

Biogeographical Ancestry Workshop

ISFG2022 – International Society for Forensic Genetics
Washington, DC – 30th August 2022

Torben Tvedebrink, PhD



Department of Mathematical Sciences – Aalborg University, Denmark

Section of Forensic Genetics – Department of Forensic Medicine
Faculty of Health and Medical Sciences – University of Copenhagen, Denmark



Welcome

Today's topic



Welcome to the half-day workshop on **Biogeographical Ancestry** at ISFG2022.

Disclaimer: Workshop is not about selecting AIMs

Website abstract (excerpt):

In recent years, biogeographical ancestry markers have gained attention in the forensic genetics community [...]

There exists several methods for modelling AISNPs [...] However, a common assumption of these approaches is that a true population exists in the reference material [...]

The workshop will discuss the strengths and weaknesses of the listed methodologies, introduce the participants to the ideas behind genogeographer.org, and show how to use this tool in relation to casework.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

1 Workshop

Agenda

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Agenda, times and breaks

Theory and hands-on



The official ISFG2022 time slots divides the workshop into two main time slots divided by a common coffee break for all workshops.

Time	Session
09:00 - 10:30	Lecture
10:30 - 11:00	Coffee break
11:00 - 13:00	Hands-on and discussions

We will have some additional small breaks during the lecture and hands-on session.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop
Agenda

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Lecture topics

Please interrupt with questions (raise hand) during the presentation

- ▶ What are AIMs
- ▶ What is the objective of biogeographical ancestry analysis?
- ▶ Solution/Approaches to analysis
 - ▶ Likelihood based methods (e.g. likelihood ratios)
 - ▶ Principal Components Analysis (PCA, e.g. EIGENSTRAT)
 - ▶ Clustering (e.g. STRUCTURE, ADMIXTURE, etc.)
 - ▶ Classification (e.g. machine learning approaches)
 - ▶ Outlier detection (e.g. GenoGeographer)

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop Agenda

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Ancestry Informative Markers

Disclaimer: Workshop is not about selecting AIMs



An **ancestry informative marker (AIM)** is a marker that can inform us about the **ancestral origin** of an individual.

Thursday morning's keynote speaker Professor Noah **Rosenberg** previously published two excellent overviews of various statistical methods for **selecting AIMs** (Rosenberg et al., 2003; Rosenberg, 2005).

Hence, this workshop is **not about** identifying new markers, but to make **proper inference** of the results of a pre-selected **set of markers**. **Chris Phillips'** scientific price lecture tomorrow morning will have more on that subject.

The panel of AIMs used throughout this workshop, has been selected in order to discriminate between individuals over **large continental distances**. However, the methodologies are not limited to this type of panels.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective

Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References



4

66



Specifically, the AISNP set considered here is the Applied Biosystems™ **Precision ID Ancestry Panel**, which includes $L = 165$ **autosomal markers (AISNPs)**.

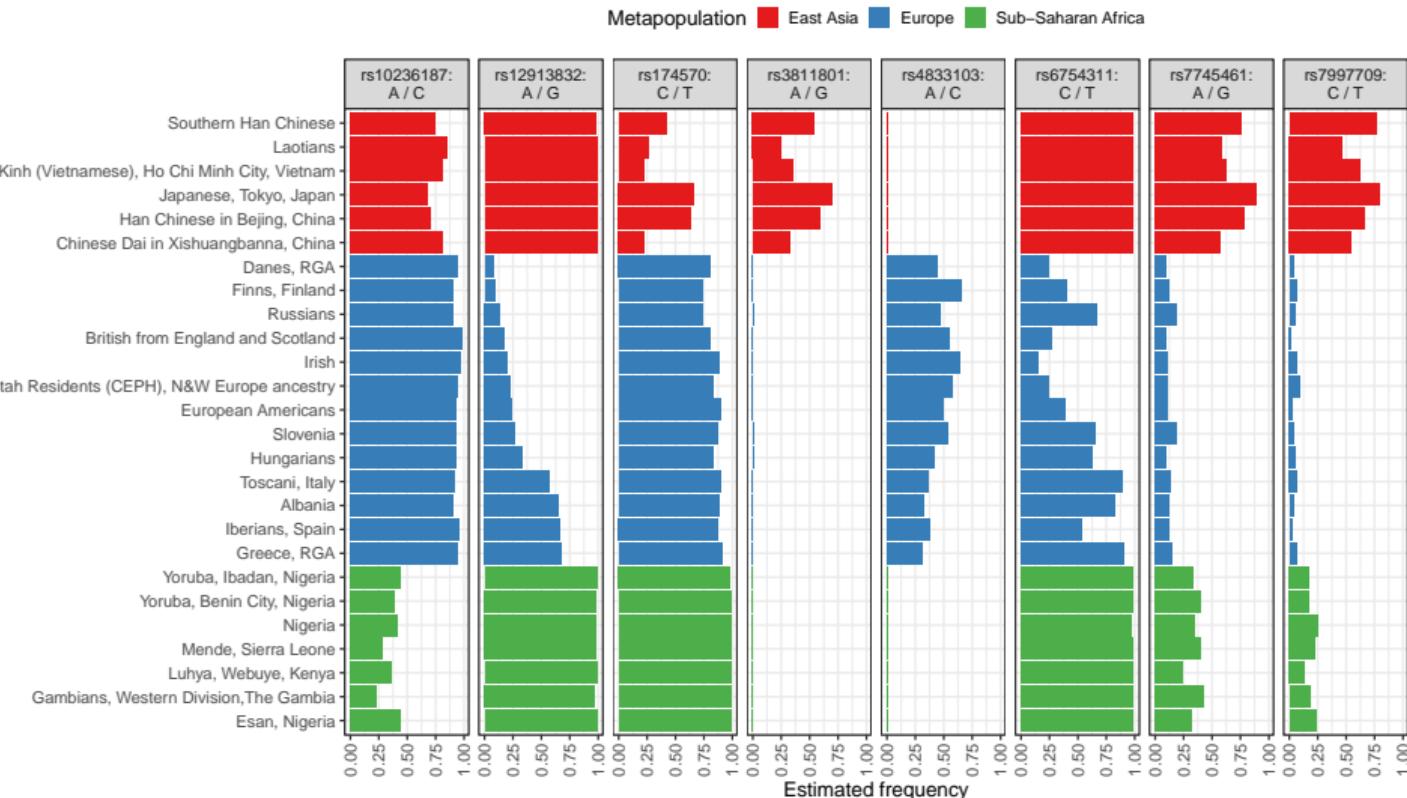
The 165 markers are a union (13 overlapping markers) of AISNPs selected by

- ▶ The Seldin-lab (Kosoy et al., 2009): **123 AISNPs**
- ▶ The Kenneth Kidd-lab (Kidd et al., 2014): **55 AISNPs**

Each marker is bi-allelic, e.g. A/C, and we denote A **allele 1**, and C allele 2, i.e. we use lexicographic ordering. Hence, an **individual** has **0, 1 or 2** copies of **allele 1**.

AIMs set

Thermo Fisher Precision ID Ancestry Panel (excerpt)



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective
Challenges
Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References



Selected markers and panels

Some remarks

When a panel is **designed** it is done with **specific application** in mind (e.g. segment populations on a global scale or identify regional and local differences). Thus, if used out of context, the panel may perform different than anticipated.

For example, the Precision ID Ancestry Panel has a **low discriminatory power among African populations**.

Markers that are included in panels to discriminate on local distances will typically be constant across most other populations (i.e. being non-informative) and basically just **add some random noise**.

For example, within GenoGeographer's Sub-Saharan African reference sample, Precision ID Ancestry Panel has **11 markers without any variability** and **18 markers where five or less** of the alternative alleles have been observed (out of 668 individuals or 1336 alleles).

Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Markers

Objective
Challenges
Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Objective of forensic AIMs analysis

Investigative leads



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective

Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

7

In **population genetics** AIMs are interesting in their own right in the study of **population structures**, anthropology and **human evolution**.

However, from a forensic point of view we are not necessarily interested in same research questions as the population geneticists are.

Within a group of people with shared ancestry, AIMs are non-informative and can not be used for person identification purposes.

However, AIMs can be used to provide **investigative leads** in cases where little else is known (e.g. no hits in DNA databases or no/uncertain witness statements)

Objective of forensic AIMs analysis

Questions



Hence, it may be interesting to ask

- ▶ which population/ethnic group/subpopulation/geographical area/region is the observed AIM profile most frequent?
- ▶ is the relative frequency of the profile in region A compared to region B?
- ▶ is likely that the profile originates from the country/region where it was found?
- ▶ the unidentified body more likely to originate from a foreign country?
And, if so – which country/region/continent?

8

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective

Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References



66

INTERNATIONAL SOCIETY FOR
FORENSIC GENETICS

Objective of forensic AIMs analysis

Questions



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective

Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References



All forensic scientists know that such questions preferably should be evaluated in terms of **likelihood ratios**, where the evidence is evaluated under two competing and mutually exclusive hypothesis.

9

$$LR = \frac{P(\text{AIM profile} \mid \text{Profile originates from region A})}{P(\text{AIM profile} \mid \text{Profile originates from region B})}$$

Well-defined hypothesis

Likelihood ratios

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers
Objective
Challenges
Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer
References

WASHINGTON, DC
ISFG 2022
INTERNATIONAL SOCIETY FOR
FORENSIC GENETICS

The use of **likelihood ratios** is advised by several commissions under the International Society of Forensic Genetics.

The hypotheses considered are typically exhaustive implying that their union constitutes **all relevant hypotheses**.

In such circumstances, the use of likelihood ratios is unproblematic (and often straight forward). When it comes to the ancestry of an individual this may, however, not be the case.

In the case of **ancestry**, the hypotheses will typically be *generated* by the **populations**, from which we have samples.

10

66

Potential issue with sample-driven hypothesis

Limited population samples

Because the estimation of the profile frequency relies on a population sample we are limited to evaluate likelihood ratios for populations, for which we have sufficient number of sampled individuals.

There exists many publicly available repositories (e.g. gnomAD) containing whole genome sequences for a broad selection of human population across the globe. However, several populations (defined by language, culture, ethnicity, geography, etc.) remain untyped (or at insufficient numbers), which limits the number of likelihood ratios we can formulate.

When limited to the sampled populations, the human evolutionary history will also influence our interpretation of the results.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective
Challenges

Approaches

Likelihood based

PCA

Clustering

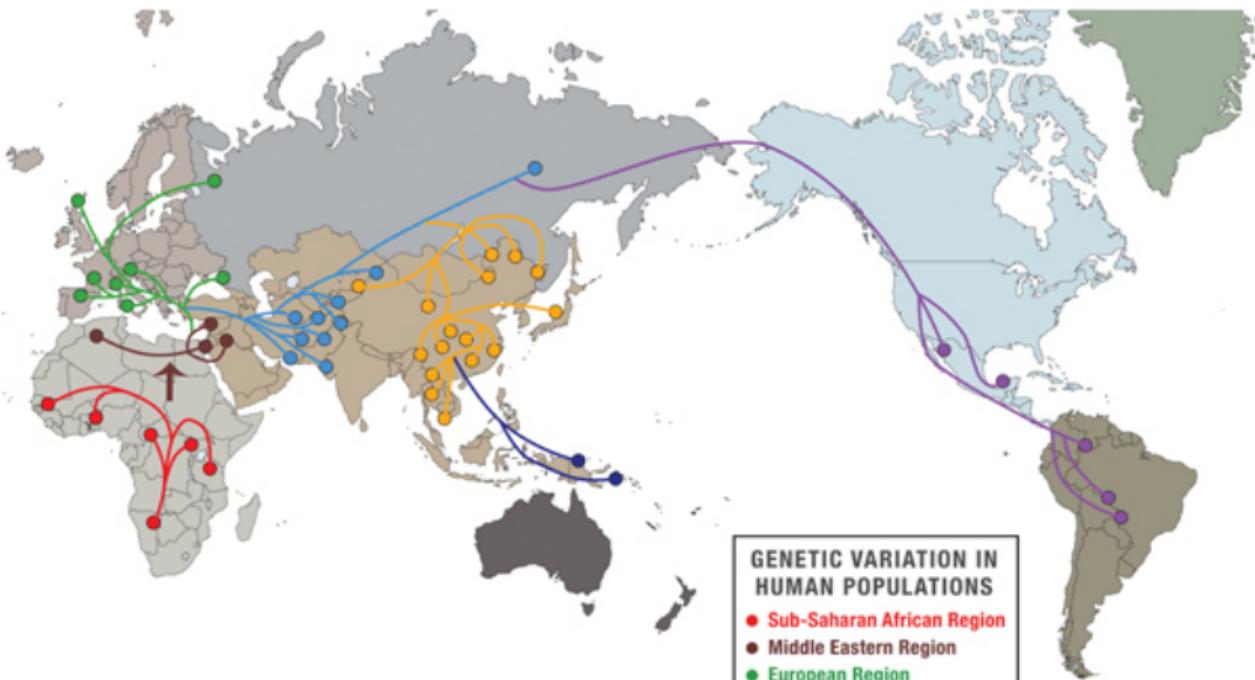
Classification

GenoGeographer

References

Human evolution

Related populations



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective

Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Because of the historical evolution, **human populations are related** through the migration patterns and other events.

Consequently, South American populations are closer to Asian population than those of Europe and Africa. Hence, an AIMs profile sampled from South America will have a higher likelihood in Asia than in Africa.

