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2 Resistance to pirimiphos-methyl in West African 4 *Anopheles* is spreading via duplication and introgression of the *Ace1* locus

Xavier Grau-Bové^{1*}, Eric Lucas¹, Dimitra Pipini¹, Emily Rippon¹, Arjèn van't Hof¹, Edi Constant², Samuel
6 Dadzie³, Alexander Egyir-Yawson⁴, John Essandoh^{1,4}, Joseph Chabi³, Luc Djogbénou^{1,5}, Nicholas J. Harding⁶,
Alistair Miles^{6,7}, Dominic Kwiatkowski^{6,7}, Martin J. Donnelly^{1,7}, David Weetman^{1*}, The *Anopheles gambiae* 1000
8 Genomes Consortium⁸

1. Department of Vector Biology, Liverpool School of Tropical Medicine, Liverpool, United Kingdom

10 2. Centre Suisse de Recherches Scientifiques en Côte d'Ivoire, Abidjan, Côte d'Ivoire

3. Department of Parasitology, Noguchi Memorial Institute for Medical Research, University of Ghana, Accra,
12 Ghana

4. Department of Biomedical Sciences, University of Cape Coast, Cape Coast, Ghana

14 5. Institut Régional de Santé Publique, Université d'Abomey-Calavi, Benin

6. Big Data Institute, Li Ka Shing Centre for Health Information and Discovery, University of Oxford, Oxford,
16 United Kingdom

7. Wellcome Sanger Institute, Hinxton, United Kingdom

18 8. www.malariagen.net/projects/ag1000g

* Corresponding authors: XGB (xavier.graubove@gmail.com), DW (david.weetman@lstmed.ac.uk)

20 Abstract

22 Vector population control using insecticides is a key element of current strategies to prevent malaria
transmission in Africa. The introduction of effective insecticides, such as the organophosphate
24 pirimiphos-methyl, is essential to overcome the recurrent emergence of resistance driven by the highly
diverse *Anopheles* genomes. Here, we use a population genomic approach to investigate the basis of
26 pirimiphos-methyl resistance in the major malaria vectors *Anopheles gambiae* and *A. coluzzii*. A combination
of copy number variation and a single non-synonymous substitution in the acetylcholinesterase gene,
28 *Ace1*, provides the key resistance diagnostic in an *A. coluzzii* population from Côte d'Ivoire that we used for
sequence-based association mapping, with replication in other West African populations. The *Ace1* and
substitution and duplications occur on a unique resistance haplotype that evolved in *A. gambiae* and
30 introgressed into *A. coluzzii*, and is now common in West Africa probably due to cross-resistance with
previously used insecticides. Our findings highlight the phenotypic value of this complex resistance
32 haplotype and clarify its evolutionary history, providing tools to understand the current and future
effectiveness of pirimiphos-methyl based interventions.

34 Introduction

Pirimiphos-methyl is an organophosphate insecticide that is widely used in control interventions
36 against populations of the malaria vector *Anopheles*, especially in Africa (Oxborough 2016; Dengela et al.
2018). Since 2013, the World Health Organization (WHO) has recommended the use of pirimiphos-methyl
38 for indoor residual spraying (IRS) interventions, the major anti-vector strategy in malaria control after
treated bednet distribution (Oxborough 2016; World Health Organization 2013). Strategic approaches to
40 vector control often rely on the use of multiple insecticides to avoid or overcome the recurrent emergence
of resistance in natural populations (World Health Organization 2018a). In that regard, various insecticide
42 classes have been used in IRS, with pyrethroids—which target the voltage-gated sodium channel—being
the dominant choice until recently (Sherrard-Smith et al. 2018; van den Berg et al. 2012). However, the
44 increase in pyrethroid resistance in *Anopheles* populations (Ranson et al. 2011) has led to a progressive
replacement with acetylcholinesterase-targeting insecticide classes, first the carbamate bendiocarb, and,
46 latterly, the organophosphate pirimiphos-methyl (Oxborough 2016). Pirimiphos-methyl is the active
ingredient in the most widely used insecticide for IRS in Africa, the spray formulation Actellic, which is
48 highly effective and has strong residual performance (Dengela et al. 2018; Sherrard-Smith et al. 2018;
Wagman et al. 2018; Abong'o et al. 2020). However, resistance has recently been reported in several
50 populations of African *Anopheles* s.l. (Kisinja et al. 2017; Chukwuekezie et al. 2020), and though control
failures have yet to be reported, it represents a clear threat to the efficacy of IRS strategies.

52 Mechanisms of resistance to pirimiphos-methyl are poorly understood, but organophosphates, as well
as carbamates, all block the action of the acetylcholinesterase enzyme (ACE1, encoded by the *Ace1* gene in
54 mosquitoes) via competitive binding to its active site (Oakeshott et al. 2005). Studies in culicine and
anopheline mosquitoes have found that non-synonymous mutations in *Ace1* can result in resistance to
56 carbamates and organophosphates other than pirimiphos-methyl (Weill et al. 2003, 2004; Feyereisen et al.
2015). The most common mutation in *Anopheles* is a glycine to serine mutation in codon 280 (G280S, also
58 known as G119S after the codon numbering of a partial crystal structure from the electric ray *Torpedo*
californica (Weill et al. 2003; Greenblatt et al. 2004; Feyereisen et al. 2015)), which is located near the active
60 site gorge of ACE1 (Cheung et al. 2018) and decreases its sensitivity to organophosphates and carbamates.

This mutation results in reduced sensitivity to the acetylcholine neurotransmitter (Bourguet et al. 1997),
62 thus carrying potential fitness costs, as demonstrated in *Culex pipiens* (Labbé et al. 2007). The resistance
allele 280S has been regularly found in natural *Anopheles* populations: *A. gambiae* s.s. (henceforth, *A. gambiae*)
64 and *A. coluzzii* from West Africa, ranging from Benin to Côte d'Ivoire (Weill et al. 2003; Dabiré et al. 2009;
Ahoua Alou et al. 2010; Essandoh et al. 2013; Weetman et al. 2015); as well as in *A. albimanus* (Liebman et al.
66 2015), *A. arabiensis* (Dabiré et al. 2014), and *A. sinensis* (Feng et al. 2015). In addition, *Ace1* is subject to
duplication polymorphisms (copy number variants, or CNVs) that co-segregate with the 280S allele in both
68 *A. gambiae* and *A. coluzzii*, and enhance resistance to carbamates and organophosphates such as
fenitrothion and chlorpyrifos-methyl (Djogbénou et al. 2008; Essandoh et al. 2013; Edi et al. 2014a;
70 Weetman et al. 2015; Assogba et al. 2015, 2016, 2018).

In this study we provide an in-depth investigation of the relationship between *Ace1* mutations and
72 pirimiphos methyl resistance in *A. gambiae* and *A. coluzzii* using whole-genome sequenced samples from the
Anopheles gambiae 1000 Genomes project (The *Anopheles gambiae* 1000 Genomes Consortium 2019; Miles et
74 al. 2017), and a wider testing of phenotyped specimens from across West Africa. In addition, we perform a
first agnostic genome-wide scan for candidate regions contributing to pirimiphos-methyl resistance in a
76 population of *A. coluzzii* from Côte d'Ivoire. Finally, we study the contemporary evolution of *Ace1* to answer
unresolved questions on the selective pressures and the pattern of inter-specific introgression associated
78 with the spread of this resistance mechanism. Earlier studies provided support for the idea that a common
resistance haplotype under positive selection might have introgressed between species (Djogbénou et al.
80 2008; Essandoh et al. 2013; Weetman et al. 2015), but they focused on a partial region of the *Ace1* gene and
did not address the relationship between introgression and the duplication, which extends beyond the
82 gene (Assogba et al. 2016; Lucas et al. 2019). Here we leverage population genomic resources from the
Anopheles gambiae 1000 Genomes to overcome these limitations. Overall, our results demonstrate a
84 widespread and dominant role for *Ace1* mutations in pirimiphos-methyl resistance, provide critical
insights into resistance diagnosis, and demonstrate that 280S alleles and *Ace1* duplications co-occur on a
86 single, swept, resistance haplotype that originated in West African *A. gambiae* and later introgressed into *A.*
coluzzii.

88 Results

Conservation and distribution of *Ace1* resistance mutations in *Anopheles*

90 We examined the frequency and distribution of the two *Ace1* mutations that have been associated with
organophosphate and carbamate resistance in *A. gambiae* and *A. coluzzii*: the *G280S* non-synonymous single
92 nucleotide polymorphism (SNP), and copy number variation (CNV) polymorphisms of *Ace1* and the
surrounding genomic region. *G280S* is sometimes known as *G119S* (Feyereisen et al. 2015) based on its
94 position in the truncated crystal structure of its homolog in the electric ray *Torpedo californica*, where ACE1
protein structure was first elucidated (Greenblatt et al. 2004). Due to a culicine-specific N-terminal
96 insertion in ACE1, the exact position of this conserved codon differs among animal orthologs
(Supplementary Material SM1). We provide a list of homologous codon positions for *Ace1* orthologs from
98 selected animal species, including common insect vectors (Supplementary Material SM2). Henceforth, we
will use *A. gambiae* s.l.-based codon coordinates and refer to this SNP as *G280S* (wild-type allele: 280G;
100 resistance allele: 280S; gene accession number: AGAP001356-RA in AgamP4.12).

In the *Anopheles* 1000 Genomes cohort (Phase 2, $n = 1142$ genomes; Figure 1) (The *Anopheles gambiae* 1000
102 Genomes Consortium 2019), the 280S resistance allele is present across West African populations of *A.*
coluzzii (Côte d'Ivoire, Burkina Faso, Ghana) and *A. gambiae* (Burkina Faso, Ghana, Guinea), with the highest
104 frequencies being attained in Ghanaian *A. gambiae* (67%) and Ivorian *A. coluzzii* (44%; Figure 1A), which is
consistent with previous results (Djogbénou et al. 2008; Dabiré et al. 2009; Ahoua Alou et al. 2010; Essandoh
106 et al. 2013). *Ace1* CNVs have a similar distribution to the SNP in West African populations, as they
overwhelmingly overlap with specimens also carrying 280S alleles (Figure 1B).

108 The combination of CNVs and 280S alleles results in multiple genotypes being observed in the *Ace1*
locus, defined by a variable number of 280S copies. We used the fraction of sequencing reads supporting
110 the *wt* and 280S alleles to estimate the number of 280S alleles in each sample (Figure 2A and 2B), which
revealed that most specimens with duplications carry both *wt* and 280S alleles at various frequencies ($n =$
112 113, orange box in Figure 2A), whereas the vast majority of non-duplicated specimens only have *wt* alleles
($n = 1021$, purple box in Figure 2A). In addition, we identify six high-copy, 280S homozygous specimens,
114 present only in the Ghanaian *A. gambiae* population in this dataset (Figure 1B).

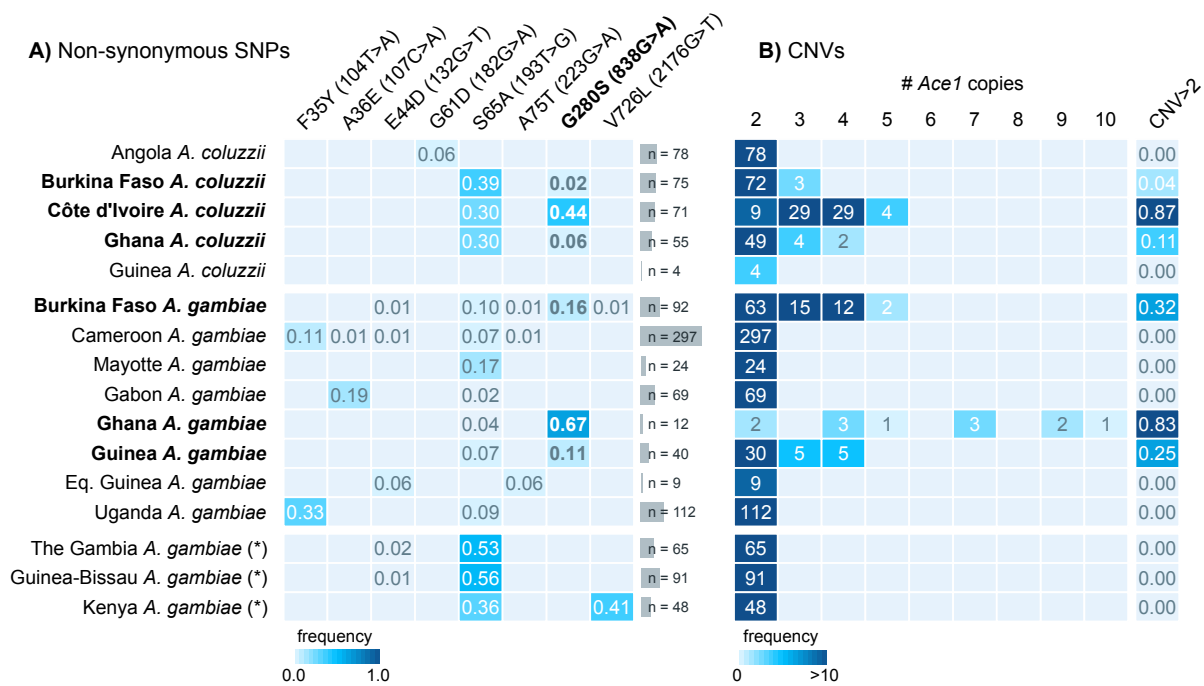


Figure 1. *Ace1* mutations in African populations. A) Frequency of non-synonymous SNPs in the *Ace1* gene in African *A. gambiae* and *A. coluzzii* populations from *Anopheles gambiae* 1000 Genomes, Phase 2. For each SNP, we indicate peptide- and transcript-level coordinates and substitutions. **B)** *Ace1* CNVs across African populations, including the frequency of specimens with >2 copies in each population. A diploid genome without duplications would have 2 copies. Populations where *G280S* and duplications are present are highlighted in bold text. Note: populations denoted with an asterisk (The Gambia, Guinea-Bissau and Kenya) have high frequency of hybridisation and/or unclear species identification.

Virtually all *Ace1* CNVs identified in the 1000 Genomes cohort share the same duplication breakpoints
 116 (Lucas et al. 2019), spanning a region ca. 200 kbp that includes a total of 11 genes (Supplementary Material
 SM5). The only exception is a single *A. gambiae* specimen from Guinea that carries a unique *wt*-homozygous
 118 duplication (asterisk in Figure 2B). This Guinea-specific CNV is shorter than the *Ace1* duplication found in
 all other samples and has different breakpoints (ca. 70 kbp, including *Ace1* and one other gene;
 120 Supplementary Material SM4), implying an independent origin. Henceforth, all mentions of *Ace1* CNVs will
 refer to the major duplication. The absence of specimens carrying the major duplication and lacking *280S*
 122 alleles strongly implies that this CNV contains both *280S* and *wt* alleles on the same chromosome, and thus
 results in permanent heterozygosity. Figure 2C summarises the four model haplotypes that can result in
 124 the genotypes observed in the 1000 Genomes dataset: (i) non-duplicated *wt*; (ii) heterozygous and (iii) *280S*-
 homozygous major duplications; and (iv) the *wt* minor duplication from Guinea.

