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Identifying natural and anthropogenic drivers of prehistoric fire regimes through simulated charcoal records

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ABSTRACT

Archaeological and paleoecological studies demonstrate that human-caused fires have long-term influences on terrestrial and atmospheric systems, including the transformation of "wild" landscapes into managed, agricultural landscapes. Sedimentary charcoal accumulations alone provide only limited information about the influence of human-caused fires on long-term fire regimes. Computational modeling offers a new approach to anthropogenic fire that links social and biophysical processes in a "virtual laboratory" where long-term scenarios can be simulated and compared with empirical charcoal data. This paper presents CharRec, a computational model of landscape fire, charcoal dispersion, and deposition that simulates charcoal records formed by multiple natural and anthropogenic fire regimes. CharRec is applied to a case study in the Canal de Navarrés region in eastern Spain to reveal the role of human-driven fire regimes during the early and middle Holocene. A statistical comparison of simulated charcoal records and empirical charcoal data from the Canal de Navarrés indicates that anthropogenic burning, following the Neolithic transition to agro-pastoral subsistence, was a primary driver of fire activity during the middle Holocene.

1. Introduction

Humans are uniquely able to use fire as a tool to deliberately create and sustain changes in their environments (Boivin et al., 2016; Bowman et al., 2011; Ellis, 2015; Roos et al., 2014; Scott et al., 2016). Regular and controlled use of fire by hominins dates to the Middle Pleistocene, but measurable impacts of anthropogenic fire on terrestrial and atmospheric systems are most evident during the last several millennia (Bowman et al., 2011; Roebroeks and Villa, 2011; Shimelmitz et al., 2014). Multiple global syntheses of archaeological and ethnographic case studies identify fire's role in political, religious, and ecological realms, including burning practices associated with land clearing, warfare, driving game, propagating beneficial plant and animal species, and fire prevention (Bliege Bird et al., 2008; Bowman et al., 2011; Pyne, 2012; Scherjon et al., 2015; Trauernicht et al., 2015). Diversity in anthropogenic fire can create variation in local and regional fire regimes; however, evidence of human-driven ignitions is not readily observable in sedimentary charcoal records, particularly when these fires co-occur with large-scale changes in climate and fuels.

This paper presents the Charcoal Record Simulation Model (CharRec), a computational model that simulates the formation of sedimentary charcoal records based on varying fire regime components, including fire frequency, intensity, size, and spatial distribution. These components can be modified to represent fire regimes shaped by varying human and climate drivers. Following a pattern-oriented modeling approach, CharRec is built using a bottom-up strategy where observable patterns within target datasets inform programming decisions (Grimm et al., 2005). This strategy allows CharRec to function as a "virtual laboratory," where multiple model outputs are compared to patterns within empirical charcoal data to identify which combinations of fire regime components mostly likely contributed to the formation of the empirical record through time (Bankes et al., 2002).

1.1. Formation and interpretation of sedimentary charcoal records

Variation in the concentration of charcoal particles from lacustrine cores or terrestrial sediment samples is commonly used to identify paleoenvironmental trends in landscape fire (Bowman et al., 2011, 2009; Whitlock and Anderson, 2003; Whitlock and Larsen, 2001). Bridging the interpretive gap between charcoal abundance and fire history has remained at the forefront of paleoecological research for several decades. The theoretical relationships between charcoal transport and accumulation were first proposed by Clark (1988a,b) and have since been expanded to consider the influence of combustion and atmospheric conditions on primary charcoal dispersal, such as fire intensity, fire size, and charcoal morphology (Adolf et al., 2018; Clark et al., 1998; Clark and Royall, 1996, 1995; Higuera et al., 2011; Leys et al., 2015, 2017; Li et al., 2017; Lynch et al., 2004; Miller et al., 2017; Peters and

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Higuera, 2007; Vachula and Richter, 2018). Fire history interpretations from these models rely on two major underlying assumptions: 1) the physics of primary charcoal transport result in spatially discernible differences in the distribution of charcoal particles following a fire; and 2) secondary charcoal transport is minimal and does not obfuscate patterns of primary deposition and fire occurrence (Higuera et al., 2007).

The distribution and abundance of primary, aerially dispersed charcoal is assumed to be a function of charcoal attributes related to fuel combustion and atmospheric conditions during a fire (Aleman et al., 2013; Clark, 1988a; Clark et al., 1998; Duffin et al., 2008; Enache and Cumming, 2007, 2006; Lynch et al., 2004; Peters and Higuera, 2007; Vachula and Richter, 2018). Generally, the relationship between these variables results in spatially differentiated dispersion, where macroscopic charcoal particles (typically > 100 μm) are dispersed close to their source and are interpreted as local in origin; microscopic charcoal particles (typically < 100 μm) can be dispersed greater distances and are typically interpreted as representing regional fires (Clark, 1988b; Clark et al., 1998; Ohlson and Tryterud, 2000). This relationship assumes that atmospheric and combustion conditions remain constant throughout the duration of a fire; while this assumption may not always hold true, transport distances based on charcoal size have been empirically validated in multiple studies (Clark and Royall, 1996; Gardner and Whitlock, 2001; Lynch et al., 2004; Ohlson and Tryterud, 2000; Pisaric, 2002; Tinner et al., 2006; Whitlock and Millspaugh, 1996). More recent work has examined the impact of varying conditions on charcoal production and the mechanisms of primary charcoal transport, concluding that particle morphology, shape, and density are also important in interpreting fire origin (Duffin et al., 2008; Leys et al., 2015, 2017; Vachula and Richter, 2018).

Secondary charcoal refers to charcoal introduced into the sedimentary record during non-fire years by geomorphological processes such as run-off, post-depositional sediment mixing, or other landscape reservoir effects. Empirical studies of post-fire slope-wash estimate that the contribution of additional charcoal from non-fire years can continue for upwards of a decade, but in quantities small enough not to mask primary deposition (Carcaillet et al., 2006; Clark, 1988a; Clark et al., 1998; Lynch et al., 2004; Patterson et al., 1987; Whitlock and Millspaugh, 1996). Mixing within the sediment column can further blur, but not entirely obscure primary charcoal deposition. Statistical methods for peak detection and sampling strategies that capture the full extent of fire return intervals help to account for these processes (Clark, 1988b; Finsinger et al., 2014; Higuera et al., 2010; Kelly et al., 2011).

Peak detection methods rely on separating a charcoal series into its background and peak components. Background charcoal refers to low-frequency variations in macro-charcoal accumulation, as well as contributions from secondary charcoal transport (Higuera et al., 2010; Kelly et al., 2011). When background charcoal is statistically removed, peak charcoal related to primary transport and deposition is distinguishable (Finsinger et al., 2014). The distinction between background and peak charcoal components may be unclear in landscapes with both natural and anthropogenic ignition sources (Bowman et al., 2011). Ethnographic examples of managed fire indicate that ignitions are often spatially circumscribed, frequent, and at low intensities (Scherjon et al., 2015), hence it is possible that local anthropogenic burning may contribute to low-frequency accumulations of macro-charcoal without clear and discernible peaks. Thus, the anthropogenic signal may be misidentified or obscured, particularly if a sampling strategy is not designed to accommodate for short fire return intervals.

1.2. Anthropogenic fire in the archaeological record

Humans have intentionally set fires for millennia to transform the arrangement or diversity of resources within their landscape (Boivin et al., 2016; Pyne, 2012). Identifying prehistoric human influences on fire regimes remains difficult due to a mismatch between available archaeological data on human activities and paleoecological data on fire and vegetation change (Bowman et al., 2011). Prominent archaeological approaches to fire have centered on detecting evidence of landscape burning in relation to food production and hunter-gatherer impacts on ancient environments. Low-level food production (Smith, 2001), "fire-stick" farming (Bird et al., 2005; Bliege Bird et al., 2013, 2008), swidden agriculture (Levin and Ayres, 2017; Roos, 2008; Roos et al., 2016; Schier et al., 2013), and mitigating resource vulnerability (Freeman and Anderies, 2012) suggest that fire was an important tool for creating predictable resource mosaics within landscapes across the globe (*North America:* Liebmann et al., 2016; Roos, 2015; Roos et al., 2010; Sullivan et al., 2015; Sullivan and Forste, 2014; Swetnam et al., 2016; Taylor et al., 2016; Van de Water and Safford, 2011; Walsh et al., 2010; *Europe:* Doyen et al., 2013; Innes et al., 2013; *Southeast Asia/Oceania:* Maxwell, 2004; McGlone, 2001; McWethy et al., 2010, 2009; Roos et al., 2016; *Neotropics:* Dull, 2004; Nevle et al., 2011).

Anthropogenic fire may also be a primary driver of fire regimes in regions with long-term histories of agricultural land-use (Carrión et al., 2010, 2001; Colombaroli et al., 2008; Vannière et al., 2008). For instance, Pitkänen et al. examined two lacustrine sediment cores from Lake Pönttölampi in eastern Finland to evaluate the formation of the local charcoal record and its association with documented "slash and burn" agricultural practices (Pitkänen et al., 1999; Pitkänen and Huttunen, 1999). By examining charcoal data in conjunction with historical maps of land-use and fire-scarred trees, Pitkänen and colleagues (1999) concluded that frequent, low-intensity fires associated with maintaining open woodlands contributed significantly to the sedimentary charcoal record and were the primary driver of local fire history. Unfortunately, the patterns reported by this study would be difficult to observe in prehistoric contexts that predate historic documents and living, fire-scarred trees. Simulation models provide an opportunity to examine multiple patterns of burning in prehistory while accommodating complex patterns of both natural and anthropogenic ignition sources. Evaluating simulations against empirical charcoal data allows multiple, alternative interpretations of prehistoric fire regimes to be tested, adapted, and improved.