If compared though a LR, one would conclude that the profile would be orders of magnitude more likely to observe in Asia than in Africa. This could potentially result in criminal investigators would search for perpetrators with Asian origins.

12

12

Because of the historical evolution, **human populations are related** through the migration patterns and other events.

Consequently, South American populations are closer to Asian population than those of Europe and Africa. Hence, an AIMs profile sampled from South America will have a higher likelihood in Asia than in Africa.

If compared though a LR, one would conclude that the profile would be orders of magnitude more likely to observe in Asia than in Africa. This could potentially result in criminal investigators would search for perpetrators with Asian origins.

However, if we had worldwide coverage of populations this issue would reduced.

12

Because of the historical evolution, **human populations are related** through the migration patterns and other events.

Consequently, South American populations are closer to Asian population than those of Europe and Africa. Hence, an AIMs profile sampled from South America will have a higher likelihood in Asia than in Africa.

If compared though a LR, one would conclude that the profile would be orders of magnitude more likely to observe in Asia than in Africa. This could potentially result in criminal investigators would search for perpetrators with Asian origins.

However, if we had worldwide coverage of populations this issue would reduced.

But we don't

The situation

Figuratively in terms of fruit



Fruit of interest



Reference database

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective

Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

13

The situation

Figuratively in terms of fruit



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective
Challenges

Approaches

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

13



We may have **exclusive** sample populations, but we do not have **exhaustive** databases of reference populations.



Fruit of interest



Reference database

Approaches and solutions

Some popular choices



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Markers

Objective
Challenges
Approaches

14

Likelihood based

PCA

Clustering

Classification

GenoGeographer

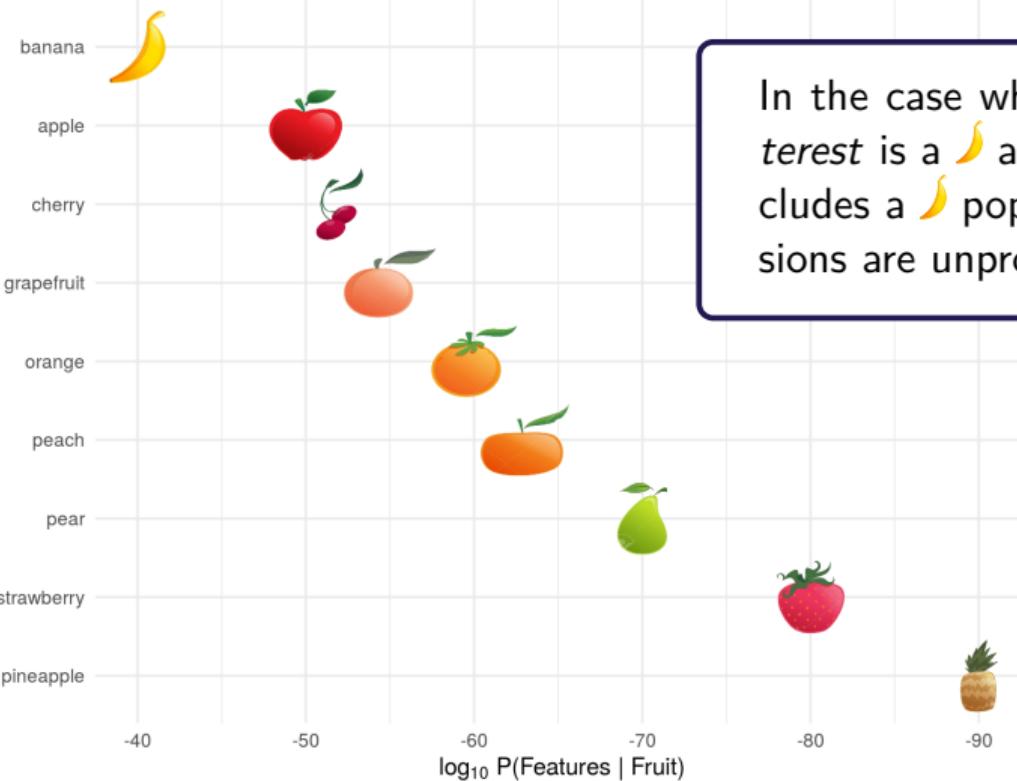
References

- ▶ Likelihood based methods (e.g. likelihood ratios as implemented in FROG-kb and Snipper)
- ▶ Principal Components Analysis (PCA, e.g. EIGENSTRAT)
- ▶ Clustering (e.g. STRUCTURE, ADMIXTURE, etc.)
- ▶ Classification (e.g. machine learning approaches)
- ▶ Outlier detection (e.g. GenoGeographer)

66

The non-exhaustive problem

Likelihood (ratio) approach



In the case where the *fruit of interest* is a 🍌 and the database includes a 🍌 population the conclusions are unproblematic.

15

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

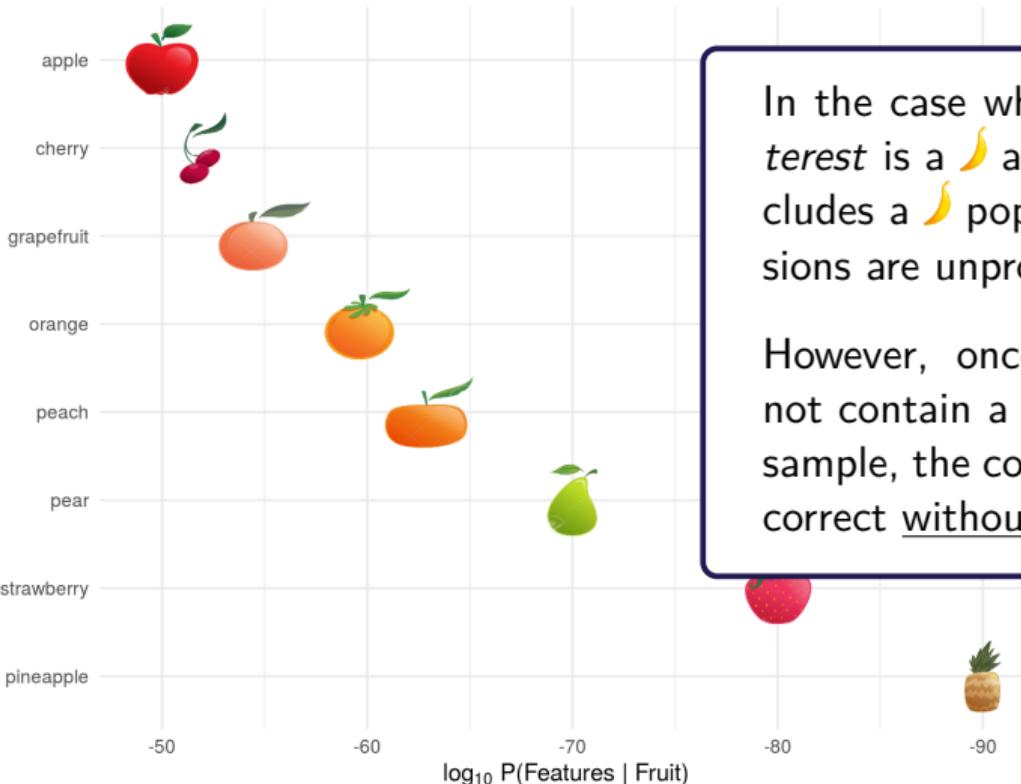
Classification

GenoGeographer

References

The non-exhaustive problem

Likelihood (ratio) approach



In the case where the *fruit of interest* is a 🍌 and the database includes a 🍌 population the conclusions are unproblematic.

However, once the database do not contain a relevant population sample, the conclusions will be incorrect without any *warnings*.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

15 Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Principal Components Analysis

PCA



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

Principal components analysis (PCA) has a long history of application in the study of **population structure**. The usage of PCA in analysis of population structure was pioneered by Menozzi et al. (1978), as an efficient way to capture the underlying structure for visualisation purposes.

PCA is able to capture **continuous admixture** between populations, implying that admixed populations typically falls on the *lines* between its *parental* populations.

McVean (2009) derived a **close link** between the populations' genealogical **coalescent times** and the **primary axes** of a PCA.

Principal Components Analysis

PCA



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

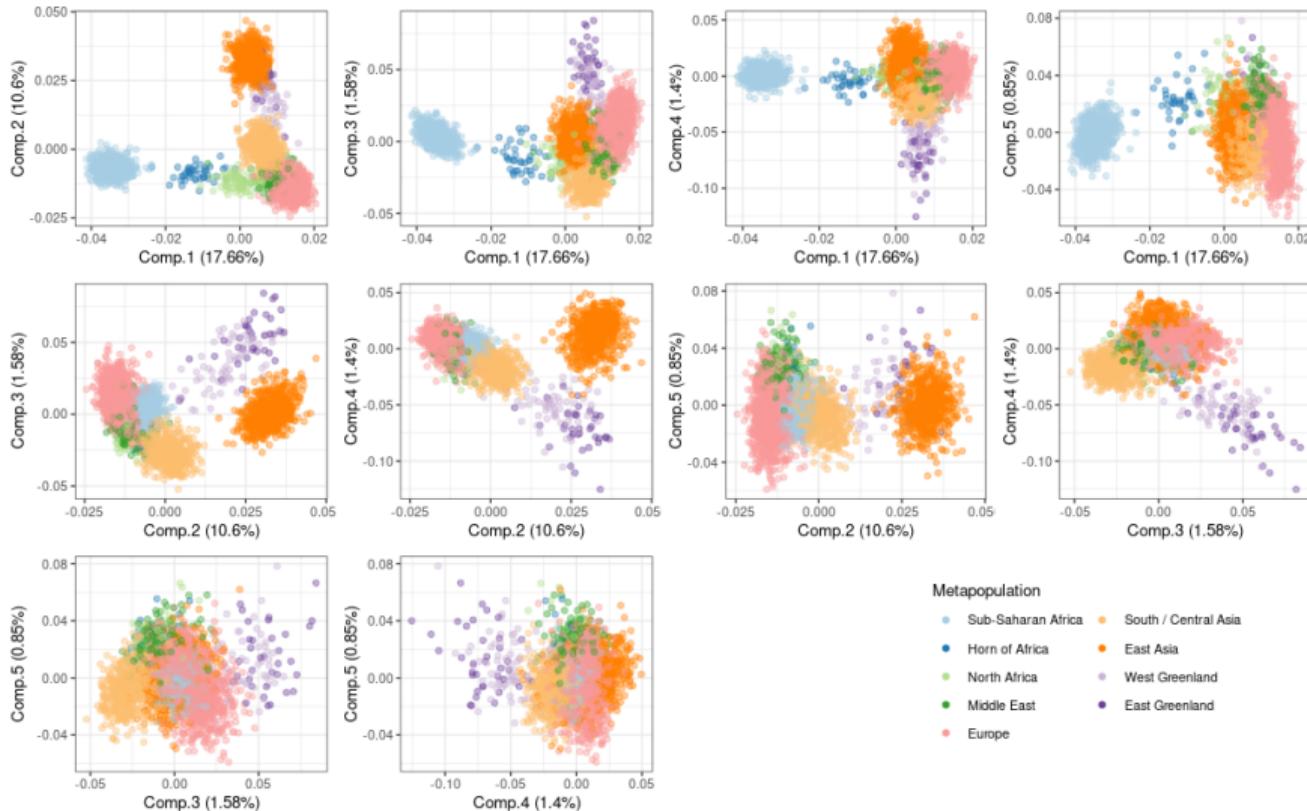
17

More recent PCA based methods for inference include SMARTPCA (Patterson et al., 2006) and **EIGENSTRAT** (Price et al., 2006). These methodologies provide further insight as to how **many PCs** are required to **capture detectable population structures** by the use of hypothesis testing on the magnitude of the PCA's eigenvalues.

However, several papers discuss some of the known pitfalls when using PCA. The most important issue to be aware of, is PCA's sensitivity to the sampling of individuals and populations. **Unbalanced sampling** of some populations forces the PCs to account for the variation caused by the **majority groups** (Novembre et al., 2008; McVean, 2009; Wangkumhang et al., 2018; Miller et al., 2020).