126 In addition to *G280S*, we found seven non-synonymous SNPs in *Ace1* with at least 1% frequency in at
 least one population (Figure 1A). None were in linkage disequilibrium with *G280S* (Supplementary Material

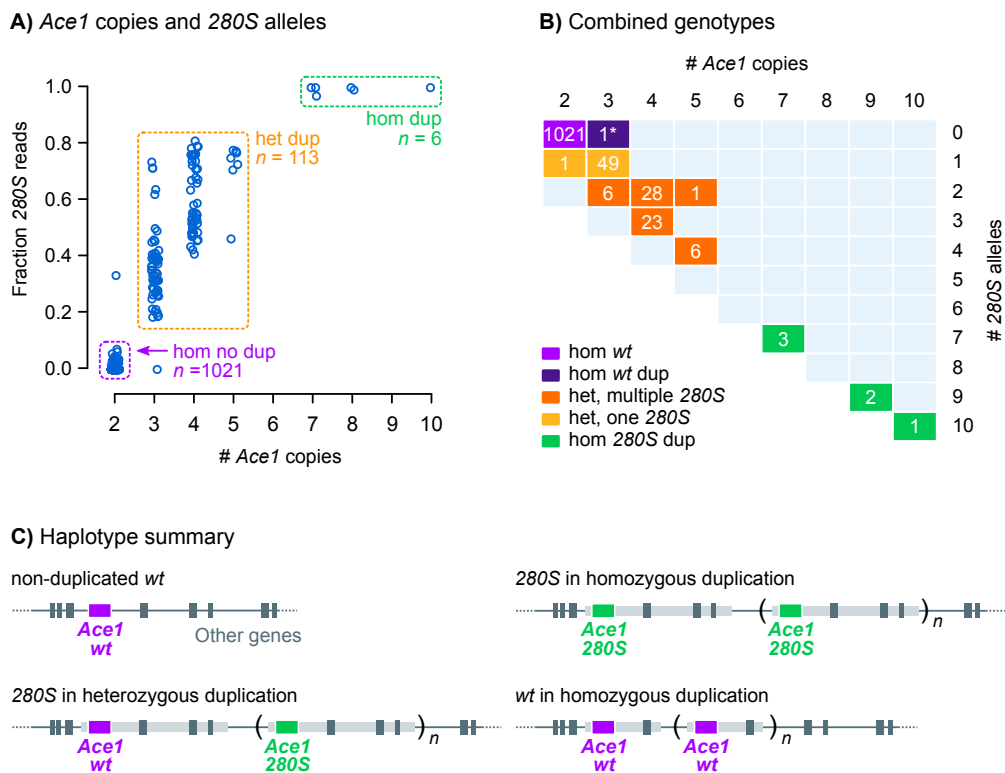


Figure 2. Combinations of *Ace1* G280S and CNV genotypes. **A)** Fraction of reads supporting 280S alleles and number of *Ace1* copies (1000 Genomes dataset, $n = 1142$). Boxes highlight groups of haplotypes: non-duplicated wt homozygotes (purple), duplicated heterozygotes (orange) and duplicated 280S homozygotes (green). **B)** Breakdown of possible genotypes at the *Ace1* locus according to *Ace1* and 280S copy number. The asterisk (*) denotes a wt-homozygous specimen from Guinea that carries an independently evolved *Ace1* duplication. **C)** Summary of haplotypes observed in the *Ace1* locus.

128 SM3), nor have any of them been previously associated with resistance (Feyereisen et al. 2015). The most
 130 salient of these additional mutations was a serine-to-alanine SNP in codon 65 (*S65A*), with frequencies of
 132 30-50% in multiple West African populations. Codon 65 maps to the anopheline-specific N-terminal
 134 insertion of ACE1 proteins (Supplementary Material SM1), which lacks predicted secondary structure and
 is far away from the active-site gorge of the enzyme (Cheung et al. 2018). This position is not conserved
 across ACE1 orthologs, being variously encoded as alanine, serine or threonine in different *Anopheles*
 species (Supplementary Material SM1).

136 Pirimiphos-methyl resistance in Ivorian *A. coluzzii* is linked to *Ace1* duplications and multiple 280S alleles

Next, we examined the association between *Ace1* mutations and resistance to pirimiphos-methyl
 138 (Figure 3). We used 71 *A. coluzzii* female mosquitoes from Côte d'Ivoire, collected from rice fields in Tiassalé

in 2012, that had been tested for resistance prior to genome sequencing. The *G280S* SNP and CNV co-occur
 140 at high frequencies in this population, with 87.3% of specimens being duplicated heterozygotes with a one
 or more *280S* alleles (Figure 3A). Specimens with at least one *280S* allele had a survival rate of 50%, as
 142 opposed to 0% in the *wt* homozygotes (Figure 3B), suggesting that *280S* is linked to pirimiphos-methyl
 resistance in this population ($p = 3.7 \times 10^{-3}$ in Fisher's exact test, Woolf-corrected odds ratio = 19.0 [95%
 144 confidence interval = 1.1 – 340.6]) but it does not fully explain the resistance phenotype. The only other
 non-synonymous SNP present in Ivorian *A. coluzzii*, *S65A*, was not associated with pirimiphos-methyl
 146 resistance ($p = 0.605$ Fisher's exact test; Supplementary Material SM6A, SM6B).

We found a strong bias towards higher *Ace1* copy numbers in resistant specimens, all of which had at
 148 least 3 copies of the *Ace1* locus and most of them had 4 or more (Figure 3B; odds ratio from a binomial
 generalised linear model [GLM] = 16.9 [5.1 – 56.6]; $p = 6.4 \times 10^{-10}$ in a χ^2 test compared to a null model).
 150 Concordantly, the estimated number of *280S* alleles was also associated with resistance (GLM odds ratio =
 10.7 [3.6 – 31.7]; $p = 8.9 \times 10^{-10}$ in χ^2 test): survival rates increased with higher number of *280S* copies (Figure
 152 3B), with a threshold apparent between individuals with zero or one copies of *280S* (11.1% survival) and
 those with two or more (77% survival). Crucially, within the group of duplicated specimens with one *280S*

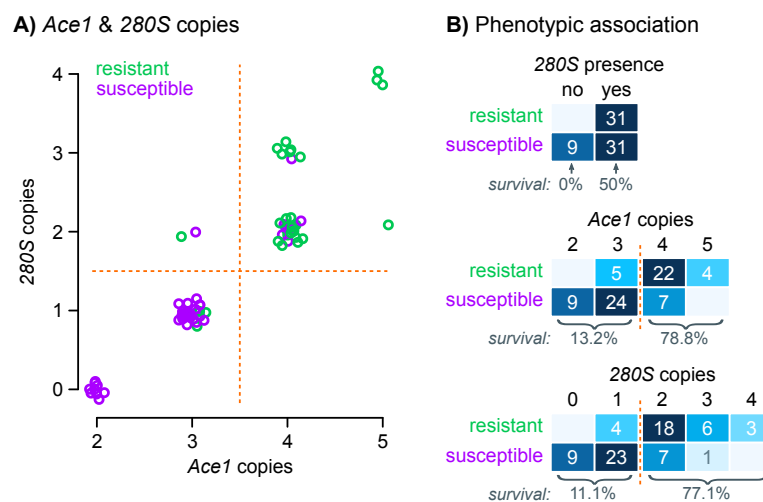


Figure 3. Genotype-phenotype association in Ivorian *A. coluzzii*. **A)** Number of *Ace1* copies compared to the estimated number of *280S* copies in Ivorian *A. coluzzii* (n=71), color-coded according to resistance phenotypes. Random jitter has been added for clarity. **B)** Cross-tabulation of pirimiphos-methyl resistance and three *Ace1* mutations in Ivorian *A. coluzzii*: *280S* allele presence, number of *Ace1* copies, and number of *280S* alleles. Orange lines denote *ad hoc* groups of genotypes where we identify changes in survival rates (included at the bottom of each table). Source data available in Supplementary Material SM6.

154 and two *wt* alleles ($n = 36$), *280S* provided no survival benefit compared to non-duplicated *wt* specimens
(Fisher's exact test $p = 0.553$; Woolf-corrected odds ratio = 3.6 [0.2 – 74.3]).

156 We also examined the combined effects of all the mutations detected in the *Ace1* locus (*280S* and *S65A*
presence, CNVs and number of *280S* alleles) in Ivorian *A. coluzzii*. We used a binomial GLM and a step-wise
158 procedure to remove non-informative variants according to the Bayesian Information Criterion (see
Methods), finding that the number of *Ace1* copies was the minimal sufficient marker to predict pirimiphos-
160 methyl resistance in this population (odds ratio = 16.9 [5.1 – 56.9]; $p = 6.43 \times 10^{-10}$ in a χ^2 test; details in
Supplementary Material SM6B).

162 **Pirimiphos-methyl resistance diagnostics are repeatable across *A. gambiae* and *A. coluzzii* populations**

164 We investigated the extent to which the role of *Ace1* and *280S* copy numbers in pirimiphos-methyl
resistance could be generalised to other populations beyond the *A. coluzzii* from Tiassalé. Specifically, we
166 surveyed *Ace1* mutations and phenotypic resistance in eight West African populations of *A. gambiae* and *A.*
coluzzii from additional locations in Côte d'Ivoire, Togo, and Ghana (Table 1 and Table 2; list of specimens
168 in Supplementary Material SM6C and SM6D).

Pirimiphos-methyl resistance was associated with *G280S* mutations in seven out of eight populations (p
170 < 0.01 in a χ^2 test comparing GLM of each genotype to a null model; Table 1). However, whilst *280S*
homozygotes were strongly associated with resistance in populations where they were present in
172 significant numbers (e.g. 95.8% survival rate in *A. coluzzii* from Korle-Bu), heterozygotes often exhibited
lower, intermediate survival rates (e.g. 49.6% in *A. coluzzii* from Korle-Bu; six out of eight populations had
174 survival rates $< 60\%$; Table 1) similar to that of the *A. coluzzii* population from Tiassalé (Côte d'Ivoire)
mentioned above (Figure 3A).

176 Following our findings for the Tiassalé population (Figure 3), we further investigated the phenotypic
variation in duplicated heterozygotes using two CNV-related variables: (i) the ratio of *280S* to *280G* alleles
178 (measured as the ratio of FAM-to-HEX dye signal in a TaqMan qPCR assay) (Bass et al. 2010); and (ii) the
estimated number of *Ace1* copies relative to a non-duplicated and *wt* Kisumu *A. gambiae* colony (Edi et al.
180 2014a) (see Methods).

Table 1. Association of resistance genotypes with pirimiphos-methyl resistance in nine West African populations of *A. coluzzii* and *A. gambiae*. For each population, we report number of sampled specimens (*n*), the number of *wt* homozygous (*wt*), heterozygous (*het*) and *280S* homozygous specimens (*hom*), survival frequency among mutated groups, and the odds ratios of survival in heterozygous and *280S* homozygous specimens (if available) in a binomial generalised linear model, and the *p*-value of this model in a χ^2 ANOVA comparison with a null model. Odds ratios (OR) are reported with 95% confidence intervals. Dagger signs (†) denote survival rates in genotypes with less than 5 specimens. Samples listed in Supplementary Material SM6C; statistical analysis in Supplementary Material SM6D. Country abbreviations: CI, Côte d’Ivoire; GH, Ghana; TG, Togo.

Population	<i>n</i>	Frequencies <i>wt</i> / <i>het</i> / <i>hom</i>	% survival <i>het</i>	OR <i>het</i>	% survival <i>hom</i>	OR <i>hom</i>	<i>p</i>
<i>coluzzii</i> Aboisso (CI)	55	42 / 13 / 0	46.1%	35.1 (3.6 – 338.0)	-	-	1.3×10^{-4}
<i>coluzzii</i> Korle-Bu (GH)	214	25 / 165 / 24	49.6%	4.2×10^7 (0 – Inf)	95.8%	9.8×10^8 (0 – Inf)	1.2×10^{-13}
<i>coluzzii</i> Weija (GH)	131	60 / 70 / 1	54.1%	7.3 (3.0 – 17.6)	100% (†)	3.7×10^7 (0 – Inf)	2.4×10^{-6}
<i>gambiae</i> Aboisso (CI)	82	3 / 45 / 34	77.8%	7.0 (0.6 – 85.4)	97%	66.0 (2.9 – 1491.2)	3.7×10^{-3}
<i>gambiae</i> Madina (GH)	172	19 / 112 / 41	58.9%	12.2 (2.7 – 55.4)	100%	9.8×10^8 (0 – Inf)	4.4×10^{-14}
<i>gambiae</i> Obuasi (GH)	140	0 / 28 / 112	17.8%	-	58.9%	6.6 (2.3 – 18.6)	6.0×10^{-5}
<i>gambiae</i> Weija (GH)	13	7 / 4 / 2	75% (†)	7.3×10^{17} (0 – Inf)	100% (†)	2.6×10^9 (0 – Inf)	1.6×10^{-3}
<i>gambiae</i> Baguida (TG)	102	0 / 14 / 88	57.1%	-	56.8%	0.9 (0.3 – 3.1)	0.982

Pirimiphos-methyl resistance was associated with CNV-related measures in heterozygotes from *A. gambiae* and *A. coluzzii* populations, according to generalised linear models that included *280S* allelic ratios and/or *Ace1* copy number as potential informative markers (Table 2). In *A. coluzzii* from Korle-Bu and Weija, as well as *A. gambiae* from Madina, both the *280S* allelic ratio and the *Ace1* copy number were included in the minimal model (at $p < 0.01$ in a χ^2 comparison with a null model); whereas in *A. coluzzii* from Aboisso the allelic ratio was the only variable associated with resistance ($p = 1.3 \times 10^{-3}$ in a χ^2). In the Obuasi *A. gambiae* heterozygotes, the minimal model only included *Ace1* copy number (at $p = 0.038$) but neither measure was strongly predictive, as was the case in *A. gambiae* from Aboisso and Baguida. Overall, these results indicate that the combination of *280S* allelic ratios and CNVs provide a similar pirimiphos-methyl resistance mechanism in heterozygotes from both species. However, diagnostic capacity appears to vary among populations, suggesting the possible existence of additional resistance mechanisms.

Table 2. Association of *Ace1* duplications with pirimiphos-methyl resistance in heterozygous specimens from seven West African populations of *A. coluzzii* and *A. gambiae*. For each population, we report number of sampled specimens (*n*), and the results of three binomial generalised linear models (GLM): (i) using the number of *Ace1* copies as the predictor variable, (ii) using the 280S-to-280G allelic ratio, and (iii) a minimal model obtained with step-wise reduction, according to the Bayesian Information Criterion (BIC). For each model, we report the *p*-value from a comparison with a null model (ANOVA χ^2 test) and odds ratios (OR) with 95% confidence intervals for the variables included in the model. Sample phenotypes and genotypes listed in Supplementary Material SM6E; statistical analysis in Supplementary Material SM6F. Country abbreviations: CI, Côte d’Ivoire; GH, Ghana; TG, Togo.

Population	<i>n</i>	GLM <i>Ace1</i> copies (single variable)		GLM 280S/280G allelic ratio (single variable)		Minimal GLM (BIC)		
		OR	<i>p</i>	OR	<i>p</i>	OR <i>Ace1</i> copies	OR allelic ratio	<i>p</i>
<i>coluzzii</i> Aboisso (CI)	11	1.3 (0.7 – 2.3)	0.361	52.9 (0.01 – 2.2 × 10 ⁵)	1.3 × 10 ⁻³	-	52.9 (0.01 – 2.2 × 10 ⁵)	1.3 × 10 ⁻³
<i>coluzzii</i> Korle-Bu (GH)	46	1.8 (1.2 – 2.6)	1.0 × 10 ⁻⁴	2.8 (1.6 – 5.1)	4.1 × 10 ⁻⁷	1.5 (0.9 – 2.3)	2.3 (1.3 – 4.0)	3.0 × 10 ⁻⁷
<i>coluzzii</i> Weija (GH)	21	0.5 (0.3 – 1.0)	0.013	3.4 (0.4 – 28.6)	0.021	0.4 (0.1 – 1.1)	50 (0.3 – 9505.0)	2.9 × 10 ⁻³
<i>gambiae</i> Aboisso (CI)	31	1.0 (0.6 – 1.5)	0.933	2.6 (0.3 – 24.9)	0.382	-	-	-
<i>gambiae</i> Madina (GH)	19	5.2 (1.1 – 23.9)	7.7 × 10 ⁻³	6.5 × 10 ⁶⁵ (0 – Inf)	2.1 × 10 ⁻⁶	8.7 × 10 ⁻²⁰ (0 – Inf)	5.5 × 10 ⁴⁵ (0 – Inf)	2.6 × 10 ⁻⁹
<i>gambiae</i> Obuasi (GH)	26	1.5 (0.9 – 2.3)	0.038	3.1 (0.85 – 10.8)	0.038	1.5 (0.9 – 2.3)	-	0.038
<i>gambiae</i> Weija (GH)	0	-	-	-	-	-	-	-
<i>gambiae</i> Baguida (TG)	13	1.4 (0.7 – 2.6)	0.350	2.9 (0.1 – 69.4)	0.498	-	-	-

192 Genome-wide identification of pirimiphos-methyl resistance variants in Ivorian *A. coluzzii*

We examined the genomes of the 71 *A. coluzzii* specimens from Côte d’Ivoire to identify additional
 194 genetic variants—other than *Ace1* G280S and duplications—that could be linked to pirimiphos-methyl
 resistance. All Ivorian specimens had been collected in the same location and time (Tiassalé, 2012), before
 196 the widespread adoption of pirimiphos-methyl in IRS interventions (Oxborough 2016; World Health
 Organization 2013). The absence of a long period of pirimiphos-methyl use prior to collection implies that
 198 adaptation to this insecticide would presumably be caused by cross-resistance with previously employed
 insecticides and/or standing variation, rather than novel selective sweeps. In accordance with this
 200 expectation of low differentiation, a principal component analysis of genetically unlinked variants (see
 Methods) did not reveal population stratification between resistant and susceptible mosquitoes (Figure 4),
 202 and average Hudson’s F_{ST} between them was low along all chromosomal arms ($F_{ST} \approx 0\%$).

