Spatial dynamics of human dispersals
Constraints on modelling and archaeological validation

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Abstract

In recent years there has been growing interest in the application of travelling wave models to the spatial dynamics of human dispersals, and their archaeological validation. These models enable predictions of the velocity of population expansion, derived from estimates of reproductive rates and of individual mobility. In this paper we discuss some intrinsic constraints on the application of such models to dispersal events which have been documented in the archaeological record. There is significant uncertainty in radiocarbon dating of first occupation at different locations, and in the reconstruction of evolving population distributions from time-averaged archaeological distribution maps. We calculate some archaeological boundary conditions for the accurate estimation of travelling wave profiles and velocities, and demonstrate their significance for two archaeological case studies: the first peopling of the Americas, and the Neolithic transition in Europe.

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1. Introduction

Radiocarbon dating has often been used to estimate the origination time, location, and rate of spread of expanding or migrating populations (e.g. [11,12,15,21]). It is also often used to trace the pattern of diffusion of cultural innovations in cases where the demographic process is unclear, such as the Neolithic transition in Europe (e.g. [2,10]).

Diagnostic artefacts are often also used as proxy markers of the diffusion of populations or of novel economic strategies (e.g. Clovis projectile points as markers of early Paleoindian dispersal into North America). A slow expansion in a uniform habitat will lead, in time, to the situation where people are living at the same densities everywhere, but where the most person-years have still been lived near the origin of the expansion. Sometimes it is assumed that the diffusion must have originated in the places where such early cultural indicators are found at greatest densities, in the expectation that they have been recovered there in greatest densities because they had been used and discarded there for the longest time. A relevant spatial demographic measure is therefore ‘cumulative occupancy’ [20]. This is the total number of person-years lived at a given location over a given period, and will reflect the duration of occupation, the initial rate of increase to demographic equilibrium, and the population density at that equilibrium.

However, quite frequently these archaeological ‘meters’ give confusing readings. The first peopling of the Americas is a case in point. The ages of the earliest radiocarbon-dated early sites do not obviously reduce as we move south and east from the assumed Beringian origin of this population expansion [8]. The recorded areas of greatest densities of Paleoindian fluted points are not located close either to the southern end of the ice-free corridor, or to the south-western margin of the Cordilleran ice sheet that would have been circumvented on the coastal migration route [3]. These paradoxes have
led some to conclude that the Americas were colonized much earlier than the weight of evidence seems to suggest [8]. Others have argued that no coherent spatial signature of a late glacial expansion is visible because the data we have are so contaminated by modern sampling biases [17].

In this paper, we shall analyze the conditions under which we might reasonably expect to find such gradients (in dates and in density of artefact discards) pointing back up to the origin of the dispersal. We shall argue, with the aid of a simple model of population expansion, that such a pattern will only survive in the modern archaeological record when some rather narrow conditions are met for the demographic parameters that determined the original population expansion. We will suggest that these conditions may well not have been met during the late glacial colonization of the Americas. By contrast, we will explain why signatures of the spread pattern across the Neolithic transition in Europe are expected to be more evident.

2. Continuum modelling of population expansions

In order to understand the spatial and radiocarbon signatures of diffusion processes (including demic expansions), we need first to build models of such processes. Any attempt to describe the aggregated behaviour of a system with large numbers of interacting elements will involve some simplifying assumptions. Ours are at two levels. Firstly, we shall make a population-level description of the demographic characteristics of demic expansion (in other words, we shall do some continuum modelling). Secondly, in describing these characteristics at the population level we shall make no special assumptions about any predominant direction of movement. Each of these assumptions raises philosophical issues that cannot be addressed here (although we address them elsewhere, Hazelwood et al. in prep.). Our position is simply that such simplifying assumptions are necessary as a first step if we are to begin to make sense of the archaeological records both of initial human dispersal, and of subsequent waves of migration and of cultural diffusion. Alternate individual-based models of human migration have been considered by Young [25].

