




Identification of a rapidly-spreading triple mutant for high-level metabolic insecticide resistance in *Anopheles gambiae* provides a real-time molecular diagnostic for antimalarial intervention deployment

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Abstract

Studies of insecticide resistance provide insights into the capacity of populations to show rapid evolutionary responses to contemporary selection. Malaria control remains heavily dependent on pyrethroid insecticides, primarily in long lasting insecticidal nets (LLINs). Resistance in the major malaria vectors has increased in concert with the expansion of LLIN distributions. Identifying genetic mechanisms underlying high-level resistance is crucial for the development and deployment of resistance-breaking tools. Using the *Anopheles gambiae* 1000 genomes (Ag1000g) data we identified a very recent selective sweep in mosquitoes from Uganda which localized to a cluster of cytochrome P450 genes. Further interrogation revealed a haplotype involving a trio of mutations, a nonsynonymous point mutation in *Cyp6p4* (I236M), an upstream insertion of a partial Zanzibar-like transposable element (TE) and a duplication of the *Cyp6aa1* gene. The mutations appear to have originated recently in *An. gambiae*

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from the Kenya-Uganda border, with stepwise replacement of the double-mutant (Zanzibar-like TE and *Cyp6p4-236M*) with the triple-mutant haplotype (including *Cyp6aa1* duplication), which has spread into the Democratic Republic of Congo and Tanzania. The triple-mutant haplotype is strongly associated with increased expression of genes able to metabolize pyrethroids and is strongly predictive of resistance to pyrethroids most notably deltamethrin. Importantly, there was increased mortality in mosquitoes carrying the triple-mutation when exposed to nets cotreated with the synergist piperonyl butoxide (PBO). Frequencies of the triple-mutant haplotype remain spatially variable within countries, suggesting an effective marker system to guide deployment decisions for limited supplies of PBO-pyrethroid cotreated LLINs across African countries.

KEYWORDS

adaptation, contemporary evolution, disease biology, ecological genetics, insects

1 | INTRODUCTION

Insecticide resistance in disease vectors has become an influential model for understanding rapid contemporary evolution but, more importantly, identifying how resistance arises and spreads is crucial for disease control. Resistance to pyrethroid insecticides in African malaria vector mosquitoes has spread to near ubiquity (Ranson & Lissenden, 2016; WHO, 2019) and, though it is often difficult to demonstrate its impact on malaria infections (Kleinschmidt, 2018), in some cases it has reached levels that threaten the effectiveness of vector control programmes (Staedke et al., 2020; Killeen & Ranson, 2018). A better understanding of resistance distribution and mechanisms will permit a more informed selection and deployment of insecticides to combat evolving mosquito populations. Whilst our understanding of the genetic basis of insecticide resistance in mosquitoes has advanced substantially (The *Anopheles gambiae* 1000 Genomes Consortium, 2020), especially in the important vector *Anopheles funestus* (Mugenzi et al., 2019), molecular diagnostics for the major vectors in the *An. gambiae* complex remain limited to a handful of mutations (Donnelly et al., 2016) which explain a relatively small fraction of the variance in phenotype (Weetman et al., 2018; Mitchell et al., 2014) or which are now at such high frequency as to provide limited diagnostic resolution (Weetman & Donnelly, 2015).

Long-lasting insecticidal nets (LLINs) are the principal tool for vector control to combat malaria, especially in sub-Saharan Africa (Bhatt et al., 2015). The majority of LLINs are treated only with pyrethroid insecticides, to which resistance is now widespread (Hancock et al., 2020). Though behavioural variation and physical or physiological modifications affecting insecticide uptake may sometimes play a role, pyrethroid resistance is caused predominantly by two distinct mechanisms. The first is resistance via point mutations in the target-site of the insecticide, for pyrethroids the Voltage-gated sodium channel (*Vgsc*), which results in decreased sensitivity to the insecticide (Clarkson et al., 2021); the second is metabolic resistance due to over-expression or altered activity of detoxification enzymes,

of which the cytochrome P450 family is commonly considered most important (Müller et al., 2008; Weedall et al., 2019). Cytochrome P450 activity is inhibited by the synergist piperonyl-butoxide (PBO), and bed nets incorporating PBO are effective against P450-mediated resistance, as demonstrated by large-scale field trials (Staedke et al., 2020; Protopopoff et al., 2018). Given the continued operational use of pyrethroid-containing nets, it is vital that we understand the genetic mechanisms that may impact their efficacy, to optimize bednet deployment, preferably using information from rapidly-applied DNA markers. In advance of a randomized control trial of PBO-LLINs (Staedke et al., 2020), we sought to characterize pyrethroid resistance mechanisms in the primary malaria vector *An. gambiae* s.s. (Lynd et al., 2019) in Uganda and Kenya.

The recent development of the *Anopheles gambiae* 1000 genomes project (Ag1000g) has led to a step change in our ability to identify DNA variation driven by selection pressure. We have been able to perform genome-wide searches for regions under recent natural selection in insecticide resistant populations across Africa, and work has shown that the strongest selective sweeps in the genome are all found around genes known to be important for resistance (The *Anopheles gambiae* 1000 Genomes Consortium, 2020, 2017). Furthermore, a whole-genome scan of copy number variants (CNVs) in the Ag1000g data revealed that increases in gene copy number were highly enriched in clusters of detoxification genes, pointing to a potentially widespread mechanism for increased gene expression (Lucas et al., 2019), which, in some cases, may elevate resistance. A number of gene duplications were observed around the *Cyp6aa/Cyp6p* gene family cluster on chromosome 2R, and the majority of these duplications included the gene *Cyp6aa1* (Figure 1). *Cyp6aa1* has been found to be overexpressed in pyrethroid resistant populations in congeneric species (Ibrahim et al., 2018; Zhou et al., 2015; Kwiatkowska et al., 2013), but it has received very little attention compared to known insecticide-metabolizing genes such as *Cyp6m2* (Mitchell et al., 2012; Edi et al., 2014), *Cyp6p3* (Müller et al., 2008) and *Cyp9k1* (Vontas et al., 2018) and its importance in resistance in *An. gambiae* remains unknown.

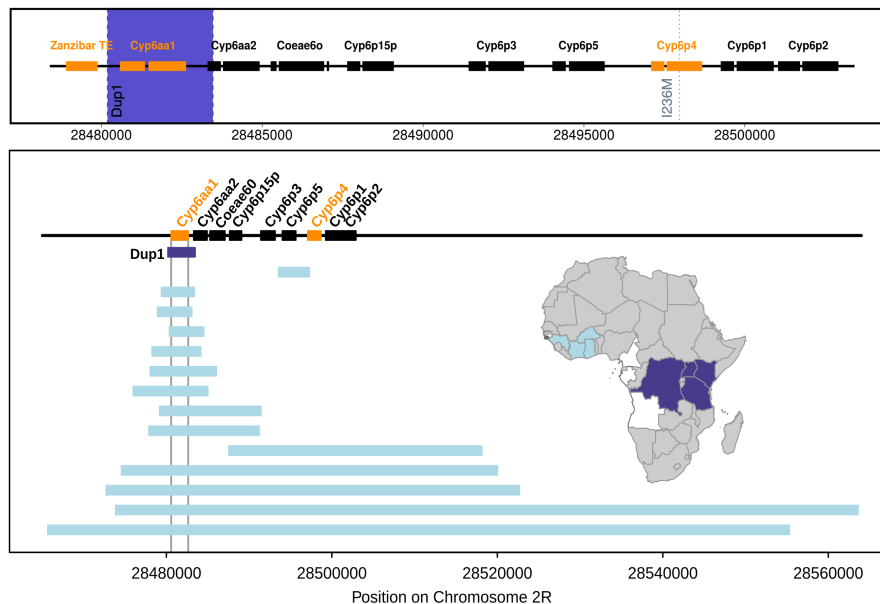


FIGURE 1 Schematic of the mutational events around the *Cyp6aa/Cyp6p* cluster on chromosome 2R in *Anopheles gambiae*. Upper panel shows the three mutational events observed in east and central African samples. Orange indicates the genes/transposable elements involved and the blue band the extent of the *Cyp6aa1-Dup1* CNV. The lower panel, redrawn from Lucas et al. (2019), shows the genomic extent and geographic distribution of the CNVs that have been observed around the *Cyp6aa/Cyp6p* cluster, 13 out of 15 include *Cyp6aa1*. The dark blue shading on the map indicates the geographic extent of *Cyp6aa1-Dup1*. Data from Uganda, Kenya and DRC are reported extensively in the main text, in addition 27.4% ($n = 84$) of *Anopheles gambiae* females sampled from northern Tanzania in 2018 were triple mutant carriers

In this study, we examined a strong selective sweep detected in the *Cyp6aa/Cyp6p* genomic region in samples of *An. gambiae* s.s. from Uganda and Western Kenya. We found that the sweep was closely associated with three mutations (a SNP in *Cyp6p4*, a duplication of *Cyp6aa1* and a partial transposable element insertion termed ZZB-TE) in tight physical and statistical linkage. The triple-mutant haplotype was associated with a high-level of pyrethroid resistance, most notably to deltamethrin. The three mutations appeared sequentially, leading to successive selective sweeps, with the triple-mutant haplotype replacing earlier variants and then apparently spreading rapidly across East and Central Africa. We show that this haplotype is under positive selection and is associated with increased expression of key cytochrome P450s and through recombinant protein expression using both an *E. coli* and an *Sf9*-baculovirus system we show that both CYP6AA1 and CYP6P4 are capable of metabolizing pyrethroid insecticides.