We thus aimed to identify signals of selection in resistant *A. coluzzii* using the population branch
204 statistic (*PBS*, Figure 5A), which identifies regions with an excess of genetic differentiation in a focal
population (here, resistant Ivorian mosquitoes) relative to a basal level of differentiation between a closely
206 related population (susceptible Ivorian mosquitoes) and a more distant control (a population of *A. coluzzii*
from Angola; see Methods). *PBS* is a powerful test to detect recent selection acting on incomplete sweeps
208 and standing variation (Yi et al. 2010; Malaspinas et al. 2016), and is therefore well-suited to investigate a
scenario—like ours—in which the population of interest has not yet diverged.

210 We estimated *PBS* along genomic windows to identify regions in which resistant Ivorian specimens had
an excess of genetic differentiation (see Methods). In total, we identified 43 genes within six regions with
212 excess differentiation in resistant *A. coluzzii* ($PBS > 0$, $FDR < 0.001$; see Methods; Figure 5A). This set of
candidates contained eleven mostly uncharacterised genes located downstream of *Ace1* and within the
214 duplicated region, two ionotropic receptors (*GLURIIb* and *GLURIIa*), and several proteases, among others
(Supplementary Material SM7). However, genetic differentiation between resistant and susceptible
216 specimens in each of these genes was low ($F_{ST} < 6\%$ in all cases; Supplementary Material SM7), which
suggests that they are unlikely to be directly associated with the resistance phenotype. The *Ace1* gene itself
218 was on the verge of the significance threshold ($FDR = 3.2 \times 10^{-3}$, $PBS = 0.031$) and exhibited low
differentiation ($F_{ST} = 1.2\%$). This apparent contradiction regarding the *Ace1* phenotypic association can be
220 explained by the fact that pirimiphos-methyl resistance is caused by a combination of mutations—a SNP
within a heterozygous duplication—that is not captured by the diploid allelic frequencies used in *PBS*
222 calculations (Yi et al. 2010).

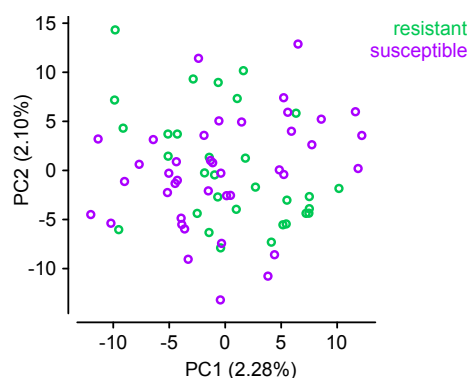


Figure 4. Principal component analysis of Côte d'Ivoire *A. coluzzii*.
PCA constructed using genotypes of 791 unlinked variants from
chromosome 3.

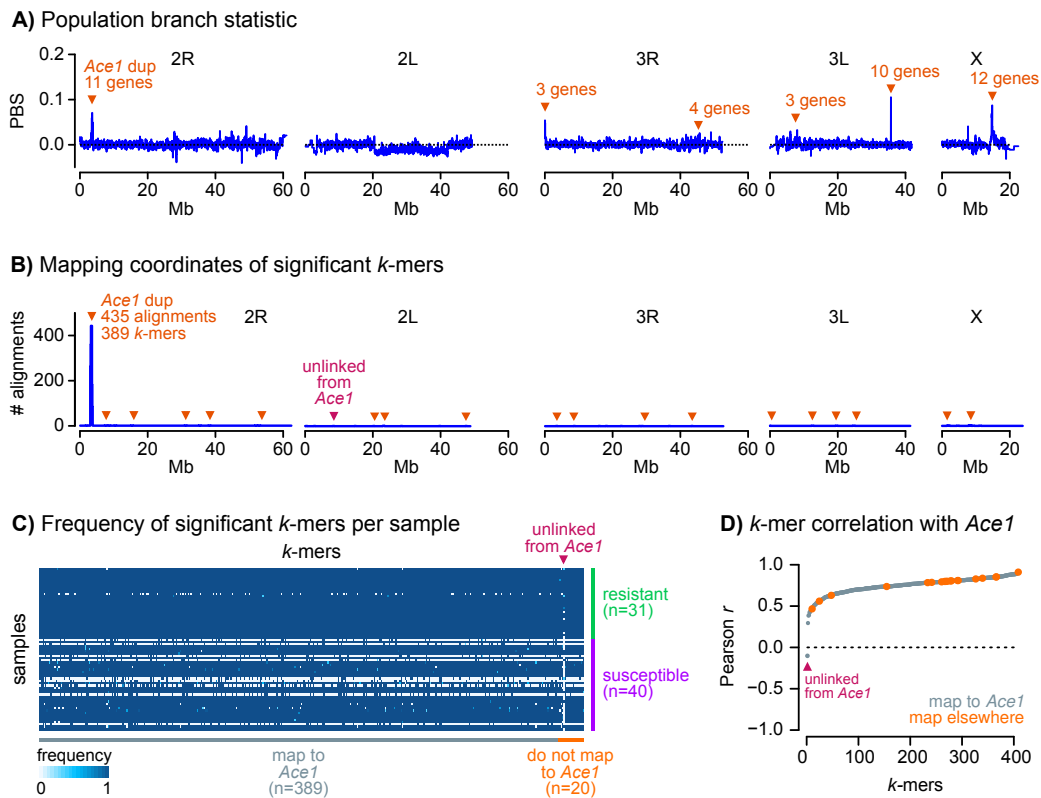


Figure 5. Genome-wide scan of variants associated with pirimiphos-methyl resistance in Ivorian *A. coluzzii*. **A)** Profile of population branching statistics along all chromosomal arms, calculated in consecutive blocks of 1000 segregating variants, using resistant and susceptible Ivorian *A. coluzzii* as populations A and B, and Angolan *A. coluzzii* as outgroup. Orange triangles indicate windows with extreme PBS values (p -values derived from a standardised distribution of PBS along each chromosomal arm, and $FDR < 0.001$), and the number of genes therein. **B)** Mapping coordinates of k -mers significantly associated with pirimiphos-methyl ($n=439$). Most k -mers map to the *Ace1* duplication region ($n=414$) or, despite mapping elsewhere in the genome ($n=24$), are correlated with *Ace1* copy number (orange triangles). Only one k -mer mapping outside of the *Ace1* duplication is not correlated with *Ace1* copy number (purple triangle). **C)** Normalised frequency of each significant k -mer ($n=439$, horizontal axis) in each genome ($n=71$, vertical axis). k -mers are sorted according to their mapping location (in *Ace1* or elsewhere), and genomes are sorted according to their phenotype (resistant/susceptible). **D)** Pearson's correlation coefficients (r) between k -mer frequency and number of *Ace1* copies in each genome ($n=439$ significant k -mers). k -mers are coloured according to their mapping location (in *Ace1* or elsewhere) and sorted by the values of r .

224 To overcome this limitation, we performed a k -mer association study comparing the resistant and
susceptible Ivorian *A. coluzzii*. k -mer association studies test for differential frequencies of tracts of
226 nucleotides of length k in different groups of genomes, and are able to identify genetic variation patterns
linked to both SNPs and structural variants, such as CNVs, without requiring a reference annotation
228 (Rahman et al. 2018). We identified *ca.* 767 million different k -mers of length $k = 31$ bp across all 71 samples
(see Methods). Among these, 9,603 k -mers were significantly enriched in resistant specimens (Spearman
230 correlation test, $FDR < 0.001$). The 9,603 significant k -mers were assembled into 446 unique sequences

composed of more than one *k*-mer (median length = 54 bp), which we then aligned to the *A. gambiae*
232 reference genome. We retained sequences that could be mapped to chromosomes 2, 3 or X (409 out of 446)
for further analysis (listed in Supplementary Material SM8). Among these, the vast majority ($n = 389$,
234 95.1%) aligned to the *Ace1* duplicated region, while the remaining significant sequences aligned in
scattered regions across the rest of the genome ($n = 20$, 4.9%; Figure 5B). Yet, 19 out of 20 *k*-mers that did
236 not map to *Ace1* had a very similar frequency profile in resistant and susceptible samples than the 389
Ace1-linked *k*-mers, being absent and present in the same genomes (Figure 5C). In fact, the *k*-mer
238 frequencies of these 19 sequences was strongly correlated with *Ace1* copy number (Pearson correlation $r >$
 0 and $p < 1 \times 10^{-4}$; Figure 5D). This suggests that these 19 *k*-mers represent a non-independent signal that
240 also reflects the association of *Ace1* mutations with resistance, and can be parsimoniously explained by
non-specific sequence alignments (see Discussion). Only one remaining sequence did not correlate with
242 *Ace1* copy number (Pearson correlation $r < 0.0$, maroon arrow in Figure 5C and 5D), indicating that it may
represent another variant involved in resistance. The primary alignment of this sequence mapped to a
244 non-coding region of chromosomal arm 2L (from 2L:8,662,023), with no proximity to any gene of known
function. Altogether, these results support the conclusion that *Ace1* mutations are the primary driver of
246 pirimiphos-methyl resistance in this *A. coluzzii* population.

Selection and introgression of *Ace1* duplications in *A. gambiae* and *A. coluzzii*

248 A high degree of geographical and phylogenetic overlap is evident between *Ace1* duplications and 280S
alleles across four countries (Côte d'Ivoire, Ghana, Burkina Faso and Guinea) and two different species (*A.*
250 *coluzzii* and *A. gambiae*; Figure 2A). Previous studies provide two key insights to understand this pattern.
First, *Ace1* duplications across West African populations have concordant breakpoints (Assogba et al. 2016;
252 Lucas et al. 2019), which suggests they share a common evolutionary origin despite their multi-species
distribution. Second, partial sequencing of *Ace1* has shown that 280S alleles share highly similar haplotypic
254 backgrounds in both West African *A. gambiae* and *A. coluzzii* (Djogbénou et al. 2008; Essandoh et al. 2013;
Weetman et al. 2015), which is suggestive of inter-specific introgression and a selective sweep. The most
256 parsimonious hypothesis linking our results and these observations would posit that (i) the high similarity
of 280S-carrying haplotypes across the *A. gambiae* - *A. coluzzii* species boundary is shared along the entire
258 duplicated region (ca. 200 kbp); and (ii) this similarity is due to a 280S-linked selective sweep around *Ace1*,

followed by duplications and the joint introgression of the duplication-280S haplotype between *A. gambiae* and *A. coluzzii*.

To test these hypotheses, we investigated genetic variation in the *Ace1* duplication using networks of haplotype similarity (Figure 6). The analysis of *Ace1* haplotypes is limited by the low density of phased variants in the vicinity of this gene (Supplementary Material SM9), caused by a combination of high sequence conservation and the difficulties in phasing haplotypes within a heterozygous duplication. To circumvent these limitations, we built four different networks around tagging variants that were in strong linkage disequilibrium with *G280S* (Huff and Rogers' $r > 0.95$) and located within the duplication (located within -26 kbp and +12 kbp from *G280S*; Supplementary Material SM9), and used these to define four sets of 280S-linked haplotypes. Then, we assumed that concordant observations among all sets of 280S-linked haplotypes would reflect genetic signatures shared with *Ace1*.

The minimum spanning tree built from haplotypes located around the first tagging variant (Figure 6A) identified a cluster of 124 identical haplotypes carrying the 280S-linked allele (Figure 6A, labelled with green text) and two larger haplotype clusters linked to the wt 280G allele (Figure 6A). The 280S cluster contains identical haplotypes from West African populations (Côte d'Ivoire, Burkina Faso, Ghana and Guinea) of both *A. coluzzii* and *A. gambiae*. On the other hand, wt-linked clusters have wider geographical distributions (including samples from West, Central and Eastern sub-Saharan Africa). The other three tagging variants show haplotype networks with a similar structure, with clusters of ca. 120 280S-linked

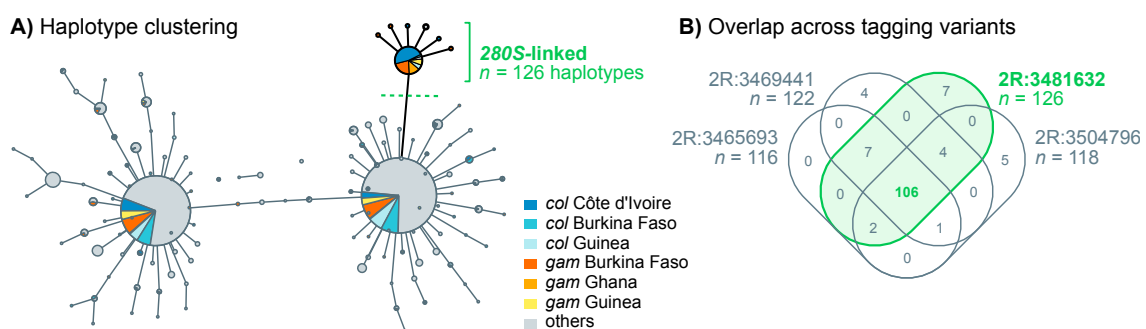


Figure 6. Haplotype clustering network around *Ace1*. **A)** Minimum spanning tree of haplotypes around the 280S-linked variant 2R:3481632 (± 300 bp, $n = 104$ phased variants). Node size reflects number of haplotypes belonging to each cluster, which are color-coded according to species and geographical origin. Edges link haplotype clusters separated by one substitution. Singleton clusters have been removed from this view (see Supplementary Material SM10). A cluster of identical haplotypes linked to the 280S-tagging variant is highlighted in green. **B)** Venn diagram representing the overlap of samples belonging to the 280S-linked haplotype clusters identified around each of the four tagging variants (Supplementary Material SM10).

identical haplotypes originating in the same *A. gambiae* and *A. coluzzii* specimens from West Africa (Figure 278 6B, Supplementary Material SM10). This result indicates that haplotype similarity between *A. gambiae* and *A. coluzzii* extends beyond the *Ace1* gene.

280 We also investigated possible signals of positive selection around the *Ace1* duplication breakpoints using Garud's H statistics, haplotypic diversity, and extended haplotype homozygosity (Figure 7, 282 Supplementary Material SM11 and SM12). The profile of Garud's H_{12} statistic in 280S-linked haplotypes showed peaks both upstream and downstream of the *Ace1* duplication (Figure 7A), which coincided with a 284 low H_2/H_1 ratio (Figure 7B) and low haplotypic diversity (Figure 7C), and is thus indicative of a hard selective sweep in this region (Garud et al. 2015; Messer and Petrov 2013). Notably, the region of extended 286 haplotype homozygosity associated with this sweep was still apparent upstream and downstream of the duplication breakpoints, i.e., far away from the focal tagging variant used to define 280S-linked haplotypes 288 (Figure 7D).

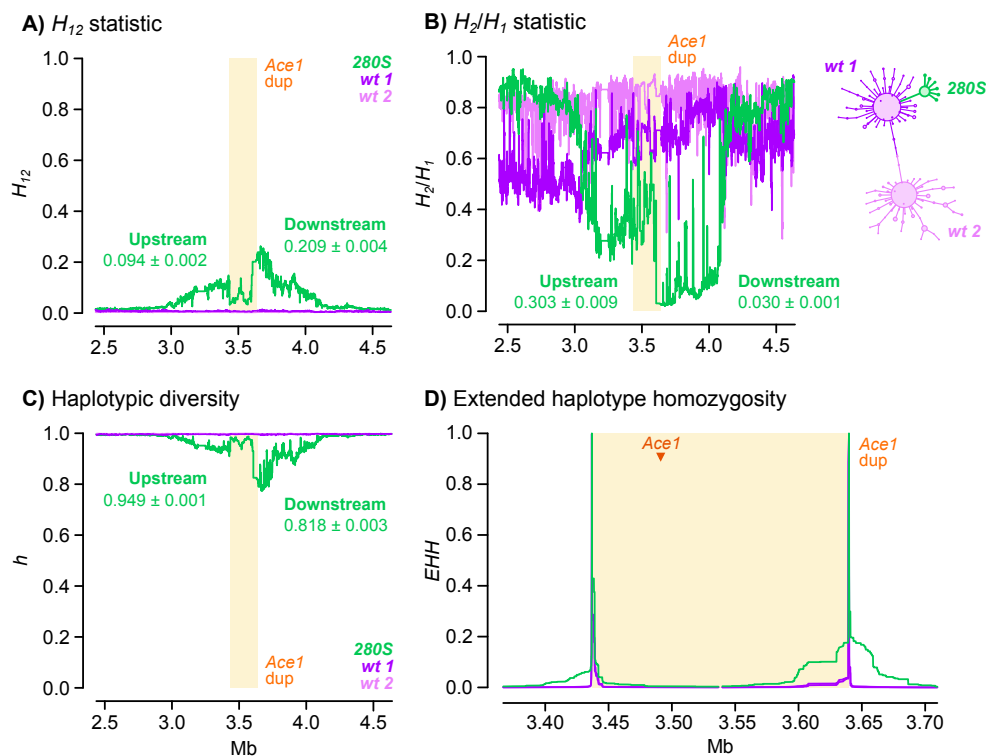


Figure 7. Positive selection around the *Ace1* duplication. A-C) Profile of Garud's H_{12} , H_2/H_1 and haplotypic diversity around the *Ace1* duplication, for haplotypes carrying the 280S- or wt-tagging variants at 2R:3481632. Statistics are calculated in blocks of 500 variants with 20% block overlap. Includes averages of each statistic upstream and downstream of the breakpoints (with standard errors from jackknife haplotype resampling). D) Extended haplotype homozygosity at the duplication breakpoints for haplotypes carrying the 280S- or wt-tagging variants at the 2R:3481632 locus. Additional plots for all tagging variants are available in Supplementary Material SM11 and SM12.

