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Bayesian Estimation of Population Size Changes by Sampling Tajima's Trees

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Abstract

The large state space of gene genealogies is a major hurdle for inference methods based on Kingman's coalescent. Here, we present a new Bayesian approach for inferring past population sizes which relies on a lower resolution coalescent process we refer to as "Tajima's coalescent". Tajima's coalescent has a drastically smaller state space, and hence it is a computationally more efficient model, than the standard Kingman coalescent. We provide a new algorithm for efficient and exact likelihood calculations for data without recombination, which exploits a directed acyclic graph and a correspondingly tailored Markov Chain Monte Carlo method. We compare the performance of our Bayesian Estimation of population size changes by Sampling Tajima's Trees (BESTT) with a popular implementation of coalescent-based inference in BEAST using simulated data and human data. We empirically demonstrate that BESTT can accurately infer effective population sizes, and it further provides an efficient alternative to the Kingman's coalescent. The algorithms described here are implemented in the R package `phylodyn`, which is available for download at <https://github.com/JuliaPalacios/phylodyn>.

1 Introduction

Modeling gene genealogies from an alignment of sequences — timed and rooted bifurcating trees reflecting the ancestral relationships among sampled sequences — is a key step in coalescent-based inference of evolutionary parameters such as effective population sizes. In the neutral coalescent model without recombination, observed sequence variation is produced by a stochastic process of mutation acting along the branches of the gene genealogy (Kingman, 1982a; Watterson, 1975), which is modeled as a realization of the coalescent point process at a neutral non-recombining locus. In the coalescent point process, the rate of coalescence (the merging of two lineages into a common ancestor at some time in the past) is a function that varies with time, and it is inversely proportional to the effective population size at time t , $N(t)$ (Kingman, 1982b; Slatkin and Hudson,

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28 1991; Donnelly and Tavaré, 1995). Our goal is to infer $(N(t))_{t \geq 0}$ which we will refer to as the
 29 “effective population size trajectory”.

30 Multiple methods have been developed to infer $(N(t))_{t \geq 0}$ using the standard coalescent model
 31 with or without recombination. Some of these methods infer $(N(t))_{t \geq 0}$ from summary statistics such
 32 as the sample frequency spectrum (SFS) (Terhorst et al., 2017; Bhaskar et al., 2015); however, the
 33 SFS is not a sufficient statistic for inferring $(N(t))_{t \geq 0}$ (Sainudiin et al., 2011). Other methods have
 34 been proposed that directly use molecular sequence alignments at a completely linked locus, *i.e.*
 35 without recombination (Griffiths and Tavaré, 1996; Kuhner and Smith, 2007; Minin et al., 2008; Li
 36 and Durbin, 2011; Drummond et al., 2012; Palacios and Minin, 2013; Gill et al., 2013). Our approach
 37 is of this type. Still other methods account for recombination across larger genomic segments (Li
 38 and Durbin, 2011; Sheehan et al., 2013; Schiffels and Durbin, 2014; Palacios et al., 2015). In spite
 39 of their variety, all these methods must contend with two major challenges: (i) choosing a prior
 40 distribution or functional form for $(N(t))_{t \geq 0}$, and (ii) integrating over the large hidden state space of
 41 genealogies. For example, several previous approaches have assumed exponential growth (Griffiths
 42 and Tavaré, 1996; Kuhner et al., 1998; Kuhner and Smith, 2007), in which case the estimation
 43 of $(N(t))_{t \geq 0}$ is reduced to the estimation of one or two parameters. In general, the functional
 44 form of $(N(t))_{t \geq 0}$ is unknown and needs to be inferred. A commonly used naive nonparametric
 45 prior on $(N(t))_{t \geq 0}$ is a piecewise linear or constant function defined on time intervals of constant
 46 or varying sizes (Heled and Drummond, 2008; Sheehan et al., 2013; Schiffels and Durbin, 2014).
 47 The specification of change points in such time-discretized effective population size trajectories is
 48 inherently difficult because it can lead to runaway behavior or large uncertainty in $(\hat{N}(t))_{t \geq 0}$.
 49 These difficulties can be avoided by the use of Gaussian-process priors in a Bayesian nonparametric
 50 framework, allowing accurate and precise estimation (Palacios and Minin, 2013; Gill et al., 2013;
 51 Lan et al., 2015; Palacios et al., 2015). More precisely, the autocorrelation modeled with the
 52 Gaussian process avoids runaway behavior and large uncertainty in $(\hat{N}(t))_{t \geq 0}$.

53 The second challenge for coalescent-based inference of $(N(t))_{t \geq 0}$ is the integration over the
 54 hidden state space of genealogies for large sample sizes. Given molecular sequence data \mathbf{Y} at a single
 55 non-recombining locus and a mutation model with vector of parameters $\boldsymbol{\mu}$, current methods rely on
 56 calculating the marginal likelihood function $\Pr(\mathbf{Y} | (N(t))_{t \geq 0}, \boldsymbol{\mu})$ by integrating over all possible
 57 coalescence and mutation events. Under the infinite-sites mutation model without intra-locus
 58 recombination (Watterson, 1975), this integration requires a computationally expensive importance
 59 sampling technique or Markov Chain Monte Carlo (MCMC) techniques (Griffiths and Tavaré,
 60 1994a; Stephens and Donnelly, 2000; Hobolth et al., 2008; Wu, 2010; Gronau et al., 2011). Moreover,
 61 a maximum likelihood estimate of $(N(t))_{t \geq 0}$ cannot be explicitly obtained; instead, it is obtained
 62 by exploring a grid of parameter values (Tavaré, 2004). For finite-sites mutation models, current
 63 methods approximate the marginal likelihood function by integrating over all possible genealogies
 64 via MCMC methods (Equation (1); Kuhner (2006); Drummond et al. (2012)). In both cases, the
 65 marginal likelihood may be expressed as

$$\Pr(\mathbf{Y} | (N(t))_{t \geq 0}, \boldsymbol{\mu}) = \int \Pr(\mathbf{Y} | \mathbf{g}, \boldsymbol{\mu}) \Pr(\mathbf{g} | (N(t))_{t \geq 0}) d\mathbf{g}, \quad (1)$$

66 in which $\Pr(\cdot)$ is used to denote both the probability of discrete variables and the density of con-
 67 tinuous variables. The integral above involves an $(n - 1)$ -dimensional integral over $n - 1$ coalescent
 68 times and a sum over all possible tree topologies with n leaves. Therefore, these methods require
 69 a very large number of MCMC samples, and exploration of the posterior space of genealogies con-

70 tinues to be an active area of research (Kuhner et al., 1998; Rannala and Yang, 2003; Drummond
71 et al., 2012; Whidden and Matsen, 2015; Aberer et al., 2016).

72 Current methods rely on the Kingman n -coalescent process to model the sample’s ancestry.
73 However, the state space of genealogical trees grows superexponentially with the number of samples,
74 making inference computationally challenging for large sample sizes. In this study, we develop a
75 Bayesian nonparametric model that relies on Tajima’s coalescent, a lower resolution coalescent
76 process with a drastically smaller state space than that of Kingman’s coalescent. In particular,
77 we approximate the posterior distribution $\Pr((N(t))_{t \geq 0}, \mathbf{g}^T, \boldsymbol{\tau} \mid \mathbf{Y}, \mu)$, where \mathbf{g}^T corresponds to
78 the Tajima’s genealogy of the sample (see Figure 1A and Section 2.4), $(\log N(t))_{t \geq 0}$ has Gaussian
79 process prior with precision hyperparameter τ that controls the degree of regularity, and mutations
80 occur according to the infinite-sites model of Watterson (1975). This results in a new efficient
81 method for inferring $(N(t))_{t \geq 0}$ called **B**ayesian **E**stimation by **S**ampling **T**ajima’s **T**rees (BESTT),
82 with a drastic reduction in the state space of genealogies. We show using simulated data that
83 BESTT can accurately infer effective population size trajectories and that it provides a more
84 efficient alternative than Kingman’s coalescent models.

85 Next, we start with an overview of BESTT, detail our representation of molecular sequence data
86 and define the Tajima coalescent process. We then introduce a new augmented representation of
87 sequence data as a directed acyclic graph (DAG). This representation allows us to both calculate the
88 conditional likelihood under the Tajima coalescent model, and to sample tree topologies compatible
89 with the observed data. We then provide an algorithm for likelihood calculations and develop an
90 MCMC approach to efficiently explore the state space of unknown parameters. Finally, we compare
91 our method to other methods implemented in BEAST (Drummond et al., 2012) and estimate the
92 effective population size trajectory from human mtDNA data. We close with a discussion of possible
93 extensions and limitations of the proposed model and implementation.

94 2 Methods/Theory

95 2.1 Overview of BESTT

96 Our objective in the implementation of BESTT is to estimate the posterior distribution of model
97 parameters by replacing Kingman’s genealogy with Tajima’s genealogy \mathbf{g}^T . A Tajima’s genealogy
98 does not include labels at the tips (Figure 1): we do not order individuals in the sample but label
99 only the lineages that are ancestral to at least two individuals (that is, we only label the internal
100 nodes of the genealogy). Replacing Kingman’s genealogy by Tajima’s genealogy in our posterior
101 distribution exponentially reduces the size of the state space of genealogies (Figure 1B). In order to
102 compute $\Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu)$, the conditional likelihood of the data conditioned on a Tajima’s genealogy,
103 we assume the infinite sites model of mutations and leverage a directed acyclic graph (DAG)
104 representation of sequence data and genealogical information. Note that the overall likelihood,
105 Eq. (1), will differ only by a combinatorial factor from the corresponding likelihood under the
106 Kingman coalescent. Our DAG represents the data with a gene tree (Griffiths and Tavaré, 1994a),
107 constructed via a modified version of the perfect phylogeny algorithm of Gusfield (1991). This
108 provides an economical representation of the uncertainty and conditional independences induced
109 by the model and the observed data.

110 Under the infinite-sites mutation model, there is a one-to-one correspondence between observed
111 sequence data and the gene tree of the data (Gusfield, 1991) (Sections 2.2-2.3). We further augment

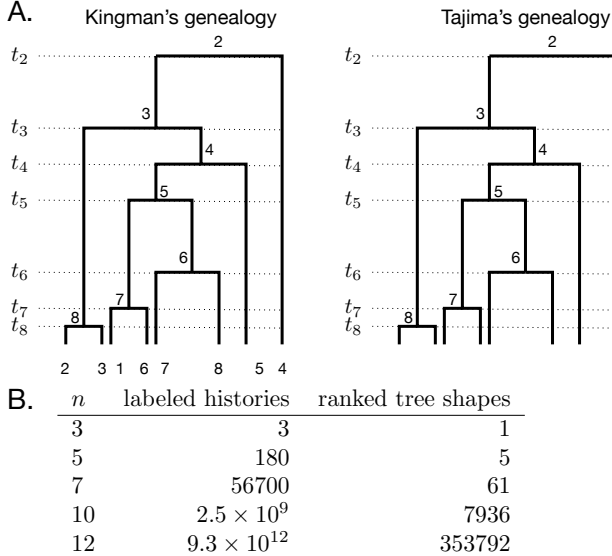


Figure 1: **For a sample of size n , the number of Tajima's genealogies is superexponentially fewer compared to the number of Kingman's genealogies.**

A: A Kingman's genealogy and a Tajima's genealogy for $n = 8$. A Kingman's genealogy (left) comprises a vector of coalescent times and the labeled topology; the number of possible labeled topologies for a sample of size n is $n!(n-1)!/2^{n-1}$. A Tajima's genealogy (right) comprises a vector of coalescent times and a ranked tree shape. In both cases, coalescent events are ranked from 2 at time t_2 to n at time t_n . Coalescent times are measured from the present (time 0) back into the past. **B:** The numbers of labeled topologies and ranked tree shapes (formulas provided in section 2.4) for different values of the sample size, n .

112 the gene tree representation with the allocation of the number of observed mutations along the
 113 Tajima's genealogy to generate a DAG (Section 2.5). The conditional likelihood $\Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu)$ is
 114 then calculated via a recursive algorithm that exploits the auxiliary variables defined in the DAG
 115 nodes, marginalizing over all possible mutation allocations (Section 2.6). We approximate the
 116 joint posterior distribution $\Pr((N(t))_{t \geq 0}, \mathbf{g}^T, \boldsymbol{\tau} \mid \mathbf{Y}, \mu)$ via an MCMC algorithm using Hamiltonian
 117 Monte Carlo for sampling the continuous parameters of the model and a novel Metropolis-Hastings
 118 algorithm for sampling the discrete tree space.

119 2.2 Summarizing sequence data \mathbf{Y} as haplotypes and mutation groups

120 Let the data consist of n fully linked haploid sequences or alignments of nucleotides at s segregating
 121 sites sampled from n individuals at time $t = 0$ (the present). Note that any labels we affix to the
 122 individuals are arbitrary in the sense that they will not enter into the calculation of the likelihood.
 123 We further assume the infinite sites mutation model of Watterson (1975) with mutation parameter
 124 μ and known ancestral states for each of the sites. Then we can encode the data into a binary
 125 matrix \mathbf{Y} of n rows and s columns with elements $y_{i,j} \in \{0, 1\}$, where 0 indicates the ancestral allele.