2 | MATERIALS AND METHODS

2.1 | Interrogation of the Ag1000g data set and identification of tagging markers

Phased whole genome sequence data from the Ag1000g data set have previously revealed a strong selective sweep in Ugandan populations around the *Cyp6aa/Cyp6p* cluster (The *Anopheles gambiae* 1000 Genomes Consortium, 2017) on chromosome 2R (Figure 1). The *Cyp6aa/Cyp6p* cluster falls within the boundaries of the 2Rc

chromosomal inversion although this inversion is not polymorphic in this population (Love et al., 2019). An isoleucine to methionine substitution in codon 236 of CYP6P4 (see extended data figure 10b in The *Anopheles gambiae* 1000 Genomes Consortium, 2017) was identified provisionally as a swept haplotype tagging SNP. Whilst there are three other nonsynonymous mutations associated with the swept haplotype the *Cyp6p4-236M* showed the highest linkage disequilibrium and was therefore prioritized for further investigation. A previous study by Lucas et al. (2019) had shown that a duplication of the *Cyp6aa1* gene was also observed in these samples (previously termed *Cyp6aa1-Dup1*). To objectively determine how these mutations segregated with the observed selective sweep (The *Anopheles gambiae* 1000 Genomes Consortium, 2017) we grouped the 206 Ugandan haplotypes ($n = 103$ diploid individuals) by similarity using the 1000 SNPs located immediately up- and downstream of the start of the *Cyp6aa/Cyp6p* gene cluster (500 nonsingleton SNPs in each direction from position 2R:28,480,576). Distances were calculated with the pairwise_distance function in scikit-allel (Miles et al., 2019) and converted to a nucleotide divergence matrix (D_{xy} statistic) by correcting the distance by the number of sequencing-accessible bases in that region. We defined clusters of highly similar haplotypes by hierarchical clustering with a cutoff distance of 0.001. This resulted in the identification of a cluster of 122 highly similar haplotypes. To determine whether the haplotype cluster showed signs of a selective sweep, we estimated the extended haplotype homozygosity (EHH) decay within each of the haplotype groupings, around two different focal loci: (i) the putative sweep SNP marker

Cyp6p4-236M (2R:28,497,967 ±200kbp; total 14,243 phased variants), and (ii) the 5' and 3' breakpoints of the *Cyp6aap-Dup1* duplication (2R:28,480,189–200kbp and 2R:28,483,475+200kbp; total 14,398 phased variants). We used the *ehh_decay* function of *scikit-allel* (Miles et al., 2019).

We also used the haplotype groupings identified above to calculate the Garud *H* statistics (Garud et al., 2015) and the haplotypic diversity at the *Cyp6aa/Cyp6p* cluster locus (coordinates 2R:28,480,576–2R:28,505,816). Specifically, we used the *moving_garud_h* and *moving_haplotype_diversity* functions in *scikit-allel* to obtain a series of estimates for each statistic in blocks of 100 variants located within the cluster, and used a block-jackknife procedure to calculate averages and standard errors of each estimate (jackknife function in *scikit-allel* misc module).

2.2 | Molecular screening of colony and wild-caught mosquitoes

Locked-nucleic acid (LNA) probe-based PCR diagnostics were designed for all three mutations (Appendix S1).

2.3 | Mosquito colonies

Genotype: phenotype association testing was performed using two colonies of *An. gambiae* s.s., BusiaUG (resistant) and Mbita (susceptible). The BusiaUG strain was established in the lab in November 2018 from Busia, eastern Uganda and exhibits high resistance to pyrethroids and organochlorines (<10% mortality following WHO exposure test; fixed for *Vgsc-995S* resistance mutation), but full susceptibility to organophosphates and carbamates. The Mbita strain was first colonized from Mbita Point, Kenya in 1999, and is fully susceptible to pyrethroids. Colonies were reared in insectaries targeted to 25–27°C and 70%–80% relative humidity.

Freshly emerged females from the Mbita line were mated with 3–5 day-old BusiaUG males and then blood fed. The offspring from this cross were then crossed back to the parental BusiaUG line. This design was chosen as resistance variants are often recessive. The resultant backcrossed 3–5-day-old females were exposed for 1 h to deltamethrin, permethrin or α -cypermethrin (the three insecticides most commonly used on LLINs) or DDT (a nonpyrethroid sodium channel antagonist), following WHO standard procedures (WHO, 2016). Mosquitoes were maintained on a 10% sugar solution after exposure and mortality was recorded 24 h post exposure.

2.4 | Wild-caught mosquitoes

2.4.1 | Democratic Republic of Congo

Anopheles gambiae s.s. were obtained from the President's Malaria Initiative supported entomological surveillance project (Wat'senga

et al., 2020) and from collections conducted by Lynd et al. (2018). Mosquitoes were collected by human landing catch or pyrethrum spray collection from 15 locations between 2013 and 2018. Resistance-phenotyped individuals were also obtained from Pwamba, Bassa and Fiwa in Nord Ubangi Province in 2016. These mosquitoes were assessed for susceptibility to deltamethrin or permethrin using a standard WHO tube assay or a cone bioassay where Permanet 3.0 (deltamethrin plus PBO) or Olyset Plus (permethrin plus PBO) were the test nets (Kwiatkowska et al., 2013).

2.4.2 | Kenya and Uganda

Collection details for specimens from contiguous areas of western Kenya and eastern Uganda have been published previously (Lucas et al., 2019; Mitchell et al., 2012; Edi et al., 2014).

2.4.3 | Tanzania

Mosquito collections were conducted in Geita, Bagamoyo and Muleba districts of Tanzania in 2018.

Mosquitoes from all collections were genotyped at the ZZB-TE, *Cyp6p4-236M* and *Cyp6aap-Dup1* loci and genotype: phenotype association testing was performed by Fisher's exact tests.

2.5 | Analysis of temporal change

The most complete time series of ZZB-TE, *Cyp6p4-236M* and *Cyp6aap-Dup1* allele frequencies were available from Kabondo, DRC; western Kenya and eastern Uganda. To model allele frequency changes over time we estimated the three parameters of the standard recursive population genetic model (allele frequency at time zero, selection coefficient and dominance coefficient) using a maximum likelihood approach assuming a binomial distribution: an approach previously applied to insecticide target-site resistance mutations (Lynd et al., 2010). The analysis was performed in R (<http://www.r-project.org>). An estimated generation time of one calendar month was used as in previous studies (Lynd et al., 2010).

2.6 | Recombinant protein and insecticide metabolism

The CYP6P4-236M variant, and its redox partner cytochrome P450 reductase gene (CPR), were expressed in *E. coli* as per standard protocols (Yunta et al., 2019) (Appendix S2). Initial efforts to generate recombinant CYP6AA1 in an *E. coli* system with optimized codon usage failed, and we therefore used an Sf9-baculovirus-based expression system. Since P450 catalytic activity is dependent on electrons supplied by NADPH via CPR, insecticide metabolism was assayed with cell pellets of CYP6P4/CPR or CYP6AA1/CPR in the

presence or absence of NADPH. The depletion of the substrate and the appearance of metabolites were monitored by reverse-phase HPLC (Appendix S3).

2.7 | Estimation of gene expression of key P450s in triple mutant haplotype

To determine whether the presence of the triple mutant haplotype type was associated with differential expression of genes, we examined individual females from the BusiaUg colony (Triple mutant Freq. 0.297; 95% CI 0.233–0.370). Two legs were removed from individual mosquitoes for DNA analysis with the remaining mosquito kept for RNA analysis. DNA was extracted from legs by boiling in STE buffer at 95°C for 90 min and individuals were genotyped using the LNA qPCR assays. RNA was then extracted individually from eight mosquitoes in each genotypic group - homozygotes for the triple mutant haplotype, wild-type homozygotes, and heterozygotes, using the Arcturus Picopure RNA isolation kit (Thermofisher). We then performed SYBR green based qPCR to measure the expression of *Cyp6aa1* and *Cyp6p4* together with the known resistance-linked variant *Cyp6p3* using the housekeeping genes 40s ribosomal protein S7 (AGAP010592) and elongation factor Tu (AGAP005128) for normalization. The $\Delta\Delta\text{CT}$ values were tested for normality and homogeneity of variances using the Shapiro-Wilks test, and the Bartlett test, respectively. A significant difference in gene expression between the genotypic groups was

determined by a two-tailed two-sample Student's *t*-test on $\Delta\Delta\text{CT}$ values, with a threshold of $p = .05$.