290 Next, we tested whether 280S alleles and the duplication spread jointly between *A. coluzzii* and *A.*
gambiae via introgression (Figure 8). We examined the chromosome-wide profile of introgression between
292 *A. gambiae* and *A. coluzzii* populations using Patterson’s *D* statistic (Durand et al. 2011; Patterson et al. 2012),
which compares allele frequencies between three putatively admixing populations (A, B and C) and one
294 outgroup (O); and can identify introgression between populations A and C ($D > 0$) or B and C ($D < 0$).
Specifically, we tested whether duplicated *A. coluzzii* from West African populations (population A)
296 introgressed with *A. gambiae* populations from West and Central Africa (C), using *wt* Angolan *A. coluzzii* as a
control (B) and *A. arabiensis* as an outgroup (O).

298 We evaluated whether the *Ace1* duplication introgressed between *A. gambiae* and *A. coluzzii* in two
scenarios: (i) in specimens with CNVs from populations with *Ace1* resistance mutations (Figure 8A), and (ii)
300 in non-duplicated specimens from the same populations (Figure 8B). We only find evidence of
introgression in the first case, i.e. between West African *A. gambiae* and *A. coluzzii* specimens carrying *Ace1*
302 duplications (Figure 8A). For example, we found evidence of introgression between duplicated Ghanaian *A.*

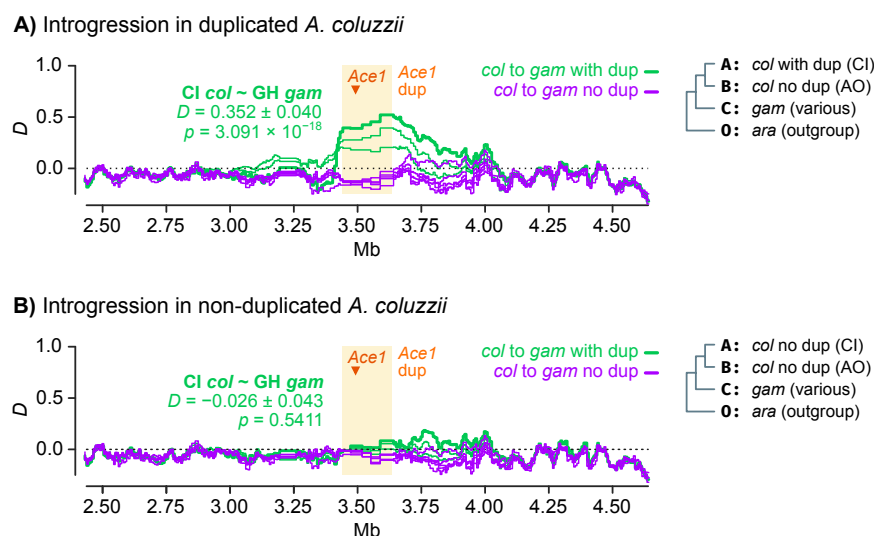


Figure 8. Introgression of the *Ace1* duplication. **A)** Profile of Patterson’s *D* statistic around the *Ace1* duplication, testing evidence of introgression between duplicated *A. coluzzii* from Côte d’Ivoire (population A) and various *A. gambiae* populations (population C) with or without duplications (green and purple lines, respectively). We used non-duplicated Angolan *A. coluzzii* as a contrast (population B) and *A. arabiensis* as outgroup (O). *D* is calculated in windows of 5,000 variants with 20% overlap, and the average value of *D* along the duplication region is shown for the Côte d’Ivoire *A. coluzzii* / Ghana *A. gambiae* comparison, with standard errors derived from block-jackknife. **B)** Id., but using non-duplicated *A. coluzzii* from Côte d’Ivoire as population A. Detailed lists of all statistical tests and replicate analyses with additional populations are available in Supplementary SM13. Species abbreviations: *gam*, *A. gambiae*; *col*, *A. coluzzii*; *ara*, *A. arabiensis*. Country abbreviations: AO, Angola; CI, Côte d’Ivoire; GH, Ghana.

gambiae and duplicated Ivorian *A. coluzzii* ($D = 0.352 \pm 0.040$, $p = 3.1 \times 10^{-18}$ from a standard distribution of
304 block-jackknifed estimates; green lines in Figure 8A); but not with non-duplicated Ivorian *A. coluzzii* ($D = -$
0.026 \pm 0.043, $p = 0.54$; green lines in Figure 8B). In all comparisons where introgression was apparent, the
306 genomic region of increased D values extended along the entire duplicated region. On the other hand,
there was no evidence of introgression in any comparison involving non-duplicated *A. gambiae* ($D \approx 0$;
308 purple lines in Figure 8A and 8B).

To establish the direction of introgression, we performed a phylogenomic analysis of haplotypes from
310 the duplicated region (Figure 9). Firstly, haplotypes with *Ace1* duplications formed a single clade
containing *A. gambiae* and *A. coluzzii* sequences to the exclusion of all non-duplicated sequences from both
312 species. Secondly, we found that duplicated sequences were phylogenetically closer to the *wt A. gambiae*

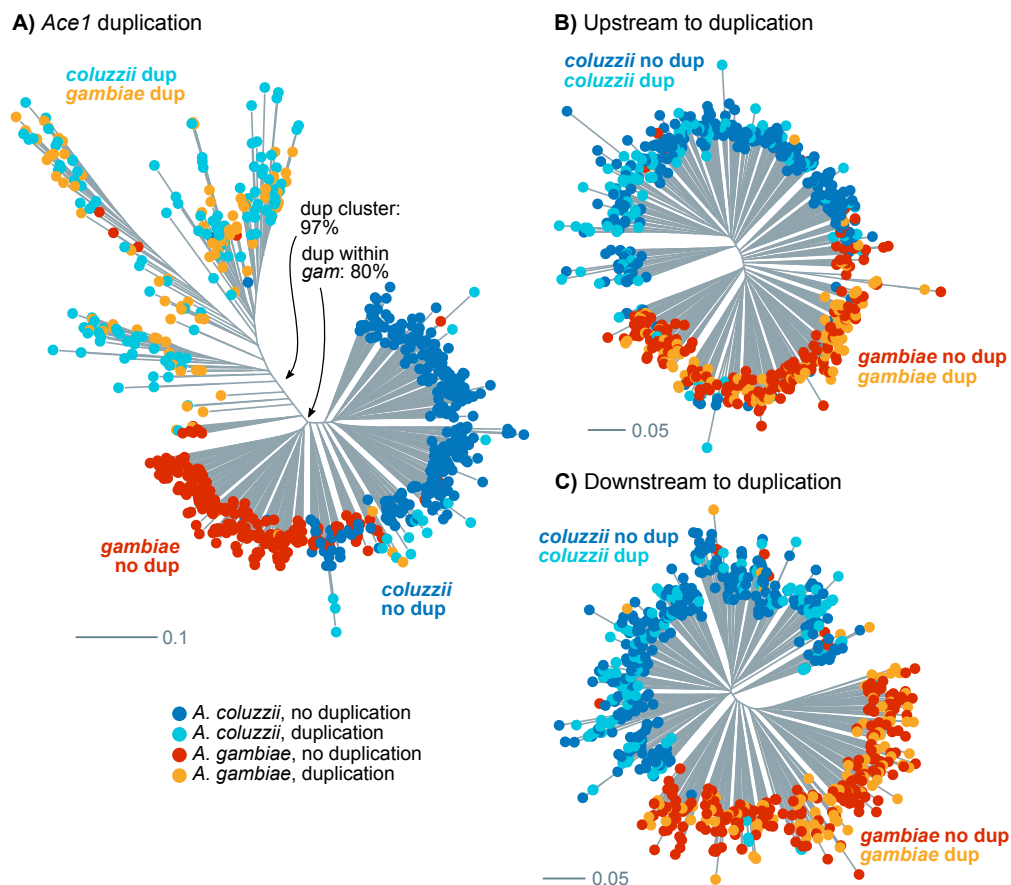


Figure 9. Phylogenetic analysis of introgression in *Ace1*. A) Maximum-Likelihood phylogenetic analysis of 690 Western African haplotypes from the *Ace1* duplicated region (2,787 phased variants), using a GTR model with ascertainment bias correction, empirical state frequencies and four Γ rate categories. B-C) Id., using variants upstream and downstream to the *Ace1* duplication (3,935 and 3,302 variants). Tips are color-coded according to species and duplication presence. Source alignments and complete phylogenies with supports in all nodes are available in Supplementary Material SM14 and SM15.

clade than to *wt A. coluzzii* (Figure 9A). Thirdly, an analysis of differences in allelic frequencies between *wt*
314 *A. gambiae*, *wt A. coluzzii* and duplicated haplotypes also indicated that the duplicated haplotypes are more
similar to *wt A. gambiae* than to *wt A. coluzzii*: the branch leading to *wt A. coluzzii* since the divergence from
316 the duplicated specimens was longer ($L = 0.0273 \pm 0.0015$ standard error) than the branch leading to *wt A.*
gambiae ($L = 0.0102 \pm 0.0011$). This topology indicates that duplicated haplotypes emerged from a *A. gambiae*
318 *wt* background and later introgressed into *A. coluzzii*. In contrast, phylogenies built from non-introgressed
regions upstream and downstream of the duplication exhibited a topology with species-specific clades
320 that included both duplicated and non-duplicated specimens (Figure 9B, C).

Altogether, these results show that the 280S resistance alleles present across West Africa appear in
322 similar genetic backgrounds irrespectively of the sampled population and species, and that this similarity
extends beyond the *Ace1* gene to encompass the entire duplicated region (Figure 6). This low haplotypic
324 diversity is due to a hard selective sweep, detectable at the duplication breakpoints (Figure 7). This
resistance haplotype, which spans *ca.* 200 kbp and includes *Ace1* and ten other genes (Supplementary
326 Material SM3) emerged in *A. gambiae* and later spread to *A. coluzzii* (Figures 8 and 9).

Discussion

328 Evolutionary history of G280S and Ace1 duplications

Our results show that pirimiphos-methyl resistance is associated with a combination of two mutations
330 in *Ace1*: the G280S SNP and CNVs. In West Africa, virtually all CNVs are found as duplications of a wide
region (*ca.* 200 kbp) that includes *Ace1* and 10 other genes (Assogba et al. 2016; Lucas et al. 2019). This
332 duplication has a unique evolutionary origin in the *A. gambiae/A. coluzzii* species pair, as its breakpoints are
consistent in all populations from both species studied so far (Assogba et al. 2016; Lucas et al. 2019). The
334 distribution of duplication-280S resistance haplotypes observed in the 1000 Genomes cohort can explained
by three evolutionary events: the G280S mutation, an internally heterozygous duplication, and inter-
336 specific introgression. Furthermore, recent sampling efforts have identified internal deletions within the
duplication in both *A. gambiae* and *A. coluzzii* (Assogba et al. 2018). Homogeneous duplications are rare in
338 the 1000 Genomes dataset but appear to be quite common in some *A. gambiae* populations, though less so
in *A. coluzzii* (Table 2; (Weetman et al. 2015; Assogba et al. 2018)).

340 At present, we cannot establish the relative order of occurrence of the SNP and CNV in *Ace1* because
these mutations are tightly linked in the 1000 Genomes dataset (Figure 2A). Nevertheless, the detection of
342 *wt* homozygous duplications in samples collected in 2002 in southern Ghana (Weetman et al. 2015)—a
country where *280S* alleles have more recently been found at high frequencies (Figure 1)—raises the
344 possibility that the SNP might have occurred on an already duplicated background. This order of events
would have initially resulted in permanent heterozygosity, providing resistance and reducing the fitness
346 costs associated with impaired acetylcholinesterase activity in the absence of insecticide (Labbé et al. 2007;
Assogba et al. 2015). If that were the case, the emergence of *280S*-homozygous duplications would require
348 either a secondary loss of a *wt* copy or a parallel *G280S* mutation in the initially heterozygous duplication.

After these two mutations, the joint duplication-*280S* resistance haplotype introgressed from *A. gambiae*
350 into *A. coluzzii* (Figures 8 and 9). This *A. gambiae* origin is consistent with earlier studies of *Ace1* variation in
West African locations, which generally reported higher frequencies of *280S* (Djogbénu et al. 2008; Dabiré
352 et al. 2009; Essandoh et al. 2013) and CNVs (Assogba et al. 2018) in *A. gambiae* than in *A. coluzzii*, as one
would expect if they had a longer evolutionary history in the former. Whilst previous studies had
354 suggested that the similarity of *280S* haplotypes in *A. coluzzii* and *A. gambiae* was due to inter-specific
introgression (Djogbénu et al. 2008; Essandoh et al. 2013; Weetman et al. 2015), they were focused on
356 partial sequencing of the *Ace1* gene and could not assess the relationship between introgression and the
wider duplicated region (*ca.* 30 times longer than the *Ace1* coding region). Furthermore, analyses focused
358 on the *Ace1* gene body can be confounded by the lack of sequence variation in this region (Supplementary
SM9). By leveraging variation in linkage disequilibrium beyond the gene, we are able identify clear
360 signatures of introgression along the entire *Ace1* duplication region (Figure 8).

Genetic basis of pirimiphos-methyl resistance in *A. coluzzii* and *A. gambiae*

362 We have uncovered a strong association between resistance to pirimiphos-methyl and the possession
of two or more copies of the *Ace1 280S* allele in *A. coluzzii* from Côte d'Ivoire (Figure 3). While the *G280S*
364 mutation alone has been previously linked to resistance to carbamates and organophosphates in multiple
insects (Weill et al. 2003, 2004; Labbé et al. 2007; Alout et al. 2007; Djogbénu et al. 2008; Dabiré et al. 2014;
366 Liebman et al. 2015; Feyereisen et al. 2015), our results indicate that resistance to pirimiphos-methyl
specifically relies on the presence of multiple *280S* alleles.

368 Across the 1000 Genomes cohort, specimens with 280S alleles can be grouped into two categories
according to the number of *Ace1* copies (Figure 2C): (i) heterozygous duplications with multiple 280S alleles
370 and/or multiple *wt*, and (ii) high-copy, 280S-homozygous specimens. Heterozygous duplications are the
most frequent combination of *Ace1* mutations (113 out of 119 samples, Figure 2B) and the only one
372 identified in the *A. coluzzii* population from Côte d'Ivoire (Tiassalé). Therefore, we decided to examine their
contribution to pirimiphos-methyl resistance in a wider array of *A. gambiae* and *A. coluzzii* populations from
374 Ghana, Côte d'Ivoire, and Togo (Tables 1 and 2). We identified a common theme in most populations
surveyed here: (i) 280S heterozygotes were the most common resistance genotype in six out of eight
376 populations analysed, including all *A. coluzzii* sampling locations and three out of five in *A. gambiae* (Table
1); and (ii) among the heterozygotes, we found that the ratio of 280S alleles and *Ace1* copy number were
378 significantly associated with resistance in five out of seven tested populations (Table 2). This provides a
wider demonstration that the combined effect of *G280S* and *Ace1* duplications is significantly associated
380 with pirimiphos-methyl resistance across multiple West African populations of both species; consistent
with a requirement for multiple copies of 280S for resistance.

