

# Genome variation and population structure in three African malaria vector species within the *Anopheles gambiae* complex

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Abstract

Population Sampling

DNA extracted from wild-caught *Anopheles* mosquitoes were submitted to the Ag1000G consortium in 23 sets by consortial partners. (chris' line)

**Table 1.** Population sampling table. Each row represents a unique latitude/longitude where 10 or more mosquitoes were collected (pie charts in **Figure 1**). Sex and species counts for each site are given. "arabiensis x gambiae" gives counts for hybrids between *An. arabiensis* and either *An. gambiae* or *coluzzii*. Sampling on the island of Mayotte consists of seven sites with low numbers at each, these were combined and latitudes/longitudes averaged due to the small size of the island. For collection data on individual samples see **Supplementary Table 1**.

country	site	lat it ud e	lon g it ud e	c o u n t s	f e m a l e	m a l e	s e x u n k n o w n	* a r a b i e n s i s x * g a m b i a e *	* c o l u z z i *	* g a m b i a e *	*g a m b i a e x * c o l u z z i *
Angola	Luanda	-8. 88 4	13 .3 02	8 1	7 7	4	0	0	0	8 1	0
Bioko	Bioko	3. 7	8. 7	1 0	1 0	0	0	0	0	1 0	0
Burkina Faso	Bana	11 .2 33	-4. 47 2	1 2 8	8 1	4 7	0	1	0	8 9	3 7
Burkina Faso	Pala	11 .1 5	-4. 23 5	7 7	6 7	1 0	0	2	0	1 1	6 4
Burkina Faso	Sou rou koud inga	11 .2 35	-4. 53 5	7 8	7 7	1	0	0	0	3 5	4 3
Burkina Faso	Mono mteng a	12 .0 6	-1. 17	1 3	1 3	0	0	0	0	1 3	0
Camero on	Mand a	5. 72 6	10 .8 68	1 2	1 2	0	0	0	0	1 2	0
Camero on	Gado Badze re	5. 74 7	14 .4 42	9 7	8 2	1 5	0	0	0	9 7	0
Camero on	Daigu ene	4. 77 7	13 .8 44	9 6	8 1	1 5	0	0	0	9 6	0
Camero on	Nkolo ndom	3. 97 2	11 .5 16	1 0	1 0	0	0	0	0	5	5
Camero on	Mayo s	4. 34 1	13 .5 58	1 1 0	9 5	1 5	0	0	0	1 1 0	0
Central African Republic	Bangu i	4. 36 7	18 .5 83	7 3	7 3	0	0	0	0	1 8	5 5
Cote d'Ivoire	Tiassa le	5. 89 8	-4. 82 3	8 0	8 0	0	0	0	0	8 0	0

country	site	lat it ude	lon g it ude	c o u n t s	f e m a l e	m a l e	s e x u n k n o w n	* a r a b i e n s i s *	* a r a b i e n s i s * x * g a m b i a e *	* c o l u z i *	* g a m b i a e *	*ga mbi ae* x *col uzzii *
Democr atic Republic of Congo	Gbad olite	4. 28 3	21 .0 17	7 6	4 4	3 2	0	0	0	0	7 6	0
Gabon	Librev ille	0. 38 4	9. 45 5	6 9	6 9	0	0	0	0	0	6 9	0
Ghana	Takor adi	4. 91 2	-1. 77 4	2 4	2 4	0	0	0	0	2 4	0	0
Ghana	Twifo Praso	5. 60 9	-1. 54 9	2 5	2 5	0	0	0	0	2 5	0	0
Ghana	Madin a	5. 66 8	-0. 21 9	2 7	2 7	0	0	0	0	1 4	1 3	0
Ghana	Kofori dua	6. 09 4	-0. 26 1	2 4	2 4	0	0	0	0	1	2 3	0
Guinea	Korab oh	9. 28	-1 0. 03	6 2	5 0	1 2	0	0	0	0	6 0	2
Guinea	Koun dara	8. 48	-9. 53	7 4	6 2	1 2	0	0	0	1 1	6 3	0
Guinea- Bissau	Antula	11 .8 91	-1 5. 58 2	6 0	6 0	0	0	0	0	0	1 5	45
Guinea- Bissau	Safim	11 .9 57	-1 5. 64 9	3 3	3 3	0	0	0	0	0	6	27
Kenya	Kilifi	-3. 51 1	39 .9 09	8 6	7 5	1 1	0	1 3	0	0	2 8	45
Malawi	Chikh wawa	-1 5. 93 3	34 .7 55	4 1	4 1	0	0	4 1	0	0	0	0
Mali	Toum ani Oulen a	10 .8 3	-7. 81	6 3	5 2	1 1	0	0	0	2	6 0	1
Mali	Kela	11 .8 8	-8. 45	2 3	2 3	0	0	0	0	0	2 3	0
Mali	Ouass orola	12 .9	-8. 16	1 3	1 3	0	0	0	0	9	4	0
Mali	Kabab ougou	12 .8 9	-8. 15	4 0	3 2	8	0	0	0	1 2	2 8	0
Mali	Doun a	13 .2 1	-5. 9	2 0	2 0	0	0	1	0	1 9	0	0
Mali	Takan	11 .4 7	-8. 33	3 1	2 5	6	0	0	0	2 6	5	0