3 | RESULTS

Hierarchical clustering of 206 Ag1000g haplotypes ($n = 103$ individual females) from *An. gambiae* s.s. from Uganda resulted in identification of a common haplotype ($n = 122$ out of 206) around the *Cyp6aa/Cyp6p* gene cluster, putatively representing a swept haplotype in this region. To characterize the signatures of selection in Ugandan haplotypes around this cluster, we examined the profile of extended haplotype homozygosity around the position of the *Cyp6p4*-236M SNP and around the CNV in *Cyp6aa1*. In both cases, we found that the putative swept haplotype had longer stretches of homozygosity than wild-type haplotypes (Figure 2). In addition, we found that *An. gambiae* s.s. from Uganda had reduced haplotypic diversity along the entire *Cyp6aa/Cyp6p* gene cluster ($h = 0.339746 \pm 0.005664$ standard error) and a combination of Garud's H statistics that was indicative of a hard selective sweep in this region (high $H_{12} = 0.821867 \pm 0.006308$ SE; low $H_2/H_1 = 0.016779 \pm 0.000228$ SE) (Garud et al., 2015). These results strongly suggest that the haplotypes we have identified have undergone a selective sweep. We then used iterative read mapping of individuals homozygous for the sweep to search for additional mutations that might be distinctive of the haplotype. This revealed that a partial copy of a Ty3/Gypsy Zanzibar transposon insertion

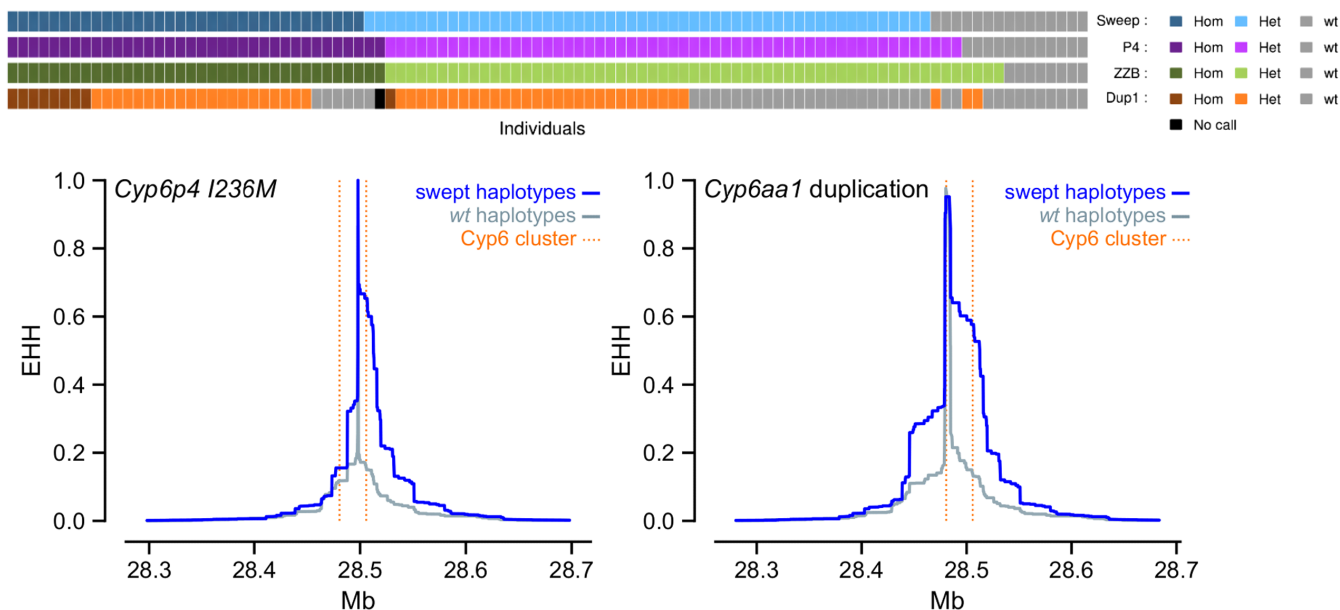


FIGURE 2 Selective sweep around the *Cyp6aa/Cyp6p* cluster in *Anopheles gambiae* from Uganda. Upper panel Showing the relationship between the selective sweep ("Sweep") and the three mutations *Cyp6p4*-236M SNP ("P4"), the ZZB-TE insertion ("ZZB") and *Cyp6aa1*-Dup1 ("Dup1"). Each vertical bar represents a single haplotype, colour-coded to show whether it is a copy of the swept haplotype (blue) and whether it carries the SNP (purple), the TE insertion (green) and the duplication (orange). The swept haplotype and the *Cyp6p4*-236M SNP overlap almost completely, while the duplication is found on a subset of these haplotypes. Lower panel extended haplotype homozygosity (EHH) plots around the *CYP6P4*-236M and *CYP6AA1*-Dup1 variants show slower loss of homozygosity in the swept haplotypes than in the wild-type

(termed ZZB-TE), lacking functional open reading frames, was linked to *Cyp6p4-236M* and *Cyp6aap-Dup1* (Figure 2).

3.1 | The evolution of the ZZB-TE, *Cyp6p4-236M* and *Cyp6aap-Dup1* haplotypes

Based upon Ag1000g data and a time series of collections from Central and East Africa, we propose the sequence of mutational events (ZZB-TE, *Cyp6p4-236M* and *Cyp6aap-Dup1*) as the most likely evolutionary history of the swept haplotype. Among the Ag1000g data (The *Anopheles Gambiae* 1000 Genomes Consortium, 2017) (see extended data Figure 1), the *Cyp6p4-236M* mutation was only observed in collections from eastern Uganda (collected in 2012) suggesting that this mutation originated in the eastern Ugandan/western Kenyan region. In a screen of collections from Uganda and Kenya predating the Ag1000g collections by 8 years (2004) (Figure 3) only the ZZB-TE insertion was detected, although the sample size was too small ($n = 4$) to conclude that the *Cyp6p4-236M* allele was absent. The *Cyp6p4-236M* mutation was first observed in this region in 2005 (frequency $Cyp6p4-236M = 0.10$) in individuals carrying the ZZB-TE mutation,

whilst the *Cyp6aap-Dup1* CNV was first recorded in 2008 (proportion of individuals with $Dup1 = 0.8\%$). This inferred sequence of events may explain why ZZB-TE and *Cyp6p4-236M* mutations are in tighter statistical linkage with each other than with *Cyp6aap-Dup1* (Figure 2), despite the closer proximity of ZZB-TE and *Cyp6aap-Dup1* (Figure 1). Given the very tight association between the ZZB-TE insertion and the *Cyp6p4-236M* SNP, we will henceforth refer to the *Cyp6p4-236M* (double mutant) haplotype and the *Cyp6aap-Dup1* (triple mutant). The double mutant haplotype shows a steady increase in frequency between 2004 and 2011 in Kenya (Figure 3); possibly in response to the introduction and subsequent intensification of bednet distribution programmes (Wat'senga et al., 2020; Yeka et al., 2012; Ministry of Health, 2019). Following its appearance in 2008, the triple mutant haplotype, rapidly increased towards fixation in both collections from Uganda and Kenya, replacing the double mutant. This haplotype replacement and the observation that the triple mutant is the only nonwild-type haplotype observed outside Kenya/Uganda (such as in Tanzania and DRC, Figures 1 and 3) strongly implies an additional selective advantage to the triple mutant. The time series data from across DRC are particularly striking both in terms of the speed of increase of the triple mutant but also the north-south