126 In order to calculate the Tajima's conditional likelihood $\Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu)$, we first record each
 127 haplotype's frequency and group repeated columns to form *mutation groups*; a mutation group
 128 corresponds to a shared set of mutations in a subset of the sampled individuals. We record the
 129 cardinality of each mutation group (*i.e.*, the number of columns that show each mutation group).
 130 In Figure 2A, there are two columns labeled "b", corresponding to two segregating sites which
 131 have the exact same pattern of allelic states across the sample. Further, two individuals carry the
 132 derived allele of mutation group "b", so in this case the frequency of haplotype 7 and the cardinality
 133 of mutation group "b" are both equal to 2. Likewise, haplotype 4 has frequency 1 and carries 5
 134 mutations that are split into mutation groups "a", "f" and "g" (the latter is not shown in Figure

135 2A, but appears in Figure 2B) of respective cardinalities 1, 3 and 1. We denote the number of
136 haplotypes in the sample as h , the number of mutation groups as m , and the representation of \mathbf{Y}
137 as haplotypes and mutation groups as $\mathbf{Y}_{h \times m}$.

138 2.3 Representing $\mathbf{Y}_{h \times m}$ as a gene tree

139 $\mathbf{Y}_{h \times m}$ (Figure 2A) can alternatively be represented as a gene tree or perfect phylogeny (Gusfield,
140 1991; Griffiths and Tavaré, 1994b). This representation relies on our assumption of the infinite sites
141 mutation model in which, if a site mutates once in a given lineage, all descendants of that lineage
142 also have the mutation *and no other individuals carry that mutation*. The gene tree is a graphical
143 representation of the haplotypes (as tips) arranged by their patterns of shared mutations. The
144 haplotype data summarized in Figure 2A corresponds to the gene tree given in Figure 2B. Details
145 of the correspondence between haplotype data and gene tree are listed below, and an additional
146 example is given in Figure 13 (Appendix E).

147 A *gene tree* for a matrix $\mathbf{Y}_{h \times m}$ of h haplotypes and m mutation groups is a rooted tree \mathcal{T} with
148 h leaves and at least m edges, such that (Figure 2B):

- 149 1. Each row of $\mathbf{Y}_{h \times m}$ corresponds to exactly one leaf of \mathcal{T} . The black numbers at leaf nodes in
150 Figure 2B are the haplotype frequencies.
- 151 2. Each mutation group of $\mathbf{Y}_{h \times m}$ is represented by exactly one edge of \mathcal{T} , which is labeled
152 accordingly (letters in Figures 2A and 2B). The red numbers along edges in Figure 2B give
153 the cardinality of each mutation group (*i.e.* the number of segregating sites in this group; see
154 Figure 2A). Some external edges (edges subtending leaves) may not be labeled, indicating
155 that they do not carry additional mutations to their parent edge. This happens when the
156 other edges emanating from its parent node necessarily correspond to other mutation groups.
- 157 3. Edges are placed in the gene tree in such a way that each path from the root to a leaf fully
158 describes a haplotype. Edges corresponding to shared mutations between several haplotypes
159 are closest to the root. For example, in Figure 2B, haplotype 4 corresponds to the leaf at which
160 one arrives starting from the root and going along edges a, g and f; in contrast, haplotype
161 7 corresponds to the leaf at which one arrives going from the root along edge b. Thus, the
162 labels and the numbers associated with the edges along the unique path from the root to a
163 leaf exactly specify a row of $\mathbf{Y}_{h \times m}$.

164 Dan Gusfield’s perfect phylogeny algorithm (Gusfield, 1991) transforms the sequence data $\mathbf{Y}_{h \times m}$
165 into a gene tree and this transformation is one-to-one. We note that the perfect phylogeny \mathcal{T} or
166 gene tree is not the same as the genealogy \mathbf{g} . While a genealogy is a bifurcating tree of individuals
167 of the sample, the gene tree is a multifurcating tree of haplotypes.

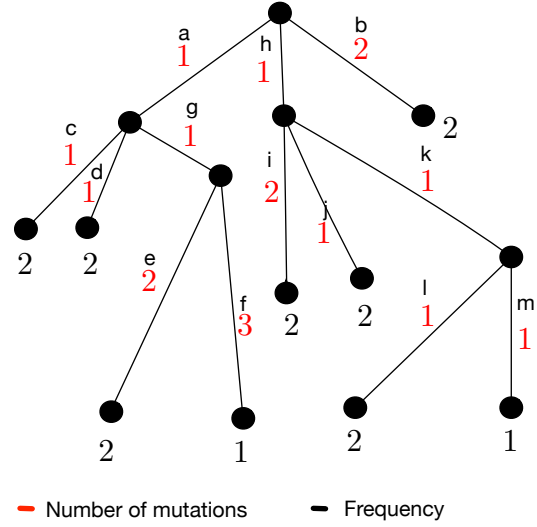
168 2.4 Tajima’s genealogies

169 Our method of computing the probability of the recoded data, $\mathbf{Y}_{h \times m}$, uses ranked tree shapes rather
170 than fully labeled histories. We refer to these ranked tree shapes as Tajima’s genealogies but note
171 they have also been called *unlabeled rooted trees* (Griffiths and Tavaré, 1995) and *evolutionary*
172 *relationships* (Tajima, 1983). In Tajima’s genealogies, only the internal nodes are labeled and they
173 are labeled by their order in time. Tajima’s genealogies encode the minimum information needed
174 to compute the probability of data, $\mathbf{Y}_{h \times m}$ which consists of nested sets of mutations, without any

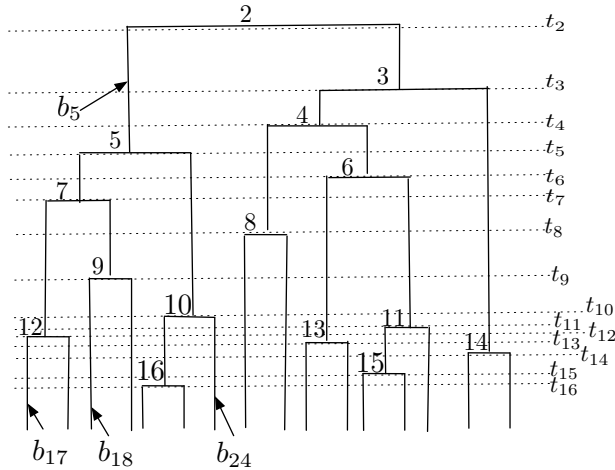
A Data (Y)

Haplotype	Frequency	a	b	c	d	e	e	f	f	f	...
1	2	1	0	0	1	0	0	0	0	0	0
2	2	1	0	0	0	1	0	0	0	0	0
3	2	1	0	0	0	0	1	1	0	0	0
4	1	1	0	0	0	0	0	0	1	1	1
5	2	0	0	0	0	0	0	0	0	0	0
6	2	0	0	0	0	0	0	0	0	0	0
7	2	0	1	1	0	0	0	0	0	0	0
8	2	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	0	0	0
	16										

B Perfect Phylogeny (\mathcal{T})



C Tajima's genealogy (g^T)



D DAG representation

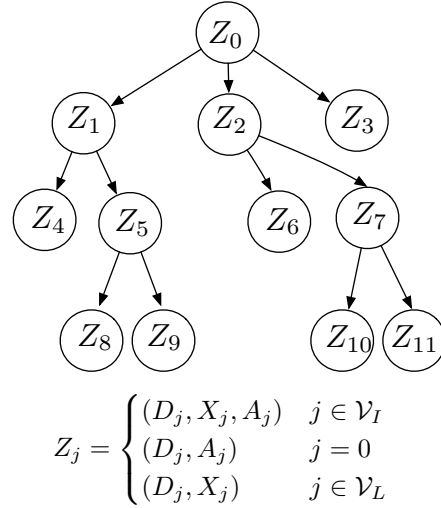


Figure 2: **Data structures employed by our method, BESTT, for calculating the conditional likelihood of the data.** **A.** Compressed data representation $Y_{h \times m}$ of $n = 16$ sequences and $s = 18$ (columns, only the first 10 of which are shown), comprised of 9 haplotypes and 13 mutation groups. Rows correspond to haplotypes and each polymorphic site is labeled by its mutation group $\{a, b, c, \dots, m\}$. **B.** Gene tree representation of the data in panel A. Red numbers indicate the cardinality of each mutation group (number of columns with the same label in panel A). Black letters indicate the mutation group (column labels in panel A), and black numbers indicate the frequency of the corresponding haplotype. **C.** A Tajima's genealogy compatible with the gene tree in panel B. Internal nodes are labeled according to order of coalescent events from the root to the tips. Coalescent event i happens at time t_i and branches are labeled b_i (see section 2.5 for details). **D.** A Directed Acyclic Graph (DAG) representation of the gene tree in panel B together with allocation of mutation groups along the branches of the Tajima's genealogy in panel C. \mathcal{V}_I denotes the set of internal nodes and \mathcal{V}_L the set of leaf nodes. A detailed description of the DAG is given in section 2.5.

175 approximations. In Figure 1A for example, it matters only that mutation group “e” occurs on a
 176 subgroup of the individuals who carry a mutation group “a” and that this is different than the
 177 subgroups carrying “c”, “d” and “f”. No other labels matter because individuals are exchangeable
 178 in the population model we assume.

179 This represents a dramatic coarsening of tree space compared to the classical leaf-labeled binary
 180 trees of Kingman’s coalescent. The number of possible ranked tree shapes for a sample of size n
 181 corresponds to the n -th term of the sequence A000111 of Euler zig-zag numbers (Disanto and
 182 Wiehe, 2013) whereas the number of labeled binary tree topologies is $n!(n-1)!/2^{n-1}$. As can be
 183 seen from Figure 1B, this provides a much more efficient way to integrate over the key hidden
 184 variable, the unknown gene genealogy of the sample, when computing likelihoods.

185 We model this hidden variable using the *vintaged and sized coalescent* (Sainudiin et al., 2015)
 186 which corresponds exactly to this coarsening of Kingman’s coalescent. As can be seen in Figure
 187 1A, we assign vintages/labels 2 through n starting at the root of the tree and moving toward the
 188 present, so that the node created by the final splitting event, which is also the first coalescence
 189 event looking back in the ancestry of the sample, is labeled n . We write t_k for the time of node
 190 k , measured from the present back into the past. We set $t_{n+1} := 0$ to be the present time. Then
 191 during the interval $[t_{k+1}, t_k)$ the sample has exactly k extant ancestors, for $k \in \{2, \dots, n\}$.

192 The coarsening of the tree topology does not change the law of the times between two coalescence
 193 events. Thus, conditional on the effective population size trajectory $(N(t))_{t \geq 0}$ and the time t_{k+1}
 194 at which the number of ancestors to the sample decreases to k , the distribution of the time during
 195 which the sample has k ancestors is given by

$$\Pr(t_k - t_{k+1} | t_{k+1}, (N(t))_{t \geq 0}) = \frac{C_k}{N(t_k)} \exp \left[- \int_{t_{k+1}}^{t_k} \frac{C_k}{N(t)} dt \right] \quad (2)$$

196 (Slatkin and Hudson, 1991), where $C_k = \binom{k}{2}$. Writing the density at $\mathbf{t} = (t_2, t_3, \dots, t_n)$ of the
 197 vector of coalescence times as a product of conditional densities, we obtain

$$\Pr(\mathbf{t} | (N(t))_{t \geq 0}) = \prod_{k=2}^n \Pr(t_k - t_{k+1} | t_{k+1}, (N(t))_{t \geq 0}). \quad (3)$$

198 We use a lower-triangular matrix denoted \mathbf{F} to represent Tajima’s genealogies; see Appendix
 199 A. The probability of a ranked tree shape was derived independently in Sainudiin et al. (2015) and
 200 Palacios et al. (2015). Specifically, for every ranked tree shape \mathbf{F} with n leaves,

$$\Pr(\mathbf{F}) = \frac{2^{n-c-1}}{(n-1)!}, \quad (4)$$

201 where c is the number of cherries in \mathbf{F} (*i.e.*, nodes subtending two leaves; $c = 3$ in Figure 10A).
 202 Note that this probability is independent of the effective population size trajectory since the choice
 203 of the pair of lineages that coalesce during an event is independent of $(N(t))_{t \geq 0}$ (recall that in
 204 Kingman’s coalescent, the coalescing pair is chosen uniformly at random among all possible pairs).
 205 Since the distribution of Tajima’s genealogies $\mathbf{g}^T = (\mathbf{F}, \mathbf{t})$ conditional on $(N(t))_{t \geq 0}$ can be factored
 206 as the product of the probability of the ranked tree shape \mathbf{F} and the coalescent times density, we
 207 arrive at

$$\Pr(\mathbf{g}^T | (N(t))_{t \geq 0}) = \frac{2^{n-c-1}}{(n-1)!} \prod_{k=2}^n \left(\frac{C_k}{N(t_k)} \exp \left[- \int_{t_{k+1}}^{t_k} \frac{C_k}{N(t)} dt \right] \right). \quad (5)$$

208 **2.5 An augmented data representation using directed acyclic graphs**

209 A key component of BESTT is the calculation of the conditional likelihood $\Pr(\mathbf{Y}|\mathbf{g}^T, \mu)$. We
 210 compute the conditional likelihood recursively over a directed acyclic graph (DAG) \mathbf{D} . Our DAG
 211 exploits the gene tree representation \mathcal{T} of the data (Figure 2B), incorporates the branch length
 212 information of the Tajima’s genealogy \mathbf{g}^T (Figure 2C) and facilitates the recursive allocation of
 213 mutations to the branches of \mathbf{g}^T . Here we detail the construction of the DAG.