country	site	lat it ude	lon g it ude	c o u n t s	f e m a l e	m a l e	s e x u n k n o w n	* a r a b i e n s i s *	* a r a b i e n s i s * g a m b i a e *	* c o l u z i *	* g a m b i a e *	* g a m b i a e * x * c o l u z i *
Mayotte	Mayotte	-1 2. 85 7	45 .1 37	2 3	1 1	1 2	0	0	0	0	2 3	0
Mozambique	Furvela	-2 3. 71 6	35 .2 99	7 4	7 4	0	0	0	0	0	7 4	0
Tanzania	Tarime	-1. 43 1	34 .1 99	4 7	4 7	0	0	4 7	0	0	0	0
Tanzania	Muleba	-1. 96 2	31 .6 51	1 7 0	1 6 0	1 0	0	1 3 7	0	0	3 2	1
Tanzania	Moshi	-3. 48 2	37 .3 08	4 0	3 9	1	0	4 0	0	0	0	0
Tanzania	Muheza	-4. 94	38 .9 48	4 3	4 3	0	0	1	0	0	3 6	6
The Gambia	Tankular	13 .4 17	-1 6. 03 3	1 9	1	0	1 8	0	0	1 4	0	5
The Gambia	Njabakunda	13 .5 5	-1 5. 9	7 4	7 4	0	0	0	0	5	5 8	11
The Gambia	Wali Kunda	13 .5 67	-1 4. 91 7	1 7 4	1 7 4	0	0	0	0	1 4 8	2	24
The Gambia	Sare Sambou Sowe	13 .5 83	-1 5. 9	1 1	1	0	1 0	0	0	1	9	1
Uganda	Nagongera	0. 77	34 .0 26	1 9 4	1 9 4	0	0	8 1	1	0	1 1 2	0
Uganda	Kihihi	-0. 75 1	29 .7 01	9 6	9 6	0	0	1	0	0	9 5	0

## Whole Genome Sequencing and Alignment

A total of 4,693 individual mosquitoes were sequenced on either Illumina HiSeq2000 (n=3,130) or Illumina HiSeqX (n=1,563) to a target coverage of 30X.

Between machine types the median number of bases sequenced per sample was 9.76Gb and 10.33Gb respectively, representing a difference in yield (two-tailed mann-whitney U p < 0.0001).

These values correspond to a yield per reference base (vs AgamP4) of 35.76X and 37.82X.

91.9% of HiSeqX runs and 80.5% of HiSeq2000 runs met the target yield of 30X.

Reads were aligned to the AgamP4 reference genome using `bwa` version `0.7.15`.

Indel realignment was performed using GATK `v3.7-0` `RealignerTargetCreator` and `IndelRealigner`.

Single nucleotide polymorphisms were called against AgamP4 using GATK `UnifiedGenotyper` `v3.7-0`.

Sample genotypes were called independently, in genotyping mode, given all possible alleles at each site, allowing parallelisation over samples.

Coverage considered at individual sites was capped at 250.

Full details of pipelines including all parameter settings are provided in supplementary.

All samples successfully completed the pipeline and entered the sample quality control (QC) process.

## **Sample QC**

The sample QC process was composed of three stages, sequence quality assurance, replicate handling, and anomaly detection.

668 samples were removed where sequencing was of insufficient quality to accurately call genotypes across the whole genome.

Exclusions were due to poor coverage (n=410), potential contamination (n=229), and the autosomal vs X coverage ratio not following the expected bimodal distribution (n=29).

Where technical replicates were available, we excluded 4 pairs (8 samples) with low genotype concordance.

Where pairs met the concordance threshold we excluded the lower quality sample.

In total 407 samples were excluded in favour of better quality samples, based on skewedness of the mean vs median.

Samples were also screened pairwise within submission sets for unexpected pairs, though none were detected.

The AG1000G-X submission set, made up of laboratory experimental crosses, was exempted from the requirements of this stage due to familial similarity and high levels of inbreeding.