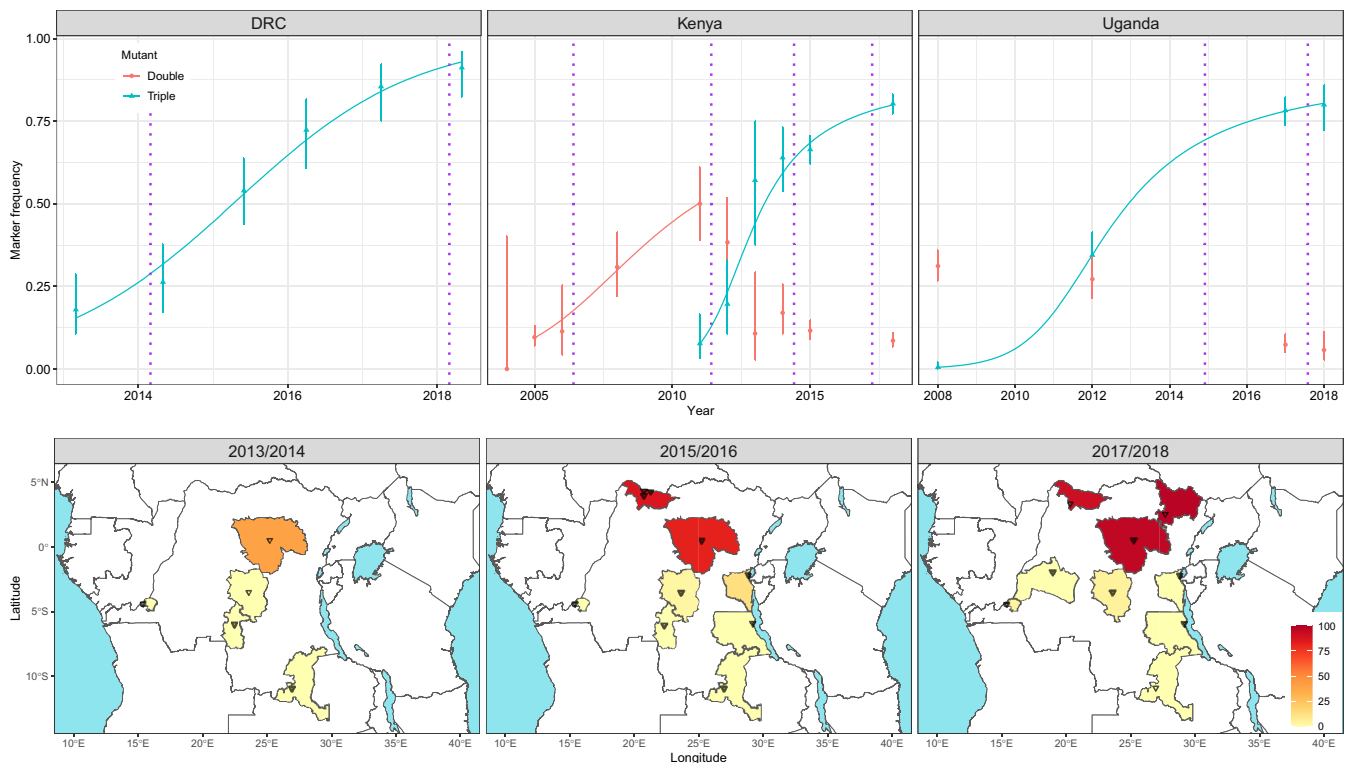


FIGURE 3 Observed and modelled changes in *Cyp6aa/Cyp6p* haplotype frequencies over time in *Anopheles gambiae* s.s. populations from DRC, Kenya and Uganda. Upper panel shows mutation frequency estimates derived from wild-caught individuals from Kabondo, DRC; western Kenya and eastern Uganda, the 95% CIs for each observed data point were calculated according to Newcombe (1998). The model data, illustrated with blue or red curves, were generated from simultaneous maximum likelihood estimates of initial frequency and selection and dominance coefficients which were then used to parameterize standard recursive allele frequency change equation. The purple dotted lines indicate approximate timings of LLIN mass coverage campaigns in the sampled locations. The lower panel shows data from DRC tracking the emergence and spread of the triple mutant haplotype. Triangles indicate collection locations within each province and the scale bar indicates triple mutant frequency

heterogeneity, with very low frequencies in the more southerly provinces (Figure 3). The cause of this north:south difference is not clear but it should be noted that LLIN distribution in DRC does not occur simultaneously across the country and that LLINs were distributed to some southerly provinces approximately 30 months after the more northerly provinces (Dolan et al., 2019).

3.2 | Identifying potential drivers of haplotype frequency increase

The genomic region into which the ZZB-TE inserted does not show histone signals of regulatory activation (H3K27ac, H3K9ac) or repression (H3K9me3), and ATAC-seq data suggests it is not in an open chromatin region (Ruiz et al., 2021). However we took two in silico approaches to determine whether the ZZB-TE insertion (748 bp) carried putative regulatory variants. The inserted region had 98.5% sequence identity to a putative enhancer (2R,45,966,598–45,966,822) identified by homology with *Drosophila melanogaster* (Ruiz et al., 2021). However, despite the similarity, the insertion lacked enhancer-like motifs (Ruiz et al., 2021) and its potential regulatory role in nearby genes is unclear. The second approach involved screening the ZZB-TE inserted sequence for putative enhancers using iEnhancer-2 L (Liu et al., 2015) and iEnhancer-EL (Liu et al., 2018). In a windowed analysis of 200 bp with a 1 bp step across the entire length of ZZB-TE both predicted that some of the windows would have strong enhancer activity, however the windows were not-concordant, precluding further analysis.

Given that cytochrome P450 mediated resistance is commonly associated with differential gene expression we performed transcription studies within the *Cyp6aa/Cyp6p* cluster between the most contrasting haplotypes, wild-type and triple mutant, present in the BusiaUg colony. The group homozygous for the triple mutant haplotype significantly overexpressed both *Cyp6aa1* (2.23-fold, 95% CI: 1.73–2.90, $p = .0003$) and *Cyp6p4* (2.57-fold, 95% CI: 1.25–5.93, $p = .039$) compared to wild-type individuals. The ratio of expression of *Cyp6aa1* broadly reflected the expected pattern based on genotype (i.e., 2:1.5:1 for triple mutant homozygotes: heterozygotes: wild-type genotypes, respectively. Figure 4). As a control we examined a neighbouring, very commonly resistance-associated gene, *Cyp6p3*, but triple mutant and wild-type homozygotes did not differ significantly in expression (1.33 fold, 95% CI: 0.64–2.74, $p > .05$).

To investigate whether resistance may be driven at least in part by an effect of the allelic variant on metabolic activity of CYP6P4, we expressed the wild-type (236I) and mutant (236M) forms in an *E. coli* based recombinant protein system (Appendix S2 and S4). Both alleles were shown to be capable of metabolizing class I (permethrin) and II (deltamethrin) pyrethroids but there was no evidence that the mutant (236M) or wild-type (236I) alleles had different rates of pyrethroid depletion. We also expressed the duplicated P450 CYP6AA1, in an *Sf9*-baculovirus protein expression system. Again, metabolism assays demonstrated that the enzyme was capable of metabolizing both deltamethrin and permethrin (Appendix S3 and

S4). Depletion of deltamethrin was 36.6% greater (SE = 3.79) in the presence of NADPH than in the control (t-test: $t = -9.67$; d.f. = 8; $p = 9.6 \times 10^{-6}$), demonstrating that CYP6AA1/CPR is capable of metabolizing deltamethrin in vitro. Similarly, permethrin was metabolized by CYP6AA1/CPR, with permethrin being depleted by 22.4% (SE = 0.63) compared to the control without NADPH (t-test: $t = -31.08$; d.f. = 14; $p = 2.55 \times 10^{-14}$).

Given clear evidence of increased expression of both *Cyp6aa1* and *Cyp6p4* in the triple mutant haplotype and the ability of both enzymes to metabolize pyrethroids in vitro, we investigated whether the mutations were significantly associated with resistance in vivo. Exposure of *An. gambiae* females from Busia, Uganda and Nord Ubangi, DRC to new LLINs in cone assays resulted in negligible mortality to the pyrethroid only LLINs, Olyset and Permanent 2.0 (Figure 5). Simultaneous exposure to pyrethroid plus the P450 inhibitor PBO in Olyset + and the top of Permanent 3.0 nets resulted in a marked reduction in resistance, demonstrating that the resistance phenotype is substantially mediated by P450s. We performed laboratory backcrosses between additional mosquitoes from Busia with the pyrethroid susceptible Mbita colony, and found that the triple mutant haplotype was significantly associated with resistance to the most commonly used type II pyrethroids in LLINs: deltamethrin (Fisher's exact test $p = 3.2 \times 10^{-6}$) and alphacypermethrin (Fisher's exact test $p = 5.9 \times 10^{-7}$) resistance although not to permethrin (Fisher's exact test $p = .06$) nor, as a control, DDT (Fisher's exact test $p = .84$) (Table 1) in WHO tube assays. Similarly, specimens collected