214 We construct the DAG using three pieces of information: the observed gene tree \mathcal{T} , a given
 215 Tajima’s genealogy \mathbf{g}^T and a latent “allocation” of mutations along the branches of the Tajima’s
 216 genealogy (Figure 3). An allocation refers to a possible mapping (compatible with the data)
 217 of the observed numbers of mutations (red numbers in Figure 2B) to branches in the Tajima’s
 218 genealogy. Figure 3A shows one possible mapping for the Tajima’s genealogy in Figure 2C; usually
 219 this mapping is not unique. Our construction of \mathbf{D} enables an efficient recursive consideration of all
 220 possible allocations of mutations along \mathbf{g}^T when computing the conditional likelihood $\Pr(\mathbf{Y} | \mathbf{g}^T, \mu)$.

221 **Constructing the DAG \mathbf{D} .** The graph structure of our DAG $\mathbf{D} = \{\mathbf{Z}, E\}$ (Figure 2D) with
 222 nodes \mathbf{Z} and edges E is constructed from a gene tree \mathcal{T} . The number of internal nodes in the DAG
 223 \mathbf{D} is the same as the number of internal nodes in \mathcal{T} . However, sister leaf nodes in \mathcal{T} with the
 224 same number of descendants are grouped together in \mathbf{D} and leaf nodes descending from edges with
 225 no mutations are treated as singletons grouped together in \mathbf{D} . For example, the leaves in Figure
 226 2B subtending from edges i and j are grouped into Z_6 in Figure 2D, as they both have haplotype
 227 frequency 2. However, the leaves subtending from the e and f edges are not grouped (and correspond
 228 to Z_8 and Z_9 in the DAG Figure 2D) since they have respective haplotype frequencies 2 and 1.
 229 We label the root node of \mathbf{D} as Z_0 and increase the index i of each node Z_i from top to bottom,
 230 moving left to right. For $i < j$, we assign a directed edge $E_{i,j}$ if the node in \mathcal{T} corresponding to Z_i
 231 is connected to the node in \mathcal{T} corresponding to Z_j . The index set of internal nodes in \mathbf{D} is denoted
 232 by \mathcal{V}_I and the index set of leaf nodes is denoted by \mathcal{V}_L .

Information carried by the nodes in \mathbf{D} . Each node in \mathbf{D} represents a vector, Z_j , which
 includes number of descendants, number of mutations and latent allocation of mutations. Although
 the number of descendants and number of mutations are part of the observed data, the allocation
 of mutations can be seen as a random variable, for ease of exposition, we use capital letters to
 denote all three types of information. We define the vector Z_j as follows:

$$Z_j = \begin{cases} (D_j, X_j, A_j) & j \in \mathcal{V}_I, \\ (D_j, A_j) & j = 0 \text{ (the root node)}, \\ (D_j, X_j) & j \in \mathcal{V}_L, \end{cases}$$

233 where D_j denotes the number of descendants of (*i.e.*, of sampled sequences subtended by) node
 234 Z_j , X_j denotes the number of mutations separating Z_j from its parent node, and A_j denotes the
 235 allocation of mutations along \mathbf{g}^T (described in detail below). The number of descendants D_j is thus
 236 the number of individuals/sequences descending from node Z_j (this information is part of \mathcal{T}). For
 237 internal nodes, X_j records the cardinality of a mutation group, represented as a red number along
 238 the edge $E_{i,j}$ of \mathcal{T} in Figure 2B, where i is the index of the parent node of Z_j . Leaf nodes in \mathbf{D}
 239 may correspond to more than one leaf nodes in \mathcal{T} , namely any sister nodes with the same number
 240 of descendants. In this case, X_j is a vector with the cardinalities of the corresponding mutation

241 groups (see for example node Z_6 in Figure 3B). In order to keep the DAG construction simple, we
 242 only allow groupings of leaf nodes and not of internal nodes with identical descendants carrying
 243 identical numbers of mutations. We note that, in principle, it would be possible to compress the
 244 number of internal nodes of the DAG by exploiting all the symmetries observed in the data.

245 **Allocation of mutation groups along \mathbf{g}^T .** The latent allocation variables $\{A_j\}$ determine a
 246 possible correspondence between subtrees in \mathbf{g}^T and nodes in \mathbf{D} : in particular, A_j indicates the
 247 branches in \mathbf{g}^T that subtend the subtrees corresponding to nodes $\{Z_k\}$ if $\{Z_k\}$ are child nodes of
 248 Z_j .

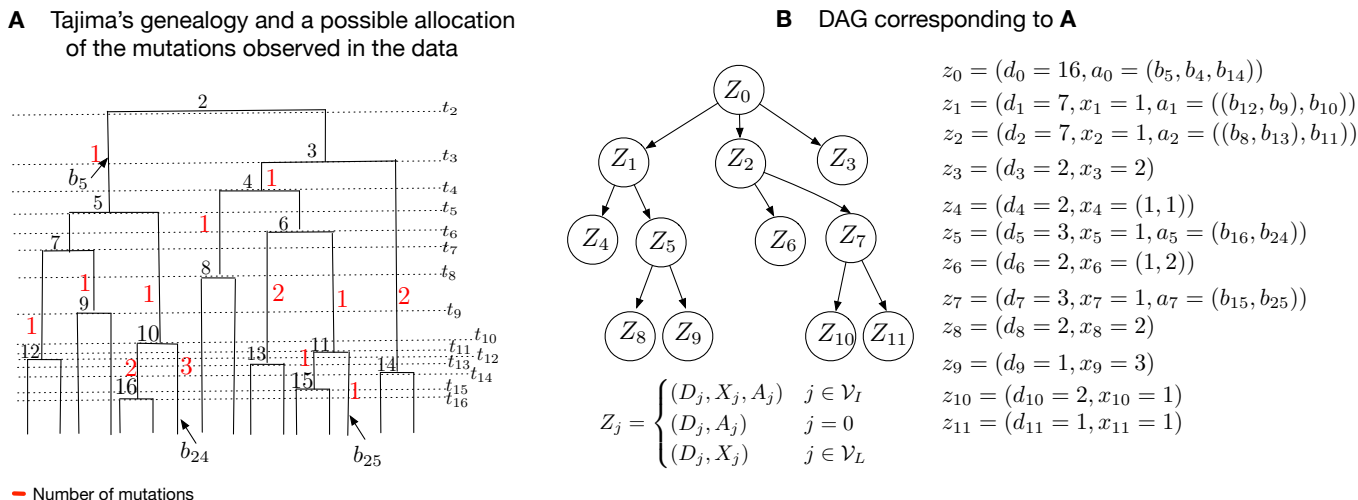


Figure 3: **DAG Construction.** **A.** A Tajima's genealogy from Figure 2C with added allocation of mutations shown in red. **B.** The corresponding augmented DAG with allocation of mutations. At the root Z_0 , there are no mutations by convention. Node Z_0 has 16 descendants across 3 subtrees of 7, 7 and 2 descendants, corresponding to nodes Z_1, Z_2, Z_3 . These three subtrees subtend from b_5, b_4 and b_{14} , respectively, in \mathbf{g}^T (Figure 3A). Node Z_1 corresponds to the tree subtending from b_5 of size 7 with $X_1 = 1$ mutation along b_5 and subtends three subtrees from (b_{12}, b_9) and b_{10} . Subtrees subtending from (b_{12}, b_9) are grouped together in leaf node Z_4 because they both have 2 descendants and have the same parent node. When leaf nodes represent more than one trees, such as Z_4 in Figure 4B, the random variable X_j is the vector $X_j = (X_{j,1}, X_{j,2}, \dots, X_{j,s_j})$ that denotes the number of mutations along the branches that subtends from the tree node j that have D_j descendants, and s_j is the number of edges subtending from Z_j .

249 Allocations of mutations to branches are usually not unique and computation of the conditional
 250 likelihood $\Pr(\mathbf{Y} | \mathbf{g}^T, \mu)$ requires summing over all possible allocations. In Figure 3A we show one
 251 such possible allocation of the mutation groups of the gene tree in Figure 2B along the Tajima's
 252 genealogy in Figure 2C. For example, mutation group "a" in Figure 2B with cardinality 1 (number
 253 in red) is a mutation observed in 7 individuals (sum of black numbers of leaves descending from edge
 254 marked a). This same mutation group, "a", is shown as a red number 1 in Figure 3A allocated to
 255 branch b_5 . If Z_j is an internal node, the number of mutations X_j is denoted as a vector of length 1.
 256 If Z_j is a leaf node, X_j can be a vector of length greater than 1. Details on notation for allocations
 257 can be found in Appendix B.

258 **2.6 Computing the conditional likelihood**

Under the infinite-sites mutation model, mutations are superimposed independently on the branches of \mathbf{g}^T as a Poisson process with rate μ . In order to compute $\Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu) = \Pr(\mathcal{T} \mid \mathbf{g}^T, \mu)$ we marginalize over the latent allocation information in the directed acyclic graph \mathbf{D} ; that is, we sum over all possible mappings of mutations in \mathcal{T} to branches in \mathbf{g}^T as follows:

$$\begin{aligned} \Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu) &= \sum_{A_0} \sum_{A_1} \dots \sum_{A_{n_I}} \Pr(\mathbf{D} \mid \mathbf{g}^T, \mu) \\ &= \sum_{A_0} \sum_{A_1} \dots \sum_{A_{n_I}} \Pr(Z_0, \dots, Z_{n_I+n_L} \mid \mathbf{g}^T, \mu) \\ &= \sum_{A_0} \sum_{A_1} \dots \sum_{A_{n_I}} \prod_{i=1}^{n_I+n_L} \Pr(Z_i \mid Z_{pa(i)}, \mathbf{g}^T, \mu) \end{aligned}$$

where $n_I = |\mathcal{V}_I|$, $n_L = |\mathcal{V}_L|$, $pa(i)$ denotes the index of the parent of node i in \mathbf{D} and we set $P(Z_0 \mid \mathbf{g}^T, \mu) = 1$ because it is assumed that there are no mutations above the root node and the length of the root branch $l_2 = 0$. Writing \mathcal{L} for the tree length of \mathbf{g}^T (*i.e.*, the sum of the lengths of all branches of \mathbf{g}^T) and factoring out a global factor $e^{-\mu\mathcal{L}}$ (due to the Poisson distribution of mutations across the genealogy) from each of the above products over $i \in \{1, \dots, n_I + n_L\}$, we have

$$\begin{aligned} &\Pr(Z_i = z_i \mid z_{pa(i)}, \mathbf{g}^T, \mu) \\ &= \begin{cases} \Pr(X_i = x_i \mid a_{pa(i)} = b_j, \mathbf{g}^T, \mu) \propto (\mu l_j)^{x_i} & \text{if } |x_i| = 1, \\ \Pr(X_i = (x_{i1}, \dots, x_{ik}) \mid a_{pa(i)} = (b_{j_1}, \dots, b_{j_k}), \mathbf{g}^T, \mu) \propto \sum_{s \in \Pi(x_i, k)} \prod_{m=1}^k (\mu l_{j_m})^{s_m} & \text{if } |x_i| = k > 1, \end{cases} \end{aligned}$$

259 where $\Pi(x_i, k)$ is the set of all permutations of $x_i = \{x_{i1}, \dots, x_{ik}\}$ divided into m_i groups of different
 260 sizes. The number of different permutations of the k values of x_i divided into m_i groups of sizes
 261 k_1, \dots, k_{m_i} is

$$|\Pi(x_i, k)| = \frac{k!}{\prod_{j=1}^{m_i} k_j!} \tag{6}$$

262 For example, assume that $x_i = \{2, 2, 2, 0, 3, 3\}$ and $a_{pa(i)} = (b_3, b_4, b_5, b_6, b_7, b_8)$ with branch lengths
 263 $\{l_3, l_4, l_5, l_6, l_7, l_8\}$. In this case, $k_1 = 3$ because there will be 3 branches with 2 mutations, $k_2 = 1$
 264 because there will be 1 branch with 0 mutations and $k_3 = 2$ because there will be 2 branches with
 265 3 mutations. The number of permutations of $k = 6$ mutations groups divided into $m_i = 3$ groups
 266 with cardinalities 2, 0, 3 of sizes 3, 1, 2 is $6!/(3!1!2!) = 60$.

267 The conditional likelihood $\Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu)$ is calculated via a backtracking algorithm (Appendix
 268 C). The algorithm marginalizes the allocations by traversing the DAG from the tips to the root.
 269 The pseudocode and an example can be found in the Appendix C.

270 **2.7 The case of unknown ancestral states**

271 Up to now, we have assumed that the ancestral state was known at every segregating site. The
 272 representation of the data \mathbf{Y} that we use in this case records the cardinalities of each mutation group
 273 and the genealogical relations between these groups, but does not assign labels to the sequences.

274 Hence, in the terminology of Griffiths and Tavaré (1995), our data corresponds to an *unlabeled*
 275 *rooted gene tree*.