2. Materials and methods

2.1. Introduction to CharRec and model design considerations

CharRec is a spatially explicit computational model developed to simulate the formation of long-term charcoal records based on empirically supported models of primary charcoal transport (Fig. 1). The model is an exploratory tool that assists researchers in interpreting how natural and anthropogenic fire regime components contribute to the formation of a sedimentary charcoal record. One of the most challenging aspects of developing computer simulations of social-ecological systems is including adequate complexity to address specific research questions while reducing the amount of uncertainty in the model structure and parameters. Pattern-oriented modeling offers a strategy for optimizing the relationship between complexity and uncertainty by focusing on multiple patterns observed in real systems at differing scales (Grimm et al., 2005). Such models focus on a small number of underlying processes that can be calibrated independently to influence the overall pattern of the system (Grimm et al., 2005:989). CharRec does not attempt to capture the extensive complexity of charcoal production, dispersion, and deposition. Instead, it utilizes four specific components that contribute to the overall patterning of primary charcoal in sedimentary records. These include fire spatial distribution, frequency, size, and intensity. These characteristics are highly susceptible to manipulation by humans, thus providing a means for testing the influence of burning practices related to land-use on the formation of charcoal records.

The following section describes the specific modules that compose CharRec and presents a statistical method for comparing simulated

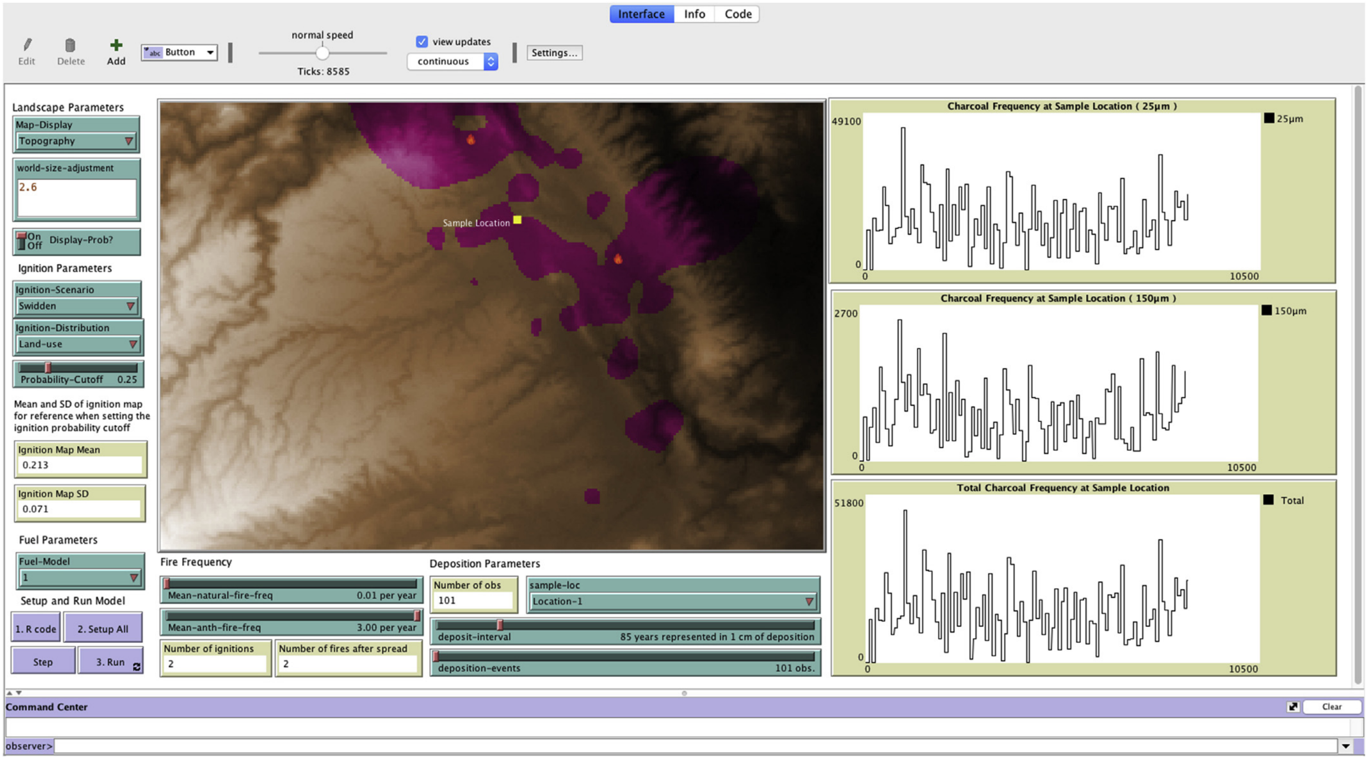

Fig. 1. CharRec interface, showing a landscape map, sample location, fires, and various user-defined ignition scenario parameters and outputs.

charcoal data against empirical datasets. CharRec is built in Netlogo Version 6.0.2, an agent-based programming language and open-access modeling environment (Wilensky, 1999). Netlogo is ideal for this modeling application because it is easily programmed and customized, has a user-friendly interface, and easily couples with other open-access GIS and statistical software. The model and the *Overview, Design concepts, and Details* (*ODD*) documentation are publicly available through the CoMSES Net Computational Model Library (Snitker, 2018).

2.2. CharRec modules and main components

CharRec is composed of five modules: 1) Landscape, 2) Ignition Scenario, 3) Burn, Disperse, and Deposit, 4) Form record, and 5) Export modules; together these simulate the formation of a sedimentary charcoal record on an annual time scale. In a simulation run, fires disperse micro- and macro-charcoal throughout the landscape, which is aggregated at a designated sampling point by a set deposition interval (e.g., 100 yr cm^{-1}). At the end of each deposition interval, charcoal counts are exported as a single observation in the charcoal record series. A diagrammatic representation of the relationship between CharRec modules is illustrated in Fig. 2.

2.2.1. Landscape module

The CharRec model landscape is a geo-referenced representation of a user-defined study area and is composed of rasters representing topographic, atmospheric, and fuel conditions. The physical terrain of the model landscape is derived from a digital elevation model (DEM) raster applied to each landscape patch (NASA, 2011). Atmospheric input rasters are created from modern local weather station measurements of wind velocity and direction (IVIA, 2015). These data are interpolated across the model landscape using WindNinja, a free software program developed by the U.S Forest Service Rocky Mountain Research Station's Fire, Fuel, Smoke Science Program (Forthofer et al., 2014). WindNinja creates patch-specific, spatially varying wind fields based on topographic variation.

Fuels in CharRec are based on the 13 fuel models developed by Anderson (1982) for predicting wildfire behavior. According to these models, fuels are grouped by load, meaning the amount and arrangement of vegetation within a stand, as well as size and moisture classes, such as fine (1-h) and larger-diameter fuels (10-h) (Anderson, 1982). Although updated models have improved accuracy in North American ecosystems (see Scott and Burgan, 2005), the original 13 models have been adapted to describe a diverse range of international ecosystems. For broad usability, CharRec uses these original models. Available dead and live biomass approximations for 1-h and 10-h fuel size classes are assigned to each landscape patch. For each simulation, a single fuel model is distributed uniformly across all patches. Potential heat release rates from combustion are calculated for all fuel model size classes (Johansen et al., 1976: Equation (1)) and used to approximate plume injection heights resulting from convective uplift (Clark, 1988a: Equation (5)). These calculations are done assuming a wind velocity of $0\ m\ s^{-1}$, thus producing the maximum potential plume injection height for each fuel class. These data are saved in CharRec as global variables for later use in the Burn, Disperse, and Deposit module.

2.2.2. Ignition scenario module

The Ignition Scenario module determines the fire regime components (fire spatial distribution, frequency, size, and intensity) used in each model run. These variables are set by the user to simulate natural or anthropogenic ignitions, thus influencing charcoal production, dispersion, and deposition in subsequent modules. First, fire frequency is determined annually by a Poisson probability distribution based on a user-defined mean-ignitions-per-year value (see Higuera et al., 2007 for a similar method). A low mean-ignitions-per-year value may result in many model years that do not have any fires burning on the landscape, while a higher value will allow for multiple fires to burn simultaneously.