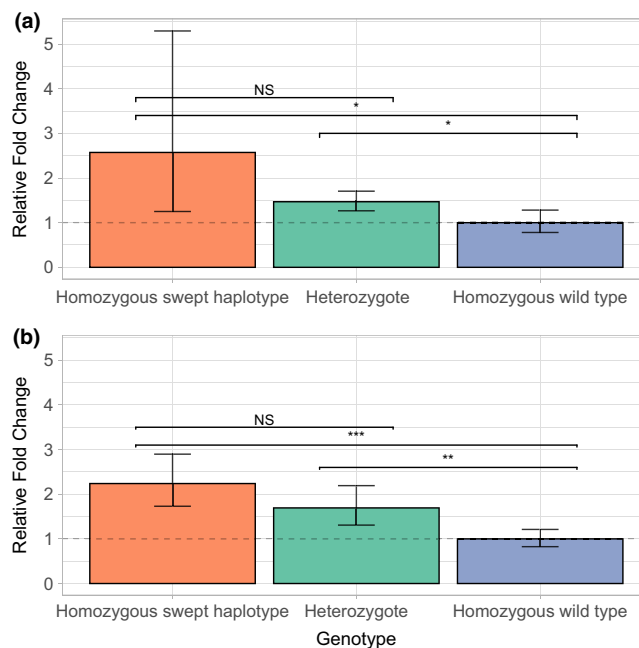


FIGURE 4 Gene expression analysis of *Cyp6p4* and *Cyp6aa1* in genotyped *Anopheles gambiae* females. Relative fold change for *Cyp6p4* (a) and *Cyp6aa1* (b), comparing individuals homozygous for the swept triple mutant haplotype and heterozygotes in the BusiaUG colony to wild-type individuals. 95% confidence intervals are shown. Asterisks indicate statistical significance in two-tailed students t-tests; *** $p \leq .001$, ** $p \leq .01$, * $p \leq .05$

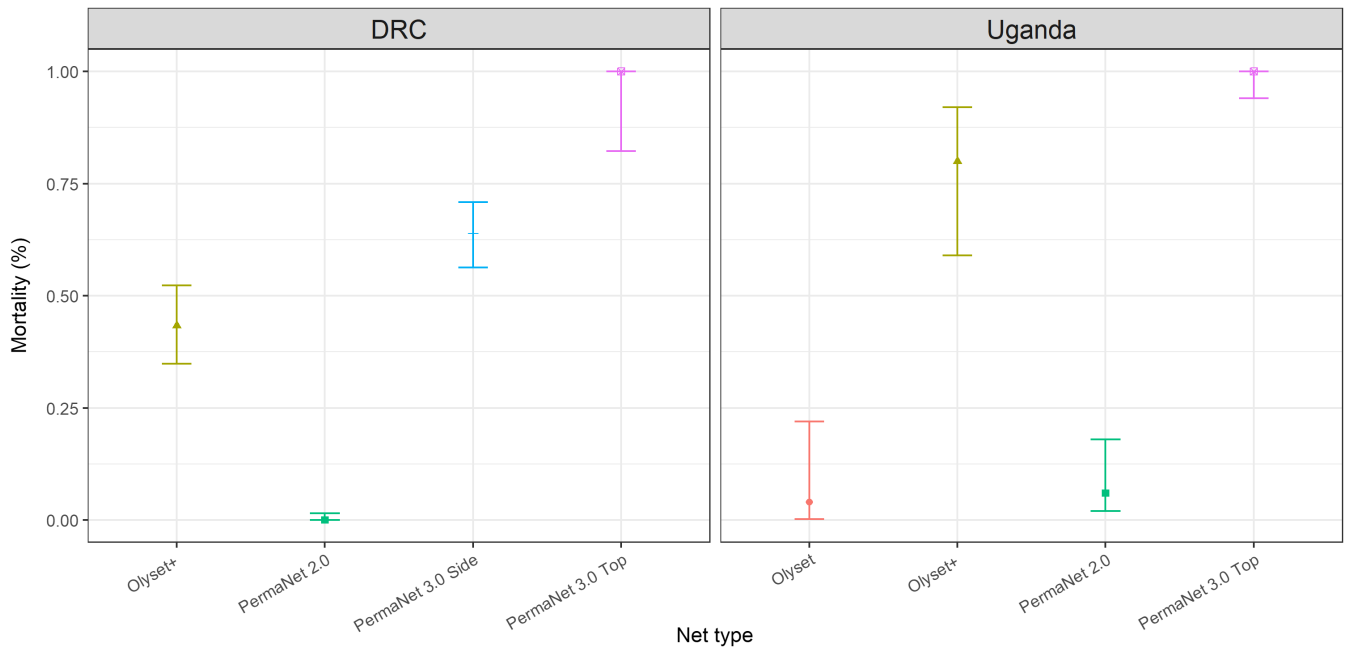


FIGURE 5 Patterns of insecticide resistance in *Anopheles gambiae* following exposure to permethrin and deltamethrin treated nets. Female *Anopheles gambiae* s.s. from the Democratic Republic of Congo (DRC) and Uganda exhibited very high resistance (low % mortality) in WHO cone assays to permethrin (Olyset) and deltamethrin (PermaNet 2.0) LLINs. There was an increase in mortality following exposure to an increased concentration of deltamethrin (PermaNet 3.0 side) and very high mortality following exposure to pyrethroid plus the P450 inhibitor piperonyl butoxide (PBO) Olyset+ and PermaNet 3.0 top. 95% confidence intervals are shown

in 2016 from the DRC showed a strong association between the triple mutant genotype and survival rate 24h post-exposure to either 0.05% deltamethrin for 1 h or 3-min exposures to deltamethrin-treated sides of a new PermaNet 3.0 net (Table 2). No association was found in samples exposed to permethrin (24h WHO tube assay) or permethrin-treated Olyset Plus nets (3-min WHO cone assay) (Table 2). Complete linkage of the three mutants in the BusiaUG colony and the DRC wild-caught collections precludes determination of the relative contribution of each of the three mutations to the resistance phenotype but taken together these results demonstrate a strong impact of the triple mutant on the efficacy of pyrethroid resistance.

4 | DISCUSSION

We have identified a series of adaptive mutations in *An. gambiae* culminating in a triple-mutant haplotype with a large effect on pyrethroid resistance and which is spreading rapidly across East and Central Africa. The mutation that is probably the oldest in this series, the insertion of ZZB-TE, was first detected in 2004 in the malaria-endemic area around Lake Victoria, with the *Cyp6p4-236M* SNP evident in 2005 samples and the third, a duplication in *Cyp6aa1* detected in 2008. In samples collected only 5 years later, the triple mutant was detected hundreds of kilometres away in the DRC. These patterns suggest both a large fitness advantage arising from the triple mutant, and a frightening speed at which resistance-conferring mutations are able to spread within and

across populations. We are not unable to unequivocally state that the triple mutant haplotypes are identical by descent in all locations. However we would argue that this is the most parsimonious explanation as it relies upon a single origin and geographic spread rather than multiple convergent mutation events. As revealed by earlier work there is very limited evidence of population differentiation in *Anopheles gambiae* across broad swathes of Africa, suggesting extensive contemporary gene flow (The *Anopheles gambiae* 1000 Genomes Consortium, 2017). Moreover there is clear evidence from haplotype analysis of insecticide resistance mutations in *Vgsc* of single origins and spread over many thousands of kilometres (Clarkson et al., 2021).

Second generation nets treated with the synergist PBO were shown to be much more effective than conventional nets in killing mosquitoes in populations where the triple mutant haplotype is present (Figure 5). Therefore the use of PBO bednets should be prioritized in the regions where this mutation is present. A strong corollary of this finding comes from the cluster randomized control trial conducted in Uganda, where the mutation is at high frequency, which demonstrated that malaria parasite prevalence in children <10years old (12% vs. 14%; Prevalence ratio = 0.84, 95% CI: 0.72–0.98; $p = .029$) and mean number of mosquitoes (density ratio = 0.25, 95% CI: 0.18–0.3; $p < .0001$) per house were significantly lower in villages that had received PBO LLINs relative to standard LLINs (Staedke et al., 2020). There is some evidence that the haplotype may be less strongly associated with resistance to permethrin than deltamethrin (and perhaps also alphacypermethrin), although both pyrethroids were metabolized by *Cyp6aa1* and *Cyp6p4*.

TABLE 1 Association between insecticide susceptibility as determined by WHO tube bioassay and triple mutant genotype in female *Anopheles gambiae* from a cross between BusiaUG and Mbita colonies

Insecticide	Phenotype	Wild-type homozygote	Heterozygote	Triple mutant homozygote	Test and p-value
α -Cypermethrin <i>n</i> = 146	Alive	1	32	24	Genotypic $p = 5.92 \times 10^{-7}$
	Dead	14	68	7	Allelic $p = 6.34 \times 10^{-5}$; OR ^a 2.74 (1.63–4.69)
Deltamethrin <i>n</i> = 60	Alive	0	0	8	Genotypic $p = 3.21 \times 10^{-6}$
	Dead	15	26	11	Allelic - cannot be calculated
Permethrin <i>n</i> = 53	Alive	1	18	7	Genotypic $p = .059$
	Dead	5	20	2	Allelic $p = .08$; OR 1.99 (.86–4.67)
DDT <i>n</i> = 65	Alive	0	14	1	Genotypic $p = 1$
	Dead	3	45	2	Allelic $p = .84$; OR 1.19 (.48–2.94)

^aOdds ratios for allelic test and associated 95% CI.