382 We also identified six high-copy, 280S-homozygous genomes sampled from the Ghanaian *A. gambiae*
population in the 1000 Genomes dataset (Figures 1 and 2). These samples had not been assayed for
384 pirimiphos-methyl resistance prior to sequencing. However, our extended genotype-phenotype analysis
in eight West African populations (Table 1) showed that (i) 280S homozygotes exhibited increased
386 resistance to pirimiphos-methyl, and that, in fact, they were the most abundant resistance allele in two *A.*
gambiae populations (Baguida and Obuasi). It is worth mentioning that survival rates among 280S
388 homozygotes were noticeably lower these two locations (56.8% - 58.9%) than in populations where
heterozygotes were more common (> 95%; Table 1). Our analyses cannot fully capture the resistance
390 landscape in these populations, because we have focused on the role of CNVs in heterozygous specimens
(as they were the most abundant resistant type in the 1000 Genomes cohort; Figure 1). Thus, we cannot
392 presently explain these differences, which may reflect an effect of different phenotyping strategies
employed in each population (see Methods), or additional resistance mechanisms. A detailed examination
394 of 280S-homozygous duplications—e.g. effects on gene dosage or fitness—could shed light onto the
phenotypic variability observed in populations with high penetrance of *Ace1* mutations.

396 Finally, we have performed a genome-wide scan in a population of *A. coluzzii* from Côte d'Ivoire
(Tiassalé) to identify loci associated with pirimiphos-methyl resistance (Figure 5). Our investigation of the
398 association between *k*-mer frequencies and resistance confirmed the overwhelming concentration of
phenotypic association in the *Ace1* duplication (Figure 5B), supporting the conclusion that it is the primary
400 driver of resistance in this population. The correlations between *Ace1* duplication and all but one of the *k*-
mers significantly associated with resistance, but mapping elsewhere in the genome strongly suggests
402 non-independence of the signals, but the exact cause of this is unclear. Whilst we cannot entirely discount
linkage disequilibrium arising from epistasis, a simpler and parsimonious explanation would be that this
404 result is caused by non-specific or incorrect sequence alignments, possibly linked to currently
unrecognised variation in the *Ace1* duplication.

406 The lack of clear signals of pirimiphos-methyl adaptation other than *Ace1* in this population may reflect
its collection at an early stage of the development of pirimiphos-methyl resistance in West Africa (Edi et
408 al. 2014b). Therefore, our genome-wide analyses would only capture pre-existing variants that were
enriched in the resistant specimens. *Ace1* mutations and duplications, which cause cross-resistance with
410 previously employed insecticides (Djogbénu et al. 2015, 2008; Essandoh et al. 2013; Edi et al. 2014a;
Assogba et al. 2015, 2016, 2018; Weetman et al. 2015), fit this definition and are sufficient to sustain high
412 levels of resistance. However, future analyses on recent collections from populations subjected to regular
pirimiphos-methyl-based IRS may reveal additional mechanisms more specifically selected by this
414 insecticide.

Implications for insecticide intervention programmes

416 Our results demonstrate that the duplication-280S haplotype represents a powerful marker to diagnose
resistance to pirimiphos-methyl in *A. coluzzii* and *A. gambiae*, permitting the spread of resistance to be
418 tracked from any preserved sample from which DNA can be extracted. Our initial survey of an *A. coluzzii*
population from Tiassalé (Côte d'Ivoire) shows that discrimination between susceptible and resistant
420 specimens can be attained with high accuracy in this population according to the number of 280S alleles.
Specifically, following the resistance thresholds apparent in Figure 3B, we can (i) classify *wt* homozygous
422 samples as susceptible (100% predictive value) and (ii) separate heterozygous individuals between those
with more *wt* than 280S alleles (susceptible) and those with equal or more 280S than *wt* alleles (resistant).

424 This would yield a positive predictive value of 77% for resistance, and a negative predictive value of 85%
for susceptibility.

426 In practice, precise quantification of the number of resistance *280S* alleles will often be difficult.
Nevertheless, we show that key variation in *Ace1* can be captured using two qPCR genotyping assays that
428 predict pirimiphos-methyl resistance in populations of *A. gambiae* and *A. coluzzii* (Table 2): (i) a
measurement of the ratio of *280S* to *280G* alleles (Bass et al. 2010), and (ii) the number of *Ace1* copies (Edi et
430 al. 2014a). Crucially, measurements of the *280S* allelic ratio can be obtained from the same assay that is
currently used for standard genotyping of the *G280S* mutation (Bass et al. 2010), which thus has good
432 diagnostic capacity in homozygotic and heterozygotic specimens. The phenotypic assays we employed
were intended to provide more accurate separation than standard dose approaches (Weetman and
434 Donnelly 2015), but the strong effect of *Ace1* CNVs and *G280S* mutations on pirimiphos-methyl resistance is
sufficiently robust for resistance diagnosis in single time-dose discriminating assays as well – as used in
436 the Ivorian *A. coluzzii* specimens from the 1000 Genomes cohort.

Furthermore, monitoring studies must note that this resistance haplotype is still evolving, especially in
438 the light of the fitness trade-offs associated with *Ace1* resistance alleles – namely, that heterozygous
duplications offset the fitness cost of *280S* alleles in the absence of insecticide exposure (Labbé et al. 2007;
440 Assogba et al. 2015), and that variably copy number can result in gene dosage disturbances (Assogba et al.
2016). A recent survey has shown that internal deletions within the duplicated region, downstream to
442 *Ace1*, are spreading in both *A. gambiae* and *A. coluzzii* (Assogba et al. 2018). The authors have proposed that
these deletions reduce the fitness costs of duplications by ameliorating deleterious changes in gene
444 expression (Assogba et al. 2018). These small deletions are absent from the Ivorian *A. coluzzii* genomes
analysed here (Lucas et al. 2019), but future genome monitoring studies could investigate their spread and
446 identify signals of selection associated with their proposed selective advantage. Likewise, the
independently evolved *Ace1* CNV that we have identified in one *A. gambiae* specimen from Guinea (Figure
448 2B, Supplementary Material SM4) might merit further attention in the future. Finally, as noted above, we
cannot rule out the possibility that, following several years of widespread use of pirimiphos-methyl for
450 IRS, additional non-target site-based resistance mechanisms might have emerged.

The duplication-*280S* haplotype pre-dates the widespread adoption of pirimiphos-methyl in 2013

452 (Oxborough 2016), which indicates that it likely spread due to its adaptive value with respect to previously
employed insecticides used in disease control or agriculture, such as carbamates (bendiocarb (Edi et al.
454 2014a; Assogba et al. 2016)) or other organophosphates (fenitrothion, chlorpyrifos-methyl (Essandoh et al.
2013; Assogba et al. 2016)). In that regard, we show that the evolution of the pirimiphos-methyl resistance
456 haplotype is deeply intertwined with that of previous insecticide adaptations, and reveal how continued
genomic monitoring studies can help us understand the influence of previous interventions on future
458 population control efforts. Furthermore, whilst current efficacy of pirimiphos-methyl in Actellic IRS
formulations appears to be retained (Sherrard-Smith et al. 2018), its potential could be limited in the
460 *Anopheles* populations where resistance to these insecticides is already common, most notably in West
Africa (Figures 1 and 2). This emphasises the crucial importance of now-commencing resistance
462 management strategies using additional IRS insecticides with alternative modes of action (Oxborough et
al. 2019).

464 **Materials and methods**

Data collection

466 We used genomic variation data from individual mosquitoes, obtained from the Phase 2 (AR1) of the
Anopheles gambiae 1000 Genomes project, as described in (Miles et al. 2017; The *Anopheles gambiae* 1000
468 Genomes Consortium 2019). This dataset consists of 1,142 wild-caught mosquitoes (1,058 females and 84
males) from 33 sampling sites located in 13 sub-Saharan African countries (listed in Supplementary
470 Material SM4), and collected at different times between 2009 and 2012 (with the exception of samples from
Gabon and Equatorial Guinea, collected in 2000 and 2002 respectively).

472 A detailed explanation of the methods used in whole-genome sequencing and variant calling can be
found in the original publications (Miles et al. 2017; The *Anopheles gambiae* 1000 Genomes Consortium
474 2019). Briefly, DNA from each specimen was extracted with a Qiagen DNeasy Blood and Tissue Kit (Qiagen
Science, US) and sequenced with the Illumina HiSeq 2000 platform (Wellcome Sanger Institute, UK) using
476 paired-end libraries (100 bp reads, 100-200 bp insert sizes), aiming at a 30× coverage per specimen. Variant
calling was performed using *bwa* (Li and Durbin 2009) 0.6.2 and the *GATK 2.7.4 UnifiedGenotyper* (Van der
478 Auwera et al. 2013). Haplotype phasing was estimated with *SHAPEIT2* (Delaneau et al. 2013), and variant

effects were predicted using *SnpEff* 4.1b (Cingolani et al. 2012). We downloaded the genotype calls, SNP
480 effect predictions, and haplotype phasing as available in *Anopheles gambiae* 1000 Genomes Phase 2 online
archive (The *Anopheles gambiae* 1000 Genomes Consortium 2017).

482 The catalog of *Ace1* CNVs in the 1000 Genomes dataset (Phase 2) was obtained from (Lucas et al. 2019).
There, the authors used calculated the coverage (sequencing depth) of each whole-genome sequenced
484 sample in non-overlapping windows along the genome (300 bp) and normalised this value so as to obtain
an expected average value of coverage = 2 in non-duplicated, diploid regions. A Gaussian HMM procedure
486 was then applied to the normalised windowed coverage data so as to call windows with heightened
normalised coverage (>2). A detailed account of these methods can be found in the original publication
488 (Lucas et al. 2019), and the results for the *Ace1* region are available in Supplementary Material SM4.

We retrieved the reference genome information for *A. gambiae* from VectorBase (Giraldo-Calderón et al.
490 2015), including the genome assembly (PEST, AgamP4 version), gene annotation coordinates in GFF format
(AgamP4.9) and gene names and descriptions.

492 **Genotype-phenotype association in Côte d'Ivoire *A. coluzzii* genomes**

As part of *Anopheles gambiae* 1000 Genomes Phase 2, 71 *A. coluzzii* specimens from Côte d'Ivoire were
494 collected and phenotyped for pirimiphos-methyl resistance before whole-genome sequencing (The
Anopheles gambiae 1000 Genomes Consortium 2019). These samples were collected as larvae in rice fields
496 near Tiassalé (coordinates: -4.823, 5.898) between May and September 2012, and were identified as *A.*
coluzzii based on PCR assay (Fanello et al. 2002). The 71 larvae were tested for resistance to pirimiphos-
498 methyl resistance using a WHO tube assay with 0.25% impregnated papers (World Health Organization
2018b), which led to the identification of 31 resistant (live) and 40 susceptible (dead) specimens.

500 We tested the association of these resistance phenotypes with various genetic variants present in *Ace1*
in this population. This includes the non-synonymous mutations *G280S* and *S65A*, the number of *Ace1*
502 copies, and the number of *280S* alleles in each individual sample (listed in Supplementary Material SM6A).

For the non-synonymous mutations, we assessed genotype-phenotype associations for each variant
504 independently using Fisher's exact test (*gmodels* R library (Warnes et al. 2018)) and estimated odds ratio
and 95% confidence intervals using the Woolf method with Haldane-Anscombe correction (*Prop.or* function

506 in the *pairwiseCI R* library (Schaarschmidt and Gerhard 2019)). For the *Ace1* and *280S* copy numbers, we used
used binomial generalised linear models (*glm* function in *R stats* library, family *binomial*) to obtain odds
508 ratio estimates for each of the four variables.

We also built a binomial generalised linear models with all four variables (*G280S* and *A65S* genotypes;
510 *Ace1* and *280S* copy number) and a step-wise procedure to remove non-informative variants from the
model (*step* function in *R stats* using $k = \log(n)$ as the degree of freedom, as required by the Bayesian
512 Information Criterion; n represents the number of samples in our dataset). The number of *Ace1* copies and
the number of mutated alleles were encoded as continuous variables, and the genotypes of *G280S* and *S65A*
514 were encoded as categorical variables. The performance of all generalised linear models was assessed
relative to a null model (intercept as the only variable) using a χ^2 test in an analysis of variance (*anova*
516 function in the *R stats* library). A detailed statistical analysis of all comparisons mentioned above can be
found in Supplementary Material SM6A and SM6B.

518 The number of *Ace1* copies in each genome of *Anopheles gambiae* 1000 Genomes Phase 2 was retrieved
from (Lucas et al. 2019). In that study, copy number states of multiple CNVs were inferred using a HMM-
520 based predictive model that took as input the normalised sequencing depth calculated along non-
overlapping 300 bp genomic windows.

522 The estimated number of *280S* alleles in each genome was estimated in the following manner: (i) we
retrieved the copy numbers of *Ace1* in each genome (C ; see above); (ii) we calculated the fraction of reads
524 supporting the reference and alternate alleles; and (iii) assigned the number of *280S* alleles (S) as the value
that minimised the difference between the fraction of alternate alleles and S/C , for all discrete S values
526 between 0 and C . For example, a genome with three *Ace1* copies ($C = 3$) and 30% of reads supporting *280S*
would carry one *280S* allele ($S = 1$), given that $S/C = 1/3 \approx 30\%$.

528 **Genotype-phenotype association in additional West African populations**

We collected 1080 female specimens of two species (*A. coluzzii* and *A. gambiae*) from six different
530 locations across West Africa (Côte d'Ivoire: Aboisso; Ghana: Madina, Korle-Bu, Weija and Obuasi; Togo:
Baguida). Species identity was determined using two methods designed to discriminate between *A.*
532 *gambiae*, *A. coluzzii* and *A. arabiensis*: a PCR of species-specific SINE insertion polymorphisms as described in

(Santolamazza et al. 2008), and a high-resolution melt curve analysis (Chabi et al. 2019). Details for each of
534 these methods, including primer sequences, are available in Supplementary Material SM6G. The complete
list of specimens, sampling times and locations, and species identification are available in Supplementary
536 Material SM6C and SM6E.

All 1080 specimens were phenotyped for pirimiphos-methyl resistance using a custom dose-response
538 assay with WHO standard tubes (World Health Organization 2018b). For the Aboisso (Côte d'Ivoire), Korle-
Bu, Weija and Madina samples, resistant specimens were determined as surviving a threshold
540 concentration of pirimiphos-methyl after exposure during the larval stage, and susceptible specimens
were identified as dead after a lower threshold dose (constant exposure time of 60 minutes). The exact
542 concentration thresholds for the dose-response assay were determined on a per-site basis, and are listed
in Supplementary Material SM6C. For example, *A. gambiae* from Aboisso were deemed resistant if they
544 survived a 1x concentration of pirimiphos-methyl (0.25%) for 60 minutes, and susceptible if they died at
0.5x concentration (0.125%). In the Obuasi (Ghana) and Baguida (Togo) populations, phenotypes were
546 determined according to survival after different exposure times (susceptible: dead after less than 45
minutes; resistant: alive after 45 minutes or more) using a single concentration of pirimiphos-methyl
548 (0.5x, 0.125%). The exact exposure time for each sample in intervals of 15 minutes are listed in
Supplementary Material SM6C.

550 Out of 1080 specimens, 909 could be assigned to one of the following populations, defined as
combinations of species and collection locations with determined resistance phenotypes: *A. coluzzii* from
552 Aboisso, Côte d'Ivoire ($n = 55$); *A. coluzzii* from Korle-Bu ($n = 214$), and Weija ($n = 131$), Ghana; *A. gambiae*
from Aboisso, Côte d'Ivoire ($n = 82$); *A. gambiae* from Baguida, Togo ($n = 102$); *A. gambiae* from Madina ($n =$
554 172), Obuasi ($n = 140$) and Weija ($n = 13$), Ghana.

For each sample, we determined the *G280S* genotype using a qPCR TaqMan assay as described by Bass *et*
556 *al.* (Bass et al. 2010) (list of samples in Supplementary Material SM6C), in which 280S- and 280G-specific
primers were labeled with different fluorescent dyes (FAM and HEX, respectively). We also calculated the
558 ratio of FAM-to-HEX fluorescent dye signal in heterozygotes, which label 280S and 280G alleles
respectively, as an index of the fraction of 280S allele copies (Edi et al. 2014a; Djogbénou et al. 2015).
560 Detailed methods for these two genotyping assays are available in Supplementary Material SM6G.

We assessed the association of *G280S* mutations with resistance for each of the populations listed above
562 using generalised linear models (*glm* function in *R stats* library, *binomial* family). The results from these
tests are available in Supplementary Material SM6D.

564 A sub-set of these 909 specimens ($n = 167$; listed in Supplementary Material SM6E) was also genotyped
for CNV polymorphisms in the *Ace1* locus using a qPCR assay and a combination of primers for *Ace1* and
566 two non-duplicated control genes (the *CYP4G16* AGAP001076; and the elongation factor AGAP005128).
Detailed methods for CNV genotyping assay are available in Supplementary Material SM6G and (Edi et al.
568 2014a). These samples were selected from the subset of heterozygotes in order to investigate the effect of
both CNVs and fraction of *280S* alleles on resistance.