Let us discuss in slightly more detail what is meant by these assumptions. First we require that any model that describes the time evolution of some populations must contain information about each individual, such as the timing of birth, reproduction and death, and the distance and direction of dispersal over the life-course. This information can be included directly for each individual or through a population-averaged quantity. An understanding of the most natural quantity can be seen by considering the two following scenarios. For a population composed of a small number of individuals it is clear that each birth/death produces a marked difference in the total population (see Fig. 1a). The dispersal pattern that results from the simple strategy in which there is no predominant direction leads to many distinct dispersal patterns as shown in Fig. 2. When presented with such dispersal data it is often impossible to interpret the underlying dispersal strategy. For example, the pattern of Fig. 2b can result both by chance from a strategy with no predominant direction, and from one that is generated by a strategy with directionally biased movement.

By contrast, for a large reproducing population, such chance variation among individuals in their reproductive histories and in their total movements over a life span is not expected to have a significant influence on the patterns observed at the level of the total population (Fig. 1b, Fig. 3). With increasing numbers of individuals the change in the population density in time and space appears almost continuous. By mathematically averaging the behaviour of individuals it becomes possible to move from an individual-based description to a continuously changing population density function in time and space. Identifying the underlying dispersal strategy becomes straightforward now that we have averaged out the chance variations. Clearly the pattern in Fig. 3a is the result of a dispersal strategy with no predominant direction and the pattern in Fig. 3b is the result of a
dispersal strategy with directed movement. This mathematical averaging is the basis by which continuum mathematical models of population dispersal are constructed.

If we allow the population to undergo both growth and dispersal then it seems natural to expect the population to disperse into regions and exploit the available resources. The consequence of such a strategy leads to a self-propagating colonization wave as will be confirmed by the mathematical modelling.

The choice of continuum modelling provides us with a simple reproducible method for calculating demic expansions. However, it does come at a price, in that we must ensure that the temporal and spatial scales of interest are large in comparison to the intrinsic population process scales. In our case these process scales are simply the generation times of individuals and their dispersal distances, respectively. In the cases of the first peopling of the Americas and of the Neolithic transition in Europe, the relevant space scales (whole continents) and the time scales (thousands of years) are clearly orders of magnitude greater than the intrinsic process scales of the average individual life cycle and of the average individual migration rate.

3. Fisher–Skellam model

The first application of continuum based models incorporating both population reproduction/death rates and dispersal was due to Fisher [9] in the study of diffusion of an advantageous gene and later to Skellam [18] in the theoretical study of population dispersal. This model, now generally referred to as the Fisher–Skellam (F–S) model, is well known for producing an advancing population front (or travelling wave solutions). The application of the Fisher–Skellam model to hominin dispersal has been considered by Young and Bettinger [26], and by the co-authors in previous works [19,20]. Here we shall quickly review the model before drawing attention to the main results required for this paper.

Essentially, the F–S model is comprised of two parts: a population growth term and a population dispersal term, written mathematically as

\[ \frac{\partial n}{\partial t} = f(n,a,K) + D \nabla^2 n \]  

(1)

where \( n(x,t) \) denotes the population density at time \( t \) and at position \( x \). \( \nabla^2 \) is the Laplacian operator, moving the population from local spatial regions of high density to those of a lower density and \( D \) is the diffusion constant affecting the rate at which the population moves down these gradients. \( f(n,a,K) \) is the population growth function which is usually taken to be logistic growth law proposed by Verhulst [24] and is widely used in theoretical population biology [16]. This function describes a self-limiting density-dependent population increase and is given by

\[ f(n,a,K) = \alpha n \left( 1 - \frac{n}{K} \right) \]  

(2)

where \( \alpha \) is the intrinsic maximum population growth rate and \( K \) is the carrying capacity, related to local environmental factors.