Fire spatial distribution is determined by the ignition probability raster applied to each landscape patch. A random-number algorithm is used to determine a fire's potential location; this algorithm is weighted to favor areas with high ignition probabilities over those with low probabilities. The range of probability values available to the random-

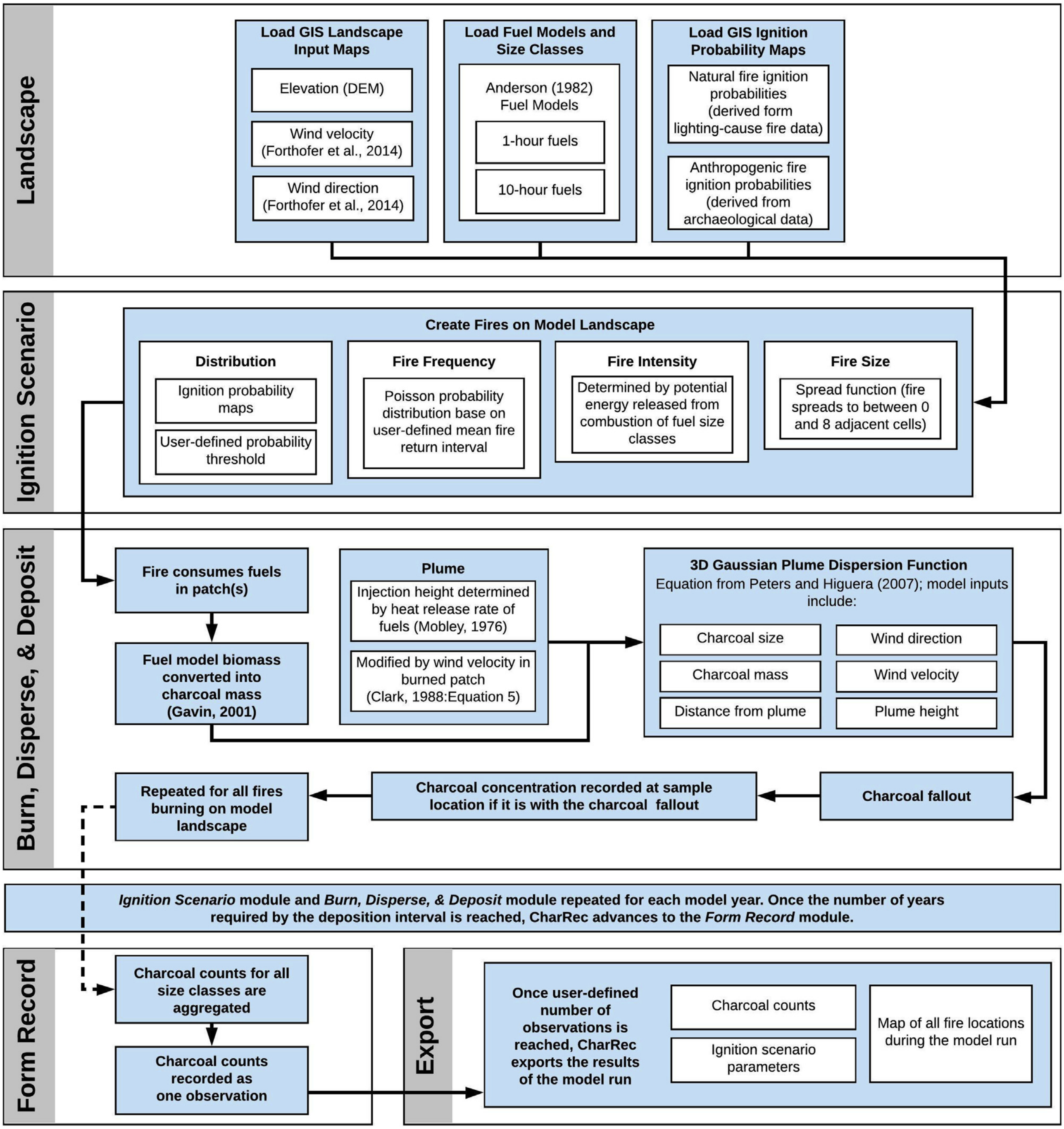

Fig. 2. Diagrammatic representation of CharRec modules and data inputs.

number algorithm is set by a user-defined probability cutoff. In practice, if the probability cutoff is set at 0, all landscape patches within the model landscape have the potential to ignite. If the probability cutoff is set at 0.5, a subset of landscape patches with ignition probabilities above or equal to 0.5 have the potential to ignite. The probability cutoff parameter allows for a range of spatial configurations to be tested.

Changes in fire size are modeled through a size function that randomly selects the number of additional patches that a fire will occupy. The number of additional patches ranges from 0 to 8; a value of 0 indicates that a fire will remain in its original patch (0.09 ha), while a value of 8 indicates the fire will occupy all adjacent patches via a shared edge or a shared vertex (0.81 ha). The intensity of the original fire is assigned to all additional fires.

Within CharRec, fire intensity refers to the amount of energy released from the combustion of fuels at each landscape patch (Keeley, 2009). Fuel size classes and plume injection heights calculated in the Landscape module are used to differentiate between fire intensities. For example, when an ignition scenario includes low-intensity fires, only plume injection heights calculated from the heat release rate of 1-h fuels are used. Ignition scenarios with high-intensity fires use plume injection heights calculated from the heat release rate of both 1-h and 10-h fuels. Although there is variation within fuel models, generally a fire consuming 1-h fuels results in a shorter plume injection height than a fire consuming both 1-h and 10-h fuels.

2.2.3. Burn, disperse, and deposit module

Once a fire ignites on a landscape patch, its intensity determines the size class of available biomass that is consumed and the injection height

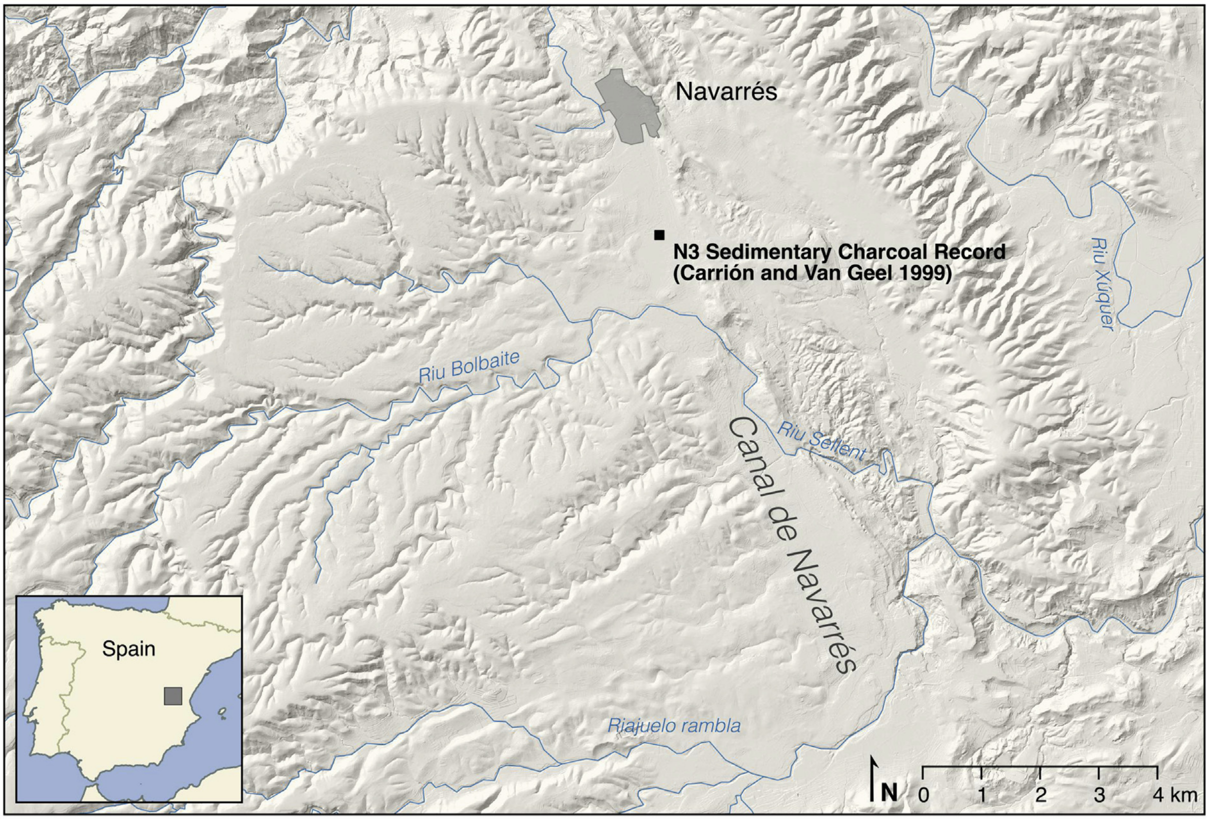

Fig. 3. Canal de Navarrés study area and location of the N3 sedimentary charcoal record collected by Carrión and Van Geel (1999).

of the resulting plume. Available biomass is converted into charcoal mass using the conversion rate published by (Gavin (2001):32). Charcoal mass is then transformed into micro- and macro-charcoal particle counts based on experimental charcoal particle size distribution data published by Pitkänen et al. (1999). Plume injection height for each fire is modified by wind velocity at the fire's patch following the empirical relationship illustrated by (Clark (1988a): Equation (5)). Finally, the amount of micro- and macro-charcoal dispersed at a given x and y distance from a fire's patch is calculated using a three-dimensional form of Clark's (1988a) Gaussian aerial transport model adapted by (Peters and Higuera (2007): Equations (1) and (2)). The equations and parameters (Table 2) are reproduced below (see Higuera et al., 2007 and Peters and Higuera, 2007 for additional Gaussian aerial transport model details):

$$\chi(x, y) = \frac{2\nu Q(x)}{u\pi C_y C_z x^{2-n}} exp\left(\frac{-y^2}{C_y^2 x^{2-n}}\right) exp\left(\frac{-h^2}{C_y^2 x^{2-n}}\right) \quad (1)$$

$$Q(x) = Q_0 exp\left\{\frac{4v_g}{nuC_z\sqrt{\pi}}\left[[-x^{n/2}e^{-\xi} + \left(\frac{h}{C_z}\right)^{2m} \times (\Gamma(-m+1) - \Gamma_\xi(-m+1))\right]\right\} \quad (2)$$

Wind direction at the fire's origin is used to determine the direction of micro- and macro-charcoal fallout. Counts of micro- and macro-charcoal are recorded only when fallout reaches the user-designated sampling site. The Burn, Disperse, and Deposit module operates simultaneously for every fire that burns on the landscape during a model year.