570 We used generalised linear models (*glm* function in *R stats* library, *binomial* family) to assess the effect of
these two variables within each of the seven populations with available CNV data (three from *A. coluzzii*,
572 four from *A. gambiae*; listed in Table 2 and Supplementary Material SM6F). Then, we obtained the minimal
significant model for each population using a stepwise reduction procedure and the BIC criterion (*step*
574 function in the *R stats* library), and assessed their fit against a null model (intercept as the only variable)
with an analysis of variance and a χ^2 test (*anova* function in *R stats*). The results from these tests are
576 available in Supplementary Material SM6F.

Haplotype clustering and analysis of selection signals in *Ace1*

578 Haplotypes along chromosome arm 2R were reconstructed using the dataset of phased variants from
the *Anopheles gambiae* 1000 Genomes Phase 2 data. Specifically, we retained phased variants that were
580 biallelic, non-singletons and segregating in at least one population.

Given the paucity of phased variants within the *Ace1* gene body (Supplementary SM9A, B) and the
582 associated difficulties in phasing the *G280S* mutation itself, we analysed the haplotypes around nearby
genetically linked variants instead. To do so, we calculated the linkage disequilibrium between position
584 *G280S* and all variants located between positions 3416800 and 3659600 along 2R (i.e., 20kbp upstream and
downstream of the duplication breakpoints [3436800-3639600]). Linkage disequilibrium was estimated
586 from genotype counts in each sample using Rogers' and Huff *r* correlation statistic (Rogers and Huff
2009) as implemented in *scikit-allel* v1.1.10 library (*rogers_huff_r*) (Miles and Harding 2017). Then, we

588 retrieved all variants with $r > 0.95$ that were also present in the subset of phased variants (four in total).
These four linked variants had minor allele frequencies similar to that of 280S in Côte d'Ivoire (43%) and
590 were located in intergenic regions -26 kbp and +12 kbp of G280S (listed in Supplementary Material SM9C).

We retrieved haplotypes surrounding each of the four tagging variants and clustered them by
592 similarity using minimum spanning trees. Specifically, we retrieved phased variants ± 300 bp of each
tagging variant (retaining variants that were biallelic, non-singletons and segregating in at least one
594 population; these regions contained between 67 and 164 phased variants depending on the analysis;
Supplementary Material SM10). We used allele presence/absence data from each haplotype to build
596 minimum spanning trees of haplotypes based on Hamming distances (breaking edges for distances >1).
This distance matrix was then used to build medium spanning trees (*minimum_spanning_tree* function in
598 SciPy 1.1.0 Python library (Jones et al. 2019), from the *sparse.csgraph* submodule). Tree visualizations were
produced using the *graphviz* 2.38.0 Python library (Ellson et al.) and the *hapclust* library (Clarkson et al.
600 2018; Clarkson and Miles 2018), and clusters of haplotypes were color-coded according to the population of
origin or the presence/absence of the alternate allele (Supplementary Material SM10).

602 We used these trees to identify groups of highly similar haplotypes linked to the 280S or *wt* alleles in
Ace1 (Supplementary Material SM11). We calculated the profile of Garud's *H* statistics (*moving_garud_h*
604 function, *scikit-allele*) (Garud et al. 2015; Messer and Petrov 2013) and haplotype diversity
(*moving_haplotype_diversity* in *scikit-allele*) around the *Ace1* duplication region in windows of consecutive
606 variants (500 variants with 20% overlap). These calculations were performed separately for the main
groups of identical haplotypes (280S-linked or *wt*-linked) as identified around each of the tagging variants
608 (minimum size = 100 haplotypes). In addition, we calculated the averages of these same statistics in the
regions immediately upstream and downstream of the duplication breakpoints (2R:3436800 - 5000 bp and
610 2R:3639600 + 5000 bp, respectively), and we calculated standard errors of these estimates using sample
jack-knifing.

612 Finally, we calculated the rates of extended haplotype homozygosity decay for each cluster
(Supplementary Material SM12), using 10,000 phased variants upstream and downstream of the
614 duplication breakpoints (*ehh_decay* function in *scikit-allele*).

Introgression analysis

616 We used Patterson's *D* statistic (Durand et al. 2011; Patterson et al. 2012) to detect introgression
between *A. coluzzii* and *A. gambiae*. We retrieved the allele frequencies of all biallelic, non-singleton
618 variants from chromosome arm 2R that were segregating in West African populations where we had
identified *Ace1* duplications (namely: 75 *A. coluzzii* from Burkina Faso, 55 from Ghana, and 71 from Côte
620 d'Ivoire; and 92 *A. gambiae* from Burkina Faso, 12 from Ghana and 40 from Guinea; total $n = 345$ genomes)
(Lucas et al. 2019), as well as Central African populations that we used as non-admixed controls (78 *A.*
622 *coluzzii* from Angola; 69 *A. gambiae* from Gabon and 297 from Cameroon). In addition, we retrieved the
genotypes at the same variant positions for the populations of *A. arabiensis* (12 genomes), *A. quadriannulatus*
624 (10), *A. merus* (10) and *A. melas* (4) populations analysed in (Fontaine et al. 2015), which we used as
outgroups in the calculation of Patterson's *D*. In total, we retained ca. 12% of the 47,817,813 variants in 2R
626 in each analysis.

To determine whether duplicated and non-duplicated populations had different introgression patterns
628 in *Ace1*, we calculated windowed means of Patterson's *D* (length 5,000 variants, 20% step;
moving_patterson_d in *scikit-allel*) using various combinations of populations with and without the *Ace1*
630 duplication (Figure 5A). This test requires genotype frequencies in four populations (two ingroups A and B;
one candidate donor/receptor C with which A or B might have introgressed; and one unadmixed outgroup
632 O) branching in a (((A,B),C),O) topology (Figure 5A). We observed the following convention: (i) we used
West African *A. coluzzii* populations as A, discriminating between duplicated and non-duplicated
634 subpopulations; (ii) we used non-duplicated *A. coluzzii* from Angola as control B; (iii) we used various *A.*
gambiae populations as C, again analysing duplicated and non-duplicated specimens within each
636 population separately; and (iv) *A. arabiensis*, *A. quadriannulatus*, *A. merus* and *A. melas* as outgroup O.

For each combination of (((A,B),C),O) populations, we calculated the average *D* statistic within the
638 duplicated (position 3,436,800 to 3,639,600, spanning 202.8 kbp around *Ace1*), and estimated its deviation
from the null expectation (no introgression: $D = 0$) with a block-jackknife procedure (block length = 100
640 variants; *average_patterson_d* function in *scikit-allel*), which we used to estimate the standard error, Z-score
and the corresponding *p* value from the two-sided normal distribution (Supplementary Material SM13).

642 In parallel, we performed a phylogenomic analysis of the reconstructed haplotypes of the *Ace1* CNV
region (position 3436800 to 3639600) in the West African populations where duplications had been
644 identified (75 *A. coluzzii* from Burkina Faso, 55 from Ghana, and 71 from Côte d'Ivoire; and 92 *A. gambiae*
from Burkina Faso, 12 from Ghana and 40 from Guinea; total $n = 345$ genomes, 690 haplotypes). Specifically,
646 we built an alignment of phased variants along the duplication (2,787 positions) and computed a
Maximum-Likelihood phylogenetic tree using *IQ-TREE* 1.6.10 (Nguyen et al. 2015). We used the GTR
648 nucleotide substitution model with ascertainment bias correction, empirical state frequencies observed
from each alignment, and four gamma distribution (Γ) categories (*GTR+F+ASC+G4* model in *IQ-TREE*). This
650 model was selected by the *IQ-TREE* implementation of *ModelFinder* (Kalyaanamoorthy et al. 2017) (*TEST*
mode) as the best-fitting model according to the BIC criterion. The best-fitting tree was found after 22,000
652 iterations (correlation coefficient threshold = 0.99). We estimated node statistical supports from 1,000 UF
bootstraps (Hoang et al. 2018; Minh et al. 2013). Using the same approach, we built two additional
654 phylogenies from genomic regions located upstream and downstream of the duplication breakpoints
(3,935 and 3,302 variants extracted from 50 kbp segments located -1Mb and +1Mb), finding the best-fitting
656 trees after 7,659 and 27,400 iterations, respectively (correlation coefficient threshold = 0.99). The resulting
phylogenetic trees were plotted, unrooted, using the *phytools* 0.6-60 (Revell 2012) and *ape* 5.3 libraries
658 (*plot.phylo*) (Paradis and Schliep 2019). Phylogenies and source alignments are available as Supplementary
Material SM14 and SM15.

660 We also used allelic frequencies within the inversion to estimate the divergence times between
specimens carrying the duplication (both *A. gambiae* and *A. coluzzii*), *wt A. coluzzii* and *wt A. gambiae*. This
662 three-way calculation of divergence times reflects the amount of allele frequency change between one of
the three groups relative to the other two, and is therefore analogous to the population branch statistic
664 (Cavalli-Sforza 1969; Yi et al. 2010). Following this logic, we estimated separately (i) the branch length of *wt*
A. coluzzii relative to the separation of *wt A. gambiae* and the duplicated sequences, and (ii) the branch
666 length of *wt A. gambiae* relative to the separation of *wt A. coluzzii* and the duplicated sequences. We
performed these calculations in non-overlapping windows of 100 variants with the *pbs* function in *scikit-*
668 *allele*, and estimated standard errors using a block-jackknifing procedure.

Genetic differentiation in *A. coluzzii* from Côte d'Ivoire

670 We assessed the degree of genetic differentiation between resistant and susceptible *A. coluzzii* from Côte
d'Ivoire. We focused on non-singleton variants that were segregating in this population. In total, 8,431,869
672 out of 57,837,885 (14.57%) variants from chromosomes 2, 3 and X were retained for further analysis.

For each chromosome arm (2R, 2L, 3R and X), we calculated genotype counts in each subpopulation
674 (resistant and susceptible), and calculated their genetic differentiation using the Hudson's F_{ST} statistic
(Hudson et al. 1992; Bhatia et al. 2013) along non-overlapping windows of 1,000 variants (*moving_hudsonfst*
676 function in the *scikit-allel* v1.1.10 library (Miles and Harding 2017) from Python 3.4). We also calculated the
average F_{ST} in each chromosomal arm, with standard errors obtained from a block-jackknife procedure
678 (using non-overlapping windows of 1,000 variants; *average_hudsonfst* function).

We calculated the normalised population branching statistic (*PBS*) (Yi et al. 2010; Malaspinas et al. 2016)
680 in non-overlapping windows of 1,000 variants along each chromosomal arm (*pbs* function in *scikit-allel*).
using resistant and susceptible Ivorian *A. coluzzii* as test populations, and *A. coluzzii* from Angola as an
682 outgroup. Angolan *A. coluzzii* ($n = 78$) were selected as outgroup due to their relative isolation relative to
West African *A. coluzzii* populations (The *Anopheles gambiae* 1000 Genomes Consortium 2019; Miles et al.
684 2017) and their putatively naive profile of organophosphate resistance (Oxborough 2016; World Health
Organization 2018a). The distribution of *PBS* estimates along each chromosomal arm was standardised to
686 unit variance (*standardize* function in *scikit-allel*), and the resulting distribution of Z-scores was used to
derive a two-sided p -value that reflected extreme values of *PBS* (highly positive or negative). We corrected
688 for multiple testing using local estimation of false discovery rates (*fdrtool* function in the *fdrtool* 1.2.15 *R*
library (Klaus and Strimmer. 2015)). Finally, we selected genomic windows with high differentiation in
690 resistant specimens (standardised *PBS* > 0, significance threshold $FDR < 0.001$).

The estimates of *PBS* and Hudson's F_{ST} in each genomic window are available as Supplementary Material
692 SM7.

We performed a principal component analysis of resistant and susceptible Ivorian *A. coluzzii*. We first
694 obtained a set of genetically unlinked variants from chromosomal arms 3R and 3L (so as to avoid the
confounding effects of chromosomal inversions in arms 2R, 2L and X). We discarded linked variants within
696 500 bp consecutive windows (using a 200 bp step), using a Rogers and Huff's r threshold value of 0.1

(*locate_unlinked* function in *scikit-allel*), and repeated this process for ten iterations for each chromosome
698 arm. This filtering procedure resulted in 791 genetically unlinked variants from both chromosomal arms.
We used the alternate allele count in each variant to construct a PCA using singular value decomposition
700 (*pca* function from *scikit-allel*), and scaling the resulting coordinates using Patterson's procedure (Patterson
et al. 2006).

702 ***k*-mer enrichment analysis in *A. coluzzii* from Côte d'Ivoire**

We obtained *k*-mer counts for each of the 71 *A. coluzzii* samples using the *count* function in *jellyfish* v.
704 2.2.10 (Marçais and Kingsford 2011), using a $k = 31$ bp (parameters: `-C -m 31 --out-counter-len 2 -s 300M --bf-size`
`10G`). To reduce the computer memory footprint of the *k*-mer count tables, the *k*-mer strings were recoded
706 as integers, split into separate lexicographical groups according to the leading nucleotides (i.e. *k*-mers
beginning with AAA, AAC, etc. were assigned to different groups), and, within each set, sorted
708 lexicographically again. In total, we recorded the frequency of 1,734,834,987 *k*-mers across 71 samples. The
resulting count tables were filtered to retain *k*-mers showing variation in the population: we discarded *k*-
710 mers present in fewer than 3 samples, or absent in fewer than 3 samples. These filters removed
967,274,879 *k*-mers, leaving 767,560,108 *k*-mers for further analysis.

712 To test whether the frequencies of any *k*-mers were associated with pirimiphos-methyl resistance,
normalised *k*-mer frequencies were obtained by dividing the *k*-mer counts by the total number of variant
714 *k*-mers in each sample. We calculated the Spearman's rank correlation of each *k*-mer frequency with the
resistance phenotype for each of the 767,560,108 *k*-mers (*cor.test* function in the *R stats* library (R Core
716 Team 2017)), correcting for multiple testing using local estimation of false discovery rates (*fdrtool* function
in *fdrtool* library (Klaus and Strimmer. 2015)), and using a significance threshold of $FDR < 0.001$.

718 Given that multiple *k*-mers can overlap a single mutation, it was likely that many of the *k*-mers
identified as significant were overlapping. We therefore took the *k*-mers that showed a significant
720 association with pirimiphos-methyl resistance and assembled them by joining any *k*-mers that overlapped
perfectly over at least 10 bp. The resulting assembled *k*-mers were aligned against the *A. gambiae* reference
722 genome using *bwa mem* version 0.7.12-r1034 (parameters: `-T 0`) (Li and Durbin 2009). The mapping
coordinates and sequences of the significant assembled *k*-mers are available in Supplementary Material

724 SM8.

A minority of assembled *k*-mers aligned in regions other than the *Ace1* duplication. To determine
726 whether this was due to mis-alignment, we correlated the frequency of these assembled *k*-mers in each
sample against the *Ace1* copy number. Frequency for each assembled *k*-mer was calculated as the mean
728 normalised frequency of all the *k*-mers that were used in its assembly. Because these *k*-mers and the *Ace1*
copy number share the property of being correlated with pirimiphos-methyl resistance phenotype, they
730 are statistically likely to have correlated frequencies even if physically unlinked. To control for this, the
residuals of *k*-mer frequency and *Ace1* copy number were calculated within each of the resistant and
732 susceptible groups of samples. Pearson's correlation was then calculated on these residuals for each of the
assembled *k*-mers (available in Supplementary Material SM8C).

734 Scripts to reproduce the *k*-mer analysis steps described above (counting, filtering, significance testing,
assembly, mapping, and *Ace1* correlation analysis) are available on Github (see Availability of data and
736 materials).

Alignment and phylogenetic analysis of ACE proteins in animals

738 To obtain a candidate list of homologs of the *Ace1* gene, we retrieved all genes belonging to the
orthogroup 339133at33208 from OrthoDB (Kriventseva et al. 2019) (682 genes in total). We aligned these
740 candidates to a curated database of predicted proteomes from 89 complete animal genomes (listed in
Supplementary Material SM2, including data sources) using Diamond 0.9.22.123 (Buchfink et al. 2014), and
742 retained all alignments with an identity >95% to any of the candidate queries (130 genes). Next, we
performed a multi-sequence alignment with MAFFT 7.310 (1,000 rounds of iterative refinement, L-INS-i
744 algorithm) (Kato and Standley 2013) of these 130 genes, together with the truncated sequence of the
Pacific electric ray *Torpedo californica* protein used for its crystal structure analysis (PDB accession number:
746 1W75) and the full-sequence of the ortholog from its close relative *T. marmorata* (Uniprot accession
number: P07692). This alignment (n=132 genes) was trimmed position-wise using trimAL 1.4 (Capella-
748 Gutiérrez et al. 2009) (*automated1* mode), and 277 conserved columns were retained. A maximum-
likelihood phylogenetic analysis of the trimmed alignment was then performed using IQ-TREE 1.6.10
750 (Nguyen et al. 2015), using a LG substitution matrix (Le and Gascuel 2008) with four Γ categories and

accounting for invariant sites (*LG+I+G4* model). *IQ-TREE* was run for 469 iterations until convergence was
752 attained (correlation coefficient ≥ 0.99). Node statistical supports were calculated using the UF bootstrap
procedure (1,000 replicates) (Hoang et al. 2018; Minh et al. 2013). Alignment visualizations (Supplementary
754 Material SM1) were obtained from Geneious 11.1.4 (Geneious 2019). Complete alignments are available as
Supplementary Material SM2.