The crucial biological parameters for the model are the so-called Malthusian growth parameter \( \alpha \), the carrying capacity \( K \) and the diffusion constant \( D \). \( D \) represents the degree of mobility of an individual (e.g. \([2]\))\(^1\). In general individuals will move from their birthplace a distance \( \lambda \) during their generation time \( \tau \). The square of this distance will in general be proportional to the time available; the constant of proportionality is the diffusion constant \( D \):

\[ D = \frac{\lambda^2}{4\tau}. \]

4. General results for a homogeneous \( K \)-surface

Solutions to the F–S equation can in general only be obtained numerically. An example of the travelling population wave for parameter values \( \alpha=1, D=1 \) and \( K=1 \) can be seen in Fig. 4. While changing the parameters \( \alpha, D \) and \( K \) leaves the generic shape of the wave

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\(^1\) This version of \( D \) assumes that there is no predominant direction of individual movements, when aggregated at the population level. This minimalist assumption is a modelling convention: we would not want to track the movements of all individuals, but we can still describe regularities in the redistributions of ensembles of individuals probabilistically (and then deterministically using a diffusion term). The assumption of undirected movement is one that we would make where we have insufficient prior knowledge of either the environmental cues or the behavioural rules that could have produced correlated decisions (and thus directionality of movement) at the population level [23].
profile unchanged it will affect the wave front width and the wave velocity (as we discuss in detail below).

The wave front region, over which the population changes from a high to a low density, can be shown through dimensional arguments to be dependent on $D$ and $\alpha$, and to have an intrinsic spatial scale $\xi \sim \sqrt{D/\alpha}$. A more useful measure of the wave width $L$ can be estimated using the maximum gradient (see [16]), as shown in Fig. 5 to be

$$L = 8\xi$$  \hspace{1cm} (3)

Notice that small values of $\alpha$ relative to those of $D$ correspond to large transition regions (wave widths), and the converse to small transition regions.

![Fig. 4. Wave propagation in dimensionless variables.](image)

![Fig. 5. Effects of $\alpha$ and $D$ on wave width.](image)

The wave speed ($v$) is also a very important quantity for population dispersal. It can be shown [14] that the speed the wave front travels is also related to $\alpha$ and $D$, tending asymptotically to approach

$$v = 2\sqrt{D\alpha}. \hspace{1cm} (4)$$

The relationship between the wave velocity $v$ and wave width can be seen in Fig. 6a. The wave profile's dependence on the carrying capacity $K$ can be seen in Fig. 6b and simply steepens the maximum gradient of the wave front by

$$\frac{\partial n}{\partial x} = \frac{K}{L}. \hspace{1cm} (5)$$

![Fig. 6. (a) Isolines of wave velocity as a function of $D$ and $\alpha$ for $v=1, 2, 3, 4$. (b) Effect of changing the carrying capacity $K$.](image)
Finally, if we integrate the population density over time at a particular location we can obtain the 'cumulative occupancy'. The cumulative population density corresponding to the travelling wave in Fig. 4 can be seen in Fig. 7. Notice that when the carrying capacity is uniform in space the cumulative density always decreases away from the origin of dispersal. The resulting long-time spatial gradient can be calculated to be

$$\frac{dn_{\text{cum}}}{dx} = -\frac{K}{v}.$$  \hspace{1cm} (5)

It is necessary to draw the reader’s attention to the two important quantities resulting from the modelling. They are the wave width $L$ and the wave velocity $v$. Notice that both these quantities depend on the population growth rate $\alpha$ and the diffusion constant $D$. Steep waves result when $D$ is low and $\alpha$ is high. By contrast, shallow waves occur in the reverse case. However, because the velocity of the wave is determined by the product of $D$ and $\alpha$ they can travel, in principle, with the same velocity, but with significantly different transitional wave profiles. This will lead to very different archaeological signatures.