The third stage used principal component analysis (PCA) to identify and exclude individual samples that were outliers based on available metadata.

A review process identified samples that could not be explained parsimoniously, and were therefore likely to be sample mix ups or instances of mislabelling.

28 samples were excluded as they respectively dominated the first principal components, indicating high divergence from all other samples and therefore likely members of other Anopheline species.

A further 82 samples were excluded as potential sample mix ups.

Following all sample QC steps, 3,483 samples (74.2%) were retained from the original cohort for analysis.

Full details including exclusion thresholds are available in supplementary.

## **Coverage**

Summary of site coverage post QC exclusions.

## **SNP filtering and quality**

Site filtering is necessary to ensure that reported variation is of highest quality.

Genomic features cause unavoidable calling errors in short-read technologies; these features include high divergence from the reference, high homology between regions, copy number variation, presence of transposable elements and others.

Using the 15 available *Anopheles* pedigrees previously described, we used the presence of mendelian error at sites as a proxy for genotype discordance.

Where previously we have used manually curated cutoffs based on observed mendelian error rates to filter sites (ref phase1, phase2), here we built a statistical model where cohort level genome annotations were used to predict the presence of mendelian error, becoming a binary classification problem.

5 of the 15 crosses were held out for validation, so performance could be evaluated against the previous site filtering scheme.

Sites were defined as PASS where all genotypes across all 10 remaining crosses were called, and no mendelian inconsistencies were observed.

Sites were defined as FAIL where a mendelian inconsistency was observed in any pedigree.

All other sites were not eligible to be included in model training.

A balanced training set was generated from the remaining 10 crosses containing XXX autosomal(?) sites.

We used a decision tree, as it provides clear unambiguous decisions, and is similar in concept to the set of filters commonly used in non-model organism genomics.

A set of trees with different parameter settings were learned, exploring the depth of trees, and the number of samples allowed at a terminal node.

Parameter settings were evaluated on an unbalanced evaluation set, consisting of XXX sites randomly sampled from the whole genome.

The leaves of the trained models contain different proportions of PASS sites, by increasing the cutoff for these proportions required to label a leaf as PASS, we were able to compute the area under the receiver operating curve (AUROC) for each parameter set.

The best performing parameter set based on AUROC was selected as the final model, the classification cutoff used was optimised based on the Youden statistic.

The resulting model was a decision tree of depth 8, with a maximum of 50 terminal nodes, where leaves were assigned to PASS where  $> 0.533$  of training data in that leaf were PASS.

All sites in the genome were then assigned to PASS or FAIL given the model inputs.

The 5 remaining cross pedigrees were used to perform a final evaluation of the approach.

The above definitions of PASS sites were retained, but independently over pedigrees, providing 5 distinct evaluation sets.

Before applying the site filters, the mendelian error rate of the 5 crosses over all autosomal sites ranged between XXX and XXX (table XXX).

The application of the site filters mask defines the accessible fraction of the genome at 70%, and reduces the mendelian error rate by a median factor of 10x on the autosomes.

In all 5 crosses the Youden score was substantially increased by a median factor of XXX.

Rather than mendelian errors, on the hemizygous chromosome we can use the more direct measure of heterozygote calls in males.

In the dataset are 220 male samples identified as gambiae/coluzzii, each of these represent an independent proxy for genotype discordance.

Pre-application of the site filters, the median heterozygosity rate on X was 0.44%, and post filtering this drops to 0.12% (table XX).

The median fold change in error rate was -1.74, with 69.97% of the X chromosome passing site filters.

? (Also some measure of GQ? when applied to the X chromosome).

Direct comparison to the phase 2 site filters is favourable; we observe similar levels of mendelian error, but with substantially higher sensitivity, yielding a higher Youden score over all crosses and chromosomes.

- Table A: Mendel errors per cross per autosome. row indices: chromosome and raw/filtered column indexes: crosses + frac accessible. ie 8 rows, and 6 columns.
- Table B: comparison of cross and X row indices: raw/filtered column indices: MER, frac accessible, Youden, each for 2 and 3. column indexes: crosses + frac accessible. ie 2 rows, and 6 columns.

Result of heterozygote calls on male X chromosome

	count	mean	min	25%	50%	75%	max	fraction_accessible
pre-filtering	220.00000	0.00476	0.00285	0.00402	0.00444	0.00522	0.01342	1.00000
post-filtering	220.00000	0.00165	0.00028	0.00078	0.00127	0.00207	0.00882	0.69970

## Genome accessibility

## SNP discovery

**Species Assignment**

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**Population Structure**

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**Genetic Diversity within Populations**

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**Insecticide Resistance**

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**Gene Drive**

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## References

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