GenoGeographer reference database

PCA– Five significant PCs



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

18

PCA

Clustering

Classification

GenoGeographer

References

Forensic application

PCA



Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Likelihood based

19

PCA

Clustering

Classification

GenoGeographer

References

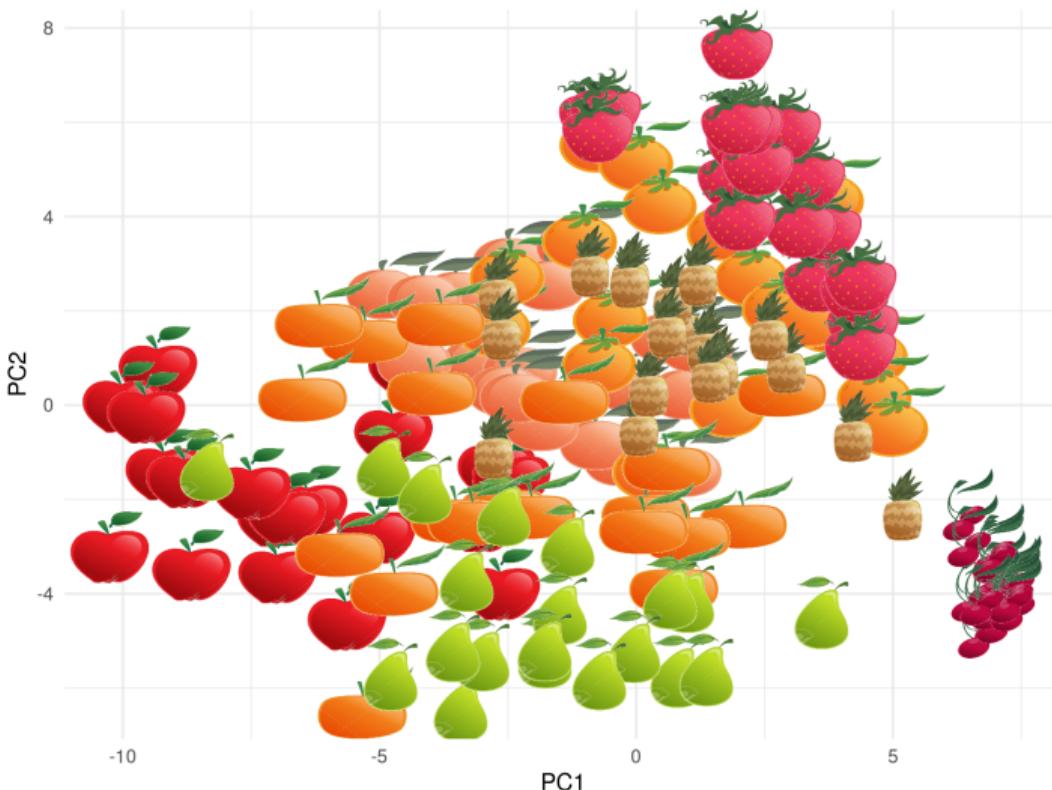
The PCA gives the projections of the AIM profiles to explain as much of the variability as possible with the first few axes. Alternatively, the best linear approximation of the profiles in a lower dimensional space.

However, from a **forensic point of view** it is rather difficult to assign a **quantitative value** to the projection of the profile of interest. The powerful feature of PCA is compression of the genetic data to provide a visual summary of the profile and reference database.

Furthermore, for a PC projection to work as intended a full profile is needed. In casework this is not always possible to genotype all markers resulting in **partial profiles**.

Fruity PCA

An example – The reference database



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

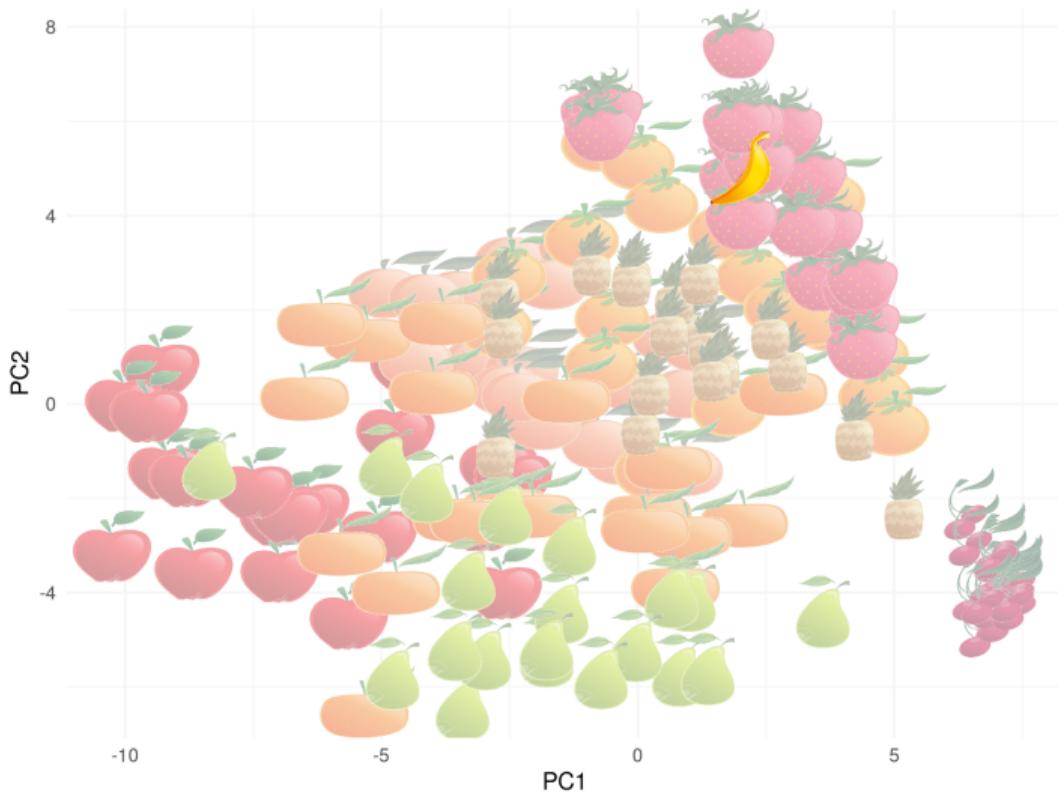
GenoGeographer

References

20

Fruity PCA

An example – The fruit of interest 



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

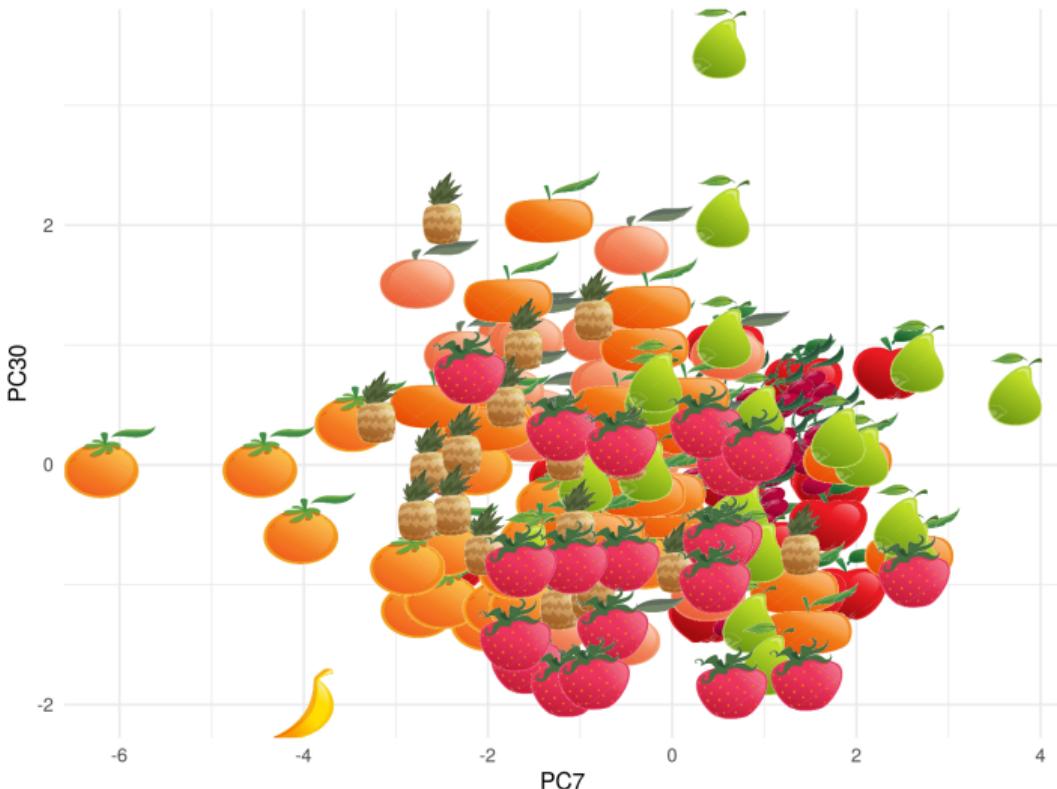
GenoGeographer

References

20

Fruity PCA

An example – On some lower projection ⚪️ and ⚪️ don't match



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

20
PCA

Clustering

Classification

GenoGeographer

References

STRUCTURE

Model-based clustering



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

21

The seminal **STRUCTURE** paper by Pritchard et al. (2000), introduced a population genetics methodology based on a statistical finite mixture model. Using a Bayesian approach, the posterior probabilities for **cluster memberships** and cluster-specific allele frequencies are estimated using a MCMC-algorithm (MCMC: Markov Chain Monte Carlo).

STRUCTURE has been used in numerous studies and has according to Google Scholar more than 30,000 citations, which indicates its **enormous influence** in the field of **population genetics** (Novembre, 2016)

STRUCTURE

Model-based clustering



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

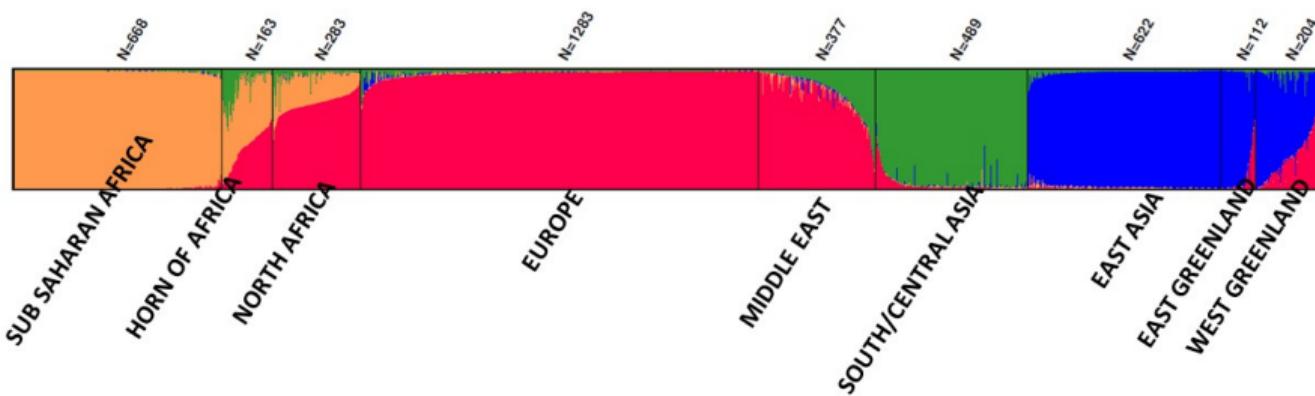
22

In essence, the initial STRUCTURE model is a simple **Hardy-Weinberg model** with the relaxation that subpopulations have different allele frequencies and individuals may inherit alleles from several subpopulations, i.e. being **admixed** (Novembre, 2016)

Following the initial publication, **several modifications** both on the population genetic model (allowing for e.g. linked markers and null alleles, Falush et al., 2003, 2007) and **computational aspects** (faster and more efficient algorithmic schemes, Tang et al., 2005; Alexander et al., 2009; Raj et al., 2014) has been suggested. See Novembre (2014, 2016) for further references and remarks.

GenoGeographer reference database

STRUCTURE- Nine metapopulations ($K = 4$)



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

23

STRUCTURE critique

Model assessment and choice of K



Because of STRUCTURE's complexity, it is hard to **conduct assessment of the model fit**. A recently published instructive tutorial (Lawson et al., 2018), provides a critical view on how to assess the outcome of STRUCTURE analysis using the tools badMIXTURE GLOBETROTTER, fineSTRUCTURE and CHROMOPAINTER (Lawson, 2018; Hellenthal et al., 2014; Lawson et al., 2012).

Furthermore, choosing the appropriate value for K , the number of population clusters, is **not a well defined problem**, i.e. only heuristic methods exists for guiding the specification of K (Pritchard et al., 2000; Novembre, 2014, 2016; Lawson et al., 2018).

Different choices of K may result in rather **different results and interpretation of the population stratification and history**.

Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

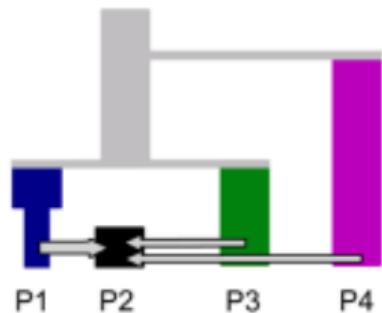
24

STRUCTURE critique

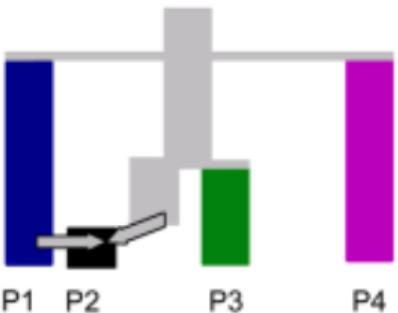
badMIXTURE (Lawson et al., 2018) – Indistinguishable admixture plots



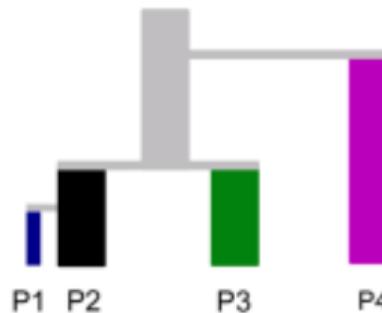
Recent Admixture



Ghost Admixture



Recent Bottleneck



Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Likelihood based

PCA

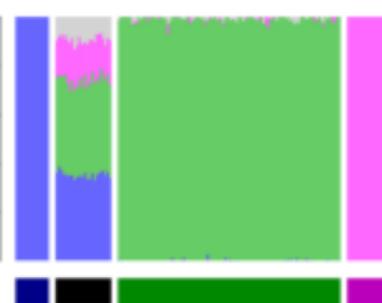
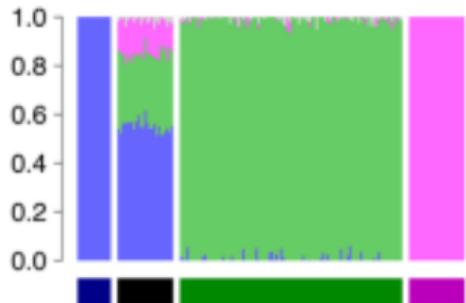
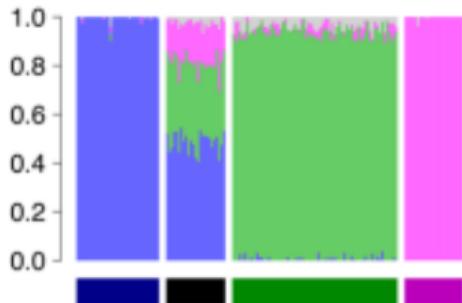
Clustering