5. General results for a heterogenous $K$-surface

What happens to the propagation of travelling waves over a heterogenous carrying capacity surface? The wave characteristics such as wave width and velocity are unaffected. However, the varying population densities at points in space are determined in some way by the $K$-surface. Provided that the $K$-surface changes on spatial scales greater than the wave width $L$ the population density follows this $K$ surface precisely. By contrast, if the surface changes on spatial scales shorter than $L$ then the resulting population density follows some spatially averaged $K$-surface. Examples of this behaviour can be seen in Fig. 8a and b, respectively.

While the variations to the travelling population wave are easy to predict, the effects on the cumulative density can be much more difficult to interpret. Consider for example a uniformly increasing $K$-surface; the travelling wave follows the increasing gradient of $K$ in a clear way, Fig. 8c. By contrast, the cumulative population resulting from such a wave is no longer the simple monotonic decay from the origin, as shown in Fig. 8d. It is now difficult to interpret the origin of these waves without a complete knowledge of the $K$-surface.

6. Archaeological detection

Having summarized the properties of Fisher–Skellam models of population expansion, we now return to the conditions for their archaeological detection. In the simplest case we can use the results of this model to indicate possible signatures that we would expect to remain in the archaeological record if our assumptions on colonization are generally upheld. Using modelling results to validate experimental field data is by no means a trivial process, especially when field data is in short supply. In situations where experiments are difficult or impossible to reproduce we are restricted by the available data. Archaeology is a prime example of a discipline in which models are weakly constrained by surviving control data. In an ideal situation we would expect to be able to determine the origin of an expansion in space and time, the velocity of expansion in different directions, and the reproductive rates and movement rates that drove that expansion. Recent attempts to derive these values for prehistoric dispersals have tried to extract the information from variation in the radiocarbon dates of early sites, and from the variable densities of discarded early artefacts [10,12,20,21]. We shall now consider the intrinsic limitations on this kind of inference. These restrictions may rule out modelling completely, if the available control data are too poor to make this worthwhile, or they may simply restrict the range of modelling parameters that can be used to validate the models.

6.1. Radiocarbon dating

Radiocarbon dating is based on the abilities to measure the carbon isotopic composition of an organic sample today, and to compare it with the estimated isotopic composition of the same sample when it was part of a living organism fixing carbon in its tissues. By quantifying the ‘missing fraction’ of the unstable radiisotope $^{14}$C, whose decay rate is known, it is possible to estimate the time elapsed since the organism’s death. Known variation in the past isotopic composition of the
atmospheric and marine carbon reservoirs requires calibration of raw isotope measurements to derive an estimate of the sample’s true age. However, even before calibration the measurement is subject to counting error or uncertainty, such that the C\textsuperscript{14} content (when translated into an uncalibrated age) is quoted as a mean with standard deviation, $t \pm \sigma$ (where $\pm \sigma$ indicates the range covered by 68.3% of the probability distribution for the date).

This error is largely an artefact of measurement precision, and the error in AMS dates is usually of the order of 50–100 years (although it may be greater with very small or very old samples). However, error can sometimes be further reduced by making multiple determinations of the age of a single event and averaging them—either by replicate dating of the same sample, or by averaging the radiocarbon ages of different samples which are assumed a priori to derive from the same past event [6]. We shall consider the idealized case in which the date is characterized by a modal age with error variance distributed symmetrically about that mean. Calibration, insofar as it changes the modal age and the size of the standard error, is still compatible with this approach. We shall not consider here the asymmetrical and irregular aspects of calibrated probability distributions, since they introduce further and significant complications into the analyses proposed below (they are, however, incorporated effectively into the statistical model of Blackwell and Buck [5]). Commonly we want to estimate the velocity of a travelling wave, using this probabilistic dating technique.