756 **Availability of data and materials**

Python 3.4.7 and *R* 3.6.2 scripts to reproduce the main analyses from the paper are available in the
758 following Github repository: github.com/xgrau/ace1-anopheles-report.

All genome variation data has been obtained from the publicly available repositories of the *Anopheles*
760 *gambiae* 1000 Genomes project (Phase 2 AR1) (The *Anopheles gambiae* 1000 Genomes Consortium 2017):
<https://www.malariagen.net/data/ag1000g-phase-2-ar1> (download instructions can be found in the
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774 **Competing interests**

The authors declare no conflicts of interest.

776 References

- 778 Abong'o B, Gimnig JE, Torr SJ, Longman B, Omoke D, Muchoki M, ter Kuile F, Ochomo E, Munga S, Samuels
AM, et al. 2020. Impact of indoor residual spraying with pirimiphos-methyl (Actellic 300CS) on
780 entomological indicators of transmission and malaria case burden in Migori County, western Kenya.
Sci Rep **10**: 1–14.
- 782 Ahoua Alou LP, Koffi AA, Adja MA, Tia E, Kouassi PK, Koné M, Chandre F. 2010. Distribution of ace-1R and
resistance to carbamates and organophosphates in *Anopheles gambiae* s.s. populations from Côte
d'Ivoire. *Malar J* **9**: 167.
- 784 Alout H, Berthomieu A, Cui F, Tan Y, Berticat C, Qiao C, Weill M. 2007. Different Amino-Acid Substitutions
Confer Insecticide Resistance Through Acetylcholinesterase 1 Insensitivity in *Culex vishnui* and *Culex*
786 *tritaeniorhynchus* (Diptera: Culicidae) from China. *J Med Entomol* **44**: 463–469.
- 788 Assogba BS, Alout H, Koffi A, Penetier C, Djogbénou LS, Makoundou P, Weill M, Labbé P. 2018. Adaptive
deletion in resistance gene duplications in the malaria vector *Anopheles gambiae*. *Evol Appl* **11**: 1245–
1256.
- 790 Assogba BS, Djogbénou LS, Milesi P, Berthomieu A, Perez J, Ayala D, Chandre F, Makoutodé M, Labbé P,
Weill M. 2015. An ace-1 gene duplication resorbs the fitness cost associated with resistance in
792 *Anopheles gambiae*, the main malaria mosquito. *Sci Rep* **5**: 14529.
- 794 Assogba BS, Milesi P, Djogbénou LS, Berthomieu A, Makoundou P, Baba-Moussa LS, Fiston-Lavier A-S,
Belkhir K, Labbé P, Weill M. 2016. The ace-1 Locus Is Amplified in All Resistant *Anopheles gambiae*
Mosquitoes: Fitness Consequences of Homogeneous and Heterogeneous Duplications ed. N. Barton.
796 *PLOS Biol* **14**: e2000618.
- 798 Bass C, Nikou D, Vontas J, Williamson MS, Field LM. 2010. Development of high-throughput real-time PCR
assays for the identification of insensitive acetylcholinesterase (ace-1R) in *Anopheles gambiae*. *Pestic*
Biochem Physiol **96**: 80–85.
- 800 Bhatia G, Patterson N, Sankararaman S, Price AL. 2013. Estimating and interpreting FST: The impact of rare
variants. *Genome Res* **23**: 1514–1521.
- 802 Bourguet D, Roig A, Toutant JP, Arpagaus M. 1997. Analysis of molecular forms and pharmacological
properties of acetylcholinesterase in several mosquito species. *Neurochem Int* **31**: 65–72.
- 804 Buchfink B, Xie C, Huson DH. 2014. Fast and sensitive protein alignment using DIAMOND. *Nat Methods* **12**:
59–60.
- 806 Capella-Gutiérrez S, Silla-Martínez JM, Gabaldón T. 2009. trimAl: a tool for automated alignment trimming

in large-scale phylogenetic analyses. *Bioinformatics* **25**: 1972–3.

- 808 Cavalli-Sforza L. 1969. Human Diversity. In *Proceedings of the 12th International Congress o Genetics*, pp. 405–
416.
- 810 Chabi J, Van't Hof A, N'dri LK, Datsomor A, Okyere D, Njoroge H, Pipini D, Hadi MP, De Souza DK, Suzuki T,
et al. 2019. Rapid high throughput SYBR green assay for identifying the malaria vectors *Anopheles*
812 *arabiensis*, *Anopheles coluzzii* and *Anopheles gambiae* s.s. Giles. *PLoS One* **14**: e0215669.
- Cheung J, Mahmood A, Kalathur R, Liu L, Carlier PR. 2018. Structure of the G119S Mutant
814 Acetylcholinesterase of the Malaria Vector *Anopheles gambiae* Reveals Basis of Insecticide
Resistance. *Structure* **26**: 130-136.e2.
- 816 Chukwuekezie O, Nwosu E, Nwangwu U, Dogunro F, Onwude C, Agashi N, Ezihe E, Anioke C, Anokwu S, Eloy
E, et al. 2020. Resistance status of *Anopheles gambiae* (s.l.) to four commonly used insecticides for
818 malaria vector control in South-East Nigeria. *Parasites and Vectors* **13**.
- Cingolani P, Platts A, Wang LL, Coon M, Nguyen T, Wang L, Land SJ, Lu X, Ruden DM. 2012. A program for
820 annotating and predicting the effects of single nucleotide polymorphisms, SnpEff: SNPs in the
genome of *Drosophila melanogaster* strain w1118; iso-2; iso-3. *Fly (Austin)* **6**: 80–92.
- 822 Clarkson C, Miles A. 2018. Hapclust. <https://github.com/malariagen/agam-vgsc-report>.
- Clarkson CS, Miles A, Harding NJ, Weetman D, Kwiatkowski D, Donnelly M, The *Anopheles gambiae* 1000
824 Genomes Consortium. 2018. The genetic architecture of target-site resistance to pyrethroid
insecticides in the African malaria vectors *Anopheles gambiae* and *Anopheles coluzzii*. *BioRxiv*.
- 826 Dabiré KR, Diabaté A, Namontougou M, Djogbenou L, Kengne P, Simard F, Bass C, Baldet T. 2009.
Distribution of insensitive acetylcholinesterase (ace-1R) in *Anopheles gambiae* s.l. populations from
828 Burkina Faso (West Africa). *Trop Med Int Heal* **14**: 396–403.
- Dabiré RK, Namontougou M, Diabaté A, Soma DD, Bado J, Toé HK, Bass C, Combarry P. 2014. Distribution
830 and Frequency of *kdr* Mutations within *Anopheles gambiae* s.l. Populations and First Report of the
Ace.1G119S Mutation in *Anopheles arabiensis* from Burkina Faso (West Africa) ed. B. Brooke. *PLoS One*
832 **9**: e101484.
- Delaneau O, Howie B, Cox AJ, Zagury JF, Marchini J. 2013. Haplotype estimation using sequencing reads. *Am*
834 *J Hum Genet* **93**: 687–696.
- Dengela D, Seyoum A, Lucas B, Johns B, George K, Belemvire A, Caranci A, Norris LC, Fornadel CM. 2018.
836 Multi-country assessment of residual bio-efficacy of insecticides used for indoor residual spraying in
malaria control on different surface types: results from program monitoring in 17 PMI/USAID-
838 supported IRS countries. *Parasit Vectors* **11**: 71.

- 840 Djogbénou L, Chandre F, Berthomieu A, Dabiré R, Koffi A, Alout H, Weill M. 2008. Evidence of Introgression
of the ace-1R Mutation and of the ace-1 Duplication in West African *Anopheles gambiae* s. s. ed. D.A.
Carter. *PLoS One* **3**: e2172.
- 842 Djogbénou LS, Assogba B, Essandoh J, Constant EA V., Makoutodé M, Akogbéto M, Donnelly MJ, Weetman
D. 2015. Estimation of allele-specific Ace-1 duplication in insecticide-resistant *Anopheles* mosquitoes
844 from West Africa. *Malar J* **14**: 507.
- Durand EY, Patterson N, Reich D, Slatkin M. 2011. Testing for Ancient Admixture between Closely Related
846 Populations. *Mol Biol Evol* **28**: 2239–2252.
- Edi C V., Djogbénou L, Jenkins AM, Regna K, Muskavitch MAT, Poupardin R, Jones CM, Essandoh J, Kétouh
848 GK, Paine MJI, et al. 2014a. CYP6 P450 Enzymes and ACE-1 Duplication Produce Extreme and Multiple
Insecticide Resistance in the Malaria Mosquito *Anopheles gambiae* ed. J. Zhang. *PLoS Genet* **10**:
850 e1004236.
- Edi CA V, Koudou BG, Bellai L, Adja AM, Chouaibou M, Bonfoh B, Barry SJE, Johnson PCD, Müller P, Dongus
852 S, et al. 2014b. Long-term trends in *Anopheles gambiae* insecticide resistance in Côte d'Ivoire. *Parasit
Vectors* **7**: 500.
- 854 Ellson J, Gansner E, Hu Y, Janssen E, North S. Graphviz - Graph Visualization Software.
<https://www.graphviz.org/about/>.
- 856 Essandoh J, Yawson AE, Weetman D. 2013. Acetylcholinesterase (Ace-1) target site mutation 119S is
strongly diagnostic of carbamate and organophosphate resistance in *Anopheles gambiae* s.s. and
858 *Anopheles coluzzii* across southern Ghana. *Malar J* **12**: 404.
- Fanello C, Santolamazza F, Della Torre A. 2002. Simultaneous identification of species and molecular forms
860 of the *Anopheles gambiae* complex by PCR-RFLP. *Med Vet Entomol* **16**: 461–464.
- Feng X, Yang C, Yang Y, Li J, Lin K, Li M, Qiu X. 2015. Distribution and frequency of G119S mutation in ace-1
862 gene within *Anopheles sinensis* populations from Guangxi, China. *Malar J* **14**: 470.
- Feyereisen R, Dermauw W, Van Leeuwen T. 2015. Genotype to phenotype, the molecular and physiological
864 dimensions of resistance in arthropods. *Pestic Biochem Physiol* **121**: 61–77.
- Fontaine MC, Pease JB, Steele A, Waterhouse RM, Neafsey DE, Sharakhov I V., Jiang X, Hall AB, Catteruccia
866 F, Kakani E, et al. 2015. Extensive introgression in a malaria vector species complex revealed by
phylogenomics. *Science* **347**: 1258524.
- 868 Garud NR, Messer PW, Buzbas EO, Petrov DA. 2015. Recent Selective Sweeps in North American *Drosophila
melanogaster* Show Signatures of Soft Sweeps ed. G.P. Copenhaver. *PLoS Genet* **11**: e1005004.

- 870 Geneious. 2019. Geneious. www.geneious.com.
- Giraldo-Calderón GI, Emrich SJ, MacCallum RM, Maslen G, Dialynas E, Topalis P, Ho N, Gesing S, Madey G,
872 Collins FH, et al. 2015. VectorBase: an updated bioinformatics resource for invertebrate vectors and
other organisms related with human diseases. *Nucleic Acids Res* **43**: D707–D713.
- 874 Greenblatt HM, Guillou C, Guénard D, Argaman A, Botti S, Badet B, Thal C, Silman I, Sussman JL. 2004. The
complex of a bivalent derivative of galanthamine with torpedo acetylcholinesterase displays drastic
876 deformation of the active-site gorge: implications for structure-based drug design. *J Am Chem Soc* **126**:
15405–11.
- 878 Hoang DT, Chernomor O, von Haeseler A, Minh BQ, Vinh LS. 2018. UFBoot2: Improving the Ultrafast
Bootstrap Approximation. *Mol Biol Evol* **35**: 518–522.
- 880 Hudson RR, Slatkin M, Maddison WP. 1992. Estimation of levels of gene flow from DNA sequence data.
Genetics **132**: 583–9.
- 882 Jones E, Oliphant T, Peterson P, others. 2019. SciPy: Open source scientific tools for Python.
- Kalyanamoorthy S, Minh BQ, Wong TKF, Von Haeseler A, Jermin LS. 2017. ModelFinder: Fast model
884 selection for accurate phylogenetic estimates. *Nat Methods* **14**: 587–589.
- Katoh K, Standley DM. 2013. MAFFT multiple sequence alignment software version 7: improvements in
886 performance and usability. *Mol Biol Evol* **30**: 772–80.
- Kisinja WN, Nkya TE, Kabula B, Overgaard HJ, Massue DJ, Mageni Z, Greer G, Kaspar N, Mohamed M,
888 Reithinger R, et al. 2017. Multiple insecticide resistance in *Anopheles gambiae* from Tanzania: A
major concern for malaria vector control. *Malar J* **16**: 439.
- 890 Klaus B, Strimmer K. 2015. fdrtool: Estimation of (Local) False Discovery Rates and Higher Criticism.
- Kriventseva E V, Kuznetsov D, Tegenfeldt F, Manni M, Dias R, Simão FA, Zdobnov EM. 2019. OrthoDB v10:
892 sampling the diversity of animal, plant, fungal, protist, bacterial and viral genomes for evolutionary
and functional annotations of orthologs. *Nucleic Acids Res* **47**: D807–D811.
- 894 Labbé P, Berthomieu A, Berticat C, Alout H, Raymond M, Lenormand T, Weill M. 2007. Independent
Duplications of the Acetylcholinesterase Gene Conferring Insecticide Resistance in the Mosquito
896 *Culex pipiens*. *Mol Biol Evol* **24**: 1056–1067.
- Le SQ, Gascuel O. 2008. An improved general amino acid replacement matrix. *Mol Biol Evol* **25**: 1307–20.
- 898 Li H, Durbin R. 2009. Fast and accurate short read alignment with Burrows-Wheeler transform.
Bioinformatics **25**: 1754–1760.
- 900 Liebman KA, Pinto J, Valle J, Palomino M, Vizcaino L, Brogdon W, Lenhart A. 2015. Novel mutations on the

- ace-1 gene of the malaria vector *Anopheles albimanus* provide evidence for balancing selection in an
902 area of high insecticide resistance in Peru. *Malar J* **14**: 74.
- Lucas ER, Miles A, Harding NJ, Clarkson CS, Lawniczak MKN, Kwiatkowski DP, Weetman D, Donnelly MJ.
904 2019. Whole-genome sequencing reveals high complexity of copy number variation at insecticide
resistance loci in malaria mosquitoes. *Genome Res* **29**: 1250–1261.
- 906 Malaspinas AS, Westaway MC, Muller C, Sousa VC, Lao O, Alves I, Bergström A, Athanasiadis G, Cheng JY,
Crawford JE, et al. 2016. A genomic history of Aboriginal Australia. *Nature* **538**: 207–214.
- 908 Marçais G, Kingsford C. 2011. A fast, lock-free approach for efficient parallel counting of occurrences of k-
mers. *Bioinformatics* **27**: 764–770.
- 910 Messer PW, Petrov DA. 2013. Population genomics of rapid adaptation by soft selective sweeps. *Trends Ecol
Evol* **28**: 659–669.
- 912 Miles A, Harding N. 2017. scikit-allele. <https://github.com/cggh/scikit-allele>.
- Miles A, Harding NJ, Bottà G, Clarkson CS, Antão T, Kozak K, Schrider DR, Kern AD, Redmond S, Sharakhov
914 I, et al. 2017. Genetic diversity of the African malaria vector *Anopheles gambiae*. *Nature* **552**: 96–100.
- Minh BQ, Nguyen MAT, von Haeseler A. 2013. Ultrafast approximation for phylogenetic bootstrap. *Mol Biol
916 Evol* **30**: 1188–95.
- Nguyen L-TT, Schmidt HA, Von Haeseler A, Minh BQ. 2015. IQ-TREE: a fast and effective stochastic
918 algorithm for estimating maximum-likelihood phylogenies. *Mol Biol Evol* **32**: 268–274.
- Oakeshott JG, Devonshire AL, Claudianos C, Sutherland TD, Horne I, Campbell PM, Ollis DL, Russell RJ. 2005.
920 Comparing the organophosphorus and carbamate insecticide resistance mutations in cholin- and
carboxyl-esterases. In *Chemico-Biological Interactions*, Vol. 157–158 of, pp. 269–275.
- 922 Oxborough RM. 2016. Trends in US President’s Malaria Initiative-funded indoor residual spray coverage
and insecticide choice in sub-Saharan Africa (2008–2015): urgent need for affordable, long-lasting
924 insecticides. *Malar J* **15**: 146.
- Oxborough RM, Seyoum A, Yihdego Y, Dabire R, Gnanguenon V, Wat’Senga F, Agossa FR, Yohannes G,
926 Coleman S, Samdi LM, et al. 2019. Susceptibility testing of *Anopheles* malaria vectors with the
neonicotinoid insecticide clothianidin; Results from 16 African countries, in preparation for indoor
928 residual spraying with new insecticide formulations. *Malar J* **18**: 264.
- Paradis E, Schliep K. 2019. ape 5.0: an environment for modern phylogenetics and evolutionary analyses in
930 R ed. R. Schwartz. *Bioinformatics* **35**: 526–528.
- Patterson N, Moorjani P, Luo Y, Mallick S, Rohland N, Zhan Y, Genschoreck T, Webster T, Reich D. 2012.