TABLE 2 Association between insecticide susceptibility as determined by WHO tube bioassay or WHO net bioassay and triple mutant genotype in wild-caught, female *Anopheles gambiae* from three locations in Nord Ubangi Province, Democratic Republic of Congo

Site	Insecticide	Bioassay	Phenotype	Wild-type homozygote	Heterozygote	Triple mutant homozygote	Test and p-value
Fiwa <i>n</i> = 161	Permethrin Tube	Tube	Alive	5	42	30	Genotypic $p = .63$
			Dead	8	49	27	Allelic $p = .42$; OR ^a 1.23 (0.76–2.00)
Fiwa <i>n</i> = 78	Deltamethrin Tube	Tube	Alive	6	14	18	Genotypic $p = 6.21 \times 10^{-3}$
			Dead	7	27	6	Allelic $p = .04$; OR 2.01 (1.01–4.06)
Bassa <i>n</i> = 95	Permethrin Tube	Tube	Alive	1	19	18	Genotypic $p = .79$
			Dead	2	32	23	Allelic $p = .63$; OR 1.21 (0.61–2.43)
Bassa <i>n</i> = 47	Deltamethrin Tube	Tube	Alive	0	3	16	Genotypic $p = 4.02 \times 10^{-3}$
			Dead	1	16	11	Allelic $p = 5.71 \times 10^{-3}$; OR 5.44 (1.41–31.28)
Pwamba <i>n</i> = 40	Deltamethrin Tube	Tube	Alive	7	9	7	Genotypic $p = .066$
			Dead	9	9	1	Allelic $p = .02$; OR 2.93 (1.07–8.39)
Fiwa <i>n</i> = 106	Olyset Plus Net	Net	Alive	6	21	30	Genotypic $p = .82$
			Dead	6	15	28	Allelic $p = .88$; OR .93 (0.49–1.77)
Fiwa <i>n</i> = 155	Permanet 3.0 Net	Net	Alive	5	26	24	Genotypic $p = 5.61 \times 10^{-4}$
			Dead	30	51	19	Allelic $p = 1.4 \times 10^{-4}$; OR 2.56 (1.54–4.31)

^aOdds ratios for allelic test and associated 95% CI.

Our results highlight the importance of gene duplications for the evolution of insecticide resistance. In *An. gambiae*, duplications have recently been shown to be concentrated in regions associated with metabolic resistance, and over 40 such duplications have been described across the genome (Lucas et al., 2019). Thirteen different duplications have so far been described that encompass *Cyp6aa1* (Figure 1), both in West and East Africa and in the two sister-species *An. gambiae* ss and *An. coluzzii* (Lucas et al., 2019). It seems likely that these other *Cyp6aa1* duplications are also associated with pyrethroid resistance. For example, in *An. coluzzii* sampled from a highly insecticide-resistant population from Cote d'Ivoire, greater than 95%

of individuals had *Cyp6aaap* duplications (Appendix S5). Five different duplications were observed in the collections from 2012 and 2017 and, whilst we detected no association with pyrethroid resistance, two duplications (*Cyp6aaap-Dup7* and *Cyp6aaap-Dup14*) showed significant increases in frequency over time. Moreover the total number of CNVs per sample (measured as presence of each of the 5 duplications, summed for each sample) increased significantly from an average of 1.59/individual in 2012 to 2.08 in 2017 (Mann Whitney U test; $p < .0001$); the mean number of duplications >2 indicates that there are multiple CNVs on the same haplotype. Duplications of the *Cyp6aa1* orthologue have been found in another important

malaria vector, *An. funestus*, from west and central Africa (Ibrahim et al., 2018). The *Cyp6aa1* orthologue in *An. funestus*, which shares an 87% identity with *An. gambiae*, was also observed to metabolize permethrin and deltamethrin and, when expressed in transformed *Drosophila*, was associated with significant increases in resistance to both permethrin and deltamethrin relative to control mosquitoes (Ibrahim et al., 2018). This evolution of multiple *Cyp6aa1* duplications suggests this is an important Africa wide resistance mechanism.

There are now several cases of insecticide resistance evolution where an initial mutation in a genomic region is followed by the spread of additional mutations on the resistant haplotype background (Clarkson et al., 2021; Schmidt et al., 2010; Jones et al., 2012; Djogbenou et al., 2009; Grau-Bové et al., 2020). It is not yet clear whether the sequence of mutations that we have identified rely on each-other for effect, and thus could only have spread sequentially, or whether each additional mutation coincidentally appeared on the background of an already common mutant haplotype. In the case of *Cyp6p4-236M* and *Cyp6aap-Dup1* it seems that the latter is more likely, although we cannot exclude the possibility that the duplication affects the regulation of *Cyp6p4*. In contrast, the putative enhancer inserted with the ZZB transposon may affect either or both of *Cyp6p4* and *Cyp6aa1*, and may thus interact with the other two mutations in ways that have yet to be determined. Transposable elements can sometimes affect gene expression of neighbouring genes (Schmidt et al., 2010) and are abundant in mosquito genomes (Neafsey et al., 2015; Nene et al., 2007). Interestingly, in the common house mosquito, *Culex pipiens*, TEs have been found in the flanking regions of the *Ester* locus, a genomic region in which many independent gene duplications have arisen and spread worldwide in response to selection from organophosphates (Buss & Callaghan, 2004). Clearly, both TEs and gene duplications are an understudied, yet common source of variation that may have important implications for vector control efforts. The appearance and rapid spread of the three mutations described here is broadly coincident with the scale up of LLIN coverage in DRC, Kenya and Uganda (Bertozzi-Villa et al., 2021). The haplotype is a strong predictive marker of high-level resistance to pyrethroids and the *Cyp6aap-Dup1* mutation which is the key identifier of the triple mutant, is easily screened with a single diagnostic assay. We suggest that this assay should be used for both insecticide resistance monitoring strategies and for informing LLIN selection (The *Anopheles gambiae* 1000 genomes consortium, 2020; Wat'senga et al., 2020; Rugnao et al., 2019).

AUTHOR CONTRIBUTIONS

Harun Njoroge, Arjen van't Hof, Mark J. I. Paine, David Weetman and Martin J. Donnelly designed the study; Harun Njoroge, Arjen van't Hof, Ambrose Oruni, Dimitra Pipini, Sanjay C. Nagi, Amy Lynd conducted laboratory and insectary experiments; Harun Njoroge, Arjen van't Hof, Sanjay C. Nagi, Amy Lynd, Eric R. Lucas, Sean Tomlinson, Xavi Grau-Bové, Daniel McDermott, Martin J. Donnelly performed analysis; Ambrose Oruni, Amy Lynd, Francis T. Wat'senga, Emile Z. Manzambi, Fiacre R. Agossa, Seth Irish, Bilali Kabula, David Weetman, Charles Mbogo conducted field collections

and phenotyping; Harun Njoroge, Eric R. Lucas, David Weetman, Martin J. Donnelly wrote the manuscript with input from all authors; Joel Bargul, Charles Mbogo, Mark J. I. Paine, David Weetman and Martin J. Donnelly supervised the study; all authors approved the final version of the manuscript.