How do we calculate the velocity of the advancing population front from radiocarbon dates? A simple estimate can be obtained by consider two points $A$ and $B$ separated by a distance $\Delta x$. Radiocarbon determinations date first occupation at $A$ to $t_A \pm$ uncertainty $\delta t_A$, and at $B$ to $t_B \pm$ uncertainty $\delta t_B$. The velocity of expansion between these two locations is simply the slope of Fig. 9 and is calculated by

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Fig. 8. (a) Slowly varying $K$-surface. (b) Quickly varying $K$-surface. (c) Wave profiles with $VK=0$ and $VK=0.1$. (d) Cumulative population density for $VK=0.1$. 
Intuitively one realizes that calculating velocities when errors in \( t \) are the same order as the time between events is incorrect. In order to obtain accurate calculation we must ensure that \( \delta t \ll \Delta t_{RC} \), with the percentage error given by relative error:

\[
\frac{v_{error}}{v_{RC}} = \frac{\delta t}{\Delta t_{RC}} = \frac{\delta t}{\Delta x}.
\]

What size is the uncertainty \( \delta t \)? As this is only a simple estimate it seems reasonable to simply take \( \delta t = \sigma \) or \( 2\sigma \) (depending on the level of uncertainty that is deemed acceptable in each case).

### 7. Detection of a founding population wave using radiocarbon data

In this section we bring together the quantitative measures described in the previous sections to determine the conditions necessary for the detection and modelling of an advancing founding population wave. The key results were the wave width \( L \) and wave speed \( v \) and the range of velocities predictable from imprecise radiocarbon determinations.

Let us first look at the leading edge or first detection of an archaeological marker. The model predicts a population density wave that is at the carrying capacity \( K \) decreasing to infinitesimally small value ahead of the population front. The first question that arises is at what population density would we expect to detect the arrival of the population. We might therefore assign a population cut-off \( n_c \) below which we are unlikely to detect the first arrival (an interesting situation arises if \( n_c \) is greater than the estimated carrying capacity \( K \); in this case we would never expect the initial population wave to be detected).

Secondly, the wave width \( L \) can have important consequences for archaeological interpretation. In order to reconstruct the passage of the population travelling front we must look on length scales or spatial separations \( \Delta x \) greater than the wave width \( L \) if we are confidently to determine whether the population front had reached a given point at a given time.

Intuitively, we might expect that steep and slow waves (low \( L \) and low \( v \)) will be the best for detecting population advance, as shown in Fig. 10a. By contrast, with shallow and fast waves it might be expected to be more difficult to determine whether we are detecting pioneer or established phase occupation, as shown in Fig. 10b. In fact, it is trivial to show for a given wave width \( L \) and velocity \( v \) that waves will be indistinguishable for a time \( dt_{fr} \),

\[
\delta t_{fr} = \frac{2L}{v} = \frac{8}{a}.
\]

where \( a \) is the population growth rate defined earlier. Thus, in principle, a fast, steep wave is best for reconstructing travelling wave parameters. However, our intuition is correct in archaeological situations, because the uncertainty in radiocarbon determinations makes fast waves hard to track accurately using that method.

We can now define criteria that must be met if we are to determine the characteristics of an expanding population front from archaeological data. The requirements are that the spatial separation between sites must obey

\[
\Delta x > L
\]

and that the temporal separation between sites must obey

\[
\Delta t > |dt_{RC}| + |dt_{fl}|
\]
Substituting Equation (3), Equation (8) and Equation (10) yields the following constraints:

\[ \Delta x > 8 \sqrt{\frac{D}{a}}, \]  
(13)

\[ \Delta t > |\delta t_A + \delta t_B| + \frac{8}{a}. \]  
(14)

What does this mean for archaeological detection of travelling waves? Firstly, the time between any pair of events sampled must be greater than the combined sum of radiocarbon errors and the F–S modelling error. While the effect of radiocarbon errors fall in general within the range 100–200 years, the modelling error is inversely dependent on the population growth rate, Equation (10). This can be very large in practice, for example with \( a = 0.01 \), \( \delta t_{FS} = 800 \) years. Therefore at any single location in space, we cannot be certain where the earliest dated event lies within the interval \( \delta t_{FS} \) which defines the wave transition period. Similarly, at any instant in time the locations of any pair of sites being sampled to detect the transition of the wave front must be separated by \( \Delta x \). The necessary spatial separation of any pair of sites being sampled will increase as the migration rate \( (D) \) increases relative to the population growth rate \( \alpha \), Equation (13). For example, in the case where \( \alpha = 0.01 \) and \( D = 100 \), the space separation of the sites would have to be at least 800 km for accurate detection of a wave at a single point in time.