Classification

GenoGeographer

References

24



Forensic application STRUCTURE



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

25

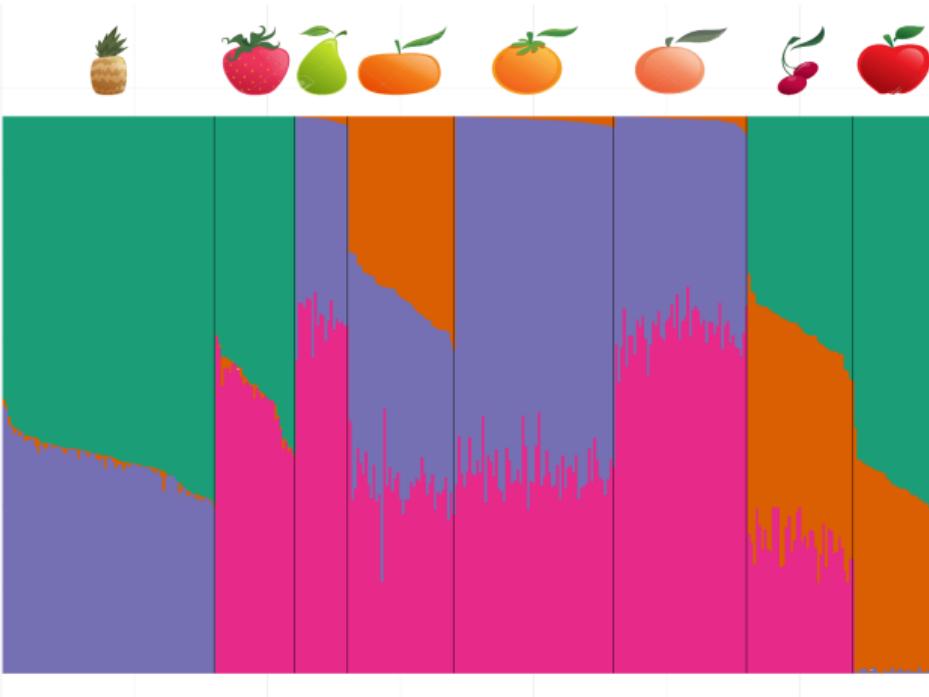
There exist several guides and tutorials for how to prepare the population data and choosing parameter settings for STRUCTURE (e.g. Porras-Hurtado et al., 2013; Santos et al., 2016, with some emphasis on forensic applications).

However, identifying which cluster the profile of interest resembles the most is difficult, which was also concluded by Porras-Hurtado et al. (2013, pp. 7):

“One disadvantage of STRUCTURE highlighted by this study is the difficulty of analyzing single genotype profiles”

Fruity STRUCTURE

An example – The reference database ($K = 4$)



Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Likelihood based

PCA

26 Clustering

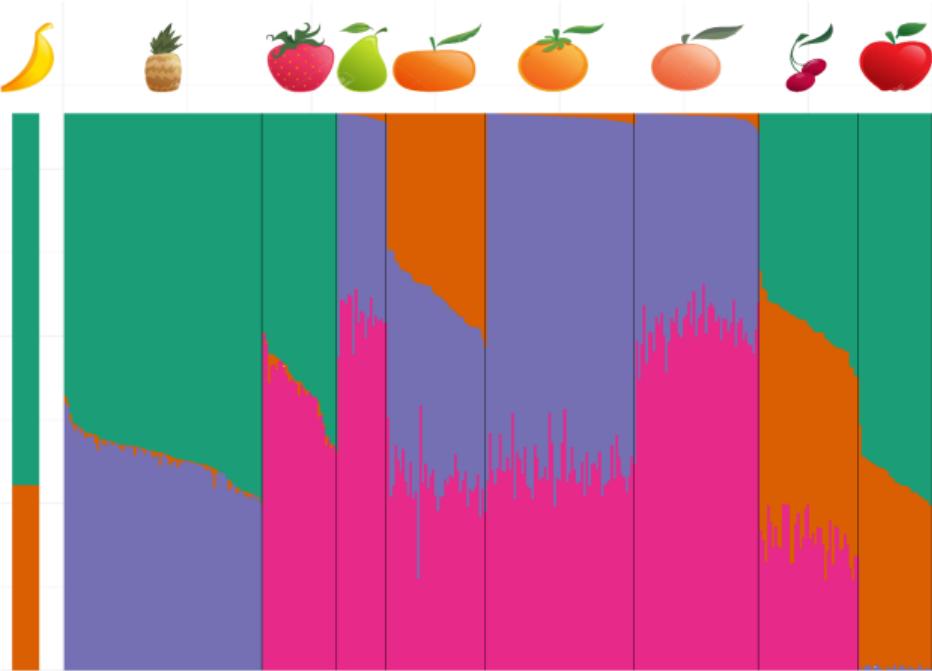
Classification

GenoGeographer

References

Fruity STRUCTURE

An example – The fruit of interest 🍉. How to assign?



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

26 Clustering

Classification

GenoGeographer

References

Classification

Likelihood based



The likelihood (ratio) approach computes the profile frequency based on the assumed population genetic model.

Assuming Hardy-Weinberg equilibrium at least marker, which are assumed to be mutually independent, this is simply the product of the estimated allele frequencies in each population:

$$\begin{aligned} P(\mathbf{G} = \mathbf{g}) &= P(G_1 = g_1, G_2 = g_2, \dots, G_L = g_L) \\ &= P(G_1 = g_1)P(G_2 = g_2) \cdots P(G_L = g_L) \\ &= \prod_{l=1}^L P(G_l = g_l) \\ &= \prod_{l=1}^L \binom{2}{x_{0l}} \hat{p}_l^{x_{0l}} (1 - \hat{p}_l)^{2 - x_{0l}}, \end{aligned}$$

where x_{0l} counts the number of allele 1 and \hat{p}_l is the estimated frequency of allele 1 at locus l .

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

27 Classification

GenoGeographer

References

Classification

Machine learning



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

28 Classification

GenoGeographer

References

However, the classification does not need to be driven by the population genetic likelihood function.

Several other algorithms have and can been used in the context of AIMs prediction. To name a few:

- ▶ Multinomial regression (e.g. McNevin et al., 2013; Cheung et al., 2017, 2018),
- ▶ Discriminant Analysis (e.g. Jombart et al., 2010),
- ▶ Classification Trees or Random Forest, and
- ▶ Neural Networks (e.g. Qu et al., 2019)

Classification

Common issues



Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

29

The above mentioned algorithms will typically all solve the problem of assigning a new observation x_0 to the most probable population used in the training dataset.

However, as previously discussed, one such population may not exist since the profile of interest, x_0 , may originate from a population not represented in the reference database. Thus, x_0 will be assigned to the **least improbable population**.

In addition, partial profiles are often also an issue for machine learning methods (as it were for PCA). In some of the input features are missing, the machine learning algorithm will typically not work out of the box.

The initial interest in developing a new tool for Biogeographical Ancestry prediction, was to answer the question:

When is a profile frequency estimate too rare (too small) to be trusted?

Following that, would there be a way to detect when the *true* population wasn't available in the reference database?

Another concern was, how many samples were needed per reference population to give reliable allele frequency estimates?

The second question could be answered using existing methodologies.

The uncertainty in allele frequencies is inversely proportional to the number of sampled alleles. This implies that fewer sample sizes increases the uncertainty in the allele frequency estimates.

Chakraborty et al. (1993) derived expressions for DNA profile frequency estimates, which we (Tvedebrink et al., 2018) adopted to assess the variability of the frequency estimates.

Simulation results (data not shown) suggested that at least $n = 75$ individuals were needed to obtain nominal coverage of the computed 95%-confidence intervals for a range of varying allele frequencies.

Hypothesis

The population of origin

To address the first question, we proposed to use a statistical likelihood ratio test framework, in order to overcome the focus on relative frequencies of AIMs profiles.

This corresponds to an **absolute measure of concordance** between an AIMs profile, x_0 , and those of a population, j .

It is informative to state the hypothesis that we are inquiring:

Hypothesis:

H_0 : The AIMs profile **originates** from population j

H_1 : The AIMs profile **does not originate** from population j .

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

Washington, DC

ISFG 2022

INTERNATIONAL SOCIETY FOR
FORENSIC GENETICS

Outlier detection

z-score approach



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

33

These hypotheses can be thought of as a way of detecting whether x_0 is an **outlier** or not **relative to sample x_j from population j** .

By arguments similar to those of **Fisher's exact test** for $r \times c$ tables, we can compute the exact distribution, from which we evaluate the expectation and variance of the likelihood ratio test (LRT) statistic.

This approach also removed the need for a lower limit on the number of reference samples in the LRT setting. Furthermore, partial profiles was not an issue since all calculations are done marker-wise.

Some mathematical details

Joint distribution

With the **independence assumption of the markers**, we just focus on a single marker.

Under the null hypothesis (cf. above), x_0 and x_j are from the same population j , where allele 1 has probability p_j .

Then we know that

$$x_0 \sim \text{bin}(2, p_j),$$

$$x_j \sim \text{bin}(2n_j, p_j)$$

$$x_+ \sim \text{bin}(2(n_j+1), p_j),$$

where $x_+ = x_0 + x_j$ is the number of allele 1 observed between *both* the reference population and x_0 among their $2n_j + 2 = 2(n_j + 1)$ alleles.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

34 Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

Some mathematical details

Conditional distributions

Conditional on x_+ (the sum of x_j and x_0), it can be shown that x_0 follows a hyper-geometric distribution (Tvedebrink et al., 2018):

$$P(X_0 = x_0 \mid X_+ = x_+) = \frac{\binom{2}{x_0} \binom{2n_j}{x_+ - x_0}}{\binom{2(n_j+1)}{x_+}},$$

where x_+ is the sufficient statistic under the null hypothesis.

The conditioning trick implies that the uncertainty about the allele frequency is modelled directly in the distribution. Hence, the smaller the reference sample is the weaker conclusions can be made.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

35 Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

The test statistic

Likelihood ratio test



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

36

$$Q(x_0, x_+) = \frac{\left(\frac{x_+}{2(n_j+1)} \right)^{x_+} \left(1 - \frac{x_+}{2(n_j+1)} \right)^{2(n_j+1)-x_+}}{\left(\frac{x_0}{2} \right)^{x_0} \left(1 - \frac{x_0}{2} \right)^{2-x_0} \left(\frac{x_+-x_0}{2n_j} \right)^{x_+-x_0} \left(1 - \frac{x_+-x_0}{2n_j} \right)^{2n_j-x_+-x_0}},$$

where $2n_j$ is the number of sampled alleles from population j .

The test statistic

Why this expression?

$$Q(x_0, x_+) = \frac{\overbrace{\left(\frac{x_+}{2(n_j+1)} \right)^{x_+} \left(1 - \frac{x_+}{2(n_j+1)} \right)^{2(n_j+1)-x_+}}^{\text{We assume the same population}}}{\overbrace{\left(\frac{x_0}{2} \right)^{x_0} \left(1 - \frac{x_0}{2} \right)^{2-x_0}}_{\text{Assumed } x_0 \text{ not from population } j} \cdot \overbrace{\left(\frac{x_+-x_0}{2n_j} \right)^{x_+-x_0} \left(1 - \frac{x_+-x_0}{2n_j} \right)^{2n_j-x_+-x_0}}_{x_j \text{ from population } j}},$$

which can be expressed as the ratio of two likelihoods

$$\approx \frac{\tilde{p}^{x_+} (1 - \tilde{p})^{2(n_j+1)-x_+}}{p_0^{x_0} (1 - p_0)^{2-x_0} \hat{p}_j^{x_j} (1 - \hat{p}_j)^{2n_j-x_j}},$$

where p_0 is the frequency of allele 1 in x_0 , \hat{p}_j in population j and \tilde{p} when they are joined together.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

37

Marker-wise z-score

Standardising $-\log Q(x_0 | x_+)$

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

38 Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

Since x_+ is the sufficient statistic under H_0 , conditioning on x_+ brings us to **Fisher's exact test**.

The numerator in $Q(x_0 | x_+)$ is a **constant when conditioning**.