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DATA AVAILABILITY STATEMENT

Sequence read alignments and variant calls from Ag1000G have been made available from the European Nucleotide Archive under study accessions PRJEB18691 and PRJEB36277 (ENA <http://www.ebi.ac.uk/ena>). Python scripts to reproduce all analyses detailed in this manuscript are available at <https://github.com/xgrau/cyp6-AgUganda>

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REFERENCES

- Bertozzi-Villa, A., Bever, C. A., Koenker, H., Weiss, D. J., Vargas-Ruiz, C., Nandi, A. K., Gibson, H. S., Harris, J., Battle, K. E., Rumisha, S. F., Keddie, S., Amratia, P., Arambepola, R., Cameron, E., Chestnutt, E. G., Collins, E. L., Millar, J., Mishra, S., Rozier, J., & Bhatt, S. (2021). Maps and metrics of insecticide-treated net access, use, and net-per-capita in Africa from 2000–2020. *Nature Communications*, 12(1), e3589.
- Bhatt, S., Rigden, D. J., Dowd, A. J., Lu, F., Wilding, C. S., Weetman, D., Dadzie, S., Jenkins, A. M., Regna, K., Boko, P., Djogbenou, L., Muskavitch, M. A. T., Ranson, H., Paine, M. J. I., Mayans, O., & Donnelly, M. J. (2015). The effect of malaria control on *Plasmodium*

- falciparum* in Africa between 2000 and 2015. *Nature*, 526(7572), 207–211.
- Buss, D. S., & Callaghan, A. (2004). Molecular comparisons of the *Culex pipiens* (L.) complex esterase gene amplicons. *Insect Biochemistry and Molecular Biology*, 34(5), 433–441.
- Clarkson, C. S., Miles, A., Harding, N. J., O'Reilly, A. O., Weetman, D., Kwiatkowski, D., Donnelly, M. J., & the *Anopheles gambiae* 1000 genomes consortium (2021). The genetic architecture of target-site resistance to pyrethroid insecticides in the African malaria vectors *Anopheles gambiae* and *Anopheles coluzzii*. *Molecular Ecology*, 30, 5303–5317.
- Djogbenou, L., Labbe, P., Chandre, F., Pasteur, N., & Weill, M. (2009). Ace-I duplication in *Anopheles gambiae*: A challenge for malaria control. *Malaria Journal*, 8, e70.
- Dolan, C. B., Ben Yishay, A., Grepin, K. A., Tanner, J. C., Kimmel, A. D., Wheeler, D. C., & McCord, G. C. (2019). The impact of an insecticide treated bednet campaign on all-cause child mortality: A geospatial impact evaluation from the Democratic Republic of Congo. *PLoS One*, 14(2), e0212890.
- Donnelly, M. J., Isaacs, A., & Weetman, D. (2016). Identification, validation, and application of molecular diagnostics for insecticide resistance in malaria vectors. *Trends in Parasitology*, 32(3), 197–206.
- Edi, C. V., Djogbénu, L., Jenkins, A. M., Regna, K., Muskavitch, M. A. T., Poupardin, R., Jones, C. M., Essandoh, J., Kétoh, G. K., Paine, M. J. I., Koudou, B. G., Donnelly, M. J., Ranson, H., & Weetman, D. (2014). CYP6 P450 enzymes and ACE-1 duplication produce extreme and multiple insecticide resistance in the malaria mosquito *Anopheles gambiae*. *PLoS Genetics*, 10(3), e1004236.
- Garud, N. R., Messer, P. W., Buzbas, E. O., & Petrov, D. A. (2015). Recent selective sweeps in north American *Drosophila melanogaster* show signatures of soft sweeps. *PLoS Genetics*, 11(2), e1005004.
- Grau-Bové, X., Tomlinson, S., O'Reilly, A. O., Harding, N. J., Miles, A., Kwiatkowski, D., Donnelly, M. J., Weetman, D., & the *Anopheles gambiae* 1000 genomes consortium (2020). Evolution of the insecticide target Rdl in African anopheles is driven by interspecific and interkaryotypic introgression. *Molecular Biology and Evolution*, 37(10), 2900–2917.
- Hancock, P. A., Hendriks, C. J. M., Tangena, J.-A., Gibson, H., Hemingway, J., Coleman, M., Gething, P. W., Cameron, E., Bhatt, S., & Moyes, C. L. (2020). Mapping trends in insecticide resistance phenotypes in African malaria vectors. *PLoS Biology*, 18(6), e3000633.
- Ibrahim, S. S., Amvongo-Adjia, N., Wondji, M. J., Irving, H., Riveron, J. M., & Wondji, C. S. (2018). Pyrethroid resistance in the major malaria vector *Anopheles funestus* is exacerbated by overexpression and overactivity of the P450 CYP6AA1 across Africa. *Genes*, 9(3), e140.
- Jones, C., Liyanapathirana, M., Agossa, F. R., Weetman, D., Ranson, H., Donnelly, M. J., & Wilding, C. S. (2012). Footprints of positive selection associated with a novel mutation (N1575Y) in the voltage gated sodium channel of *Anopheles gambiae*. *Proceedings of the National Academy of Sciences of the United States of America*, 109, 6614–6619.
- Killeen, G. F., & Ranson, H. (2018). Insecticide-resistant malaria vectors must be tackled. *Lancet*, 391(10130), 1551–1552.
- Kleinschmidt, I., Bradley, J., Knox, T. B., Mnzava, A. P., Kafy, H. T., Mbogo, C., Ismail, B. A., Bigoga, J. D., Adechoubou, A., Raghavendra, K., Cook, J., Malik, E. M., Nkuni, Z. J., Macdonald, M., Bayoh, N., Ochomo, E., Fondjo, E., Awono-Ambene, H. P., Etang, J., ... Donnelly, M. J. (2018). Implications of insecticide resistance for malaria vector control with long-lasting insecticidal nets: A WHO-coordinated, prospective, international, observational cohort study. *Lancet Infectious Diseases*, 18(6), 640–649.
- Kwiatkowska, R. M., Platt, N., Poupardin, R., Irving, H., Dabire, R. K., Mitchell, S., Jones, C. M., Diabaté, A., Ranson, H., & Wondji, C. S. (2013). Dissecting the mechanisms responsible for the multiple insecticide resistance phenotype in *Anopheles gambiae* s.s., M form, from Vallee du Kou, Burkina Faso. *Gene*, 519(1), 98–106.
- Liu, B., Fang, L., Long, R., Lan, X., & Chou, K.-C. (2015). iEnhancer-2L: A two-layer predictor for identifying enhancers and their strength by pseudo k-tuple nucleotide composition. *Bioinformatics*, 32(3), 362–369.
- Liu, B., Li, K., Huang, D.-S., & Chou, K.-C. (2018). iEnhancer-EL: Identifying enhancers and their strength with ensemble learning approach. *Bioinformatics*, 34(22), 3835–3842.
- Love, R. R., Redmond, S. N., Pombi, M., Caputo, B., Petrarca, V., & Della Torre, A., *Anopheles gambiae* 1000 genomes consortium & Besansky, N. J. (2019). In silico karyotyping of chromosomally polymorphic malaria mosquitoes in the *Anopheles gambiae* complex. *G3 (Bethesda)*, 9(10), 3249–3262.
- Lucas, E., Miles, A., Harding, N. J., Clarkson, C. S., Lawniczak, M. K. N., Kwiatkowski, D. P., Weetman, D., Donnelly, M. J., & *Anopheles gambiae* 1000 genomes consortium (2019). Whole genome sequencing reveals high complexity of copy number variation at insecticide resistance loci in malaria mosquitoes. *Genome Research*, 29, 1250–1261.
- Lynd, A., Gonahasa, S., Staedke, S. G., Oruni, A., Maiteki-Sebuguzi, C., Dorsey, G., Opigo, J., Yeka, A., Katureebe, A., Kyohere, M., Hemingway, J., Kamya, M. R., & Donnelly, M. J. (2019). LLIN evaluation in Uganda project (LLINEUP) – a cross-sectional survey of species diversity and insecticide resistance in 48 districts of Uganda. *Parasites and Vectors*, 12, e94.
- Lynd, A., Weetman, D., Barbosa, S., Yawson, A. E., Mitchell, S., Pinto, J., Hastings, I., & Donnelly, M. J. (2010). Field, Genetic and modelling approaches show strong positive selection acting upon an insecticide resistance mutation in *Anopheles gambiae* s.s. *Molecular Biology and Evolution*, 27, 1117–1125.
- Lynd, A., Oruni, A., van't Hof, A. E., Morgan, J. C., Naego, L. B., Pipini, D., O'Kines, K. A., Bobanga, T. L., Donnelly, M. J., & Weetman, D. (2018). Insecticide resistance in *Anopheles gambiae* from the northern Democratic Republic of Congo, with extreme knockdown resistance (kdr) mutation frequencies revealed by a new diagnostic assay. *Malaria Journal*, 17, e412.
- Miles, A., Ralph, P., Rae, S., & Pisupati, R. (2019). Cggh/scikit-allele. *Zenodo*. Ministry of Health, Republic of Kenya. (2019). *Insecticide Resistance Management Plan, Kenya 2020–2024*. Ministry of Health, Republic of Kenya.
- Mitchell, S., Stevenson, B. J., Müller, P., Wilding, C. S., Egyir-Yawson, A., Field, S. G., Hemingway, J., Paine, M. J. I., Ranson, H., & Donnelly, M. J. (2012). Identification and validation of a gene causing cross-resistance between insecticide classes in *Anopheles gambiae* from Ghana. *Proceedings of the National Academy of Sciences of the United States of America*, 109, 6147–6152.
- Mitchell, S. N., Rigden, D. J., Dowd, A. J., Lu, F., Wilding, C. S., Weetman, D., Dadzie, S., Jenkins, A. M., Regna, K., Boko, P., Djogbenou, L., Muskavitch, M. A. T., Ranson, H., Paine, M. J. I., Mayans, O., & Donnelly, M. J. (2014). Metabolic and target-site mechanisms combine to confer strong DDT resistance in *Anopheles gambiae*. *PLoS One*, 9, e92662.
- Mugenzi, L. M. J., Menze, B. D., Tchouakui, M., Wondji, M. J., Irving, H., Tchoupo, M., Hearn, J., Weedall, G. D., Riveron, J. M., & Wondji, C. S. (2019). Cis-regulatory CYP6P9b P450 variants associated with loss of insecticide-treated bed net efficacy against *Anopheles funestus*. *Nature Communications*, 10, e4652.
- Müller, P., Warr, E., Stevenson, B. J., Pignatelli, P. M., Morgan, J. C., Steven, A., Yawson, A. E., Mitchell, S. N., Ranson, H., Hemingway, J., Paine, M. J. I., & Donnelly, M. J. (2008). Field-caught permethrin-resistant *Anopheles gambiae* overexpress CYP6P3, a P450 that metabolises pyrethroids. *PLoS Genetics*, 4(11), e1000286.
- Neafsey, D. E., Waterhouse, R. M., Abaim, M. R., Aganezov, S. S., Alekseyev, M. A., Allen, J. E., Amon, J., Arcà, B., Arensburger, P., Artemov, G., Assour, L. A., Basseri, H., Berlin, A., Birren, B. W.,