More generally, in many cases where we have a radiocarbon record of a dispersal process, we can now see that we will be severely constrained in our ability accurately to predict colonization rate in terms of the F–S model.

8. Detecting a founding population wave from time-averaged archaeological find densities

In this section we consider the problems encountered when attempting to match modelled and archaeological data for cumulative occupancy. The simplest case occurs when the carrying capacity remains approximately constant over the region of interest. In this case it is easy to show that the calculated cumulative occupancy gradients tend quickly to

\[ \frac{dn_{cum}}{dx} = -\frac{K}{v} \]

as was illustrated earlier. Defining the minimum gradient that may be detected archaeologically requires a clear understanding of spatial scales and resolution and is also problem-dependent. This problem becomes even more complex for heterogeneous \( K \)-surfaces as we have demonstrated for a simple linearly increasing \( K \)-surface (Fig. 8).

While we cannot at this time define the archaeological conditions for such detection, we proceed by estimating the period during which this spatial information, if extractable, would remain before being washed out by the heterogeneous \( K \)-surface. We can estimate this time by constructing (in the best-case scenario) the following simple model where the waves are relatively steep (low \( L \)) and travel at a velocity \( v \) from A to B. The difference in cumulative density can then be simply estimated to be

\[ \frac{\Delta n_{cum}}{\Delta x} = (K_B - K_A) \frac{t}{\Delta x} - \frac{K_B}{v}. \]  
(15)
It is easy to show that if site B possesses a larger carrying capacity than site A, then any gradient in cumulative occupancy pointing back towards the origin of the dispersal will be washed out (due to the difference in carrying capacities), in a time

\[ t_{\text{wash}} = \frac{K_B}{K_B - K_A} \frac{\Delta x}{v}. \]  

(16)

After this time, \( t_{\text{wash}} \), the cumulated occupancy surface begins to be indistinguishable from the carrying capacity surface.

9. Applications

We have demonstrated that demic expansion as modelled using the Fisher–Skellam equations is a travelling wave process, in which the wave width and speed are determined by population-averaged reproductive and dispersal rates. We have also demonstrated that radiocarbon dating (an inherently probabilistic technique, with an absolute limit to its precision) can only reveal gradients in the ages of sites along an axis of colonization subject to an upper limit for both wave speed and wave width. Some recent models have, in effect, created a dichotomy between population expansions with high \( a \) and low \( D \) (small \( L \)), steep waves, and those with low \( a \) and high \( D \) (large \( L \)), shallow waves (e.g. [4,7]). We will help provide an insight into this dichotomy using two archaeological examples.

9.1. Steep and relatively slow waves

The Neolithic transition in Europe is a case where travelling wave characteristics have been estimated quite precisely from radiocarbon data, and appear to be consistent with a steep and slow travelling wave ([1,2], cf. [10]). Ammerman and Cavalli-Sforza [1,2] indicate that they believe \( 10-30 \text{ km} \) to be a plausible value for the average individual’s movement between birth and reproduction in subsistence farming societies, with a maximum rate of increase of \( 3\% \) per year. These values give us (assuming a generation time \( \tau = 25 \text{ years} \)) \( D = 1-9, \ 5.03, \ v = 0.35-1 \text{ km/yr} \), which is close to the empirical overall value of \( v \approx 1 \text{ km/yr} \) observed archaeologically. The relevant space scale of this process in Europe (\( \sim 3000 \text{ km} \)) is more than an order of magnitude greater than the wave width (\( L = \Delta x = 138 \text{ km} \)), and the time scales for the transition in Europe (\( \sim 3000 \text{ years} \)) are correspondingly greater than the value for \( \Delta t_{\text{FS}} \) in this case (267 years), hence the wave should be easily detectable in this case—which may explain why the data fit well empirically.