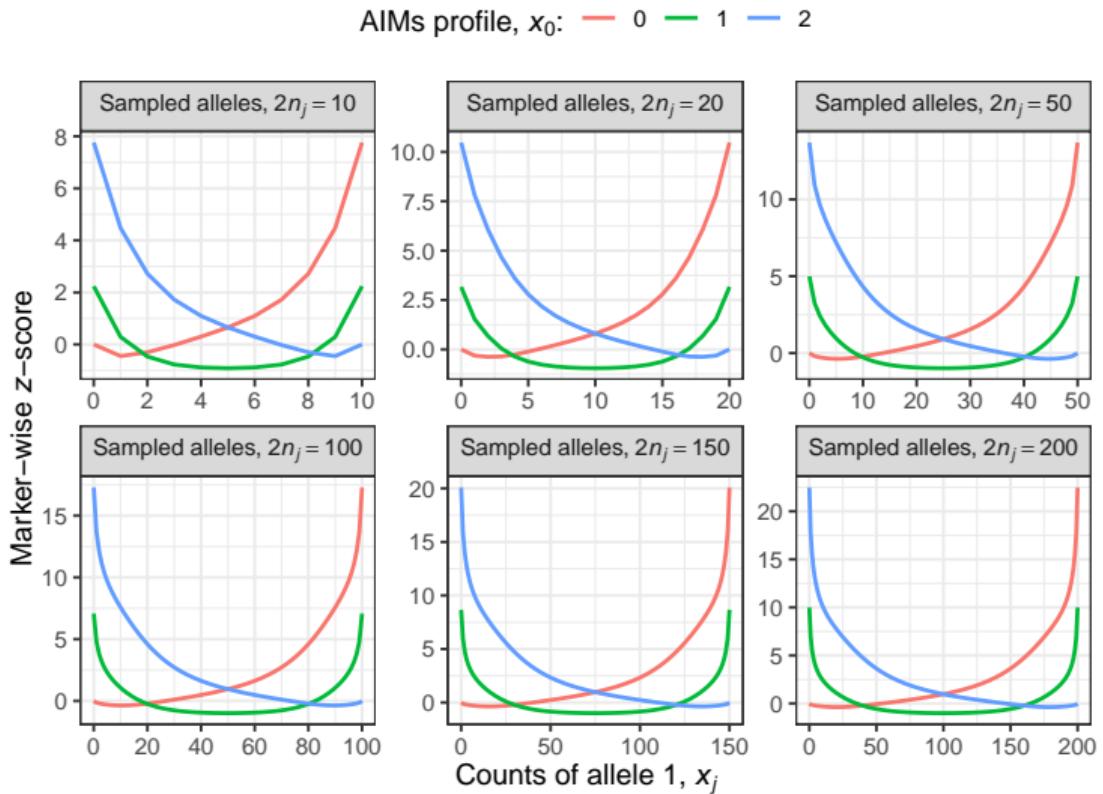
The distribution of $x_0 | x_+$ is **hyper-geometric**. Hence, the expectation and variance are easily computed over x_0 as this only takes the values of $\{0, 1, 2\}$.

We can standardise $-\log Q(x_0 | x_+)$ by **subtracting the expectation** and **dividing by the standard deviation**:

$$z = \frac{-\log Q(x_0 | x_+) + \mathbb{E}[\log Q(x_0 | x_+)]}{\sqrt{\mathbb{V}[\log Q(x_0 | x_+)]}}.$$

Marker-wise z-score

Visual representation



Biogeographical
Ancestry

Torben Tvedebrink
[\[genogeographer.org\]](http://genogeographer.org)

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

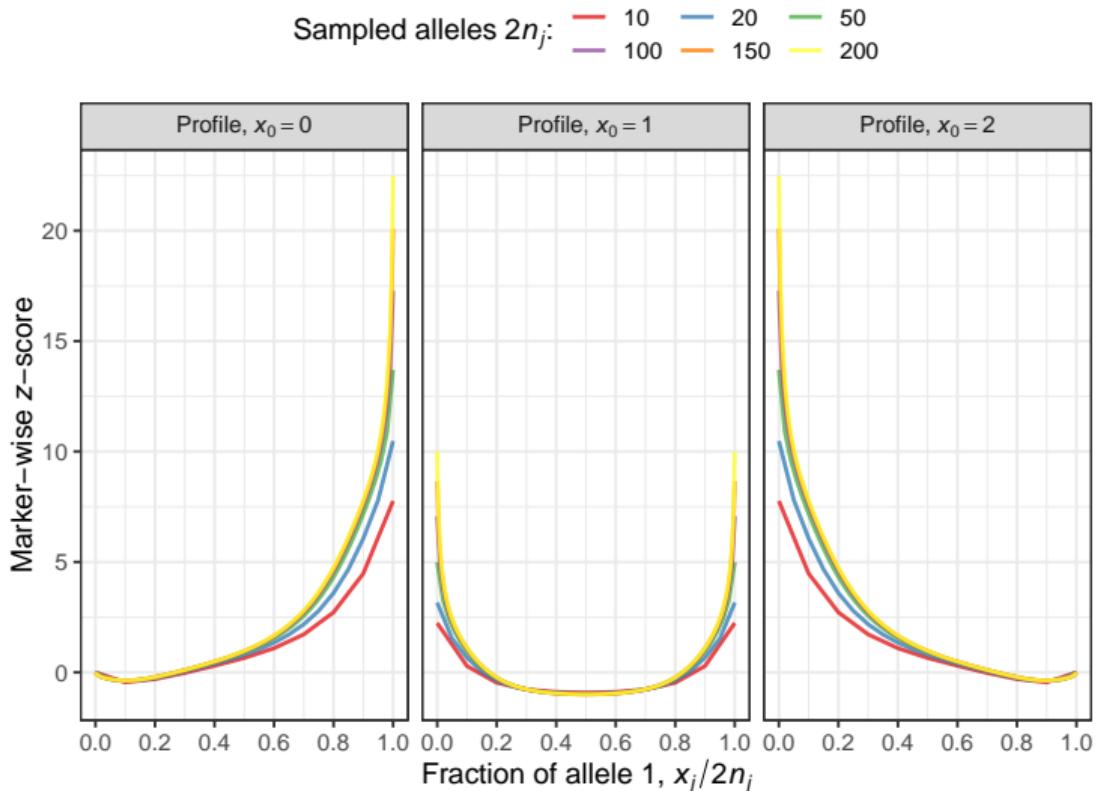
Admixed profiles

References

38

Marker-wise z-score

Visual representation



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

38 Fisher's exact test

Importance sampling

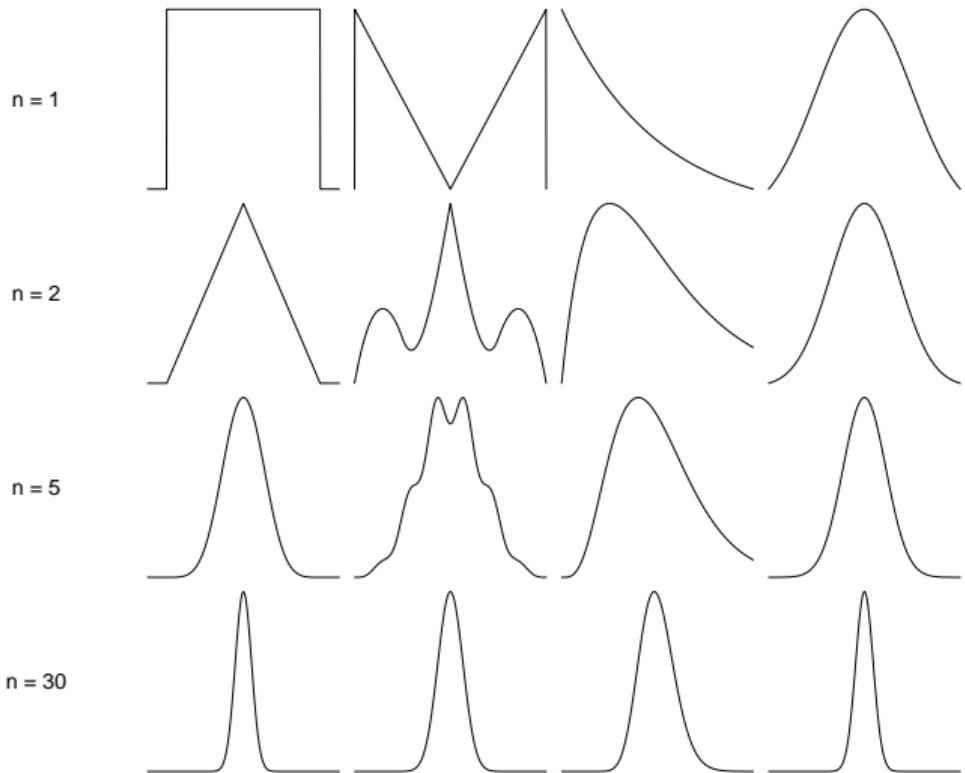
Validation study

Admixed profiles

References

Central Limit Theorem (CLT)

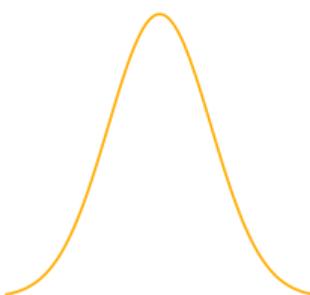
Visual proof



When the sample size,
 n , increases the
distribution of the
average

$$\bar{x} = \frac{1}{n}(x_1 + x_2 + \dots + x_n)$$

will approach a normal
distribution:



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

39

Summing over markers

Normal approximation

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

40

By **assuming independence** among markers, we sum over the L markers in order to **aggregate the evidence**:

$$z = \frac{\sum_{l=1}^L \{-\log Q(x_{0l} | x_{+l}) + \mathbb{E}[\log Q(x_{0l} | x_{+l})]\}}{\sqrt{\sum_{l=1}^L \mathbb{V}[\log Q(x_{0l} | x_{+l})]}}.$$

Using a variant of the central limit theorem (CLT), we may assume that the profile-wise z-score approximately follows a **standard normal distribution**.

Due to the LRT approach, the test is **one-sided** with large values being critical to the null hypothesis.

p-value

Normal approximation



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

41

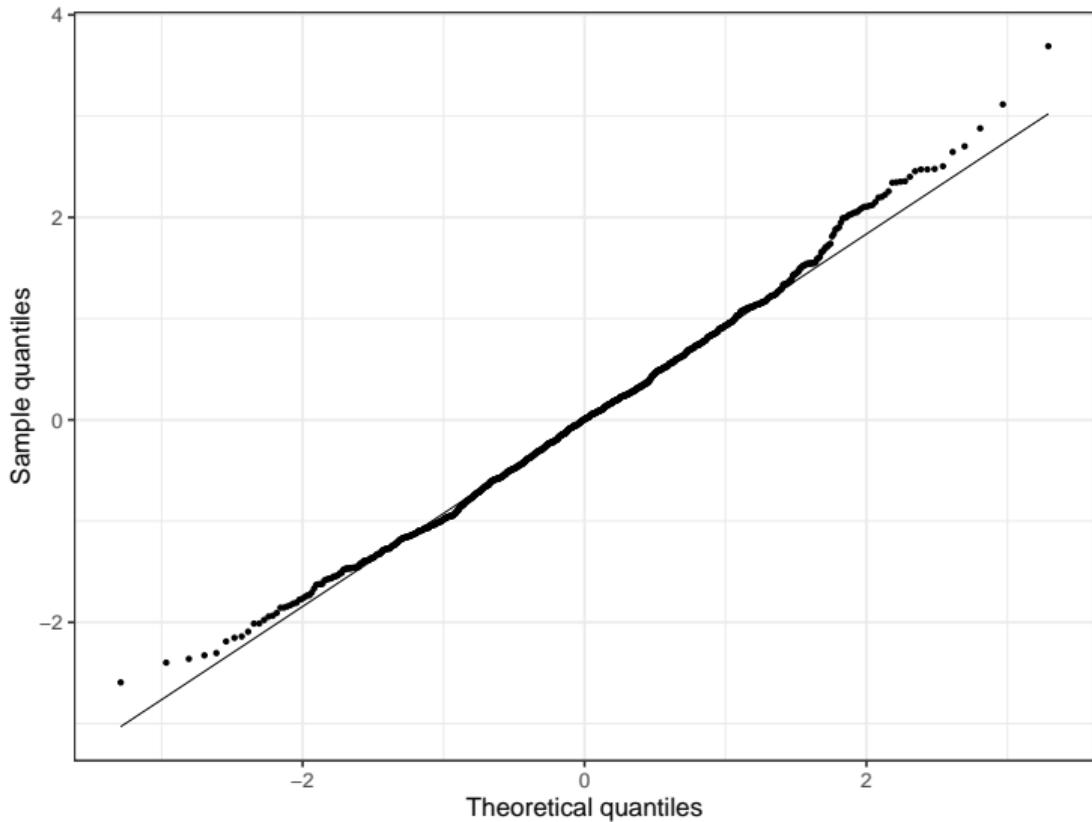
Hence, we can **compute a *p*-value** in order to **reject or accept the null hypothesis**.

However, simulations under the null hypothesis indicates that the **tails are slightly heavier** than a normal distribution (cf. next slide)

Furthermore, in cases where several alleles are close to being fixed in the population, the effective number of independent *stochastic* elements may be too small for the CLT. It may also be that only a **partial profile** is available causing the same challenge.