276 When the ancestral types are not known, the data (now denoted \mathbf{Y}^0) may be represented as
 277 an unlabeled *unrooted* gene tree. By the remark following Equation (1) in Griffiths and Tavaré
 278 (1995), if s is the number of segregating sites, then there are at most $s + 1$ unlabeled rooted gene
 279 trees that correspond to the unrooted gene tree of the observed data ($\mathcal{R}(Y^0)$). By the law of total
 280 probability (see also Equation (10) in Griffiths and Tavaré (1995)), the conditional likelihood of \mathbf{Y}^0
 281 can be written as the sum over all compatible unlabeled rooted gene trees $Y^{(i)}$ of the probability
 282 of $Y^{(i)}$ conditionally on \mathbf{g}^T . That is:

$$\Pr(\mathbf{Y}^0 | \mathbf{g}^T, \mu) = \sum_{i=1}^{\mathcal{R}(Y^0)} P(\mathbf{Y}^{(i)} | \mathbf{g}^T, \mu), \quad (7)$$

283 where each of the $\mathbf{Y}^{(i)}$ corresponds to a unique unlabeled rooted gene tree compatible with the
 284 unrooted gene tree \mathbf{Y}^0 and $\mathcal{R}(Y^0)$ denotes the number of those unlabeled rooted gene trees. In the
 285 following sections, we shall assume that the ancestral type at each site is known.

286 2.8 Bayesian inference of the effective population size trajectory

287 Our posterior distribution of interest is

$$\Pr(\gamma, \mathbf{g}^T, \tau | \mathbf{Y}, \mu) \propto \Pr(\mathbf{Y} | \mathbf{g}^T, \mu) \Pr(\mathbf{g}^T | \gamma) \Pr(\gamma | \tau) \Pr(\tau), \quad (8)$$

where $(\log N(t))_{t \geq 0} = (\gamma(t))_{t \geq 0} \sim \mathcal{GP}(\mathbf{0}, \mathbf{C}(\tau))$ has a Gaussian process prior with mean $\mathbf{0}$ and
 covariance function $\mathbf{C}(\tau)$ (Rasmussen and Williams, 2006). This specification ensures $(N(t))_{t > 0}$ is
 non-negative. In our implementation, we assume a regular geometric random walk prior, that is,
 $\gamma_1 = \log N(t_1^*), \dots, \gamma_B = \log N(t_B^*)$ at B regularly spaced time points in $[0, T]$ with

$$\text{Cov}[\gamma_i, \gamma_j] = \text{Cov}[\log N(t_i^*), \log N(t_j^*)] = \tau \min(t_i^*, t_j^*).$$

288 The parameter τ is a length scale parameter that controls the degree of regularity of the random
 289 walk. We place a Gamma prior with parameters $\alpha = .01$ and $\beta = .001$ on τ , reflecting our lack of
 290 prior information in terms of high variance about the smoothness of the logarithm of the effective
 291 population size trajectory.

292 We approximate the posterior distribution of model parameters via a MCMC sampling scheme.
 293 Model parameters are sampled in blocks within a random scan Metropolis-within-Gibbs framework.
 294 Our algorithm initializes with the corresponding Tajima genealogy of the UPGMA estimated tree
 295 implemented in `phangorn` (Schliep, 2011). Given an initial genealogy, our algorithm initializes N_e
 296 and τ with the method of (Palacios and Minin, 2012) implemented in `phylodyn` (Karcher et al.,
 297 2017). We then proceed to generate (1) a sample of the vector of effective population sizes and
 298 precision parameter as described in section 2.8.2, (2) a sample of the vector of coalescent times
 299 as described in 2.8.3 and 2.8.4 where we modify a single coalescent time, and (3) a sample of
 300 ranked tree shape as described in 2.8.1 in each iteration. To summarize the effective population
 301 size trajectory, we compute the posterior median and 95% credible intervals pointwise at each grid
 302 point in $[0, \hat{T}]$, where \hat{T} is the maximum time to the most recent common ancestor sampled.

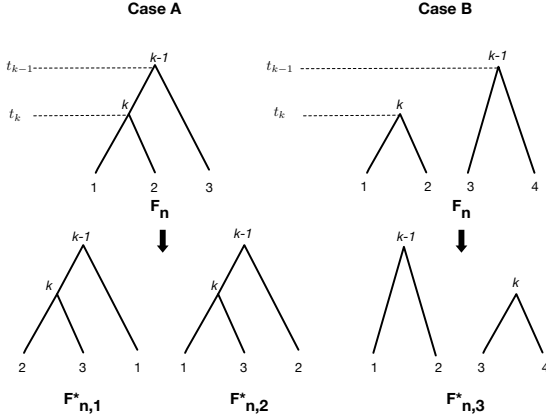


Figure 4: **Markov moves for topologies** First row: possible coalescent patterns (Case A or Case B) for a given topology F_n . Second row: possible Markov moves in Case A ($F_{n,1}^*$ and $F_{n,2}^*$) and Case B ($F_{n,3}^*$). k indexes the coalescent interval sampled. Numerical labels at the tips are added for convenience: conditionally on a given F_n , tips can be labeled (vintage) or not (singleton). Figure is adapted from Figures 2, 3 and 4 of Markovtsova et al. (2000).

303 2.8.1 Metropolis-Hastings updates for ranked tree shapes

304 There is a large literature on local transition proposal distributions for Kingman’s topologies (Kuh-
 305 ner et al., 1998; Rannala and Yang, 2003; Drummond et al., 2012; Whidden and Matsen, 2015;
 306 Aberer et al., 2016). In this paper, we adapted the local transition proposal of Markovtsova et al.
 307 (2000) to Tajima’s topologies. We briefly describe the scheme below and provide a pseudocode
 308 algorithm in Appendix C (Algorithm 3).

309 Given the current state of the chain $\{\gamma, \tau, \mathbf{g}^T\} = \{\gamma, \tau, \mathbf{F}_n, \mathbf{t}\}$, we propose a new ranked tree
 310 shape \mathbf{F}^* in two steps: (1) we first sample a coalescent interval $e_k = (t_{k+1}, t_k)$ uniformly at random,
 311 where $k \sim U(\{3, \dots, n\})$. Note that we will never select the interval (t_3, t_2) at the top of the tree
 312 (see Figure 10A). Given k , we focus solely on the coalescent events at times t_k and t_{k-1} . For step
 313 (2), there are two possible scenarios. Case A: The lineage created at time t_k , labeled k , coalesces
 314 at time t_{k-1} (first row of Figure 4A). Case B: Lineage k does not coalesce at time t_{k-1} (Figure 4B).
 315 In Case A, we choose a new pair of lineages at random to coalesce at time t_k from the 3 lineages
 316 subtending k and $k-1$ (excluding k), and we coalesce the remaining lineage with k at t_{k-1} ($F_{n,1}^*$
 317 and $F_{n,2}^*$ in Figure 4). In Case B, we invert the order of the coalescent events; that is, the two
 318 lineages descending from k are set to coalesce at time t_{k-1} and lineages descending from $k-1$ are
 319 set to coalesce at time t_k . ($F_{n,3}^*$ a in Figure 4). Note that the numerical labels 1, 2, 3 are included
 320 to clarify the picture: lineages subtending both Case A and Case B can be either labeled (if there
 321 is a vintage subtending that lineage) or not (if there is a singleton). The transition probability
 322 $q(\mathbf{F}_n^* | \mathbf{F}_n)$ is given by the product of the probabilities of the two steps. The new ranked tree shape
 323 \mathbf{F}_n^* is accepted with probability given by the Metropolis-Hastings ratio defined below:

$$a_{\mathbf{F}_n} = \min \left\{ 1, \frac{\Pr(\mathbf{Y} | \mathbf{F}_n^*, \mathbf{t}, \mu) \Pr(\mathbf{F}_n^*) q(\mathbf{F}_n | \mathbf{F}_n^*)}{\Pr(\mathbf{Y} | \mathbf{F}_n, \mathbf{t}, \mu) \Pr(\mathbf{F}_n) q(\mathbf{F}_n^* | \mathbf{F}_n)} \right\} \quad (9)$$

324 We note that our proposal can result in the same ranked tree shape. However, we tested alterna-
 325 tive proposals that precluded this event and we did not find any notable difference in the overall
 326 performance of the MCMC algorithm.

327 2.8.2 Split Hamiltonian Monte Carlo updates of (γ, τ)

328 To make efficient joint proposals of γ and τ , we use the Split Hamiltonian Monte Carlo method
 329 proposed by Lan et al. (2015). Conditioned on \mathbf{g}^T , the target density becomes $\pi(\gamma, \tau) \propto \Pr(\mathbf{t} |$

330 $\gamma)\Pr(\gamma | \tau)\Pr(\tau)$. This is the same target density implemented in Karcher et al. (2017) for fixed
 331 coalescent times \mathbf{t} .

332 2.8.3 Hamiltonian Monte Carlo updates of coalescent times

333 Given the current state $\{\gamma, \tau, \mathbf{g}^T\} = \{\gamma, \mathbf{F}_n, \mathbf{t}, \tau\}$, we propose a new vector of coalescent times with
 334 target density $\pi(\mathbf{t}') \propto P(\mathbf{Y} | \mathbf{F}_n, \mathbf{t}', \mu)P(\mathbf{t}' | \gamma)$ by numerically simulating a Hamilton system with
 335 Hamiltonian

$$H(\log(\mathbf{t}'), \mathbf{s}) = -\log(\pi(\log(\mathbf{t}'))) + \frac{1}{2}\mathbf{s}^T\mathbf{M}\mathbf{s}, \quad (10)$$

where \mathbf{s} is the momentum vector assumed to be normally distributed. The system evolves according to:

$$\begin{aligned} \frac{\partial \mathbf{s}}{\partial x} &= \nabla \log \pi(\log(\mathbf{t}')) \\ \frac{\partial \mathbf{t}'}{\partial x} &= \mathbf{M}\mathbf{s} \end{aligned} \quad (11)$$

We use the *leapfrog* method (Neal, 2011) with step size ϵ and a p Poisson with mean 10 distributed number of steps to simulate the dynamics from time $x = 0$ to $x = p\epsilon$. Each leapfrog step of size ϵ follows the trajectory:

$$\begin{aligned} \mathbf{s}_{x+\epsilon/2} &= \mathbf{s}_x + \frac{\epsilon}{2}\nabla \log \pi(\log(\mathbf{t}'_x)) \\ \mathbf{t}'_{x+\epsilon} &= \mathbf{t}'_x + \epsilon\mathbf{M}\mathbf{s}_{x+\epsilon/2} \\ \mathbf{s}_{x+\epsilon} &= \mathbf{s}_{x+\epsilon/2} + \frac{\epsilon}{2}\nabla \log \pi(\log(\mathbf{t}'_{x+\epsilon})) \end{aligned} \quad (12)$$

336 For our implementation, we set the mass matrix $\mathbf{M} = \mathbf{I}$, the identity matrix. We simulate the
 337 Hamiltonian dynamics of the logarithm of times to avoid proposals with negative values. Solving the
 338 equations of the Hamilton system requires calculating the gradient of the logarithm of the target
 339 density with respect to the vector of log coalescent times. The gradient of the log conditional
 340 likelihood (score function) is calculated at every marginalization step in the algorithm for the
 341 likelihood calculation.

342 At the beginning of Section 2.8, we described how we assume a regular geometric random walk
 343 prior on $(N(t))_{t \geq 0}$ at B regularly spaced time points in $[0, T]$. Ideally, the window size T must be
 344 at least t_2 , the time to the most recent common ancestor (TMRCA). However, t_2 is not known.
 345 Our initial values of coalescent times \mathbf{t} are obtained from the UPGMA implementation in *phangorn*
 346 (Schliep, 2011) with times properly rescaled by the mutation rate, and we set $T = t_2$. We initially
 347 discretize the time interval $[0, T]$ into B intervals of length $T/(B-1)$. As we generate new samples
 348 of \mathbf{t} , we expand or contract our grid according to the current value of t_2 by keeping the grid interval
 349 length fixed to $T/(B-1)$, effectively increasing or decreasing the dimension of γ .

350 2.8.4 Local updates of coalescent times

351 In addition to HMC updates of coalescent times, we propose a move of a single coalescent time (ex-
 352 cluding the TMRCA t_2) chosen uniformly at random and sampled uniformly in the intercoalescent

353 interval; that is, we choose $i \sim U(\{n, n-1, \dots, 3\})$ and $t_i^* \sim U(t_{i+1}, t_{i-1})$. This is a symmetric
 354 proposal and the corresponding Metropolis-Hastings acceptance probability is

$$a_{t^*} = \min \left\{ 1, \frac{\Pr(\mathbf{Y} \mid \mathbf{F}_n, \mathbf{t}^*, \mu) \Pr(\mathbf{t}^* \mid \gamma)}{\Pr(\mathbf{Y} \mid \mathbf{F}_n, \mathbf{t}, \mu) \Pr(\mathbf{t} \mid \gamma)} \right\}. \quad (13)$$

355 While these updates may seem unnecessary in light of the Hamiltonian updates of coalescence
 356 times (Section 2.8.3), we observed better performance of our MCMC sampler by including this
 357 additional proposal. One reason may be our choice of \mathbf{M} in section 2.8.3 that does not account for
 358 the geometric structure of the posterior distribution of coalescent times. However, a better choice
 359 of \mathbf{M} comes with higher computational burden than a simple local update of coalescent times.

