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Radiocarbon dates as data: quantitative strategies for estimating colonization front speeds and event densities

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A B S T R A C T

Archaeological analysis of large-scale prehistoric population history requires us to estimate rates of spatial spread during dispersals, and rates and magnitudes of temporal contraction during crashes. Using OxCal's MCMC sampling routine, I introduce and demonstrate a simple and easily implemented method of estimating front speeds that takes due account of the uncertainty in the archaeological data (in both dates and distances), and argue that this method is more appropriate than those most often used in front speed estimation at present. I also propose a simple and easily implemented method of estimating event densities as a demographic proxy, as an alternative to summed calibrated probability distributions. I argue that this alternative is a significantly better technique, and show that its use also enables us to identify individual archaeological dates that are exerting particularly strong influence on the results, so that we can efficiently allocate our attention when assessing the possible effects of exogenous sampling uncertainty. To illustrate these methods I re-analyse two published datasets relating to the early Paleoindian colonization of North America. My results with the new technique indicate that even with a very noisy dataset, there was clear evidence in the framework of the INTCAL04 calibration curve for a drastic reduction in archaeological event densities following the Younger Dryas onset, followed by a prolonged period of reduced human activity, and a possible renewed phase of rapid growth after the Younger Dryas termination and onset of the Holocene. However, the revised estimate of the Younger Dryas marine reservoir offset in the INTCAL09 calibration curve for ~12,550–12,900 cal BP changes the picture significantly, by flattening the peak in Clovis-age events and pushing it forward in time into the early Younger Dryas itself.

1. Introduction

Modelling large-scale human dispersals requires us to consider the rate at which the population increases locally, and the rate at which people migrate (in cases where more than one population is involved, we must also consider the nature of their interactions). In population ecology, the simplest model of the nonlinear dynamics of such processes is a reaction-diffusion system defined by Fisher (1937) and Kolmogorov et al. (1937), and applied to population expansion by Skellam (1951). In recent years an enormous amount of work has been done by biologists using this system to model the spread of invasive species, and numerous modifications and extensions have been proposed to improve the match between the modelled dynamics and those observed in the real world (see recent reviews for biologists by Hastings et al. (2005); for interdisciplinary physicists by Fort and Pujol (2008); and for archaeologists by Steele (2009)).

Much effort has been expended estimating speeds of spatial population expansion for archaeologically documented dispersal episodes, initially to confirm predictions of front speeds in the Fisher model from independently estimated population growth and migration rates, and more recently to assess how far the classic Fisher model falls short of reality in its treatment of human mobility patterns in a dispersal phase. Numerous archaeologists have suggested that radiocarbon dating can be used for this purpose, yielding estimates of the timing of passage of the expanding population front at different spatial locations. For the spread of farming, Ammerman and Cavalli-Sforza (1971, 1984) fitted a linear regression to dates and distances from Jericho, finding a mean front speed of about 1 km yr^{-1}. Pinhasi et al. (2005) fitted a linear regression to dates from a set of 735 Neolithic sites in Europe and the Near East using various origins and two possible distance measures, and found an average front speed in the range 0.6–1.3 km yr^{-1}. For earlier episodes of hunter-gatherer dispersal, Fort et al. (2004) estimated by regression a mean speed of late glacial recolonization of northern Europe of 0.8 yr^{-1} (0.4–1.1 km yr^{-1} at the 95% confidence interval).

An appropriate case study for these techniques is the first peopling of the Americas. For the last 50 years it has been the majority academic view that the North American Clovis culture represents the earliest successful colonization phase, in which

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hunter-gatherers invaded the continent south of the ice sheets from a Beringian source population. However radiocarbon dates have subsequently constrained the Clovis phase to an increasingly short interval, most recently to between ~11,050 ^{14}C yr bp and ~10,800 ^{14}C yr bp, or (in calendar years) a maximum range of 13,250–12,800 cal BP and a minimum range of 13,125–12,925 cal BP (Waters and Stafford, 2007). Meanwhile dates from sites in South American, including the southernmost part of that continent, have been confirmed for the same time range (Steele and Politis, 2009). This has led some scholars to propose a colonization model including multiple dispersals, perhaps synchronous but geographically separated (Steele and Politis, 2009; for congruent arguments from human genetics see Hellenthal et al., 2008; Perego et al., 2009). The problem with this new model is that it accommodates the empirical archaeological data, but does not yet explain those data with a plausible demographic account of the dispersal process. Such demographic models have, on the other hand, been well-developed for the Clovis-first model (e.g. Steele et al., 1998; Alroy, 2001).

Consequently, some scholars remain loyal to the Clovis-first model and have re-analyzed the empirical archaeological data and explored alternative demographic colonization scenarios to try and reconcile them. For example, Hamilton and Buchanan (2007) found a statistically significant trend for North American Clovis-age sites to become younger with distance from a postulated origin at the southern end of the 'ice-free corridor': their regression analysis indicated a front speed in the range 5–8 km yr^{-1}. To obtain this they analyzed a set of 23 radiocarbon-dated sites, including eleven that Waters and Stafford (2007) had accepted as reliable in terms of the association with Clovis artefacts; six that Waters and Stafford (2007) had rejected because they either lacked precise and accurate dates for Clovis artefacts, or lacked diagnostic Clovis artefacts to associate with accurate and precise dates; and six additional sites that had not been included at all in Waters and Stafford's (2007) own survey (see Fig. 1). They allowed the 'Clovis age' to extend rather later in time than many scholars would accept, so that the period which they were modeling covered about 600 calendar years straddling the Younger Dryas Boundary, and interpreted their results in terms of a modified Fisher-KPP-type colonization model, which takes account of the possibility that population expansion along the main axis of a fractal network such as a river basin will occur at a speed that is significantly different to that expected with conventional isotropic diffusion over a uniform surface. For unbiased random walkers, confinement onto a fractal network of this kind will in fact both reduce the front's initial velocity and cause it to decelerate over time (Campos et al., 2004), except where there is a bias to move in one direction (e.g. downstream) at junctions (Bertuzzo et al., 2007). In such a situation and where this bias is very strong in relation to the local growth rate, the whole population may even migrate in the preferred direction along the river system's main axis (although the trailing front will contract at a slower rate than the expansion of the advancing front), at a rate which is ultimately limited only by the typical individual's speed of movement.