- 932 Ancient Admixture in Human History. *Genetics* **192**: 1065–1093.
- Patterson N, Price AL, Reich D. 2006. Population Structure and Eigenanalysis. *PLoS Genet* **2**: e190.
- 934 R Core Team. 2017. R: A Language and Environment for Statistical Computing.
- Rahman A, Hallgrímsdóttir I, Eisen M, Pachter L. 2018. Association mapping from sequencing reads using
936 k-mers. *Elife* **7**.
- Ranson H, N’Guessan R, Lines J, Moiroux N, Nkuni Z, Corbel V. 2011. Pyrethroid resistance in African
938 anopheline mosquitoes: what are the implications for malaria control? *Trends Parasitol* **27**: 91–98.
- Revell LJ. 2012. phytools: an R package for phylogenetic comparative biology (and other things). *Methods*
940 *Ecol Evol* **3**: 217–223.
- Rogers AR, Huff C. 2009. Linkage disequilibrium between loci with unknown phase. *Genetics* **182**: 839–44.
- 942 Santolamazza F, Mancini E, Simard F, Qi Y, Tu Z, della Torre A. 2008. Insertion polymorphisms of SINE200
retrotransposons within speciation islands of *Anopheles gambiae* molecular forms. *Malar J* **7**: 163.
- 944 Schaarschmidt F, Gerhard D. 2019. pairwiseCI: Confidence Intervals for Two Sample Comparisons.
- Sherrard-Smith E, Griffin JT, Winskill P, Corbel V, Pannetier C, Djénontin A, Moore S, Richardson JH, Müller
946 P, Edi C, et al. 2018. Systematic review of indoor residual spray efficacy and effectiveness against
Plasmodium falciparum in Africa. *Nat Commun* **9**: 4982.
- 948 The *Anopheles gambiae* 1000 Genomes Consortium. 2017. Ag1000G Phase 2 AR1 data release. *MalariaGEN*.
<https://www.malariagen.net/data/ag1000g-phase-2-ar1>.
- 950 The *Anopheles gambiae* 1000 Genomes Consortium. 2019. Genome variation and population structure among
1,142 mosquitoes of the African malaria vector species *Anopheles gambiae* and *Anopheles coluzzii*.
952 *bioRxiv* 864314.
- van den Berg H, Zaim M, Yadav RS, Soares A, Ameneshewa B, Mnzava A, Hii J, Dash AP, Ejov M. 2012. Global
954 Trends in the Use of Insecticides to Control Vector-Borne Diseases. *Environ Health Perspect* **120**: 577–
582.
- 956 Van der Auwera GA, Carneiro MO, Hartl C, Poplin R, del Angel G, Levy-Moonshine A, Jordan T, Shakir K,
Roazen D, Thibault J, et al. 2013. From fastQ data to high-confidence variant calls: The genome
958 analysis toolkit best practices pipeline. *Curr Protoc Bioinforma* **11**: 11.10.1.
- Wagman J, Gogue C, Tynuv K, Mihigo J, Bankineza E, Bah M, Diallo D, Saibu A, Richardson JH, Kone D, et al.
960 2018. An observational analysis of the impact of indoor residual spraying with non-pyrethroid
insecticides on the incidence of malaria in Ségou Region, Mali: 2012-2015. *Malar J* **17**.

- 962 Warnes GR, Bolker B, Lumley T, from Randall C. Johnson are Copyright SAIC-Frederick RCJC, by the
Intramural Research Program IF, of the NIH, Institute NC, for Cancer Research under NCI Contract
964 NO1-CO-12400. C. 2018. *gmodels: Various R Programming Tools for Model Fitting*.
- Weetman D, Donnelly MJ. 2015. Evolution of insecticide resistance diagnostics in malaria vectors. *Trans R*
966 *Soc Trop Med Hyg* **109**: 291–3.
- Weetman D, Mitchell SN, Wilding CS, Birks DP, Yawson AE, Essandoh J, Mawejje HD, Djogbenou LS, Steen K,
968 Rippon EJ, et al. 2015. Contemporary evolution of resistance at the major insecticide target site gene
Ace-1 by mutation and copy number variation in the malaria mosquito *Anopheles gambiae*. *Mol Ecol* **24**:
970 2656–2672.
- Weill M, Lutfalla G, Mogensen K, Chandre F, Berthomieu A, Berticat C, Pasteur N, Philips A, Fort P,
972 Raymond M. 2003. Insecticide resistance in mosquito vectors. *Nature* **423**: 136–137.
- Weill M, Malcolm C, Chandre F, Mogensen K, Berthomieu A, Marquine M, Raymond M. 2004. The unique
974 mutation in *ace-1* giving high insecticide resistance is easily detectable in mosquito vectors. *Insect*
Mol Biol **13**: 1–7.
- 976 World Health Organization. 2018a. *Global report on insecticide resistance in malaria vectors: 2010–2016*. Genève.
World Health Organization. 2013. *Report of the Sixteenth WHOPES Working Group Meeting*. Genève.
- 978 World Health Organization. 2018b. *Test procedures for insecticide resistance monitoring in malaria vector*
mosquitoes. 2nd ed. World Health Organization, Genève.
- 980 Yi X, Liang Y, Huerta-Sanchez E, Jin X, Cuo ZXP, Pool JE, Xu X, Jiang H, Vinckenbosch N, Korneliussen
TS, et al. 2010. Sequencing of 50 Human Exomes Reveals Adaptation to High Altitude. *Science* **329**: 75–78.

982

Supplementary Material legends

984 **Supplementary Material SM1. Homology of *Ace1* mutations. A)** Alignment of ACE homologs (protein
sequences) in selected species (*A. gambiae*, *Culex quinquefasciatus*, *Aedes aegypti*, *Homo sapiens*, and *Torpedo*
986 *californica*), used to determine the homology of non-synonymous mutations in this gene (*A65S* and *G280S*
are highlighted). **B)** Alignment of ACE protein homologs in 20 culicine species, focusing on the vicinity of
988 codon 280 (highlighted). **C)** Maximum-Likelihood phylogenetic analysis of ACE homologs from 89 animals
(listed in Supplementary Material SM2, including data sources and accession numbers).

990 **Supplementary Material SM2. Alignments of ACE homologs. A)** Peptide coordinates of *A. gambiae Ace1*
codon 280 in orthologs of *Ace1* from 89 animal genomes. **B)** Alignment of *Ace1* homologs from 89 animal
992 genomes. **C)** Data sources, accession numbers, species abbreviation and taxonomy of the 89 animal
genomes used in the analysis of ACE homology.

994 **Supplementary Material SM3. *Ace1* mutations.** Coordinates of non-synonymous mutations in *Ace1* and
frequencies in each population of the *Anopheles gambiae* 1000 Genomes Phase 2 dataset. Species codes: *A.*
996 *gambiae*, gam, *A. coluzzii*, col. Population codes: Angola, AOcol; Burkina-Faso, BFcol and BFgam; Côte
d'Ivoire, CIcol; Cameroon, CMgam; Mayotte, FRgam; Gabon, GAgam; Ghana, GHcol and GHgam; The
998 Gambia, GM; Guinea, GNcol and GNgam; Equatorial Guinea, GQgam; Guinea-Bissau, GW; Kenya, KE; Uganda,
UGgam.

1000 **Supplementary Material SM4. Samples from *Ag1000G* Phase 2.** List of samples from the *Anopheles gambiae*
1000 Genomes Phase 2 dataset with accession numbers, sample metadata (population and region of origin,
1002 collection date, species, sex), and summary of the main *Ace1* mutations in each sample (genotypes in the
G280S mutation, number of reads supporting *280G* and *280S* alleles, number of CNVs). CNV coordinates and
1004 copy number from Lucas *et al.* (2019).

Supplementary Material SM5. Genes in *Ace1* duplication. List of genes in the *Ace1* duplication region,
1006 with genomic coordinates along the 2R chromosomal arm.

Supplementary Material SM6. Phenotype-genotype association analyses. A) Genotypes of *G280S* and
1008 *A65S* mutations in *A. coluzzii* samples from Côte d'Ivoire (*Anopheles gambiae* 1000 Genomes Phase 2), and

resistance phenotype to pirimiphos-methyl. **B)** Phenotype-genotype association tests for the 71 Ivorian *A. coluzzii* samples. Includes summaries of single-variable GLM models for the following variables: 280S presence (including a subset of samples with only one 280S allele), 65S, CNV and number of 280S alleles. Also includes the minimal model obtained using stepwise reduction of a starting multi-variable model (BIC criterion). Model significance is measured with ANOVA comparison with null model (no variables) and a χ^2 test. **C)** G280S genotypes and pirimiphos-methyl resistance phenotype for 1080 mosquitoes from West African populations of *A. gambiae* and *A. coluzzii* collected from six locations. For each sample, we also report collection dates, geographical locations, and details of the species identification, genotyping, and phenotyping (concentrations, exposure time). **D)** Phenotype-genotype association tests for G280S alleles in eight West African populations. Includes summaries of GLM models for each population. Model significance is measured with ANOVA comparison with null model (no variables) and a χ^2 test. **E)** Number of *Ace1* copies and pirimiphos-methyl resistance phenotypes for 167 mosquitoes from the same West African populations. **F)** Phenotype-genotype association tests for CNV mutations (*Ace1* copies [CNV] and 280S-to-280G allele ratio [ratio_FAM_HEX]) in West African populations. Includes summaries of GLM models for each population and each variable separately, and a minimal GLM obtained using the BIC criterion from an initial model with both variables. Model significance is measured with ANOVA comparison with null model (no variables) and a χ^2 test. **G)** Protocols for species identification and *Ace1* mutation genotyping, including primer sequences.

Supplementary Material SM7. Genetic differentiation in Ivorian *A. coluzzii*. **A)** Genetic differentiation statistics (Hudson's F_{ST} and *PBS*) between resistant and susceptible *A. coluzzii* from Côte d'Ivoire, in windows of 10,000 variants along the genome. *PBS* values are calculated using Angolan *A. coluzzii* as outgroup, and we also report a Z-score and *p*-value derived from a two-sided normal distribution. **B)** Genes overlapping the regions of high *PBS* ($FDR < 0.001$ and standardised *PBS* > 0).

Supplementary Material SM8. k-mer analysis in Ivorian *A. coluzzii*. **A)** Alignment coordinates of *k*-mers that are significantly associated with pirimiphos-methyl resistance in Ivorian *A. coluzzii* samples from the *Anopheles gambiae* 1000 Genomes Phase 2. For each *k*-mer, we report the alignment sequence and coordinates, and whether it overlaps the *Ace1* gene or the *Ace1* duplication. This table includes both primary and secondary alignments as reported by *bwa mem*, as well as non-aligned *k*-mers (chromosome

“NA”). **B)** Correlation of alignment frequencies and *Ace1* copy number in each sample, for each of the 409 *k*-
1038 mers that mapped to chromosomal arms 2R, 2L, 3R, 3L or X. We report Pearson’s correlation coefficients
(*r*) and *p*-values. **C)** Sequences of the 446 assembled *k*-mers that are significantly associated with
1040 pirimiphos-methyl resistance. **D)** Frequencies of the 9,603 *k*-mers (before assembly) in each of the Côte
d’Ivoire *A. coluzzii* samples (*Anopheles gambiae* 1000 Genomes Phase 2, n=71).

1042 **Supplementary Material SM9. Identification of tagging variants for *Ace1* 280S.** **A)** Density of phased
variants in the *Ace1* duplication region, from *Anopheles gambiae* 1000 Genomes Phase 2. **B)** Density of phased
1044 variants within the *Ace1* duplication, focusing on the *Ace1* gene body. **C)** Linkage disequilibrium between
the *G280S* alleles and nearby phased variants (Huff and Roger’s *r*), highlighting the coordinates of four
1046 nearby variants tightly linked to *280S* alleles, and their frequencies in Côte d’Ivoire *A. coluzzii*. The four
linked and phased variants can be used to tag the *280S* haplotype.

1048 **Supplementary Material SM10. Haplotype networks around the *Ace1* tagging variants.** Minimum
spanning tree networks built from phased variants located around each of the four tagging variants
1050 (panels A to D). Each node in the network is colored according to its population composition (left panels)
or linkage to the *280S* or *wt* alleles in *Ace1* (right panels).

1052 **Supplementary Material SM11. Signals of selection in the *Ace1* duplication.** Garud *H* statistics and
haplotype diversity in *280S*-linked and *wt*-linked haplotypes in the genomic window around the *Ace1*
1054 duplication breakpoints, calculated for each of the main haplotype clusters defined around each of the
four tagging variants (panels A to D; haplotype clusters from Supplementary Material SM10). For each
1056 tagging variant and duplication breakpoint (upstream/downstream), we report the average value of each
statistic and standard errors from sample jack-knifing.

1058 **Supplementary Material SM12. Extended haplotype homozygosity in the *Ace1* duplication.** Extended
haplotype homozygosity (*EHH*) of *280S*-linked and *wt*-linked haplotypes in the genomic window around the
1060 *Ace1* duplication breakpoints, calculated for each of the main haplotype clusters defined around each of
the four tagging variants (panels A to D; haplotype clusters from Supplementary Material SM10). For each
1062 tagging variant and duplication breakpoint (upstream/downstream), we report the area under the *EHH*
curve (*a*) and the distance around the duplication breakpoint where *EHH*>0.05 and *EHH*>0.95.

1064 **Supplementary Material SM13. Introgression of the *Ace1* duplication.** Patterson *D* statistics to test
introgression of the *Ace1* duplication region between various populations of *A. coluzzii* (populations A/B), *A.*
1066 *gambiae* (populations C) and multiple outgroup species (population O). Specifically, we use *A. coluzzii* from
Côte d’Ivoire (Cicol), Ghana (GHcol) and Burkina-Faso (BFcol) with and without duplications (labelled as
1068 TRUE and FALSE respectively) as populations A; *A. coluzzii* from Angola as population B (always labelled as
FALSE); and various *A. gambiae* populations C from Ghana (GHgam), Burkina-Faso (BFgam), Guinea
1070 (GNgam), Gabon (GAgam) and Cameroon (CMgam) with and without duplications (TRUE and FALSE labels,
respectively); and four different outgroup species (panels A to D: *A. arabiensis*, *A. melas*, *A. merus* and *A.*
1072 *quadriannulatus*). For each comparison, we report the average *D* statistic from the *Ace1* duplicated region
with standard errors, and Z-scores and *p*-values derived from standardised *D* values (unit variance).

1074 **Supplementary Material SM14. Haplotype alignments. A)** Alignment of phased variants from within the
Ace1 duplication region (2R:3,436,800-3,639,600), using 345 samples from West African populations
1076 (*Anopheles gambiae* 1000 Genomes) with *Ace1* duplications (Guinea *A. gambiae*, Côte d’Ivoire *A. coluzzii*, Ghana
A. gambiae and *A. coluzzii*, Burkina Faso *A. gambiae* and *A. coluzzii*). **B)** Id., from a region upstream of the
1078 duplication (50 kbp starting at 3,436,800 – 1 Mb). **C)** Id., from a region downstream of the duplication (50
kbp starting at 3,639,600 + 1 Mb).

1080 **Supplementary Material SM15. Haplotype phylogenies.** Maximum-Likelihood phylogenetic analyses of
haplotypes from within the *Ace1* duplication (A), upstream (B) and downstream (C) regions. Trees are
1082 unrooted. Tips are color-coded according to duplication presence/absence and species. UF bootstrap
supports indicated in each node.