360 2.8.5 Multiple Independent loci

361 Thus far, we have assumed our data consist of a single linked locus of s segregating sites. We can
 362 extend our methodology to l independent loci with s_i segregating sites for $i = 1, \dots, l$. In this case,
 363 our data $\vec{\mathbf{Y}} = (\mathbf{Y}_1, \dots, \mathbf{Y}_l)$ consist of l aligned sequences with elements $\{0, 1\}$, where 0 indicates
 364 the ancestral allele as before. We then jointly estimate the Tajima's genealogies $\{\mathbf{g}_i^T\}_{i=1}^l$, precision
 365 parameter τ , and vector of log effective population sizes γ through their posterior distribution:

$$\Pr(\gamma, \{\mathbf{g}_i^T\}_{i=1}^l, \tau \mid \vec{\mathbf{Y}}, \mu) \propto \left\{ \prod_{i=1}^l \Pr(\mathbf{Y}_i \mid \mathbf{g}_i^T, \mu_i) \Pr(\mathbf{g}_i^T \mid \gamma) \right\} \Pr(\gamma \mid \tau) \Pr(\tau). \quad (14)$$

366 In Equation (14), we enforce that all loci follow the same effective population size trajectory but
 367 every locus can have its own mutation rate μ_i .

368 3 Results

369 3.1 The performance of BESTT in applications to simulated data

370 We tested our new method, BESTT, on simulated data under four different demographic scenarios.
 371 Note that in this section, $N(t)$ is rescaled to the coalescent time scale, meaning that $1/N(t)$ is the
 372 pairwise rate of coalescence at time t in the past relative to the rate at the present time zero. We
 373 simulated genealogies under four different population size trajectories:

- 374 1. A period of exponential growth followed by constant size:

$$N(t) = \begin{cases} 1 & \text{if } t \in [0, 0.1), \\ \exp(1 - 10t) & \text{if } t \in [0.1, \infty). \end{cases} \quad (15)$$

- 375 2. A trajector with instantaneous growth:

$$N(t) = \begin{cases} 1 & \text{if } t \in [0, 0.05), \\ 0.05 & \text{if } t \in [0.05, \infty). \end{cases} \quad (16)$$

- 376 3. An exponential growth: $N(t) = 25e^{-5t}$

377 4. A constant trajectory: $N(t) = 1$

378 Given a genealogy of length $L = \sum_{j=2}^n j(t_j - t_{j+1})$, where $t_j - t_{j+1}$ is the intercoalescent length
 379 while there are j lineages, we drew the total number of mutations (segregating sites) s according
 380 to a Poisson distribution with parameter μL . We then placed the mutations uniformly at random
 381 along the branches of the genealogy. For each of the s mutations, we assigned the mutant type
 382 to individuals descending from the branch where the mutation occurred and the ancestral type
 383 otherwise.

384 We summarize our posterior inference $\hat{N}(t)$ by the posterior median and 95% Bayesian credible
 385 intervals after 200 thousand iterations and thinned every 10 iterations with 100 iterations of burn
 386 in. Our initial number of change points for $N(t)$ was set to 50 over the time interval $(0, t_2)$, where
 387 t_2 is the initialized time to the most recent common ancestor; however, over the course of MCMC
 388 iterations, this number could increase or decrease according to the posterior distribution of t_2 .

389 We assess accuracy and precision of our estimates using the sum of relative errors (SRE)

$$SRE = \sum_{i=1}^k \frac{|\hat{N}(\omega_i) - N(\omega_i)|}{N(\omega_i)}, \quad (17)$$

390 where $\hat{N}(\omega_i)$ is the estimated effective population size trajectory at time ω_i . Second, we computed
 391 the mean relative width as

$$MRW = \sum_{i=1}^k \frac{|\hat{N}_{up}(\omega_i) - \hat{N}_{lo}(\omega_i)|}{kN(\omega_i)}, \quad (18)$$

392 where $\hat{N}_{up}(\omega_i)$ corresponds to the 97.5% upper limit and $\hat{N}_{lo}(\omega_i)$ corresponds to the 2.5% lower
 393 limit of the estimated posterior distribution of $N(\omega_i)$. In addition, we measured how well the 95%
 394 credible intervals cover the truth and compute the envelope measure, ENV :

$$ENV = \frac{\sum_{i=1}^k \mathbf{1}(\hat{N}_{lo}(\omega_i) \leq N(\omega_i) \leq \hat{N}_{up}(\omega_i))}{k} \quad (19)$$

395 We first simulated 3 datasets of $n = 10$ individuals with an average number of 100 segregating
 396 sites under different types of population size trajectories: constant, exponential growth and instan-
 397 taneous growth. Results are depicted in the first column of Figure 8. Posterior medians and 95%
 398 credible intervals are shown as black curves and gray shaded areas respectively. The trajectory used
 399 to simulate the data is depicted as a dashed line. Figure 8 shows that our BESTT method recovers
 400 the constant and exponential growth trajectories very well but the instantaneous growth scenario
 401 is less accurate and with high uncertainty (wide credible intervals). In all three cases, our envelope
 402 measure is above 95%. Performance measures on all simulations are summarized in Table 1.

403 We analyzed the effect of increasing the number of segregating sites, the number of samples and
 404 the number of independent genealogies on posterior inference with BESTT. In all three cases, we
 405 expect our method to better recover the truth. Figure 5 shows our results on simulated data under
 406 a population size trajectory with instantaneous growth (Equation 16) of $n = 10$ individuals with
 407 31, 63 and 120 segregating sites. As expected, our method recovers the truth with higher precision
 408 (MRW) and accuracy (SRE) when we increase the number of segregating sites. Increasing the
 409 number of segregating sites may result in more constraints in the gene tree. For $n = 10$, there are
 410 7936 possible ranked tree shapes, however for the datasets simulated with 31, 63 and 102 segregating
 411 sites, there are only 2582 ± 32 , 2670 ± 34 and 556 ± 7 ranked tree shapes compatible with their

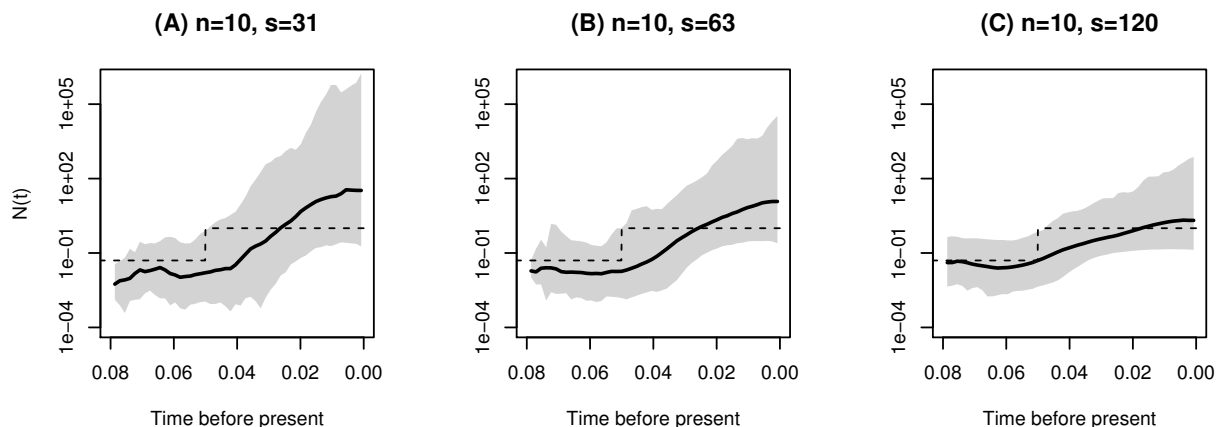


Figure 5: **Varying the number of segregating sites.** Posterior inference from simulated data of $n = 10$ sequences under a population size trajectory with instantaneous growth (dashed lines). s is the number of segregating sites. Posterior medians are depicted as solid black lines and 95% Bayesian credible intervals are depicted by shaded areas.

412 corresponding gene trees. These numbers were estimated by importance sampling (Cappello and
 413 Palacios, 2019).

Table 1: Empirical measures of performance in the simulations described in the text

Simulation	% ENV	SRE	MRW
Instantaneous growth($n=10,s=31$)	96	5.87	124352
Instantaneous growth ($n=10,s=63$)	100	2.15	2296
Instantaneous growth ($n=10,s=120$)	98	0.53	80
Instantaneous growth ($n=25$)	90	0.40	3.43
Instantaneous growth ($n=35$)	92	0.31	3.16
Constant	100	0.30	1.16
Exponential	100	0.35	5.45
Exp. & const. ($n=10, 1$ locus)	100	4.31	22608
Exp. & const. ($n=10, 5$ loci)	100	2.37	309.1
Exp. & const. ($n=10, 10$ loci)	100	0.16	4.19

414 As another performance assessment, we simulated datasets from a population size trajectory
 415 with instantaneous growth with varying number of samples. We simulated datasets with $n = 10$,
 416 25 and 35 samples with 215 expected number of segregating sites. Our results depicted in Figure
 417 6 show that our method performs better in terms of SRE and MRE when the number of samples
 418 increases. Similarly, precision (MRW) and accuracy (SRE) increases when inference is done from
 419 a larger number of independent datasets. Finally, Figure 7 shows our results from 1, 5 and 10
 420 datasets simulated from 1, 5 and 10 independent genealogies of 10 individuals with a population
 421 size trajectory of growth followed by a constant period (Equation 15). As expected, our method's

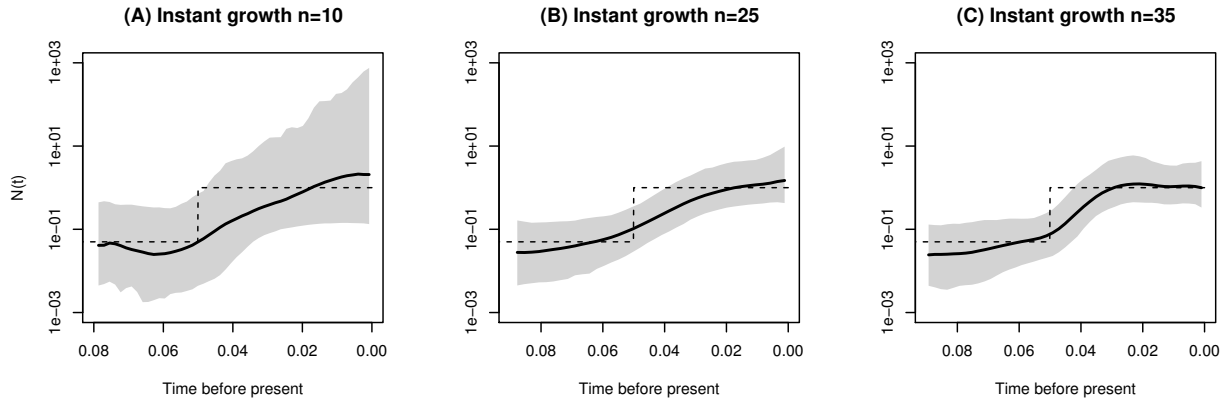


Figure 6: **Varying the number of samples under a population size trajectory with instantaneous growth.** Posterior inference from simulated data of $n = 10, 25$ and 35 sequences under the population size trajectory with instantaneous growth. Shaded areas correspond to 95% credible intervals, solid lines to posterior median and dashed line to the truth.

422 performance substantially increases by increasing the number of independent datasets.

423 3.2 Comparison to other methods

424 To our knowledge, there is no other method for inferring (variable) effective population size over
 425 time from haplotype data that assumes the infinite sites mutation and a nonparametric prior on
 426 $N(t)$, therefore we cannot have a direct comparison of our method to others. Moreover, our method
 427 is the only one that explicitly averages over Tajima genealogies instead of Kingman genealogies.
 428 BEAST (Drummond et al., 2012) is a program for analyzing molecular sequences that uses MCMC
 429 to average over the Kingman tree space and it is therefore a good reference for comparison to our
 430 method. We compared our results to the Extended Bayesian Skyline Plot method (EBSP) (Heled
 431 and Drummond, 2008) and the Skygrid method (Gill et al., 2013) implemented in BEAST.

432 Since the infinite sites mutation model is not implemented in BEAST, we first converted our
 433 simulated sequences of 0s and 1s to sequences of nucleotides by sampling s ancestral nucleotides
 434 uniformly on $\{A, T, C, G\}$ and assigning one of the remaining 3 types uniformly at random to be
 435 the mutant type. This corresponds to a simulation of the Jukes-Cantor mutation model (Jukes and
 436 Cantor, 1969) that is currently implemented in BEAST.

437 We compare the results of BESTT to those of BEAST EBSP and Skygrid (Drummond et al.,
 438 2005, 2012) in Figure 8. We note that results from BEAST are generated from 10 million iterations
 439 and thinned every 1000 iterations, while results from BESTT are generated from 200 thousand
 440 iterations.

441 We compared our point estimates $\hat{N}(t)$ from all methods to the ground truth for each simulation
 442 (Table 2). In two cases, BESTT has better envelope than BEAST. For the exponential growth
 443 simulation (Figure 8, second row) the BEAST EBSP result has better SRE and MRW, however,
 444 the credible intervals are uneven with very wide intervals at the ends. In all cases, the BEAST
 445 Skygrid results have wider credible intervals. For the instantaneous growth simulation (Figure
 446 8, third row), BEAST EBSP did not generate many simulations beyond the time point 0.06, for
 447 this reason we recomputed the performance statistics for the overlapping time interval $(0, 0.06)$.

