, 2010; Harrison et al., 2010; Archibald et al., 2013). Today, fuel availability limits fire in the relatively dry regions of southeastern Iberia and climate conditions limit fire in the wetter regions of northern Iberia (Pausas and Paula, 2012). Changes in climate through time affect fire regimes through changing vegetation type and productivity, influencing fuel dryness and controlling the occurrence of lightning ignitions. The direct influence of climate conditions on fire regimes can be amplified or dampened depending on post-fire vegetation regrowth (Gil-Romera et al., 2010; Tepley et al., 2018; Hurteau et al., 2019). Furthermore, changes in the fire regime can also influence vegetation type (Baudena et al., 2010; D'Onofrio et al., 2018; Halofsky et al., 2020; Pausas and Bond, 2020). There is a considerable body of evidence from Iberia that provides insight into the dynamics of climate and vegetation during the Holocene, including changes in lake levels (e.g. Morellón et al., 2008; González-Sampériz et al., 2017; Morellón et al., 2018; Schröder et al., 2018), isotopic records from speleothems (e.g. Moreno et al., 2017; Baldini et al., 2019; Budsky et al., 2019; Thatcher et al., 2020; Benson et al., 2021), pollen assemblages (e.g. Broothaerts et al., 2018; López-Sáez et al., 2020) and sea-surface temperatures from adjacent ocean regions (e.g. Rodrigues et al., 2009; Chabaud et al., 2014; Schirrmacher et al., 2019; Gomes et al., 2020). However, it is difficult to use these types of record to separate out the influence of potential individual drivers of changes in fire regimes. Statistical approaches have been used to disentangle the multivariate impacts of different drivers on fire in the recent past (e.g. Bistinas et al., 2014; Andela et al., 2017; Forkel et al., 2019; Harrison et al., 2021) and similar techniques could be applied to palaeofires given sufficient independent quantitative reconstructions of climate variables and vegetation characteristics. Although there are a limited number of site-based quantitative reconstructions of temperature or moisture changes during the Holocene based on pollen (e.g. Kaufman et al., 2020; Ilvonen et al., 2022) and chironomid data (Muñoz Sobrino et al., 2013; Tarrats et al., 2018), the only large-scale mapped reconstructions of climate variables (Mauri et al., 2015) are based on interpolation from a geographically biased set of sites concentrated in northern mountain or coastal regions. Similarly, the available quantitative reconstructions of vegetation characteristics for the region (Zanon et al., 2018; Githumbi et al., 2022) have limited spatial coverage or temporal resolution and focus on a limited range of vegetation types. Thus, a thorough statistical analysis of the interacting drivers of fire over the Holocene period is currently not possible.

Our results suggest that human activities had little impact on fire during the interval from 10,000 to 3500 cal. BP. This does not preclude a role for humans in the later Holocene, and indeed other studies have suggested that human influences are more recognisable in the last few millennia (e.g. Fletcher et al., 2007; Gil-Romera et al., 2010; Anderson et al., 2011). The role of other factors, such as climate or climate-induced changes in vegetation, during the earlier part of the Holocene could be investigated using the statistical approaches that have previously been used to analyse and disentangle the multivariate drivers of fire in the recent past (e.g. Bistinas et al., 2014; Andela et al., 2017; Forkel et al., 2019). These methods could also be used to identify when a strong regional signal of human influence on fire emerges. Further insights could be gained through the calibration of the charcoal data to provide quantitative reconstructions of the fire regime (see e.g. Hennebelle et al., 2020; Shen et al., 2021) or the use of alternative data sources that might provide information on other aspects of the fire regime, such as charcoal morphology or anatomy (e.g. Umbanhowar and McGrath, 1998; Iglesias and Whitlock, 2014) or combustion biomarkers (e.g. Argiriadis et al., 2018; Kong et al., 2021). Radiocarbon-based reconstructions of population changes could also be compared with and complemented by alternative approaches to reconstruct anthropogenic land-use changes (e.g. Gaillard et al., 2010; Pirzamanbein et al., 2014; Fyfe et al., 2015). Further research using other sources of data on human impact and the application of emerging techniques to enhance coverage of fire history (see e.g. Shen et al., 2021) would help test the reliability of our results. Similarly, the application of the techniques used in this research to other areas could help assess the general applicability of our findings.

5. Conclusions

We have used sedimentary charcoal and radiocarbon dates on archaeological material to reconstruct changes in fire and human populations between 10,000 and 3500 cal. BP for Iberia and examined the impact of the spread of the Neolithic on fire regimes. Whilst region-wide fire and population changes are evident from our reconstructions, these changes do not occur in concert. Correlation and SEA analyses indicate that rapid population changes are not associated with changes in fire regimes. Furthermore, there are no changes in fire regime associated with the immediate influence of the spread of Neolithic agriculture and the resulting change in land use. There is also no significant relationship between population size and fire activity. While further research to disentangle the multivariate drivers of fire regimes is necessary to quantify the precise nature of human influence during this time, at a region-wide scale our research indicates that human influence is likely of less importance to fire regimes than other environmental influences during the early and middle Holocene in Iberia.

Data availability

The charcoal data is available from the University of Reading Research Data Archive (https://doi.org/10.17864/1947.000369). See S16 for plots of the 32 individual records of charcoal influx through time utilised in this analysis. The radiocarbon data is available from the University of Reading Research Data Archive (http://doi.org/10.17864/1947.000340). The code utilised in generating fire and population reconstructions, as well as cross-analysis of the data is available at (https://github.com/sweeney-l/Iberian_fire_history).

Author contributions

Luke Sweeney: Conceived and designed the analysis, Collected the data, Performed the analysis, Wrote the paper. **Sandy P. Harrison**: Conceived and designed the analysis, Contributed data or analysis tools, Wrote the paper. **Marc Vander Linden**: Conceived and designed the analysis, Contributed data or analysis tools, Wrote the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

LS acknowledges support from the Leverhulme Centre for Wildfires, Environment and Society. SPH acknowledges support from the ERC-funded project GC 2.0 (Global Change 2.0: Unlocking the past for a clearer future; grant number 694481). Some of the charcoal data were extracted from the Global Charcoal Database (https://www.paleofire.org/index.php), and we gratefully acknowledge contributors to this effort and the curators of the database. We thank colleagues in the Leverhulme Centre for Wildfires, Environment and Society (https://centreforwildfires.org/) and from the SPECIAL group at the University of Reading (https://research.reading.ac.uk/palaeoclimate/) for discussions during the development of this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2022.107562.

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