9.2. Shallow and relatively fast waves

The absence of a clear spatial gradient in initial dates of the first peopling of the Americas indicates that the expansion was of a different type. It was, by implication, rapid (high \( v \), cf. [11,21]). It is also an implication that the wave speed was determined more by unusually high exploratory mobility than by exceptionally rapid reproductive increase (i.e. there was a high ratio of \( D \) to \( a \), giving a broad and shallow wave profile—large \( L \)). In a previous study we suggested \( 300 \text{ km} \) to be a plausible value for the average individual’s movement between birth and reproduction in this unique pioneer dispersal episode by sophisticated hunter-gatherers, with a maximum rate of increase of \( 1\% \) to \( 3\% \) per year, giving \( D = 900, \ a = 0.01-0.03 \) [20]. These values imply \( v = 6-10 \text{ km/yr} \), which is consistent with some estimates based on archaeological evidence (e.g. [21]). The space scale of the continent of North America south of the ice sheets is similar to that of Europe (max. diameter of the order \( \sim 4000-5000 \text{ km} \)), but the interface profile of this modelled wave is much broader (\( L = \Delta x = \sim 1400-2400 \text{ km} \)), and with the lower value of \( a \) it only just fits into the continent. It is therefore unlikely that a true travelling wave would have been generated here. These values are certainly greater than many of the pairwise separation distances in that small sample of Clovis sites whose radiocarbon ages are generally accepted [22], and may explain why it has been so hard to discern the spatial signature of an expansion process in that particular archaeological sample. In addition, the intrinsic time scale of the dispersal process (300–700 radiocarbon years [22]) is not greater than the error term \( \Delta t_{\text{FS}} = \sim 267-800 \text{ years} \). It is probable that if we are to identify pioneer-phase occupancy, we must use some additional archaeological criteria. Various two-phase models of the colonization process and its archaeological signatures are proposed by Kelly and Todd [13], Housley et al. [12], and Davies [7], and these may provide such supplementary forms of evidence.

In one of our previous studies, Fisher–Skellam modelling has been applied to human dispersal into North America south of the ice sheets [20]. Archaeologically, in such cases we may wish to take numbers of sites or of discarded artefacts (such as the fluted projectile points of the early colonizers of North America) as markers of cumulative occupancy [3,20]—an appropriate conflation when the large-scale record is time-averaged across both initial and established phases of settlement, when the original per capita/per year discard rates can be reasonably assumed to have been constant in space and time, and when the record has been sampled in an unbiased manner today. These simplifying assumptions are very large and naive, but they do enable us to begin to model the archaeological signature of a dispersal process using archaeological
data (time-averaged artefact and site densities) as our indicators. We have previously shown that where this dispersal process involved movement up gradients of carrying capacity (as in dispersal towards the southeast from a possible origin in Alberta), the cumulated density of evidence for human occupation would be greatest in the more productive environments—and the initial pioneer gradient washed out—when the indicator artefact maps have been time-averaged over one thousand years or more (Fig. 11). Substituting the model values used by Steele et al.[20] ($D=900$, $K$ ranging from $\sim 1$ p.p. $100$ km$^2$ at the origin to $\sim 7$ p.p. $100$ km$^2$ in the southeast, cf. Fig. 11) into the equation for $t_{wash}$, Equation (16), we find indeed that over a distance $\Delta x=5000$ km, a cumulative occupancy gradient pointing back to the origin will wash out after $\sim 1000$ years for $\alpha=0.01$, and after $\sim 500$ years for $\alpha=0.03$. We have now shown analytically why this pattern, which matches observed gradients in density of recorded Paleoindian fluted points, is in fact consistent with a late glacial Beringian origin for the dispersal.

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