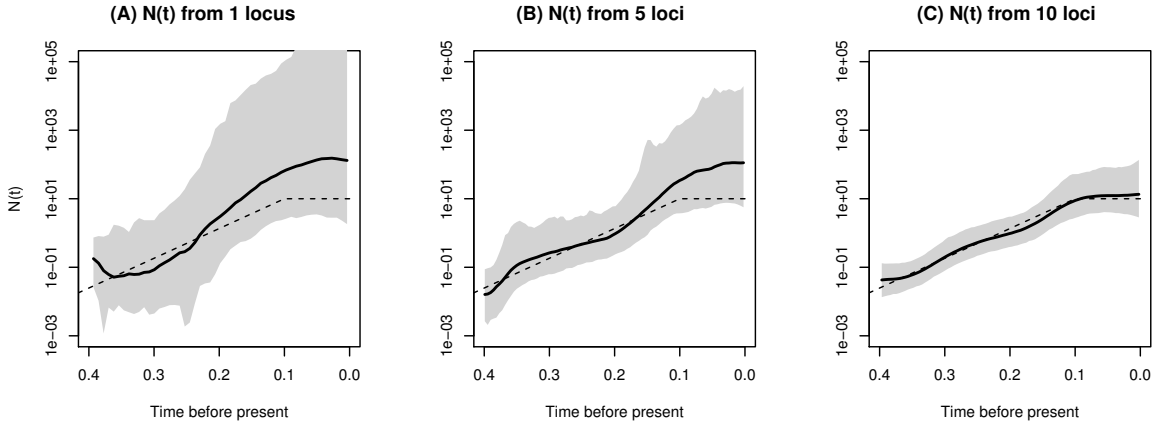


Figure 7: **Multiple independent datasets.** Posterior inference from simulated data of $n = 10$ sequences under exponential followed by constant trajectory (eq. 15). **(A)** Inference from a single simulated dataset, **(B)** from 5 independently simulated datasets, and **(C)** from 10 independently simulated datasets. Shaded areas correspond to 95% credible intervals, solid black lines show posterior medians and dashed lines show the simulated truth.

448 In this interval, BESTT outperforms both methods implemented in BEAST in terms of envelope
 449 and SRE. The last column of Figure 8 shows the posterior distribution of the time to the most
 450 recent common ancestor (TMRCA). For the case of constant population size, the true value of
 451 the TMRCA is contained in the 95% BCI estimated with BESTT but it is not contained in the
 452 95% BCIs estimated with the two methods implemented in BEAST. In the exponential growth
 453 simulation, the true TMRCA is contained in the 95% BCIs estimated with the three methods
 454 and the instant growth method, the true TMRCA is not contained in the 95% BCIs of the three
 455 methods.

Table 2: Performance comparison between BESTT and BEAST in simulations

Simulation	% ENV			SRE			MRW		
	BESTT	EBSP	Skygrid	BESTT	EBSP	Skygrid	BESTT	EBSP	Skygrid
Constant	100	100	100	0.3	0.24	0.24	1.16	1.49	4.41
Exponential	100	97	100	0.35	0.26	0.29	5.45	2.56	46.13
Inst. growth	97	94	100	0.61	2.65	22.6	105.6	14.95	>1000

456 We note that BEAST Bayesian Skygrid (Gill et al., 2013) is a more comparable method to
 457 BESTT since it assumes Gaussian process priors on $\log N(t)$ like BESTT.

458 3.3 Computational performance of BESTT

459 BESTT approximates the posterior distribution (a) $\Pr((N(t))_{t \geq 0}, \mathbf{g}^T, \boldsymbol{\tau} \mid \mathbf{Y}, \mu)$, where \mathbf{g}^T is a
 460 Tajima's genealogy instead of (b) $\Pr((N(t))_{t \geq 0}, \mathbf{g}, \boldsymbol{\tau} \mid \mathbf{Y}^*, \mu)$, where \mathbf{g} is a Kingman's genealogy

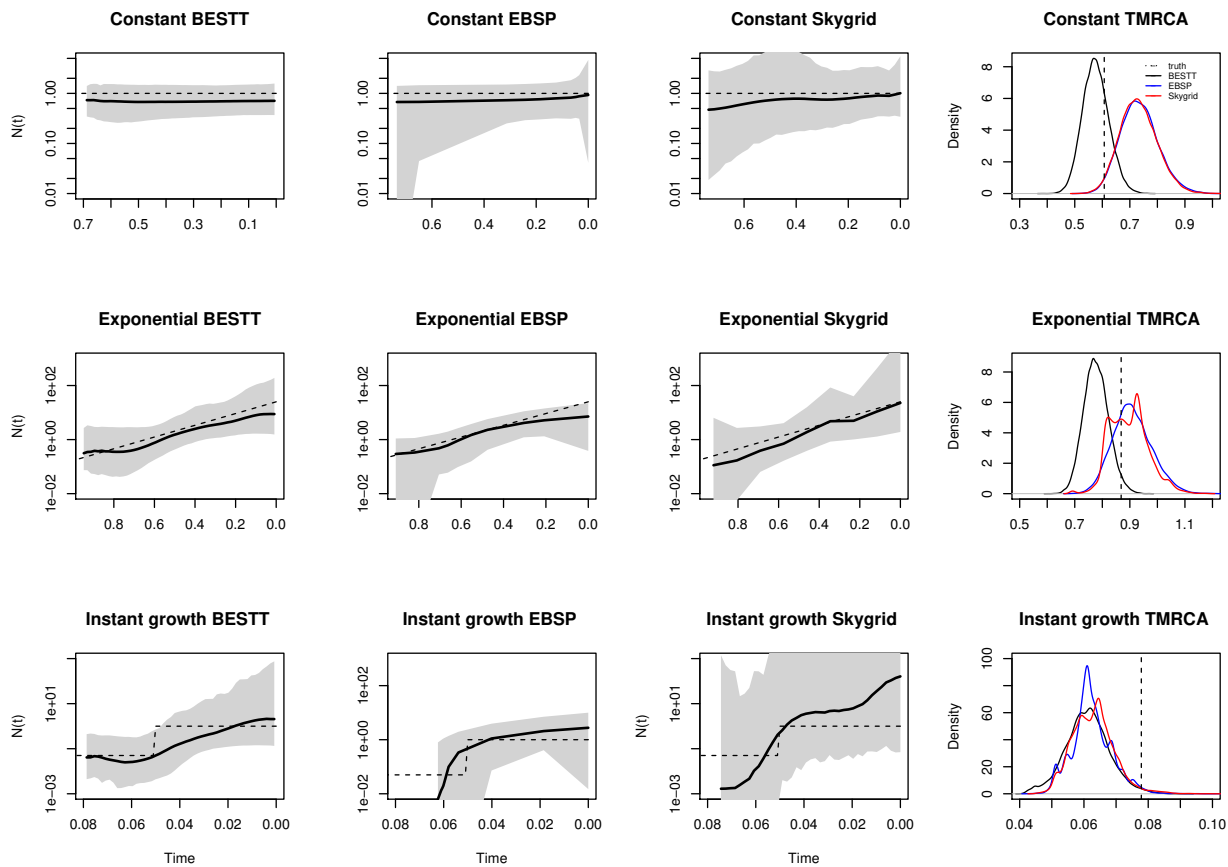


Figure 8: **BESTT and BEAST Comparison.** Posterior inference from simulated data of $n = 10$ sequences under constant, exponential and instantaneous growth trajectories (rows) obtained from our method BESTT (first column), BEAST EBSP (second column) and BEAST Skygrid (third column). Shaded areas correspond to 95% credible intervals, solid black lines show posterior medians and dashed lines show the simulated truth. In the fourth column, we show the posterior density of the time to the most recent common ancestor (TMRCA) from the three methods: BESTT (black), BEAST EBSP (blue) and BEAST Skygrid (red). The true value of the TMRCA is depicted as a vertical dashed line.

461 and \mathbf{Y}^* is the labeled data, in order to estimate $(N(t))_{t>0}$. These two posterior distributions
 462 are the same when every individual of the sample has its own private mutation group and no
 463 shared mutation groups. Otherwise, the number of Tajima’s trees compatible with observed data
 464 \mathbf{Y} , *i.e.* Tajima’s trees \mathbf{g}^T such that $\Pr(\mathbf{g}^T \mid \mathbf{Y}) > 0$, is smaller than the number of Kingman’s
 465 trees compatible with observed labeled data \mathbf{Y}^* (Cappello and Palacios, 2019). That is, we are
 466 required to estimate the posterior of a smaller number of trees. For this reason, we argue that
 467 Tajima’s coalescent is a more efficient model than Kingman’s coalescent for estimating the posterior
 468 distribution of $(N(t))_{t \geq 0}$. However, a single conditional likelihood calculation $\Pr(\mathbf{Y} \mid g^T, \mu)$ requires
 469 the sum over all possible allocation of mutation groups to branches of \mathbf{g}^T . Our algorithm only
 470 accounts for allocations constrained by the DAG and the ranked tree shape of \mathbf{g}^T . For the data
 471 depicted in Figure 2A,B and \mathbf{g}^T of Figure 2C, there are only 8 different possible allocation “paths”
 472 of all mutation groups to branches. In Appendix C we detail how our algorithm finds these paths.
 473 The number of paths depends on the number of subtrees with the same family size path in the
 474 DAG and in the ranked tree shape. In the best case, our algorithm will find a path in $O(no)$,
 475 where no is the number of nodes in the gene tree. In general, the number of allocation paths will
 476 be much smaller than the number of labeled trees compatible with a ranked tree shape. In our
 477 implementation, we estimate posterior (a) with MCMC. The main difference between our MCMC
 478 algorithm and the MCMC algorithm implemented in BEAST is the tree topology sampler. While
 479 our MCMC algorithm explores the space of ranked tree shapes with local move proposals of ranked
 480 tree shapes, BEAST explores the space of labeled, ranked tree shapes with local move proposals
 481 of labeled trees. A formal assessment of the efficiency of our MCMC algorithm and its comparison
 482 to the MCMC implementation in BEAST is beyond the scope of this manuscript and subject of
 483 future research.

484 4 Inferring human population demography from mtDNA

485 We selected $n = 35$ samples of mtDNA at random from 107 Yoruban individuals available from the
 486 1000 Genomes Project phase 3 (The 1000 Genomes Project Consortium, 2015). We retained the
 487 coding region: base pairs 576 – 16,024 according to the rCRS reference of Human Mitochondrial
 488 DNA (Anderson et al., 1981; Andrews et al., 1999) and removed 38 indels. Of the 260 polymor-
 489 phic sites, we retained 240 sites compatible with the infinite sites mutation model. The final file
 490 is available in <https://github.com/JuliaPalacios/phyloodyn>. To encode our data as 0s and 1s,
 491 we use the inferred root sequence **RSRS** of Behar et al. (2012) to define the ancestral type at
 492 each site. To rescale our results in units of years, we assumed a mutation rate per site per year of
 493 1.3×10^{-8} (Rebolledo-Jaramillo et al., 2014). We compare our results with the Extended Bayesian
 494 Skyline method (Drummond et al., 2012) implemented in BEAST in Figure 9. When applying
 495 BEAST, we assumed the Jukes-Cantor mutation model. Both methods detect an inflection point
 496 around 20kya followed by exponential growth. The mean time to the most recent ancestor (TM-
 497 RCA) inferred for these YRI mtDNA samples with BESTT is around 170kya with a 95% BCI of
 498 (142868, 207455), while the mean TMRCA inferred with BEAST is around 160kya with a 95% BCI
 499 of (133239, 196900). In Appendix D, we include two more comparisons of BESTT and BEAST.

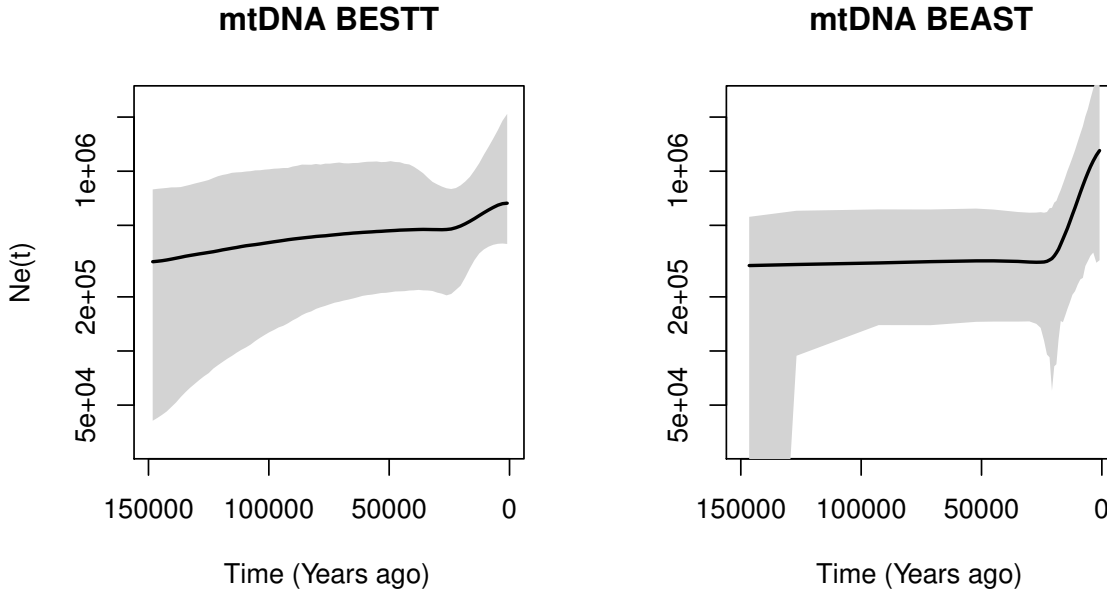


Figure 9: Posterior inference of female effective population size from 35 mtDNA samples from Yoruban individuals in the 1000 Genomes Project using our method BESTT (first plot) and the BEAST Extended Bayesian Skyline Plot (second plot). Posterior median curves are depicted as solid black lines and 95% credible intervals by shaded regions.