Approximately normal distributed

Slightly heavier tails – 1,000 simulated profiles



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

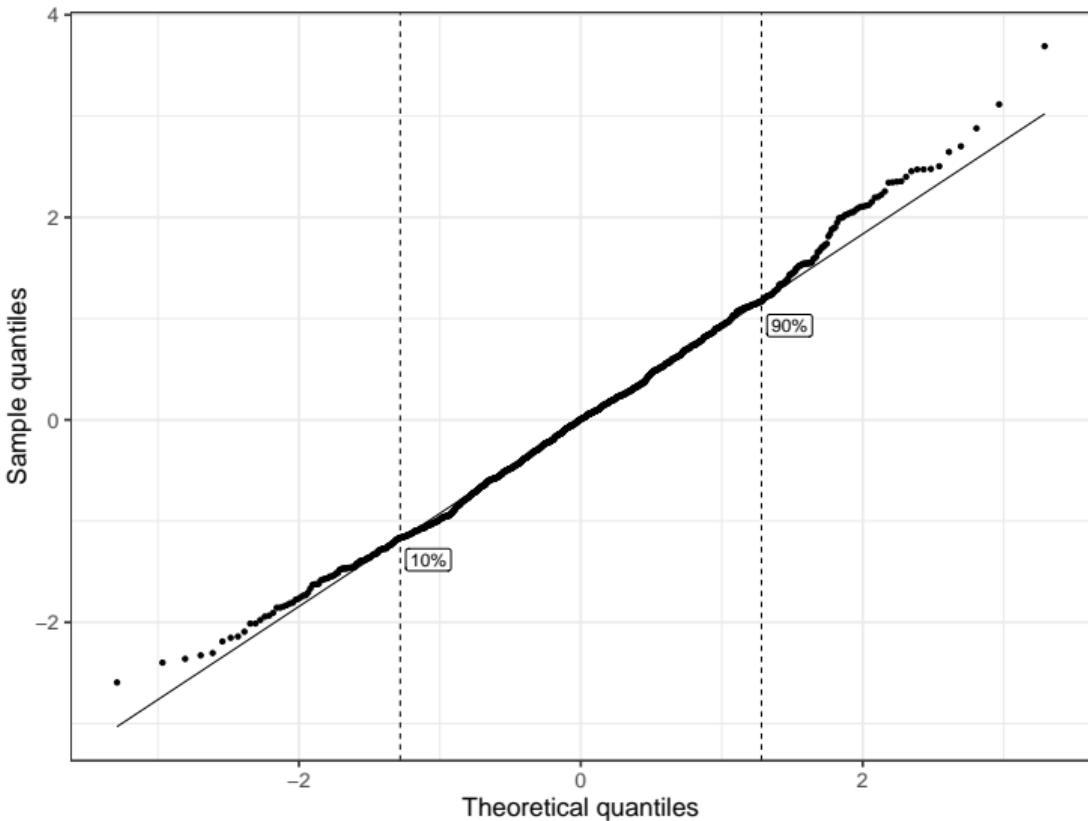
Admixed profiles

References

42

Approximately normal distributed

Slightly heavier tails – 1,000 simulated profiles



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

42

Importance sampling

Exponential tilting

Hence, if the p -value falls **below 0.10** we evaluate the p -value using **importance sampling**. Let $z(\mathbf{x}_0)$ denote z -score for a given profile, \mathbf{x}_0 . The p -value of interest is

$$\hat{P}(z(\mathbf{x}_0^{\text{obs}}) \leq z(\mathbf{x}_0)) = \frac{1}{m} \sum_{i=1}^m \mathbb{I}(z(\mathbf{x}_0^{\text{obs}}) \leq z(\mathbf{x}_{0,i})) \frac{P(\mathbf{x}_{0,i} \mid \mathbf{x}_+)}{q(\mathbf{x}_{0,i} \mid \mathbf{x}_+; \theta)},$$

where q is the proposal distribution and $\mathbf{x}_{0,i} \sim q, i = 1, \dots, m$.

We use **exponential tilting** to derive an efficient proposal distribution for simulating the p -value,

$$q(\mathbf{x}_0 \mid \mathbf{x}_+; \theta) = \exp\{\theta z(\mathbf{x}_0) - \kappa(\theta)\} P(\mathbf{x}_0 \mid \mathbf{x}_+),$$

where $\kappa(\theta)$ is the cumulant generating function.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

43

Exponential tilting

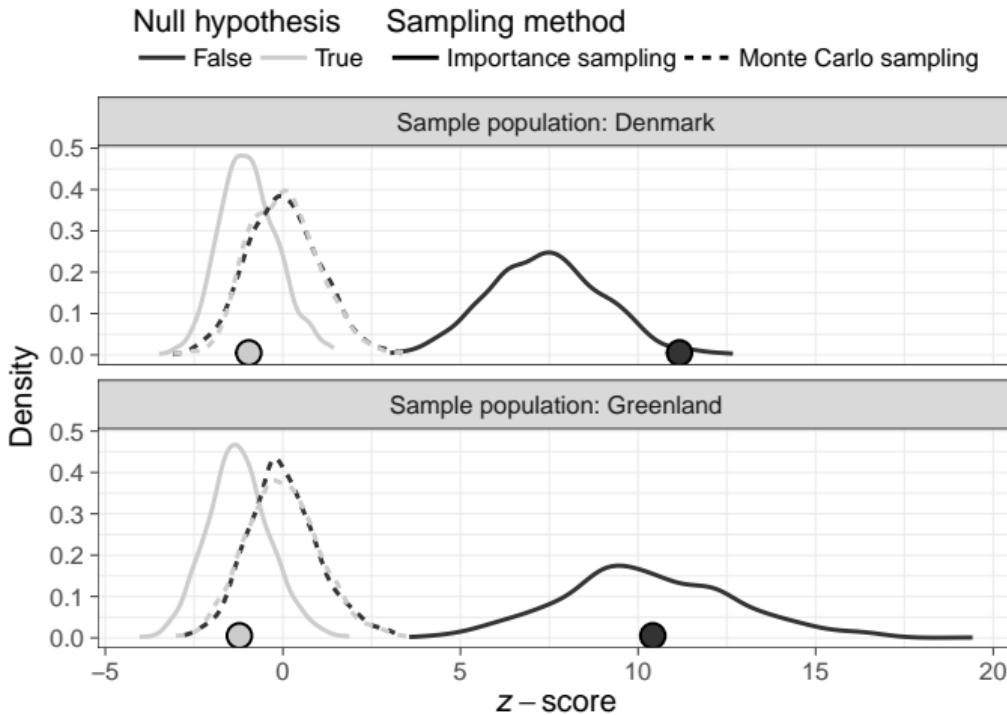
Example: non-zero p -values even in extreme cases

Profile sampled from
“Sample population”.

Density estimates of
distribution used to
estimate p -values.

Using the CLT
approximation, the
incorrect observation
will get a p -value of 0.

Importance sampling
fixes this issue.



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

44

From a logical point of view, an individual can belong to **at most one** of the exclusive (i.e. non-overlapping) reference populations.

For **each reference population**, the profile of interest is tested as belonging to that population.

However, based on the available information (i.e. genotyped loci and samples in the reference populations) it **may not be possible to reject** the incorrect null hypotheses. This implies that one or more populations can be the population of origin for the profile.

On the other hand, if the profile does not resemble any of the populations, then it will be **rejected in all of them**.

More accepted populations

LRs

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

In case more than one population has been accepted (null hypothesis not rejected), it implies that the profile is not too extreme relative to the observed allele frequencies of those populations.

However, one of them may still be more plausible than the others. In this case it is safe to use the pairwise likelihood ratios as the hypothesis tests have shown concordance between population samples and the profile of interest.

46

Pairwise likelihood ratios

Variance of log likelihood ratios

To assess if the AIMs profile, x_0 , is more likely in population j than in population k , we compute the LR :

$$\widehat{LR}_{jk} = \frac{\hat{P}(x_0 | H_j)}{\hat{P}(x_0 | H_k)},$$

where $\hat{P}(x_0 | H)$ is based on the estimates of allele frequencies, \hat{p}_{jl} .

Chakraborty et al. (1993) derived an expression of the variance of $\hat{P}(x_0 | H_j)$, where the **variance increases as the sample size n_j decreases**.

The validity of the variance approximations depends on allele frequency estimates being **close to the true frequencies**.

We can use the variance estimates to construct approximate **95%-confidence intervals (CI)** for the LRs.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

47

Evaluating the weight of evidence

Decision rule

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

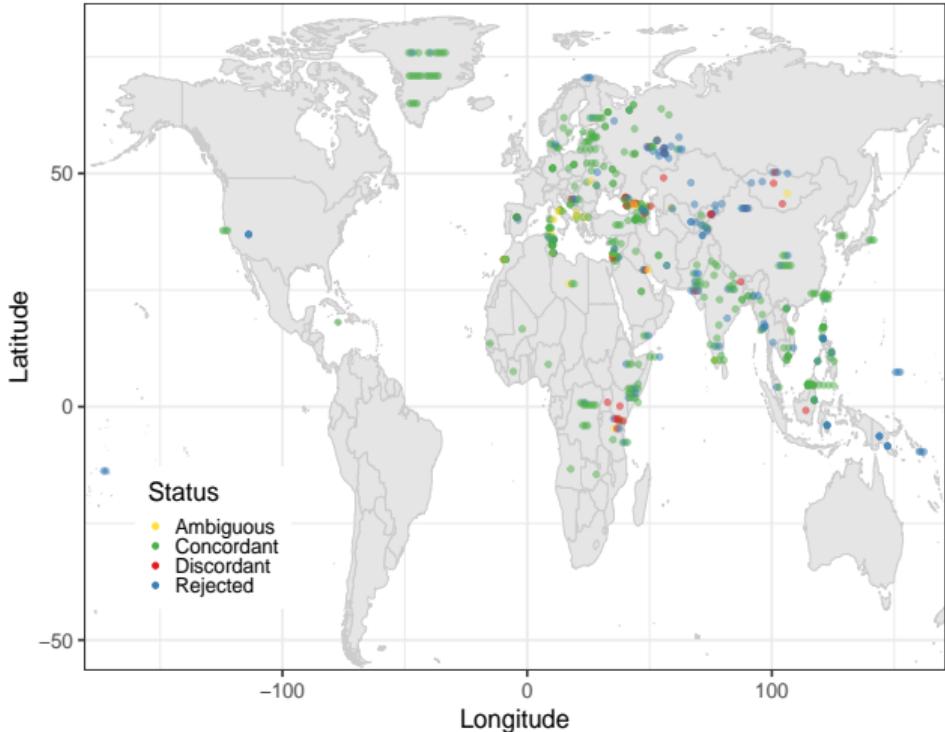
References

For **each population** among the reference populations, we **compute the z-score**.

- ▶ If **all null hypotheses are rejected**, we take this as evidence of the fact that **there is no relevant population** among the reference populations.
- ▶ If **one or more hypotheses are accepted**, we compute *LRs*, where at **least one** of the two populations in the ratio **was accepted** (i.e. has a *p*-value above the significance level, e.g. 0.05).
- ▶ In case of two (or more) accepted populations, the CI's can be used to assess if one population is significantly more plausible than the others.

Validation study

Geographically scattered test samples (566 samples from 90 different countries)



Joint work with Helle S. Mogensen, Claus Børsting, Vania Pereira and Niels Morling, published in FSI:Genetics (Mogensen et al., 2020).