In addition to tracking an expanding population front, archaeologists have recently begun to estimate initial local population growth rates and subsequent dynamics (including episodes of rapid depopulation, sometimes related to extreme climatic events). A number of recent studies have addressed this problem by graphing summed calibrated probability distributions (SCPDs) for all the radiocarbon dates in their datasets (e.g. Gkiasta et al., 2003; Gamble et al., 2005; Shennan and Edinborough, 2007). The peaks and troughs in these SCPDs, where these are sufficiently robust to be more than mere artefacts of the inflections of the calibration curve, are interpreted as evidence of population fluctuations; it is suggested that bias in archaeological sampling effort (for instance, where the well-funded excavation of a site has yielded unusually many dates in proportion to the volume of archaeological material) can be countered by averaging dates from each site and occupation phase. For the terminal Pleistocene settlement history of North America, Firestone, Kennett and colleagues (Firestone et al., 2007; Kennett et al., 2008a,b, 2009) have identified a possible extraterrestrial impact event at or just prior to the Younger Dryas Boundary (YDB), itself a climatic extreme event that spanned the interval ca. 12,900 cal BP (NGRIP, Rasmussen et al., 2006; cf. Bakke et al., 2009) to ca. 12,700 cal BP (Brauer et al., 2008; Blockley et al., 2008; Hua et al., 2009; evidence from the NGRIP core suggests that the vegetation cover and consequent dust flux responses extended across two centuries, Steffensen et al., 2008) and which many believe to be associated with a population crash in early Paleoindian North America. Consistent with their commitment to a Clovis-age colonization model and to the idea of a steady filling-up of the continent by an expanding population of colonizing hunter-gatherers, Buchanan et al. (2008) countered these claims by charting SCPDs for a large set of radiocarbon-dated events from late Pleistocene and early Holocene North American archaeological sites, arguing that their chart shows a steady increase in population size over time with no significant reversal to this growth trend at

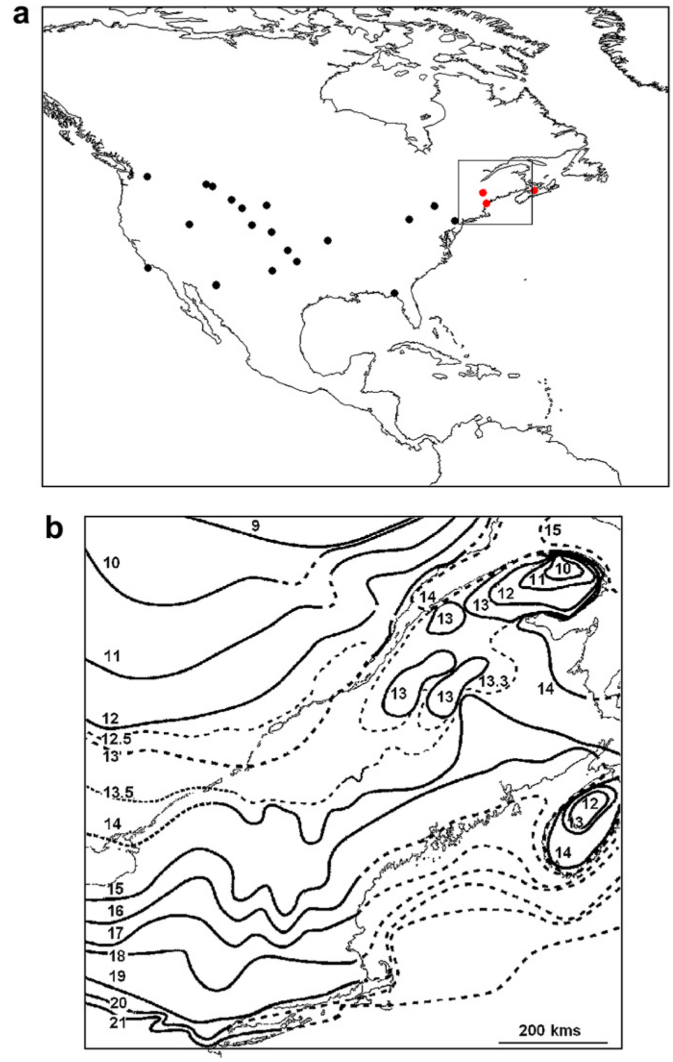

Fig. 1. (a) Map showing the sites analysed by Hamilton and Buchanan (2007) and reanalysed here. The three youngest sites (Debert, Hedden, Vail) are indicated by red circles. (b) The Laurentide ice sheet margins for the deglaciation period in the region where the three youngest sites are located, redrawn after Richard (2009); dates are in calendar years BP.