2.2.4. Form Record and export modules

Sediment accumulation rates in CharRec are determined by a user-defined deposition interval, which sets how many years represent 1 cm of deposition. Once the number of model years in the deposit interval is reached, the Form Record module aggregates charcoal counts at the sample location into a single observation of micro- and macro-charcoal. A complete CharRec simulation is run for a user-defined number of deposit interval observations. At the end of the simulation, the Export module collates all charcoal count observations created by the Form Record module, as well as ignition scenario variables used during the simulation, and exports them as a comma-separated values file. A map of all fire locations created during the simulation is also exported in raster format.

2.2.5. Statistical comparison of model outputs to an empirical charcoal record using LDA

Linear discriminant analysis (LDA) is a statistical method for classification that reduces a dataset into a lower dimensional space while maximizing the separation between multiple classes (Duda et al., 2001). LDA is a flexible and robust classification technique that does not require data standardization (i.e. z-score transformation) or normal distributions, making it an ideal candidate for comparing CharRec outputs to empirical sedimentary charcoal data. LDA uses an initial dataset to form linear combinations of predictor variables that emphasize differences between classification groups. The resulting linear discriminants can then be used to classify new data, generating posterior probabilities of classification group membership for each observation in the new dataset. The best-fit classification for each new observation is determined by the highest posterior probability. The distribution of posterior probabilities for other classification groups provides insight into the quality of the best-fit classification.

When comparing CharRec simulated charcoal data to an empirical charcoal record, the unique ignition scenario parameters from each complete simulation constitutes a classification group. Linear discriminants for charcoal data created by CharRec are used to predict ignition scenario membership for each micro- and macro-charcoal observation in the empirical dataset. The ignition scenario with the highest posterior probability is considered a ‘best-fit’ for a given observation in the empirical dataset. Prediction quality for the best-fit ignition scenario is assessed by comparing its posterior probability to the mean probability of all classification groups in the original dataset; the greater a best-fit ignition scenario's deviation from the mean posterior probability, the higher its prediction quality.

2.3. *Evaluating the Canal de Navarrés sedimentary charcoal record with CharRec*

To demonstrate the utility of CharRec and evaluate potential natural or anthropogenic drivers of fire regimes in an empirical test case, a series of simulated records were generated for comparison with a terrestrial sedimentary charcoal record from the Canal de Navarrés, Valencia, Spain (Fig. 3). The Canal de Navarrés (39° 06′ N, 0° 41′ W) is a flat-bottomed valley located at the intersection of the Iberian and Baetic mountain systems. The area is semiendorheic due to tectonic activity, creating small lakes, peatlands, and travertines throughout the region (La Roca et al., 1996). The valley and much of surrounding uplands are currently intensively cultivated, but abandoned areas support *matorral* species such as *Quercus coccifera*, *Erica* sp., *Ulex europaeus,* and occasional stands of *Pinus halepensis*.

Previous research in the Canal de Navarrés has identified archaeological material dating to the end of the Middle Pleistocene, but for the purposes of this case study, only archaeological periods during the late Pleistocene and early/middle Holocene are addressed (see Table 1). Investigations into the early agricultural history in Canal de Navarrés began in the 1940s with the excavation of Ereta de Pedregal, an open-air site located in the center of the valley. Initial testing and later excavations revealed structures and artifacts dating to the late Neolithic and Bell Beaker periods (Fletcher Valls, 1964; Menéndez Amor and Florschütz, 1961; Pla Ballester et al., 1983). In the decades since, the Canal de Navarrés has been studied extensively as part of a multi-year, joint research program by Arizona State University and the University of Valencia to systematically collect archaeological and paleoecological data in an effort to better understand the evolution of agro-pastoral landscapes (Diez Castillo et al., 2016; García Puchol et al., 2014; Snitker et al., in press). Recent archaeological survey results indicate relatively ephemeral land-use during the late Pleistocene and early Holocene, including the early (7600–6800 BP) and middle (6800–6000 BP) Neolithic periods. This trend is interrupted by a marked increase in artifact densities during the late Neolithic (6000–4500 BP) and Bell Beaker periods (4500–3800 PB), suggesting agricultural land-use intensification (Snitker et al., in press).

Three terrestrial sedimentary cores (referred to as N1, N2, and N3) were collected and analyzed from peat deposits near Ereta del Pedregal to track long-term changes in vegetation, fire, and climate (Carrión and Dupré, 1996; Carrión and Van Geel, 1999). These records indicated a substantial increase in charcoal concentrations and shift from pine-to oak-dominated vegetation communities at approximately 7000 BP (Fig. 4A–B). The introduction of agricultural burning by Neolithic farmers likely caused these changes, but it is difficult to determine how this process may have occurred, as well as the relative importance of anthropogenic and natural ignitions, from charcoal and pollen data alone.

Table 1
Temporal ranges for archaeological periods during the late Pleistocene and early/middle Holocene in the Canal de Navarrés.

Archaeological Period	Temporal Range
Bell Beaker	4500–3800 BP
Late Neolithic	6000–4500 BP
Middle Neolithic	6800–6000 BP
Early Neolithic	7600–6800 BP
Late Mesolithic	8600–7600 BP
Early Mesolithic	11,000–8600 BP
Late Upper Paleolithic	13,000–11,000 BP

Table 2
Parameters used in equations (1) and (2). Reproduced from Peters and Higuera (2007).

Parameter	Description
x	Distance downwind (m)
y	Distance crosswind (m)
v_g	Deposition velocity (m s^{-1})
Q_0	Source strength (m^2 × 100)
u	Mean wind speed (see Sutton, 1947) (m s^{-1})
C_y, C_z	Diffusion constants ($C_y = 0.21$, $C_z = 0.12$; see Sutton, 1947) (m$^{1/8}$)
h	Source height (m)
n	Measure of turbulence near ground (1/4; see Sutton, 1947) (dimensionless)
m	$n/(4-2n)$ (dimensionless)
ξ	$h^2/(x^{2-n} C_z^2)$ (dimensionless)
$(\Gamma(-m+1) - \Gamma_\xi(-m+1))$	$= -m\int_\xi^\infty e^{-t} t^{m-1}\,dt$ (dimensionless)

To evaluate the extent to which Neolithic anthropogenic burning or natural ignitions shaped the fire regimes in the Canal de Navarrés, a series of simulated charcoal records were produced using CharRec and compared to N3, the most detailed charcoal record collected and analyzed by Carríon and Van Geel (1999). Multiple ignition scenarios were designed with combinations of fire spatial distribution, frequency, size, and intensity to emulate lightning-ignited fires and two models of Neolithic burning. Modeled Neolithic fires included frequent low-intensity broadcast burning associated with pastoral land-use, and frequent high-intensity, spatially confined fires related to land clearing and swidden agriculture. Ignition probability maps (Fig. 5) for natural and anthropogenic ignition scenarios were generated using available data on lightning-caused fire locations (EFFIS, 2014) and archaeological survey data from the Canal de Navarrés (Diez Castillo et al., 2016; García Puchol et al., 2014; Snitker et al., in press). The N3 sedimentary charcoal record contains dated deposits spanning the last 25,000 years, but only charcoal concentrations from the late Pleistocene through early/middle Holocene (13,000–3800 BP) and two size classes (micro-charcoal: 25–150 µm; macro-charcoal: > 150 µm) were simulated to evaluate fire regimes before, during, and after the transition to agro-pastoral economies. Fuel models adapted for the Canal de Navarrés by the *Instituto para la Conservación de la Naturaleza* were used in this simulation (MAPA, 1989). Details about ignition scenarios and data inputs are shown in Table 3.

3. Results

3.1. *Sensitivity analysis*

To evaluate the sensitivity of CharRec to changes in the ignition scenario, a series of sensitivity tests were conducted on a randomly generated model landscape (see Table 4 for sensitivity parameters). To identify the minimum number of charcoal observations needed to build a representative sample for each ignition scenario, a sample of low-intensity, high-intensity, and mixed-intensity scenarios were modeled to simulate 1000 observations each. The variance within a random sample of 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 observations of each scenario was calculated and compared across ignition scenarios. Results indicated that 300 observations are the fewest needed to capture most variance within each ignition scenario. This number of observations was used in sensitivity analyses and all further model experiments (see Barton et al., 2015 for more details on this approach).