500 5 Discussion

501 The size of emergent sequencing datasets prohibits the use of standard coalescent modeling for infer-
 502 ring evolutionary parameters. The main computational bottleneck of coalescent-based inference
 503 of evolutionary histories lies in the large cardinality of the hidden state space of genealogies. In
 504 the standard Kingman coalescent, a genealogy is a random labeled bifurcating tree that models the
 505 set of ancestral relationships of the samples. The genealogy accounts for the correlated structure
 506 induced by the shared past history of organisms and explicit modeling of genealogies is fundamen-
 507 tal for learning about the past history of organisms. However, the genomic era is producing large
 508 datasets that require more efficient approaches that efficiently integrate over the hidden state space
 509 of genealogies.

510 In this manuscript we show that a lower resolution coalescent model on genealogies, the “Tajima’s
 511 coalescent”, can be used as an alternative to the standard Kingman coalescent model. In particu-
 512 lar, we show that the Tajima coalescent model provides a feasible alternative that integrates over a
 513 smaller state space than the standard Kingman model. The main advantage in Tajima’s coalescent
 514 is to model the ranked tree topology as opposed to the fully labeled tree topology as in Kingman’s
 515 coalescent.

516 *A priori*, the cardinality of the state space of ranked tree shapes is much smaller than the
 517 cardinality of the state space of labeled trees. However, in this manuscript we show that when the
 518 Tajima coalescent model is coupled with the infinite sites mutation model, the space of ranked tree
 519 shapes is constrained by the data and the reduction on the cardinality of the hidden state space of
 520 Tajima’s trees is even more pronounced than expected.

521 In order to leverage the constraints imposed by the data and the infinite-sites mutation model,
522 we apply Dan Gusfield’s perfect phylogeny algorithm (Gusfield, 1991) to represent sequence align-
523 ments as a gene tree. We exploit the gene tree representation for conditional likelihood calculations
524 and for exploring the state space of ranked tree shapes.

525 For the calculation of the likelihood of the data conditioned on a given Tajima’s genealogy, we
526 augment the gene tree representation of the data with the Tajima’s genealogy and map observed
527 mutations to branches. We define a directed acyclic graph (DAG) with the augmented gene tree.
528 This new representation as a DAG allows for calculating the likelihood as a backtracking algorithm
529 that transverses the gene tree from the leaves to the root. Our implementation’s computational
530 bottleneck lies in the likelihood calculation. Given a Tajima’s genealogy, our likelihood algorithm
531 sums over all possible allocation of mutation groups to branches. Although this number is generally
532 much smaller than the number of labeled genealogies, our algorithm can be further optimized. In
533 future studies, we will explore a sum-product type of algorithm for the likelihood calculation. In
534 the present implementation we are able to infer effective population size trajectories from samples
535 of size $n \approx 35$ in a regular personal laptop computer within few hours.

536 Our statistical framework draws on Bayesian nonparametrics. We place a flexible geometric
537 random walk process prior on the effective population size that allows us to recover population
538 size trajectories with abrupt changes in simulations. The inference procedure proposed in this
539 manuscript relies on Markov chain Monte Carlo (MCMC) methods with 3 large Gibbs block updates
540 of: coalescent times, effective population size trajectory and ranked tree shape topology. We use
541 Hamiltonian Monte Carlo updates for continuous random variables: coalescent times and effective
542 population size; and a Metropolis Hastings sampler for exploring the space of ranked tree shapes.
543 For exploring the genealogical space, Markovtsova et al. (2000) suggest a joint local proposal for
544 both coalescent times and topology. Here we restrict our attention to the topology alone. A future
545 line of research includes the development of a joint local proposal of coalescent times and ranked
546 tree shapes. We also envision that a joint sampler of coalescent times and effective population size
547 trajectories should improve mixing and convergence.

548 Our method does not model recombination, population structure or selection. It assumes com-
549 pletely linked and neutral segments from individuals from a single population, and the infinite sites
550 mutation model. While this model is a good approximation for some human molecular data, it
551 is not appropriate for modeling molecular data from other organisms such as pathogens and viral
552 populations. Finally, haplotype data of many organisms is usually sparse with few unique haplo-
553 types presented at high frequencies. Since our algorithm exploits molecular data at the haplotype
554 level, our proposed method is ideally suited for this scenario where the space of ranked tree shapes
555 is drastically smaller than the space of labeled topologies.

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684 tions under the infinite sites model. IEEE/ACM Transactions on Computational Biology and
685 Bioinformatics, 7(4):611–618.

686 Appendix A Matrix representation of a ranked tree shape

687 Our algorithms exploit the following encoding of a ranked tree shape by a triangular matrix of size
688 $n \times n$, which we denote by \mathbf{F} (Figure 10). Recall that, by convention, $t_{n+1} = 0$ and $t_1 = +\infty$.

First, we declare that $\mathbf{F}_{i,j} = 0$ if $j > i$. Next, the number of lineages through time is encoded on the diagonal of \mathbf{F} : $\mathbf{F}_{i,i} = i$ for i in $\{2, 3, \dots, n\}$. Finally, for $j < i$, the entry $\mathbf{F}_{i,j}$ denotes the number of lineages that do not coalesce in the time interval (t_{i+1}, t_j) ; in particular, $\mathbf{F}_{i,1} = 0$ and for every i in $\{2, 3, \dots, n\}$, $\mathbf{F}_{n,i}$ denotes the number of singletons (*i.e.*, external branches that have not coalesced) in the time interval (t_{i+1}, t_i) (Figure 10). Other statistics of the ranked tree shape can be expressed in terms of the corresponding matrix \mathbf{F} . Among them, the number c of cherries is equal to the number of times that the number of singletons decreases by 2 between lines i and $i - 1$, since such an event means that the coalescence separating these two epochs was that of two external branches. That is,

$$c = \sum_{i=3}^n \mathbf{1}_{\{\mathbf{F}_{n,i} - \mathbf{F}_{n,i-1} = 2\}}.$$

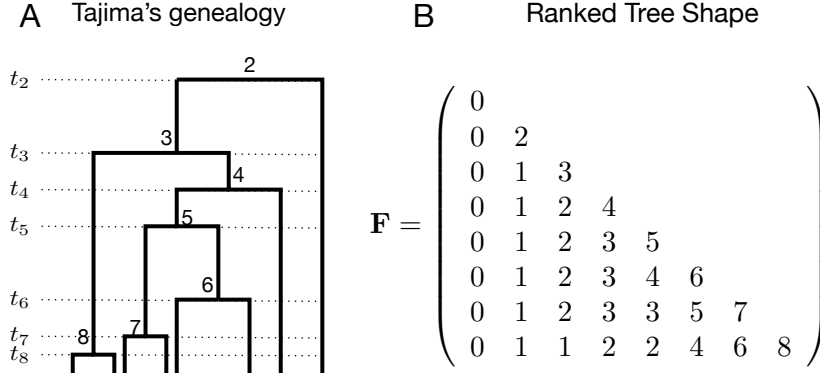


Figure 10: **Ranked tree shape** Left: Example of a Tajima's genealogy (redrawn from Figure 1A) with coalescent events ranked from 2 at time t_2 to n at time t_n . Right: The corresponding \mathbf{F}_n matrix, with $n = 8$, that encodes the ranked tree shape information of the Tajima's genealogy on the left. $\mathbf{F}_{i,j}$ denotes the number of lineages that do not coalesce in the time interval (t_{i+1}, t_j) . In particular, $\mathbf{F}_{n,i}$ for i in $\{2, 3, \dots, n\}$ denotes the number of singletons (external branches that have not coalesced) in the time interval (t_{i+1}, t_i) .

689 Appendix B

690 **Detailed allocation of mutation groups along \mathbf{g}^T .** The latent allocation random variables
691 $\{A_j\}$ are constrained by the information in the Tajima's genealogy \mathbf{g}^T . In a given \mathbf{g}^T , every subtree
692 is labeled by its ranking from past to present (Figure 10). Subtree i is subtended by branch b_i with
693 length l_i , for $i = 2, \dots, n$. We will assume that l_2 , the length of the root branch, is 0. Let c be
694 the number of cherries (nodes with two leaves) in \mathbf{g}^T ; the two branches of a given cherry share the
695 same label $b_j \in \{b_{n+1}, \dots, b_{n+c}\}$. The actual label of external branches is arbitrary but, for ease of
696 exposition in our figures, we first label the cherries' branches from left to right by $\{b_{n+1}, \dots, b_{n+c}\}$;
697 singleton branches are labeled from left to right by $b_{n+c+1}, \dots, b_{2n-c}$ (Figure 2C). As mentioned
698 before, the length of X_j is the number of the corresponding sister nodes in \mathcal{T} that were grouped
699 together in forming node Z_j . In this case, $A_j = (A_{j,1}, \dots, A_{j,|ch(j)|})$ denotes a collection of $|ch(j)|$
700 vectors of branch labels in \mathbf{g}^T subtending the child-node subtrees of node Z_j . $A_{j,1}$ corresponds to
701 the branch subtending from the leftmost child node of Z_j on \mathbf{D} , $A_{j,2}$ corresponds to the branch
702 subtending from the next child node of Z_j , etc., and $A_{j,|ch(j)|}$ corresponds to the branch subtending
703 from the rightmost child node of Z_j on \mathbf{D} . Observe that, since we group some of the leaf nodes in
704 \mathcal{T} into a single node in \mathbf{D} , any $A_{j,k}$ may be a vector of branch labels; for example $A_{1,1} = (b_{12}, b_9)$
705 and $A_{1,2} = b_{10}$ in Figure 3B.

706 Appendix C

707 **Algorithms for conditional likelihood calculation.** The following two algorithms detail the
708 calculation of $\Pr(\mathbf{Y} \mid \mathbf{g}^T, \mu)$. \mathbf{Y} is encoded in *GeneTree*, the observed data as a Tree structure.
709 Each node in *GeneTree* has number of descendants (or lineages) and mutation information attached
710 to it. Tajima's genealogy \mathbf{g}^T is encoded as *Fpath* that contains the ranked tree shape \mathbf{F}_n and *times*
711 that contains the vector of coalescent times \mathbf{t} multiplied by the mutation rate μ .

Algorithm 1 Calculate Likelihood($Fpath, times, GeneTree$) procedure

Input: $GeneTree, FPath$ **Output:** Log Likelihood LL

- 1: Initiate $pool$ to be the set of leave nodes of $GeneTree$ with at least one descendant. Initiate LL and $index$ to be zero. Initiate $current_path$ to be empty.
 - 2: Call $CalcLL_recursive(LL, index, current_path, Fpath, times, Genetree)$.
 - 3: **return** LL
-

Algorithm 2 $CalcLL_recursive(LL, index, current_path, Fpath, times, Genetree)$ procedure

- 1: **if** $index = len(path)$ {When a complete path node is found} **then**
 - 2: **for** $node$ in $tree$ **do**
 - 3: Calculate log likelihood based on $times$ and number of mutations of $node$ in $current_path$.
 - 4: Accumulate to total log likelihood LL
 - 5: **end for**
 - 6: **else**
 - 7: **for** $node$ in $pool$ **do**
 - 8: Check compatibility of the $node$, according to the given $Fpath$.
 - 9: **if** $node$ is compatible with $Fpath$ **then**
 - 10: Update $node$ by assigning it to the current step in $Fpath$
 - 11: Update $pool$. If a $node$ has been mapped entirely, remove $node$ from pool, update its parent $node$, and potentially add parent node to $pool$ if parent node has not been entirely assigned.
 - 12: Append this $node$ to $current_path$
 - 13: Call $CalcLL_recursive(LL, index + 1, current_path, Fpath, Genetree)$
 - 14: Restore previous $node, pool$ and $current_path$
 - 15: **end if**
 - 16: **end for**
 - 17: **end if**
-

712 To illustrate our algorithms 1 and 2, we use our example of Figures 2 and 3. Algorithm 1 initiates
713 the $pool$ with nodes $Z_3, Z_4, Z_6, Z_8, Z_{10}$. Then, Algorithm 2 cycles through this list. Assume the
714 first node is Z_8 . This node has $d_8 = 2$ descendants and the *ancestry* is $Z_8 - Z_5 - Z_1 - Z_0$ with sizes:
715 $2 - 3 - 7 - 16$. On the other hand, the first coalescent event (from present to past) labeled 16 in \mathbf{g}^T
716 (Figure 3A) has ancestry with sizes: $2 - 3 - 7 - 16$. Therefore, this node is *compatible*. The node
717 is removed from the pool, its parent node added to the pool and Z_8 is assigned to the path. At
718 this time $current_path = Z_8$ and the $pool$ becomes: $Z_3, Z_4, Z_5, Z_6, Z_{10}$. The algorithm then cycles
719 through this list and picks Z_{10} . This node has size ancestry $2 - 3 - 7 - 16$. On the other hand the
720 second coalescent event labeled 15 has size ancestry: $2 - 3 - 5 - 7 - 9 - 16$. Since the node size
721 ancestry is contained in the second coalescent event's size ancestry, this node is *compatible*. The
722 current path becomes $current_path = Z_8 - Z_{10}$ and pool becomes Z_3, Z_4, Z_5, Z_6, Z_7 . We continue
723 this procedure until we reach the path $current_path = Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 -$
724 $Z_6 - Z_1 - Z_2 - Z_1 - Z_2 - Z_0$.
725 Once a path is found, the algorithm back tracks the path until there is one compatible node and
726 the path continues to grow. A sequence of back tracking and growing is the following:

- 727 1. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2 - Z_1 - Z_2 - Z_0$
- 728 2. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2 - Z_1 - Z_2$
- 729 3. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2 - Z_1$
- 730 4. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2$
- 731 5. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1$
- 732 6. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6$
- 733 7. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4$
- 734 8. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5$
- 735 9. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_6$
- 736 10. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_6 - Z_4$
- 737 11. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_6$
- 738 12. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5$
- 739 13. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4$
- 740 14. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6$
- 741 15. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1$
- 742 16. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2$
- 743 17. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2 - Z_1$
- 744 18. $Z_8 - Z_{10} - Z_3 - Z_6 - Z_4 - Z_7 - Z_5 - Z_4 - Z_6 - Z_1 - Z_2 - Z_1 - Z_0$

745 The first sequence of steps 1–8, the path decreases. This happens because there are not alternative
746 compatible paths until that point when the sequence starts to grow until step 10. At step 10, the
747 algorithm does not find a compatible way to keep growing the path so the algorithm starts to back
748 track again until step 12. From steps 12 to 18, the algorithm grows the path until a complete new
749 path has been found. A complete path has the correspondence of coalescent events to nodes in gene
750 tree. The first element of the path: Z_8 corresponds to the coalescent event at time t_8 , the second
751 element of the path Z_{10} corresponds to the second coalescent event at time t_7 . The last element of
752 the path is Z_0 when all sequences coalesce at time t_2 . In this example, the algorithm finds 8 paths.
753 Once the paths are found, the algorithm computes the likelihood and the result is the sum of the
754 likelihoods of the 8 paths.

755

756 **Markovian proposal of ranked tree shapes.** The following algorithm generates a new
757 ranked tree shape from a Markovian proposal and outputs the corresponding transition probabili-
758 ties. This proposal is used in section 2.8.1.

Algorithm 3 Transition proposals for ranked tree shapes

Input: \mathbf{F}_n **Output:** \mathbf{F}_n^* , $q(\mathbf{F}_n | \mathbf{F}_n^*)$, $q(\mathbf{F}_n^* | \mathbf{F}_n)$

1. Set $\mathbf{F}_n = \mathbf{F}_n^*$.
2. Sample with uniform discrete probability a coalescent event k from the set $\{3, \dots, n\}$. Set $q_1 = \frac{1}{n-2}$.
3. **If** lineage k coalesces at time t_{k-1} (Figure 4, Case A)

If the lineages coalescing at time t_k are singletons (Figure 4, Case A, lineages 1 and 2 in \mathbf{F}_n)

- (a) No sampling required to distinguish between two singletons. Set $q_2 = 1$.
- (b) Update \mathbf{F}_n^* : merge one singleton with the lineage coalescing at $k-1$ (excluding lineage k) in \mathbf{F}_n , then merge the second singleton at time t_{k-1} with lineage k .
- (c) Compute the probability q'_2 of restoring the ordering of \mathbf{F}_n^* to \mathbf{F}_n .

Else

- (a) Sample one the lineages coalescing at time t_k with uniform discrete probability. Set $q_2 = \frac{1}{2}$.
- (b) Update \mathbf{F}_n^* : merge the sampled lineage with the one coalescing at time t_{k-1} in \mathbf{F}_n . At time t_{k-1} , merge the lineage not sampled with the new lineage k .
- (c) Compute the probability q'_2 of restoring the ordering of \mathbf{F}_n^* to \mathbf{F}_n .

Else (Figure 4, Case B)

Swap the coalescent events. Lineages descending from k are now set to coalesce at time t_{k-1} and lineages previously descending from $k-1$ are now set to coalesce at time t_k . Set $q_2 = 1$ and $q'_2 = 1$.

4. $q(\mathbf{F}_n^* | \mathbf{F}_n) = q_1 q_2$, $q(\mathbf{F}_n | \mathbf{F}_n^*) = q_1 q'_2$.
-

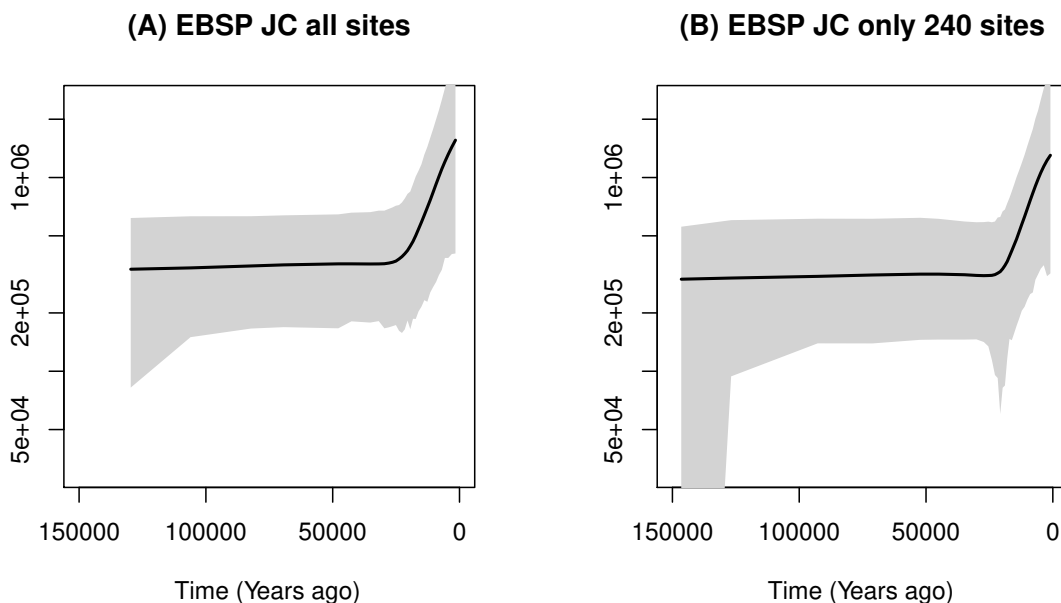


Figure 11: Posterior inference of female effective population size from 35 mtDNA samples from Yoruban individuals in the 1000 Genomes Project using BEAST EBSP (first plot) from all 15409 sites and the BEAST EBSP (second plot) from the 240 segregating sites retained. In both cases, the mutation model assumed is Jukes Cantor (JC). Posterior median curves are depicted as solid black lines and 95% credible intervals by shaded regions.

759 Appendix D

760 We replicated the BEAST EBSP Analysis of the 35 Yoruban individuals from the 1000 Genomes
 761 Project phase 3 using the whole mtDNA coding region consisting of 15409 sites. In both cases
 762 we assumed the Jukes-Cantor mutation model (Jukes and Cantor, 1969). Figure 11 shows the
 763 comparison between EBSP inference from the 240 segregating sites retained in section 4 that are
 764 compatible with the infinite sites mutation model assumption. In both cases we recover very similar
 765 trajectories.

766 In addition, we compared our results with BEAST Bayesian Skyline Plot (BSP) (Drummond
 767 and Rodrigo, 2000). For our reduced dataset of 240 segregating sites, we could not generate valid
 768 inference of $N(t)$ with Metropolis-Hastings acceptance probability greater than 0. Instead we were
 769 able to generate results with BEAST BSP from the complete dataset of 15409 sites. The comparison
 770 of our method from 240 segregating sites to BEAST BSP from 15409 sites is depicted in Figure 12.

771 Appendix E

772 In Figure 13A, we show the data from Figure 2A with an additional haplotype (10) with frequency
 773 1 and an additional column grouped with mutation group h (not shown in the table). In 13B we
 774 show the corresponding perfect phylogeny. This new perfect phylogeny has a new tip with black
 775 label 1 (frequency) subtending from a branch with 0 mutations (red label). The path from the leaf

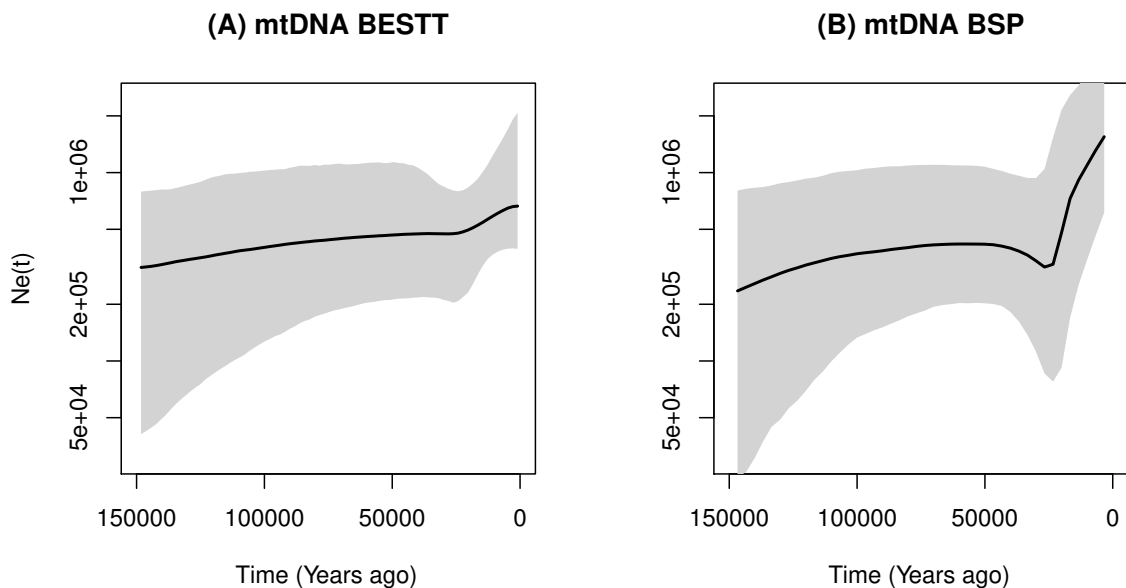


Figure 12: Posterior inference of female effective population size from 35 mtDNA samples from Yoruban individuals in the 1000 Genomes Project using our BESTT (first plot) from only 240 segregating sites and the BEAST BSP (second plot) from all the 15409 sites. Posterior median curves are depicted as solid black lines and 95% credible intervals by shaded regions.

776 to the root shows that this haplotype has a unique mutation corresponding to mutation group *a*.
 777 We note that mutation group labels carry no information. We incorporate the labels in the Figure
 778 for ease of exposition. Since mutation group h has now multiplicity 2, the branch labeled h has
 779 now a red label 2.

A Data (\mathbf{Y})

Haplotype	Frequency	a	b	c	d	e	e	f	f	f	...
1	2	1	0	0	1	0	0	0	0	0	0
2	2	1	0	0	0	1	0	0	0	0	0
3	2	1	0	0	0	0	1	1	0	0	0
4	1	1	0	0	0	0	0	0	1	1	1
5	2	0	0	0	0	0	0	0	0	0	0
6	2	0	0	0	0	0	0	0	0	0	0
7	2	0	1	1	0	0	0	0	0	0	0
8	2	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	0	0	0
10	1	1	0	0	0	0	0	0	0	0	0

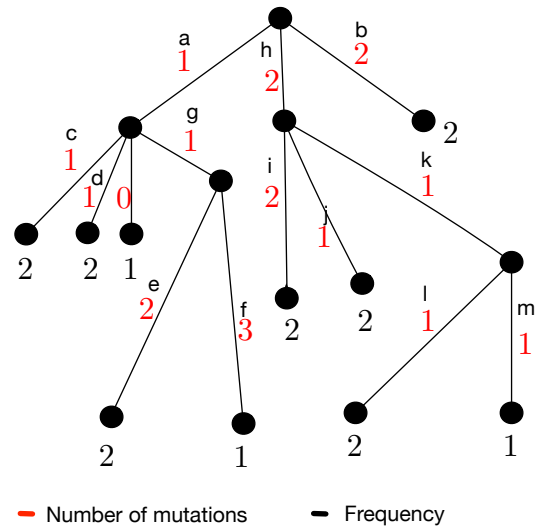
B Perfect Phylogeny (\mathcal{T})

Figure 13: **Second example of Perfect Phylogeny.** **A.** Compressed data representation $\mathbf{Y}_{h \times m}$ of $n = 17$ sequences and $s = 19$ (columns, only the first 10 of which are shown), comprised of 10 haplotypes and 13 mutation groups. This data table has one more haplotype (10) and one more mutation labeled h than the example of Figure 2. **B.** Gene tree representation of the data in panel A. Red numbers indicate the cardinality of each mutation group (number of columns with the same label in panel A). Black letters indicate the mutation group (column labels in panel A), and black numbers indicate the frequency of the corresponding haplotype.