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

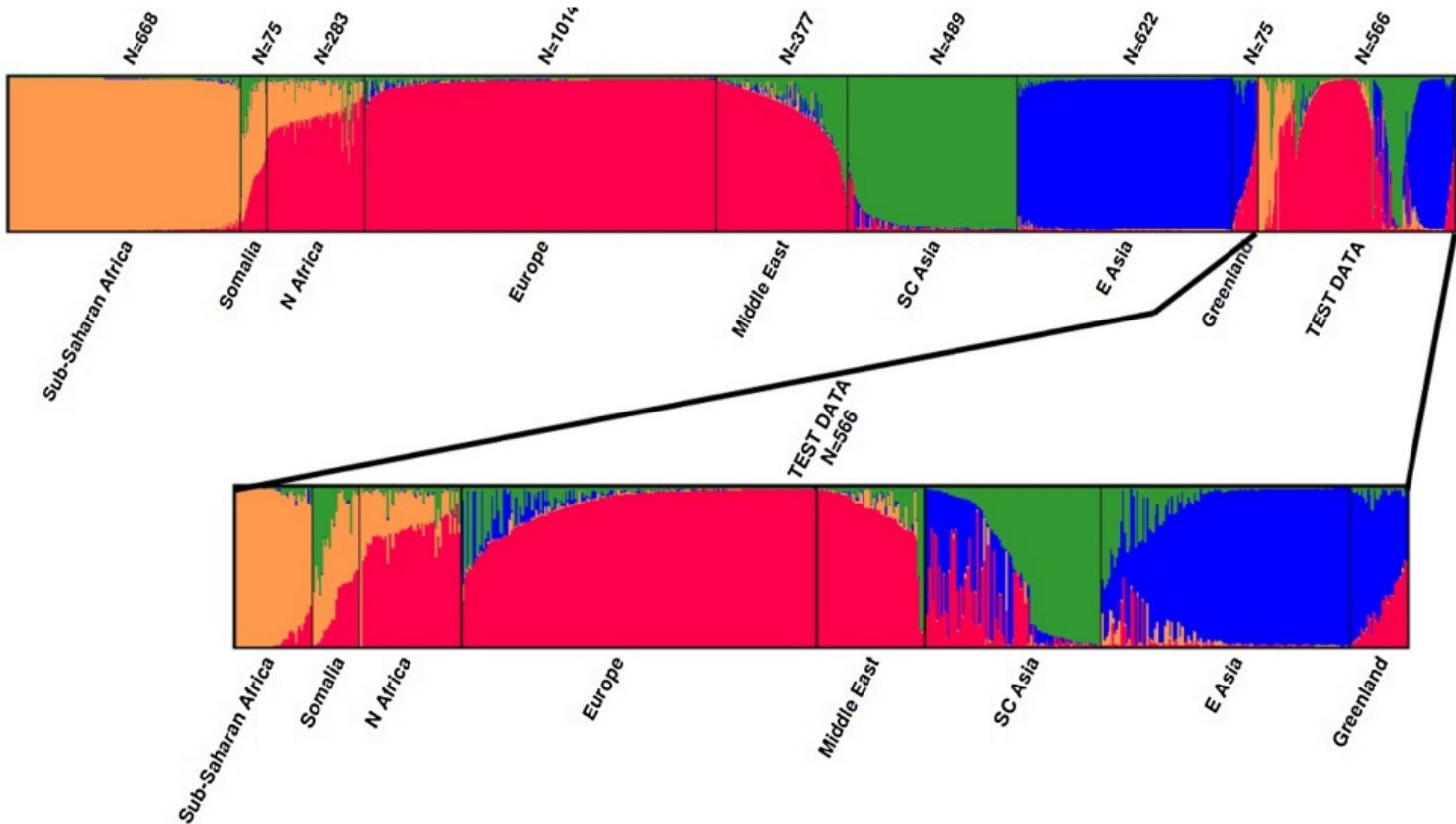
References

49

66

Validation study

STRUCTURE analysis



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

Validation study

Density estimates of z-scores. Large z-scores critical to hypothesis



Biogeographical
Ancestry

Torben Tvedebrink
genogeographer.org

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

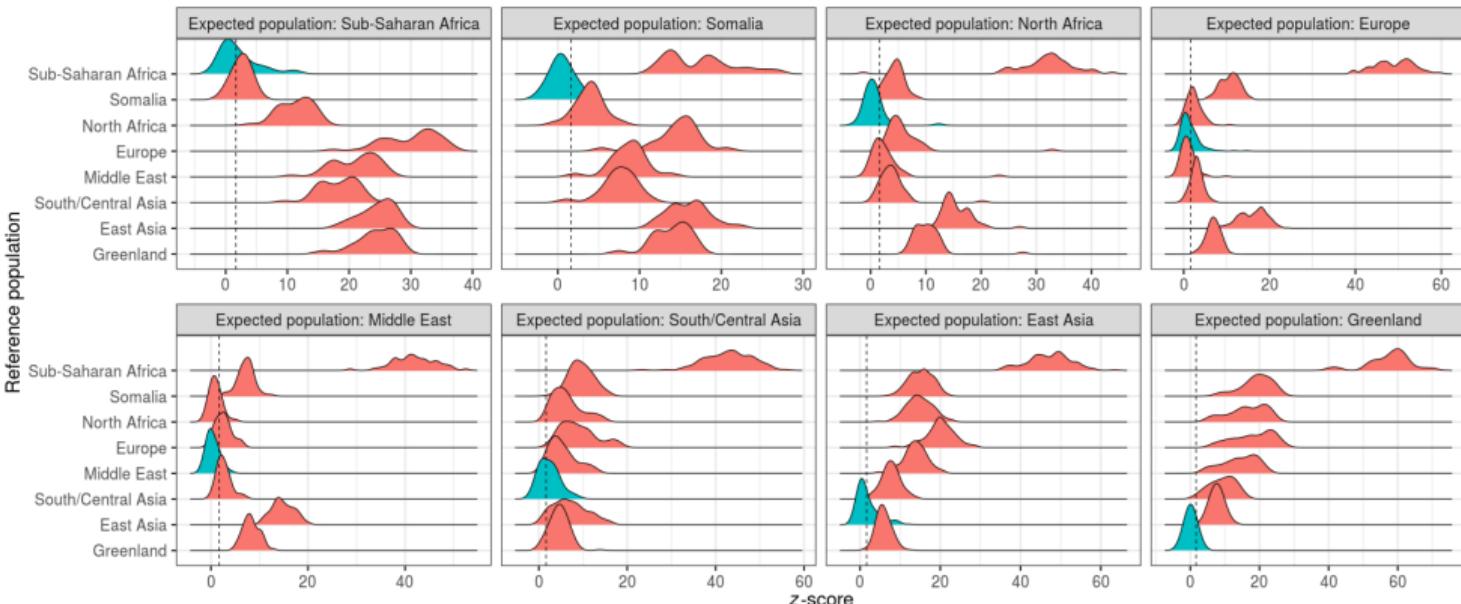
Importance sampling

Validation study

Admixed profiles

References

51



Brier score

Deeper insight into STRUCTURE (1/3)



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

52

For each of the reference samples, STRUCTURE estimates the admixture components, $\mathbf{q}_i = (q_i^{(1)}, \dots, q_i^{(K)})$, where $\sum_{k=1}^K q_i^{(k)} = 1$ by definition.

Based on these, we may compute the average admixture component for each of the reference metapopulations, by taking the average over the admixture components for the samples belonging to this meta-population:

$$\bar{\mathbf{q}}_j = (\bar{q}_j^{(1)}, \dots, \bar{q}_j^{(K)}), \quad \text{with} \quad \bar{q}_j^{(k)} = n_j^{-1} \sum_{i \in R_j} q_i^{(k)}, \quad k = 1, \dots, K,$$

where R_j is the set of the n_j samples from meta-population j .

Brier score

Deeper insight into STRUCTURE (2/3)



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

52

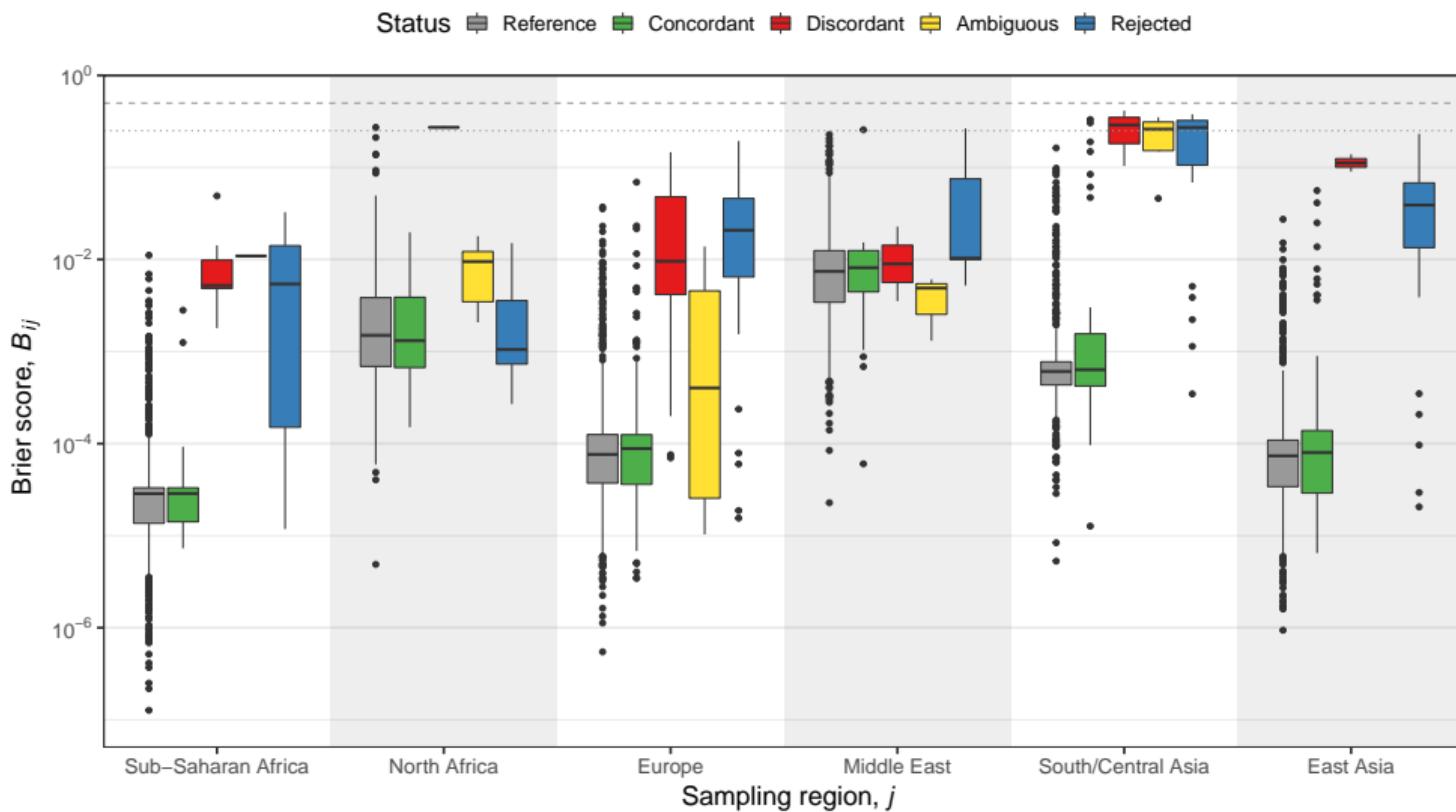
STRUCTURE admixture components was also computed for each of the test samples. For each test sample i , we computed a Brier score deviation between the test sample and the average for the reference metapopulation j :

$$B_{ij} = \frac{1}{K} \sum_{k=1}^K (q_i^{(k)} - \bar{q}_j^{(k)})^2.$$

The closer B_{ij} is 0 the more similar is sample i to metapopulation j in terms of STRUCTURE admixture components.

Brier score

Deeper insight into STRUCTURE (3/3)



Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

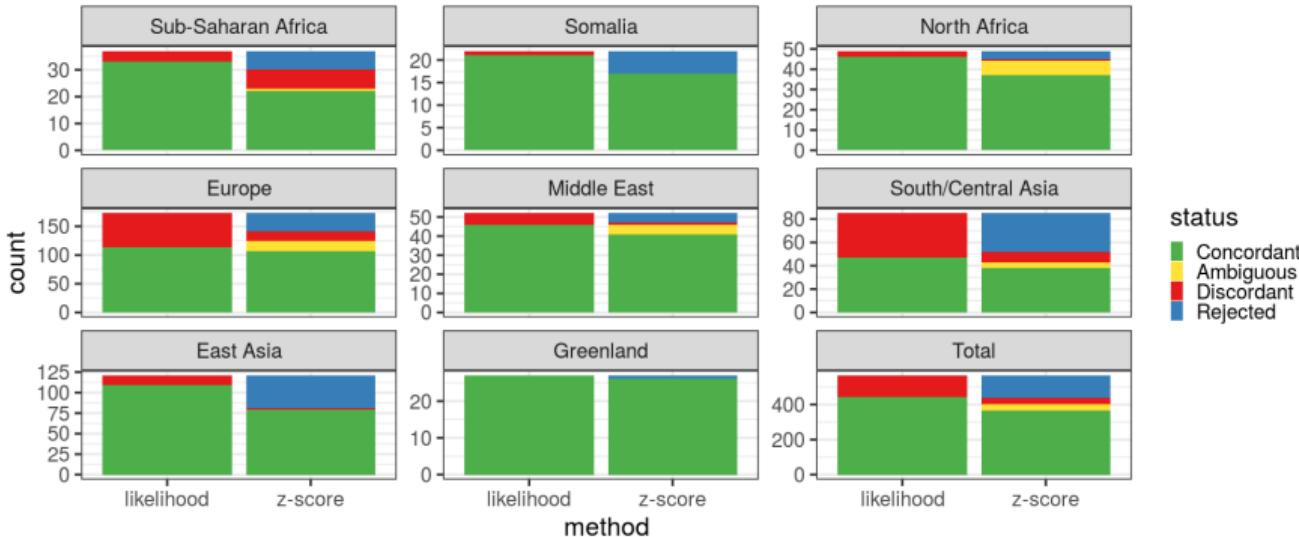
52

66

WASHINGTON, DC
ISFG 2022
INTERNATIONAL SOCIETY FOR
FORENSIC GENETICS

Validation study

- A reduction in the error rate by a factor of three!



Based on the **likelihood** the **error rate is 21.9%**. When when using the **z-score approach** with the rejection and ambiguous options, the **error rate is 8.2%**.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

Admixed profiles

1st order: Parents from different populations

Our validation study indicated that some of the profiles may have had **admixed origin** – i.e. parents from different populations.

The only methodological adjustment is to allocate the **ambiguous alleles at heterozygous markers** to one of the parental populations (for homozygous markers same allele is inherited from each population):

$$P(\text{Allele comes from population } j \mid x_0 = 1) = \frac{p_j + p_{\bullet}}{p_{+} - 2p_{\bullet}},$$

where $p_{\bullet} = p_1 p_2$ and $p_{+} = p_1 + p_2$ and p_j is the allele frequency in population j .

Thus, if $p_2 \approx 0$, we have that $p_{\bullet} \approx 0$ and $p_{+} \approx p_1$ suggesting that $P(\text{Allele comes from population 1} \mid x_0 = 1) \approx 1$ (and conversely for $j = 2$).