Model sensitivity was evaluated using a one-factor-at-a-time (OFAT)

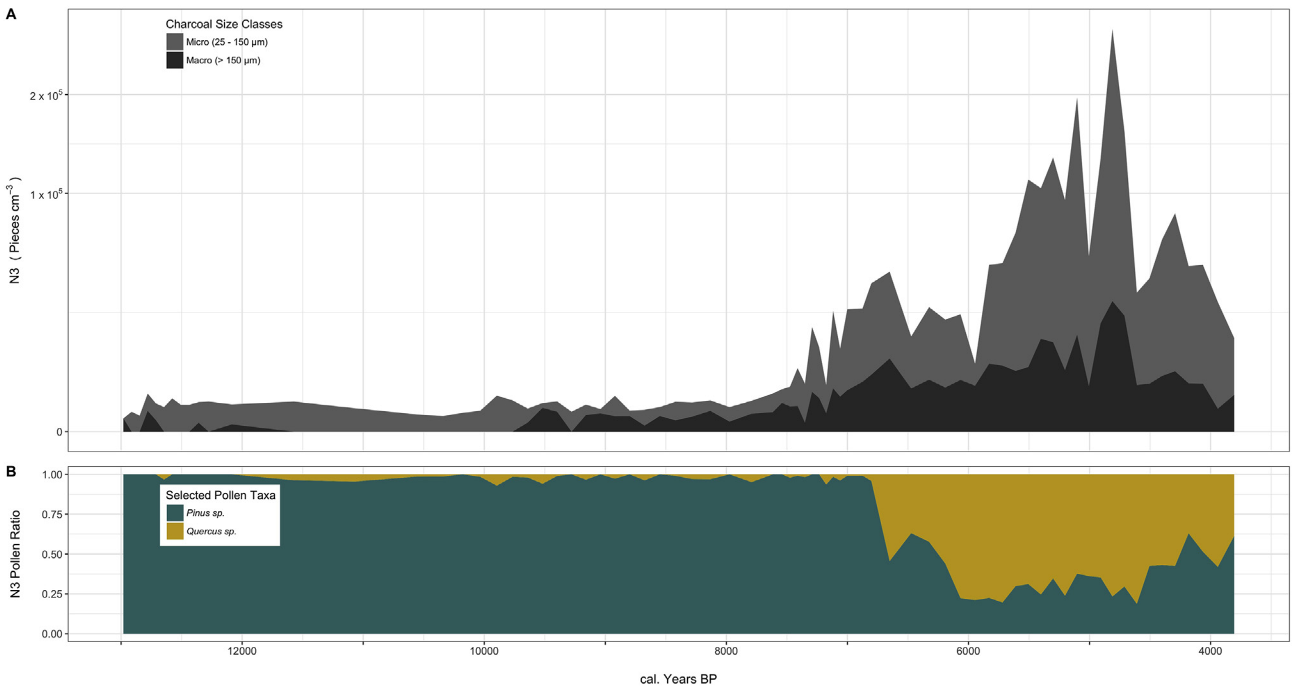

Fig. 4. Summary of N3 sedimentary charcoal record empirical data; A) micro- and macro-charcoal counts (note square root transformation of y-axis to highlight low charcoal counts from 13,000 to 8000 BP); B) ratio of *Pinus* sp. and *Quercus* sp. pollen counts from the N3 record.

methodology, where one ignition scenario parameter is changed at a time, while keeping all others at baseline values. Charcoal counts generated from all sensitivity tests were z-score transformed and described by a linear regression model. Fig. 6A–C presents linear model coefficients and their 95% confidence intervals for each test. CharRec charcoal counts are most sensitive to changes in fuel model and fire intensity in all parameter combinations that were tested. Fuel models are readily distinguishable within the tests, but intensity does cause some overlap between confidence intervals for low-intensity and mixed-intensity fires (Fig. 6A). Differences between fire frequency and spatial distribution (Fig. 6B–C) are very stable and are primarily differentiated by fire intensity. With only a few exceptions, linear model coefficients and their confidence intervals for these ignition scenario parameters do not overlap, suggesting that simulated charcoal records can be discerned based on their inputs.

3.2. Comparison to the N3 charcoal record from the Canal de Navarrés

3.2.1. Ignition scenarios

A total of 2400 simulated charcoal records were modeled in CharRec to represent a diverse set of natural, pastoral, and swidden ignition scenarios (see Table 3), resulting in 720,000 individual observations of micro- and macro-charcoal. LDA was applied to all 2400 simulated records, generating linear discriminants for each ignition scenario. Linear discriminants were used to classify the empirical micro- and macro-charcoal counts from N3 into best-fit ignition scenarios based on the posterior probability of group membership. Best-fit ignition scenarios were assembled chronologically to create a composite simulated charcoal record that reflects changes in fire regime components through time. A comparison of the empirical charcoal data from N3 and the composite simulated record generated by CharRec is illustrated in Fig. 7A–B.

CharRec simulations indicate that the N3 charcoal record is best described by a range of natural ignition scenarios leading up to the transition to Neolithic agro-pastoral land-use. During the transition between the late Mesolithic and early Neolithic periods, charcoal counts increase, and best-fit scenarios fluctuate between natural and pastoral ignitions. At approximately 7400 BP, ignitions stabilize with pastoral fires as the dominant scenario throughout the remainder of the early and middle Neolithic periods. Both micro- and macro-charcoal counts in both the N3 charcoal record and the simulated composite record significantly increase during the late Neolithic period and continue at elevated accumulation rates through the Bell Beaker Period.

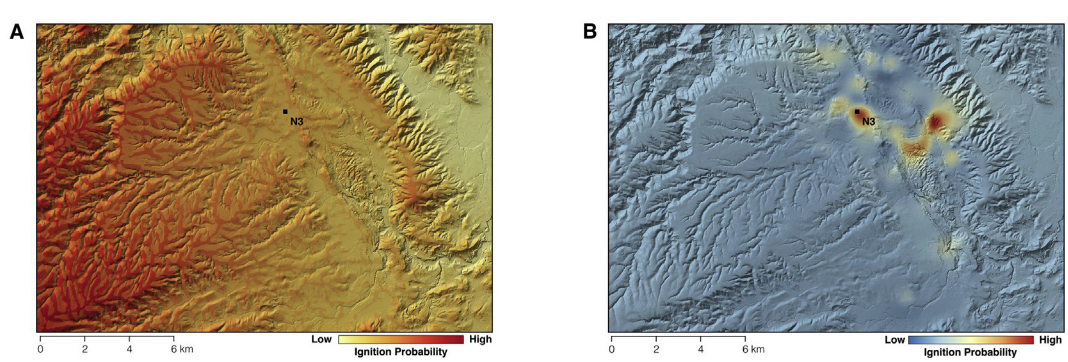

Fig. 5. Ignition probability maps for A) lightning-caused fires and B) anthropogenic fires in the Canal de Navarrés.

Table 3
CharRec model parameters used to simulate N3, an empirical sedimentary charcoal record from the Canal de Navarrés (Carrión and Van Geel, 1999).

CharRec Module	Variable Description	Input(s)	Units	Data Source/Citation
Model Landscape	Elevation	30 m resolution elevation raster	m	NASA, 2011
	Wind velocity	30 m resolution wind velocity raster	m sec^{-1}	IVIA, 2015; Forthofer et al., 2014
	Wind direction	30 m resolution wind direction raster	degrees	IVIA, 2015; Forthofer et al., 2014
	Fuels (1-h and 10-h)	Fuel Models 1, 4, and 6 adapted to Spanish ecosystems	–	MAPA, 1989
	Natural ignition probability	30 m resolution probability raster generated from regional lightning-caused fires during 1990–2010	–	EFFIS, 2014
	Anthropogenic ignition probability	30 m resolution probability raster generated from Neolithic artifact density in Canal de Navarrés	–	Snitker et al., in press
Ignition Scenario	*Pastoral*			
	Frequency	0.1–3.0 by 0.1; mean annual fire frequency	fires yr^{-1}	–
	Size	1 - 9 patches; depends on size function	–	–
	Intensity	Low-intensity; 1-h fuels	–	–
	Spatial distribution	0–0.9 by 0.1; probability thresholds for anthropogenic ignition probability raster	–	–
	Swidden			
	Frequency	0.1–3.0 by 0.1; mean annual fire frequency	fires yr^{-1}	–
	Size	1 patch	–	–
	Intensity	High-intensity; 1- and 10-h fuels	–	–
	Spatial distribution	0–0.9 by 0.1; probability thresholds for anthropogenic ignition probability raster	–	–
	Natural (lightning)			
	Frequency	0.1–2.0 by 0.1; mean annual fire frequency	fires yr^{-1}	–
	Size	1 - 9 patches; depends on size function	–	–
	Intensity	Mixed-intensity; variable fuel size classes	–	–
	Spatial distribution	0–0.9 by 0.1; probability thresholds for natural ignition probability raster	–	–
Form Record	Deposition interval	85; Average sedimentation rate for N3 charcoal record from 13,000 to 3000 cal. BP	yr cm^{-1}	Carrión and Van Geel, 1999

3.2.2. Fire regime parameters

The fire regime parameters contributing to each of the best-fit ignition scenarios are described in Fig. 8A–D. The most striking patterns in these data are the sudden constriction in spatial distribution throughout the entirety of the Neolithic period and the transition to low-intensity fires in fuel model 6 (Fig. 8C–D). These trends are complimented by a slight increase in fire frequency during the early, middle and late Neolithic periods (Fig. 8A). Finally, it is worth noting that fires are consistently small throughout the entire composite simulated charcoal record, with most fires below 0.1 ha in size (Fig. 8B). Mean fire size does increase during the Neolithic period, but remains relatively small with values fluctuating between approximately 0.05 and 0.1 ha.

Table 4
CharRec model parameters used in sensitivity testing.