- Blandin, S. A., Brockman, A. I., Burkot, T. R., Burt, A., ... Besansky, N. J. (2015). Highly evolvable malaria vectors: The genomes of 16 anopheles mosquitoes. *Science*, 347(6217), e1258522.
- Nene, V., Wortman, J. R., Lawson, D., Haas, B., Kodira, C., Tu, Z. J., Loftus, B., Xi, Z., Megy, K., Grabherr, M., Ren, Q., Zdobnov, E. M., Lobo, N. F., Campbell, K. S., Brown, S. E., Bonaldo, M. F., Zhu, J., Sinkins, S. P., Hogenkamp, D. G., ... Severson, D. W. (2007). Genome sequence of *Aedes aegypti*, a major arbovirus vector. *Science*, 316(5832), 1718-1723.
- Newcombe, R. G. (1998). Two-sided confidence intervals for the single proportion: Comparison of seven methods. *Statistics in Medicine*, 17, 857-872.
- Protopopoff, N., Mosha, J. F., Lukole, E., Charlwood, J. D., Wright, A., Mwalimu, C. D., Manjurano, A., Mosha, F. W., Kisinza, W., Kleinschmidt, I., & Rowland, M. (2018). Effectiveness of a long-lasting piperonyl butoxide-treated insecticidal net and indoor residual spray interventions, separately and together, against malaria transmitted by pyrethroid-resistant mosquitoes: A cluster, randomised controlled, two-by-two factorial design trial. *Lancet*, 391(10130), 1577-1588.
- Ranson, H., & Lissenden, N. (2016). Insecticide resistance in African anopheles mosquitoes: A worsening situation that needs urgent action to maintain malaria control. *Trends in Parasitology*, 32(3), 187-196.
- Rugnao, S., Gonahasa, S., Maiteki-Sebuguzi, C., Opigo, J., Yeka, Y., Katureebe, A., Kyohere, M., Lynd, A., Hemingway, J., Donnelly, M. J., Dorsey, G., Kamya, M. R., & Staedke, S. G. (2019). LLIN evaluation in Uganda project (LLINEUP): Factors associated with childhood parasitaemia and anaemia 3 years after a national long-lasting insecticidal net distribution campaign: A cross-sectional survey. *Malaria Journal*, 18, e207.
- Ruiz, J. L., Ranford-Cartwright, L. C., & Gómez-Díaz, E. (2021). The regulatory genome of the malaria vector *Anopheles gambiae*: Integrating chromatin accessibility and gene expression. *NAR Genomics and Bioinformatics*, 3(1), lqaa113.
- Schmidt, J. M., Good, R. T., Appleton, B., Sherrard, J., Raymant, G. C., Bogwitz, M. R., Martin, J., Daborn, P. J., Goddard, M. E., Batterham, P., & Robin, C. (2010). Copy number variation and transposable elements feature in recent, ongoing adaptation at the Cyp6g1 locus. *PLoS Genetics*, 6(6), e1000998.
- Staedke, S. G., Gonahasa, S., Dorsey, G., Kamya, M. R., Maiteki-Sebuguzi, C., Lynd, A., Katureebe, A., Kyohere, M., Mutungi, P., Kigozi, S. P., Opigo, J., Hemingway, J., & Donnelly, M. J. (2020). Effect of long-lasting insecticidal nets with and without piperonyl butoxide on malaria indicators in Uganda (LLINEUP): A pragmatic, cluster-randomised trial embedded in a national LLIN distribution campaign. *Lancet*, 395, 1292-1303.
- The *Anopheles gambiae* 1000 genomes consortium. (2017). Natural diversity of the malaria vector *Anopheles gambiae*. *Nature (London)*, 552, 96-100.
- The *Anopheles gambiae* 1000 genomes consortium. (2020). Genome variation and population structure among 1142 mosquitoes of the African malaria vector species *Anopheles gambiae* and *Anopheles coluzzii*. *Genome Research*, 30(10), 1533-1546.
- Vontas, J., Grigoraki, L., Morgan, J., Tsakireli, D., Fouseini, G., Segura, L., Niemczura de Carvalho, J., Nguema, R., Weetman, D., Slotman, M. A., & Hemingway, J. (2018). Rapid selection of a pyrethroid metabolic enzyme CYP9K1 by operational malaria control activities. *Proceedings of the National Academy of Sciences of the United States of America*, 115(18), 4619-4624.
- Wat'senga, F., Agossa, F., Manzambi, E. Z., Illombe, G., Mapangulu, T., Muyembe, T., Clark, T., Niang, M., Ntoya, F., Sadou, A., Plucinski, M., Li, Y., Messenger, L. A., Fornadel, C., Oxborough, R. M., & Irish, S. R. (2020). Intensity of pyrethroid resistance in *Anopheles gambiae* before and after a mass distribution of insecticide-treated nets in Kinshasa and in 11 provinces of the Democratic Republic of Congo. *Malaria Journal*, 19(1), e169.
- Weedall, G. D., Mugenzi, L. M. J., Menze, B. D., Tchouakui, M., Ibrahim, S. S., Amvongo-Adjia, N., Irving, H., Wondji, M. J., Tchoupo, M., Djouaka, R., Riveron, J. M., & Wondji, C. S. (2019). A cytochrome P450 allele confers pyrethroid resistance on a major African malaria vector, reducing insecticide-treated bednet efficacy. *Science Translational Medicine*, 11(484), eaat7386.
- Weetman, D., & Donnelly, M. J. (2015). Evolution of insecticide resistance diagnostics in malaria vectors. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, 109(5), 291-293.
- Weetman, D., Wilding, C. S., Neafsey, D. E., Muller, P., Ochomo, E., Isaacs, A. T., Steen, K., Rippon, E. J., Morgan, J. C., Mawejee, H. D., Rigden, D. J., Okedi, L. M., & Donnelly, M. J. (2018). Candidate-gene based GWAS identifies reproducible DNA markers for metabolic pyrethroid resistance from standing genetic variation in east African *Anopheles gambiae*. *Scientific Reports*, 8, e2920.
- WHO. (2016). *Test procedures for insecticide resistance monitoring in malaria vector mosquitoes (Second edition)* (p. 56). World Health Organization.
- WHO. (2019). *World malaria report 2019* (p. 232). World Health Organization.
- Yeka, A., Gasasira, A., Mpimbaza, A., Achanb, J., Nankabirwa, J., Nsoby, S., Staedke, S. G., Donnelly, M. J., Wabwire-Mangen, F., Talisuna, A., Dorsey, G., Kamya, M. R., & Rosenthal, P. J. (2012). Malaria in Uganda: Challenges to control on the long road to elimination I. Epidemiology and current control efforts. *Acta Tropica*, 121(3), 184-195.
- Yunta, C., Hemmings, K., Stevenson, B., Koekemoer, L. L., Matambo, T., Pignatelli, P., Voice, M., Nász, S., & Paine, M. J. I. (2019). Cross-resistance profiles of malaria mosquito P450s associated with pyrethroid resistance against WHO insecticides. *Pesticide Biochemistry and Physiology*, 161, 61-67.
- Zhou, D., Liu, X., Sun, Y., Ma, L., Shen, B., & Zhu, C. (2015). Genomic analysis of detoxification supergene families in the mosquito *Anopheles sinensis*. *PLoS One*, 10(11), e0143387.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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