Also, if $p_1 \approx p_2$ we have that $p_{\bullet} \approx p_1^2$ and $p_{+} \approx 2p_1$ yielding $P(\text{Allele comes from population 1} \mid x_0 = 1) \approx 1/2$ as expected.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

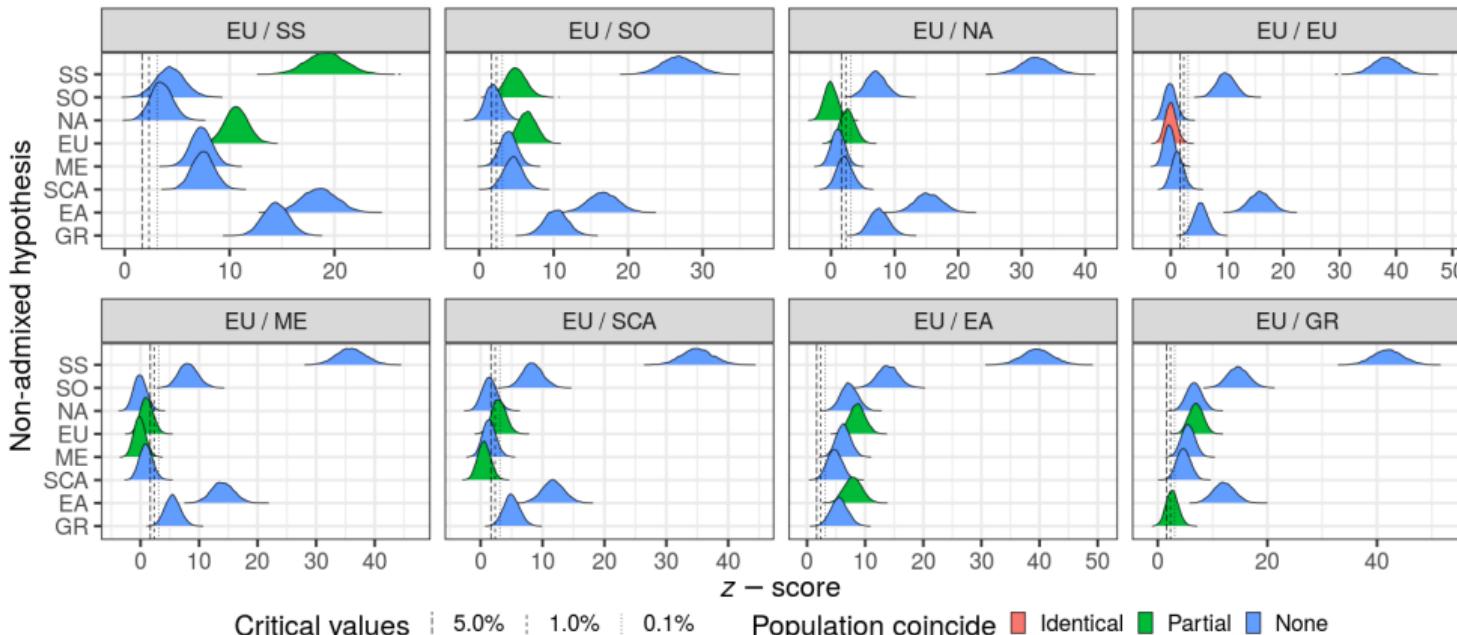
54

1st order admixed profiles

Simulation study - z-scores (excerpt of European admixtures)



Simulation populations



SS: Sub-Saharan Africa
ME: Middle East

SO: Somalia
SCA: South/Central Asia

NA: North Africa
EA: East Asia

EU: Europe
GR: Greenland.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

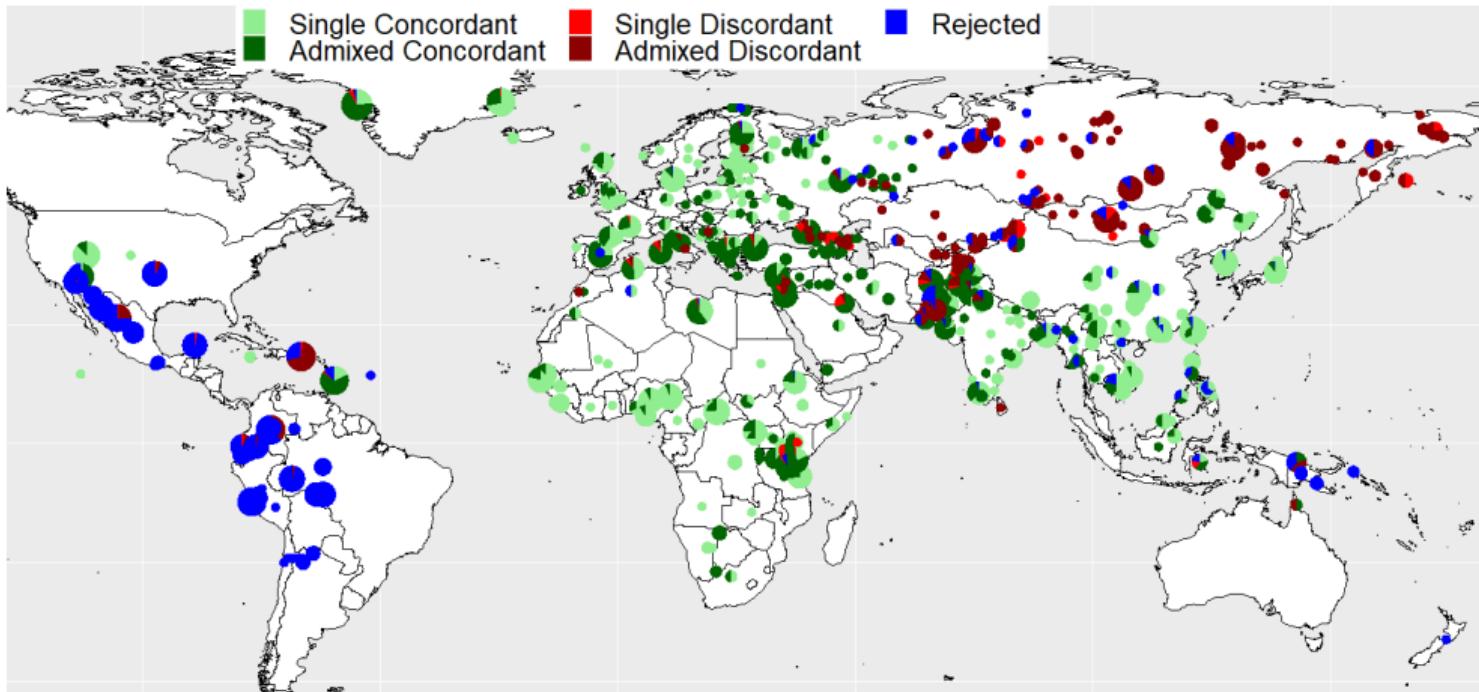
Validation study

Admixed profiles

References

Recent validation study (Poster P138)

Update of AIMS population data and test with the GenoGeographer admixture module



Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Fisher's exact test

Importance sampling

Validation study

Admixed profiles

References

56

66

Summary



- ▶ **Pairwise likelihood ratios are not sufficient** for assessing the weight of evidence for AISNP profiles
- ▶ The likelihood ratio test (z-score) **is not dependent on known allele frequencies**
- ▶ Its similarity to **Fisher's exact test** ensures a sound statistical approach
- ▶ The **GenoGeographer.org** enables fast and flexible analysis using a well-defined framework
- ▶ The use of **metapopulations** reduces the risk of making too specific statements about the country/area/population of origin
- ▶ **1st order admixtures** (and in theory, higher order) can be handled within the same framework.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

References (1/9)

Alexander, D. H., J. Novembre, and K. Lange (2009). Fast model-based estimation of ancestry in unrelated individuals. *Genome Research* 19, 1655–1664.

Chakraborty, R., M. R. Srinivasan, and S. F. Daiger (1993). Evaluation of standard error and confidence intervals of estimated multilocus genotype probabilities and their implications in dna forensics. *Am J Hum Genet* 52, 60–70.

Cheung, E. Y., M. E. Gahan, and D. McNevin (2017). Prediction of biogeographical ancestry from genotype: a comparison of classifiers. *Int J Legal Med* 131, 901–912.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

58

References (2/9)

Cheung, E. Y. Y., M. E. Gahan, and D. McNevin (2018). Prediction of biogeographical ancestry in admixed individuals. *Forensic Sci Int Genet* 36, 104–111.

Falush, D., M. Stephens, and J. K. Pritchard (2003). Inference of population structure using multilocus genotype data: Linked loci and correlated allele frequencies. *Genetics* 164, 1567–1587.

Falush, D., M. Stephens, and J. K. Pritchard (2007). Inference of population structure using multilocus genotype data: dominant markers and null alleles. *Mol. Ecol. Notes* 7, 574–578.

Hellenthal, G., G. B. J. Busby, G. Band, J. F. Wilson, C. Capelli, D. Falush, and S. Myers (2014). A genetic atlas of human admixture history. *Science* 343(6172), 747–751.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

59

References (3/9)

- Jombart, T., S. Devillard, and F. Balloux (2010). Discriminant analysis of principal components: a new method for the analysis of genetically structured populations. *BMC Genetics* 11(94), 1–15.
- Kidd, K. K. et al. (2014). Progress toward an efficient panel of SNPs for ancestry inference. *Forensic Sci Int Genet* 10, 23–32.
- Kosoy, R., et. al, and M. F. Seldin (2009). Ancestry Informative Marker Sets for determining continental origin and admixture proportions in common populations in America. *Hum Mutat* 30(1), 69–78.
- Lawson, D. (2018). *badMIXTURE: Validating Structure With Chromosome Painting*. R package version 0.0.0.9000.
- Lawson, D. J., G. Hellenthal, S. Myers, and D. Falush (2012, 01). Inference of population structure using dense haplotype data. *PLOS Genetics* 8(1), 1–16.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

60

References (4/9)

Lawson, D. J., L. van Dorp, and D. Falush (2018). A tutorial on how not to over-interpret STRUCTURE and ADMIXTURE bar plots. *Nat Commun* 9(3258).

McNevin, D., C. Santos, A. Gómez-Tato, J. Álvarez-Dios, M. Casares de Cal, R. Daniel, C. Phillips, and M. V. Lareu (2013). An assessment of bayesian and multinomial logistic regression classification systems to analyse admixed individuals. *Forensic Science International: Genetics Supplement Series* 4, e63–e64.

McVean, G. (2009). A genealogical interpretation of principal components analysis. *PLOS Genetics* 5(10), 1–10.

Menozzi, P., A. Piazza, and L. L. Cavalli-Sforza (1978). Synthetic maps of human gene frequencies in europeans. *Science* 201, 786–792.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

61 References

References (5/9)

- Miller, J. M., C. I. Cullingham, and R. M. Peery (2020). The influence of a priori grouping on inference of genetic clusters: simulation study and literature review of the DAPC method. *Heredity* 125(5), 269–280.
- Mogensen, H. S., T. Tvedebrink, C. Børsting, V. Pereira, and N. Morling (2020). Ancestry prediction efficiency of the software genogeographer using a z-score method and the ancestry informative markers in the precision id ancestry panel. *Forensic Science International: Genetics* 44, 102154.
- Novembre, J. (2014). Variations on a common STRUCTURE: New algorithms for a valuable model. *Genetics* 197(3), 809–811.
- Novembre, J. (2016). Pritchard, stephens, and donnelly on population structure. *Genetics* 204(2), 391–393.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

62

References (6/9)

- Novembre, J. et al. (2008). Interpreting principal component analyses of spatial population genetic variation. *Nat Genet* 40, 646–649.
- Patterson, N., A. L. Price, and D. Reich (2006). Population structure and eigenanalysis. *PLoS Genetics* 2(12), e190.
- Porras-Hurtado, L., Y. Ruiz, C. Santos, C. Phillips, Á. Carracedo, and M. Lareu (2013). An overview of STRUCTURE: applications, parameter settings, and supporting software. *Frontiers in Genetics* 4, 98.
- Price, A., N. Patterson, R. Plenge, et al. (2006). Principal components analysis corrects for stratification in genome-wide association studies. *Nat Genet* 38, 904–909.
- Pritchard, J. K., M. Stephens, and P. J. Donnelly (2000). Inference of population structure using multilocus genotype data. *Genetics* 155, 945–959.

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

63

References (7/9)

- Qu, Y., D. Tran, and W. Ma (2019). Deep learning approach to biogeographical ancestry inference. *Procedia Computer Science* 159, 552–561.
- Raj, A., M. Stephens, and J. K. Pritchard (2014). faststructure: Variational inference of population structure in large snp data sets. *Genetics* 197, 573–589.
- Rosenberg, N., L. Li, R. Ward, and J. Pritchard (2003). Informativeness of genetic markers for inference of ancestry. *American Journal of Human Genetics* 73, 1402–1422.
- Rosenberg, N. A. (2005). Algorithms for selecting informative marker panels for population assignment. *Journal of Computational Biology* 12(9), 1183–1201.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

64

References (8/9)

Santos, C., C. Phillips, A. Gomez-Tato, J. Alvarez-Dios, Á. Carracedo, and M. V. Lareu (2016). Inference of ancestry in forensic analysis ii: Analysis of genetic data. In W. Goodwin (Ed.), *Forensic DNA Typing Protocols*, Volume 1420 of *Methods in Molecular Biology*, pp. 255–285. Springer.

Tang, H., J. Peng, P. Wang, and N. Risch (2005). Estimation of individual admixture: Analytical and study design considerations. *Genet Epidemiol* 28, 289–301.

Tvedebrink, T. (2022). Review of the forensic applicability of biostatistical methods for inferring ancestry from autosomal genetic markers. *Genes* 13(1), 141.

Biogeographical Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

References

65

References (9/9)

Biogeographical
Ancestry

Torben Tvedebrink
[genogeographer.org]

Workshop

AIMs

Likelihood based

PCA

Clustering

Classification

GenoGeographer

Tvedebrink, T., P. S. Eriksen, H. S. Mogensen, and N. Morling (2018). Weight of the evidence of genetic investigations of ancestry informative markers. *Theoretical Population Biology* 120, 1–10.

Wangkumhang, P. et al. (2018). Statistical methods for detecting admixture. *Current Opinion in Genetics & Development* 53, 121–127.

66 References