CharRec Module	Variable Description	Input(s)	Units
Model Landscape	Elevation	Randomly generated 30 m resolution elevation raster	m
	Wind velocity	Randomly generated 30 m resolution wind velocity raster	m sec^{-1}
	Wind direction	Randomly generated 30 m resolution wind direction raster	degrees
	Fuels (1-h and 10-h)	Fuel Models 1, 4, and 6 adapted to Spanish ecosystems	–
Ignition Scenario	*High-intensity*		
	Frequency	0.5–3.0 by 0.5; mean annual fire frequency	fires yr^{-1}
	Size	1 patch	–
	Intensity	10-h fuels	–
	Spatial distribution	0.1–0.9 by 0.2; probability thresholds	–
	Low-intensity		
	Frequency	0.1–3.0 by 0.1; mean annual fire frequency	fires yr^{-1}
	Size	1 patch	–
	Intensity	1-h fuels	–
	Spatial distribution	0.1–0.9 by 0.2; probability thresholds	–
	Mixed-intensity		
	Frequency	0.1–3.0 by 0.1; mean annual fire frequency	fires yr^{-1}
	Size	1 patch	–
	Intensity	Mixed intensity; variable fuel size classes	–
	Spatial distribution	0.1–0.9 by 0.2; probability thresholds	–
Form Record	Deposition interval	85	yr cm^{-1}

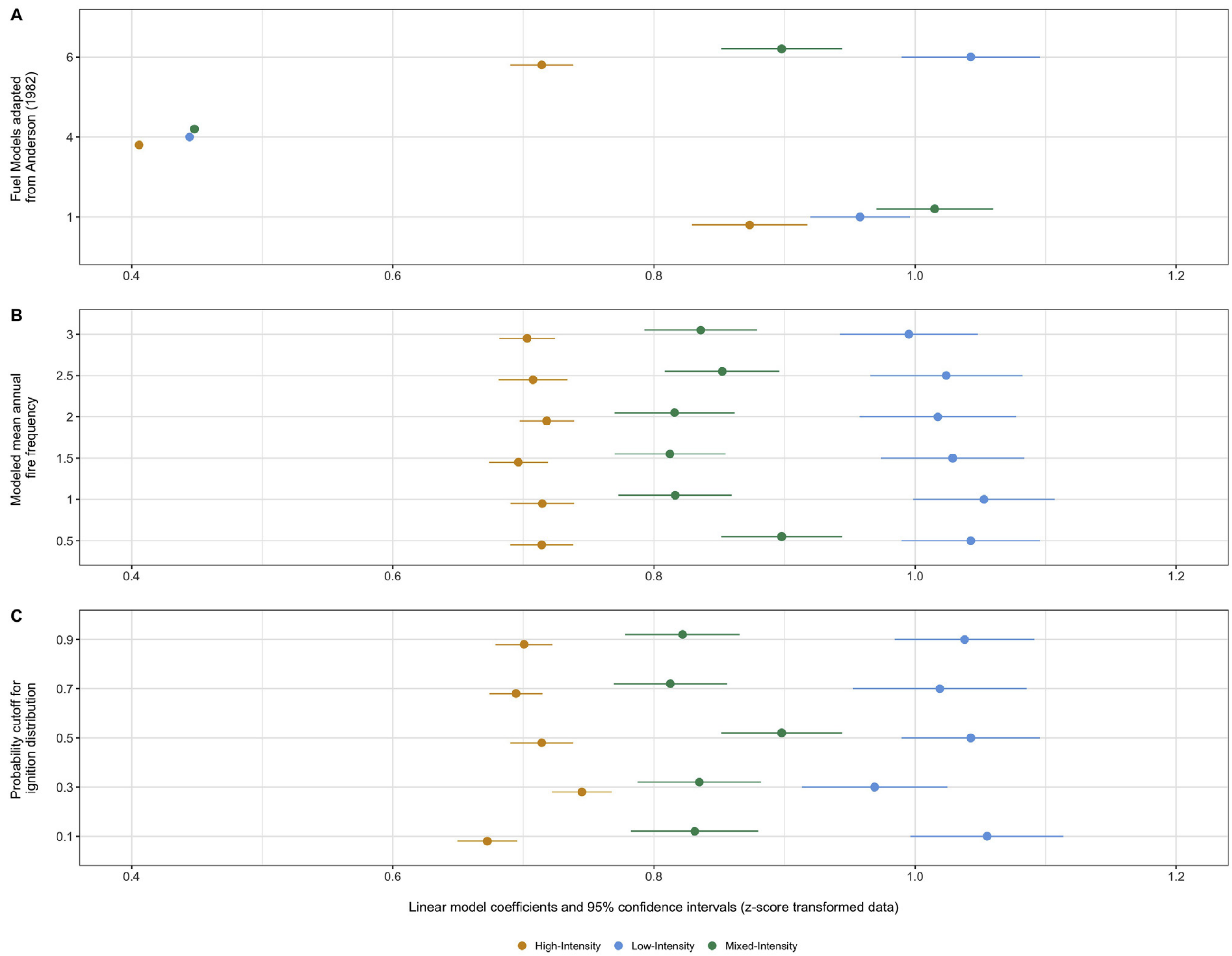

Fig. 6. Linear coefficients and 95% confidence intervals describing CharRec outputs from sensitivity runs; A) sensitivity of CharRec ignition scenarios to changes in fuel model; B) sensitivity of CharRec ignition scenarios to changes in mean annual fire frequency; C) sensitivity of CharRec ignition scenarios to changes in probability cutoff for ignition distribution.

4. Discussion

4.1. Drivers of early and middle Holocene fire regimes in the Canal de Navarrés

The composite simulated charcoal record generated through CharRec provides a robust tool for interpreting the N3 charcoal record in terms of the anthropogenic and natural fire regime components that contributed to its formation. Variations in fire regime parameters through time provide specific insights the spatial and temporal dimensions of fire on the landscape and how they relate to human land-use decisions. The following discussion of the model results is interpreted in the context of the archaeological and paleoecological data from the Canal de Navarrés.

Broadly, the CharRec simulated charcoal record indicates that increased charcoal accumulations in the Canal de Navarrés during the early and middle Holocene was driven by intensifying Neolithic land-use, not climate. Simulated records during late Pleistocene and early Holocene (13,000–7600 BP) demonstrated that fires were primarily natural and caused by regional lightning strikes across a wide geographic area, resulting in the accumulation of background charcoal. The presence of some variation during this period in the N3 charcoal record may be accounted for by the ephemeral occupations by Mesolithic hunter-gatherers (Innes et al., 2013; Innes and Blackford, 2003; Zvelebil, 1994) or fluctuations in climate (Carrión et al., 2010). The Younger Dryas and other aridity events documented through regional pollen sequences are not easily distinguishable in the simulated or empirical charcoal accumulations (López de Pablo and Gómez Puche, 2009). However, changes in best-fit ignition scenarios from 9600 to 9400 BP and 8200–7900 BP do correspond with increased aridity and lower temperatures observed in other records, suggesting fires were still natural (Burjachs et al., 2016).

At the beginning of the early Neolithic, fires were likely still regional, with some indications that anthropogenic fire was emerging as a presence on the landscape. Fire intensity, spatial distribution, and fuels reflect a similar pattern suggesting pastoral fire was present, but not a driving force in shaping the regional fire regime. Archaeological survey results from the Canal de Navarrés support this conclusion, indicating that early Neolithic occupations were not specifically identifiable from surface assemblages. Occupations were likely episodic, with periods of low-intensity land-use followed by extended hiatuses (Snitker et al., in press).

At the end of the early Neolithic (7200–6800 BP) and throughout the middle Neolithic (6800–6000 BP), simulations suggest that fires became consistently larger and more frequent. Fires are also restricted to areas with the highest densities of Neolithic artifacts, implying the establishment of regular, patterned anthropogenic burning related to Neolithic pastoral practices in the region. Fuel models represented in the simulated records also transitioned from closed communities in model 4, to more open woodland in model 6. Patterns of regular, low-

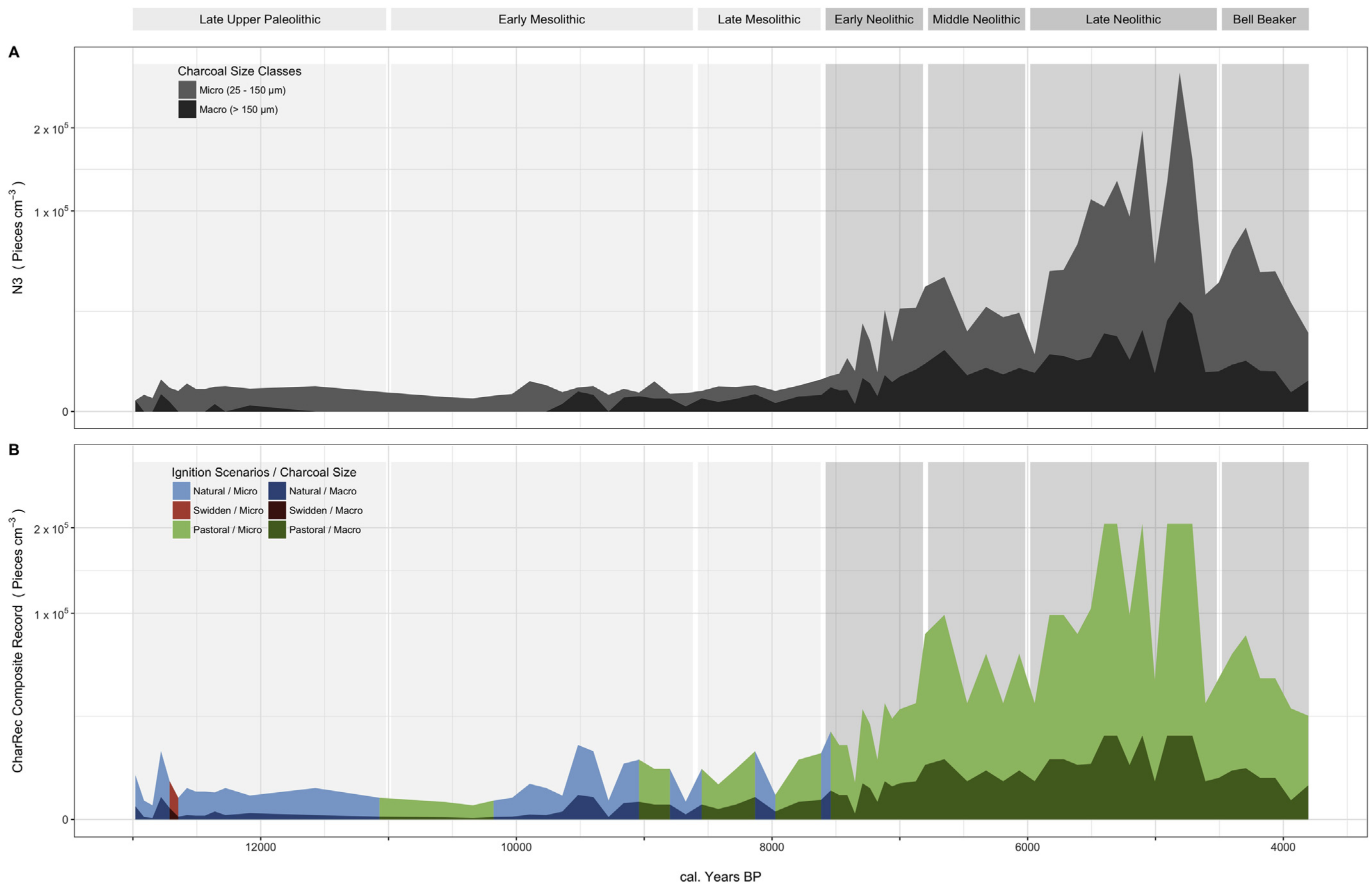

Fig. 7. Comparison of A) N3 micro- and macro-charcoal counts; B) composite, simulated CharRec charcoal counts (note square root transformation of y-axis to highlight low charcoal counts from 13,000 to 8000 BP). Late Pleistocene and early Holocene archaeological periods highlighted in light grey and Neolithic periods highlighted in dark grey.

intensity burning were likely intentionally used to create open, matorral vegetation communities, amenable to grazing. Post-fire resprouting genera, such *Quercus*, are able to outcompete reseeding genera such as *Pinus*, resulting in a sudden reduction in pine pollen like that observed between approximately 7000–6000 BP by Carrión and Van Geel (1999) (see Pausas, 1999 for a discussion of Mediterranean plant responses to fire).

Finally, the N3 and simulated charcoal record both show a substantial increase in charcoal accumulations during the late Neolithic (6000–4500 BP) and Bell Beaker (4500–3800 BP) periods. CharRec model runs also indicate that fire frequencies were highest during this period and low-intensity pastoral fires were spatially constrained to lowland and transitional areas in the valley bottom and margins. Fig. 9A–B illustrate the extent of the spatial differentiation between simulated fires from the late Neolithic and Bell Beaker periods as compared to the late Pleistocene and early Holocene. The degree of spatial constriction during later periods, coupled with increased fire frequency and charcoal accumulation, points to patterns of land-use intensification and permanent settlement. The establishment of the nearby site of Ereta del Pedregal during the late Neolithic and its continued use through the Bell Beaker period supports this conclusion (Pla Ballester et al., 1983). Additionally, data from surface artifact assemblages point to increased diagnostic artifact density during these periods in areas of transitional elevation on the valley margins, like those highlighted in Fig. 9B. Although the N3 charcoal record does not extend beyond 3800 BP, the anthropogenic burning patterns that intensified during the late Neolithic and Bell Beaker periods likely played a role in establishing and maintaining an enduring agricultural landscape, whose legacy is apparent in the Canal de Navarrés today.

4.2. *Future CharRec developments and applications*

4.2.1. *Improving CharRec simulations of the N3 charcoal record*

Fig. 10A–B illustrate a moving window Pearson's r between CharRec and N3 data, as well as posterior probabilities of best-fit ignition scenarios through time. These two measures are used to evaluate the quality of the CharRec simulated charcoal record and its ability to describe the N3 empirical charcoal data. CharRec simulated charcoal records correlate well with the empirical data from N3, except for approximately 10,000–7800 BP (Fig. 10A). Classification group probabilities are also low throughout the entirety of the pre-Neolithic periods, with relatively little distinction between the likelihood of the best-fit ignition scenario and the probability of all other ignition scenarios (Fig. 10B). Diminished model performance from 13,000 to 7800 BP is likely due to low charcoal counts, making the variation in the record difficult to accurately replicate. This limitation will need to be addressed before CharRec can be applied to other sedimentary charcoal records where the empirical data is less robust.

The current version of CharRec allows for several potential avenues to improving the model's ability to simulate sedimentary charcoal record formation. These include: 1) increasing the diversity of ignition scenarios to capture the subtle variation in the low-frequency, micro-charcoal accumulations; and 2) adding more sophistication to the atmospheric and combustion conditions that influence aerial charcoal dispersion, and 3) incorporating the effects of secondary charcoal transport and stratigraphic mixing. First, current ignition scenarios in CharRec provide a limited representation of the diversity of fire intensities and spatial configurations possible within the Canal de Navarrés study area. The inclusion of additional archaeological and

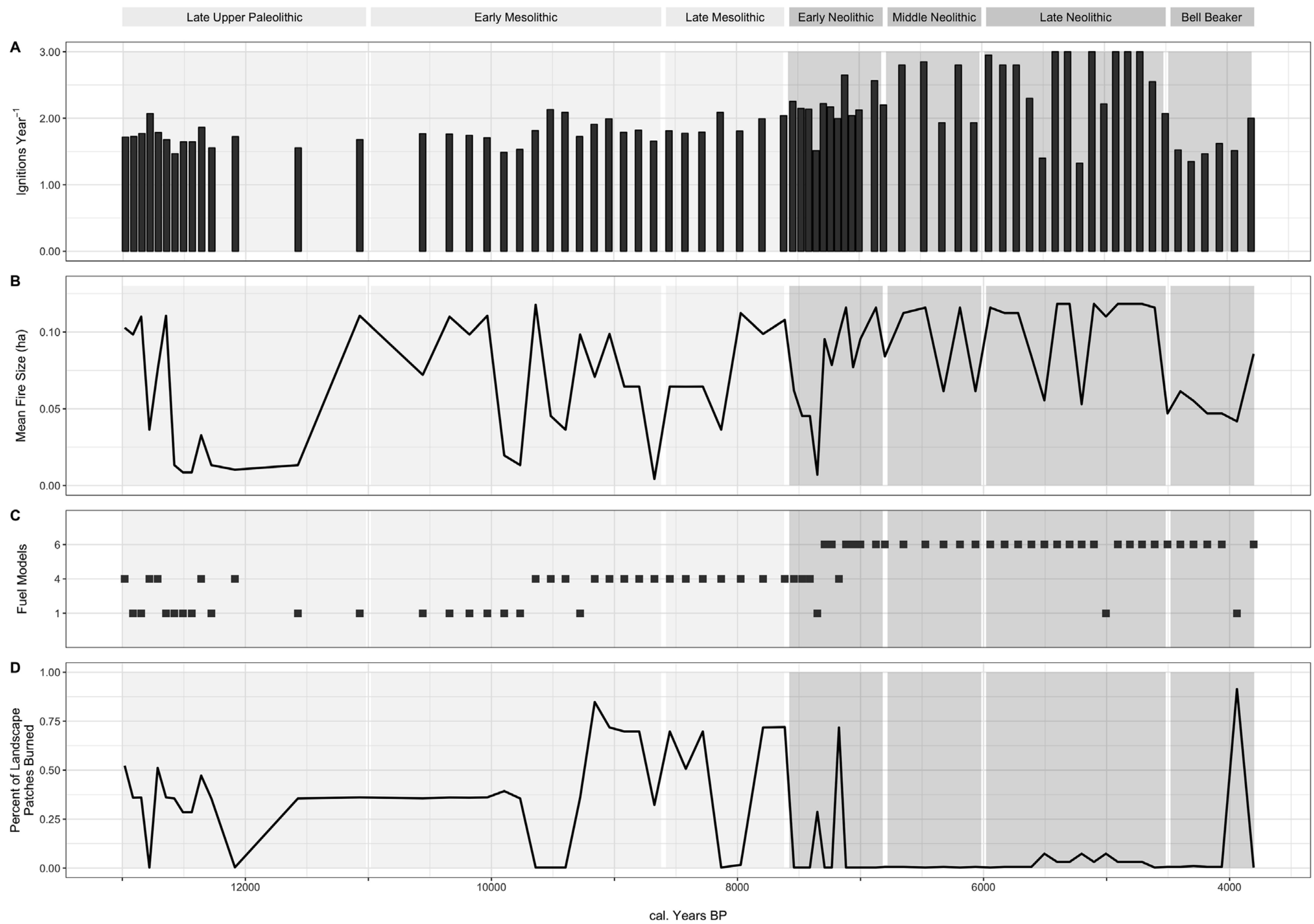

Fig. 8. Fire regime parameters from best-fit CharRec ignition scenarios through time; A) simulated ignitions per year; B) simulated mean fire size; C) fuel models used by best-fit ignition scenarios; D) spatial distribution of simulated fires as measured by the percent of the model landscape burned during all 300 repetitions of the best-fit CharRec ignition scenario. Late Pleistocene and early Holocene archaeological periods are highlighted in light grey and Neolithic periods highlighted in dark grey.

ethnographic analogs would be beneficial in connecting landscape fire parameters to specific types of prehistoric land-use, settlement pattern, and frequency at which a patch is re-burned (Bliege Bird et al., 2013; Scherjon et al., 2015). Equally, expanding natural ignition scenarios to reflect variation in the number and size of lightning-caused fires, in response to droughts or aridity, may also help increase model accuracy. Possible improved ignition scenarios could include a range of new configurations, such as larger, more intense (consuming 100-h or 1000-h fuels) regional fires or a combination of multiple intensities, possibly emulating the intermittent occupation of the Canal de Navarrés by Mesolithic hunter-gatherers.

Second, the current fire ecology literature highlights a need for considering the complex influence atmospheric and combustion conditions in primary charcoal production and transport (Adolf et al., 2018; Leys et al., 2015, 2017; Tinner et al., 2006; Vachula and Richter, 2018). The relationship between micro- and macro-charcoal production

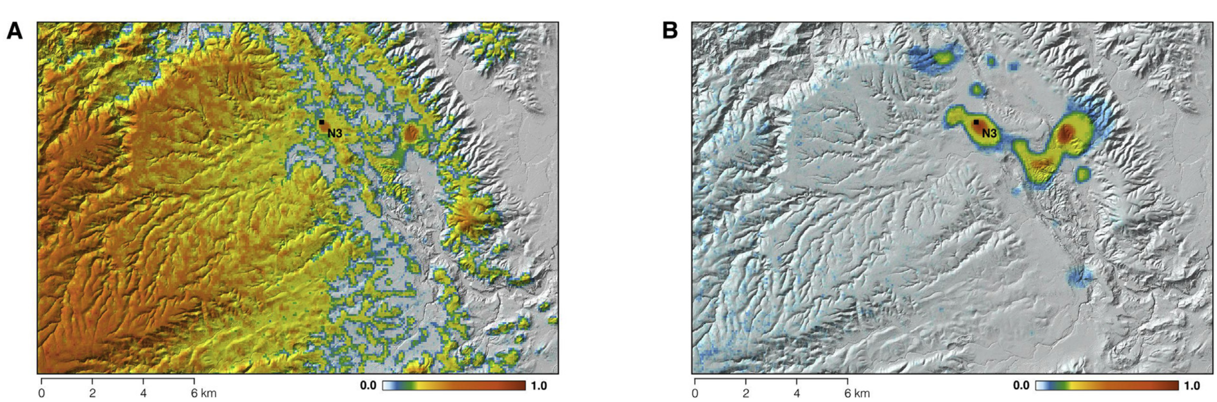

Fig. 9. Aggregated distribution of fires for all 300 repetitions of best-fit ignition scenarios during the A) late Pleistocene and early Holocene interval; B) late Neolithic and Bell Beaker interval. Indexed values range from 0 to 1 and represent the frequency a patch was burned for each period.

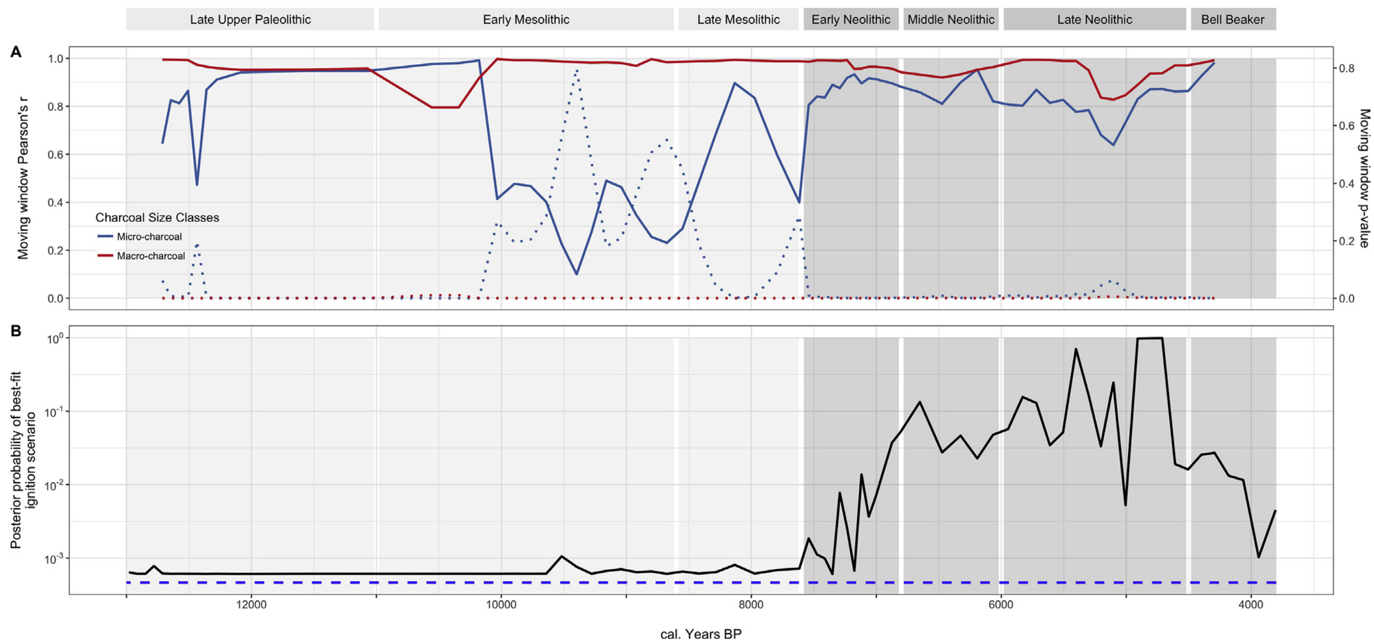

Fig. 10. Evaluation of CharRec model performance in simulating the N3 sedimentary charcoal record from the Canal de Navarrés. A) Solid lines indicate moving window Pearson's r correlation coefficient calculated between empirical and simulated charcoal counts (window size is 9 observations) and dotted lines indicate moving window p-values; B) posterior probabilities for best-fit ignition scenarios shown in black, while the mean posterior probability for all 2400 ignition scenario models is indicated by the blue, dashed line. Deviation from the mean posterior probability is an indicator of good model performance (note log10 transformation of y-axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and dispersion could be improved by drawing from a wider range of published size-distribution data from experimental fires in other regions. Charcoal particle size-distribution, density, and morphology are only recently the focus of research to understand their influence on transport during and after a fire (Aleman et al., 2013; Duffin et al., 2008; Li et al., 2017; Scott, 2010; Vachula and Richter, 2018). Model improvements to incorporate variation in charcoal metrics, as they relate to fire intensity and fuel type, could be readily added to the current model structure. Furthermore, additional complexity in representing fuels should be incorporated into subsequent versions of CharRec due to the model's sensitivity to this input. Including multiple fuel types within the model landscape, a fire spread model that considers fuels structure, or simple fuel succession models have the potential to substantially impact model results and interpretations.

Finally, the simple aggregation procedure used in CharRec to create each centimeter of deposition should be tested to determine if the addition of secondary deposition and stratigraphic mixing modules are needed. Lacustrine charcoal studies have demonstrated that post-depositional mechanisms must be considered in choosing sampling intervals and making fire history interpretations (Bradbury, 1996; Clark, 1988a; Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996). These processes are less intensively studied in terrestrial sedimentary charcoal series, but the inclusion of functions to describe the potential contribution of secondary charcoal deposition and sediment mixing could be added to CharRec to evaluate their influence on the model's performance (Higuera et al., 2007). Although the model improvements described here are not exhaustive, then do provide logical next steps for model improvements within the pattern-oriented modeling approach. Despite its current limitations, CharRec is able to generate results that provide new insights into drivers of prehistoric fire regimes in the Canal de Navarrés study area that would not be possible from the N3 charcoal data alone.

4.2.2. *Future applications*

CharRec is a flexible modeling tool and “virtual laboratory” designed to explore the relationship between natural and anthropogenic drivers of fire regimes. Future applications are not limited to the emergence of agro-pastoral fire regimes or the landscape used in the comparison with the Canal de Navarrés. CharRec relies on fundamental relationships between fire regime components and charcoal dispersion, as well as a user-defined model landscape and ignition scenario inputs, meaning it can be customized to operate in any landscape. Using many of the same parameters, other nearby empirical charcoal records could be simulated and compared to the results observed in the Canal de Navarrés to evaluate the consistency of Neolithic land-use impacts across the region. Other applications in the Mediterranean could include examining historical changes in fire regimes related to documented land-use transitions, such as changes in land tenure during the Medieval Islamic period (711 CE–1238) in Valencia or rural re-organization after the Black Death (1348 CE–1351) in the rest of western Mediterranean (Claramunt Rodríguez et al., 2014). CharRec can be employed to identify fire regime drivers outside of Mediterranean ecosystems by adapting the fuel models and landscapes the local specifics. New World applications may include identifying the degree to which Native American burning practices have shaped pre-contact fire regimes in the currently fire-prone western United States.

Simulating charcoal record formation through CharRec provides a reliable method for identifying anthropogenic fire in empirical sedimentary charcoal records and connecting the spatial and temporal dimensions of land-use to their formation. This work has implications for understanding the pace and scale of human influence on fire regimes and landscape transformation in prehistory. With the emerging interest in tracing the prehistoric roots of the Anthropocene, models like CharRec are becoming increasing more important in answering the difficult and often tangled questions regarding the feedbacks between humans and their environments in long-term-social ecological systems.

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