

RESEARCH ARTICLE

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Normal adult survival but reduced *Bemisia tabaci* oviposition rate on tomato lines carrying an introgression from *S. habrochaites*

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Abstract

Background: Host plant resistance has been proposed as one of the most promising approaches in whitefly management. Already in 1995 two quantitative trait loci (*Tv-1* and *Tv-2*) originating from *S. habrochaites* CGN1.1561 were identified that reduced the oviposition rate of the greenhouse whitefly (*Trialeurodes vaporariorum*). After this first study, several others identified QTLs affecting whitefly biology as well. Generally, the QTLs affecting oviposition were highly correlated with a reduction in whitefly survival and the presence of high densities of glandular trichomes type IV. The aim of our study was to further characterize *Tv-1* and *Tv-2*, and to determine their role in resistance against *Bemisia tabaci*.

Results: We selected F₂ plants homozygous for the *Tv-1* and *Tv-2* QTL regions and did three successive backcrosses without phenotypic selection. Twenty-three F₂BC₃ plants were phenotyped for whitefly resistance and differences were found in oviposition rate of *B. tabaci*. The F₂BC₃ plants with the lowest oviposition rate had an introgression on Chromosome 5 in common. Further F₂BC₄, F₂BC₄S₁ and F₂BC₄S₂ families were developed, genotyped and phenotyped for adult survival, oviposition rate and trichome type and density. It was possible to confirm that an introgression on top of Chr. 5 (*OR-5*), between the markers rs-2009 and rs-7551, was responsible for reducing whitefly oviposition rate.

Conclusion: We found a region of 3.06 Mbp at the top of Chr. 5 (*OR-5*) associated with a reduction in the oviposition rate of *B. tabaci*. This reduction was independent of the presence of the QTLs *Tv-1* and *Tv-2* as well as of the presence of trichomes type IV. The *OR-5* locus will provide new opportunities for resistance breeding against whiteflies, which is especially relevant in greenhouse cultivation.

Keywords: Whitefly, Life history traits, Fine mapping, *Tv-1*, *Tv-2*, Trichome type IV

Background

Tomato is one of the most important vegetables worldwide. It is host for a broad range of pathogens and pests. Among the pests affecting tomato production whiteflies are the most important in terms of costs and distribution. There are more than 1500 species of whiteflies [1], of which *Bemisia tabaci* Group Mediterranean-Middle East-Asia Minor I and *Trialeurodes vaporariorum* (Westwood) are the biggest threats in commercial tomato production. *Bemisia tabaci* affects tomato production directly (i.e.

phloem consumption, irregular ripening of the fruits) and indirectly (virus transmission) causing yield losses that can range from 50% to 100% of the potential production [2,3].

Among the possible control methods, host plant resistance has been proposed as one of the most promising for insect pest management [4,5]. Resistance to whiteflies was found in several wild relatives of tomato (*Solanum pennellii*, *S. habrochaites*, *S. lycopersicum* var. *cerasiforme*, *S. pimpinellifolium*, *S. galapagense*) [6-14]. In these species, whitefly resistance is associated with the presence of high densities of glandular trichomes (type I, IV and VI) and with the presence of specific secondary metabolites (a.o. 7-epizingiberene, 2-tridecanone, and acyl sugars) [14-17]. The species *S. habrochaites* contains accessions

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(formerly known as *Lycopersicon hirsutum* fr. *glabratum*) that accumulate methyl ketones, of which the synthesis is located in the glandular head of type VI trichomes [18-20]. *Solanum habrochaites* also contains accessions (formerly known as *Lycopersicon hirsutum* fr. *typicum*) that accumulate sesquiterpenes which are synthesised in type IV trichomes [17]. In *S. pennellii*, *S. pimpinellifolium* and *S. galapagense* the synthesis of acyl sugars is associated with the presence in high densities of trichomes type IV [12,15,16,21]. Although also some accessions of *S. cheesmaniae* accumulate high levels of acyl sugars, they lack type IV trichomes [14]. The *Mi1-2* gene, which confers resistance to several species of root-knot nematodes (*Meloidogyne* spp.) [22], plays a role in the resistance against insects, e.g. some isolates of potato aphid (*Macrosiphum euphorbiae* Thomas) [23,24], the sweet potato whitefly (*B. tabaci*) [25] and the tomato psyllid (*Bactericera cockerelli*) [26]. This resistance is independent of the presence of glandular trichomes and acyl sugar concentration [27].

QTL mapping studies have been carried out to identify genomic regions involved in whitefly resistance. Maliepaard *et al.* [28] focused on resistance against the greenhouse whitefly *T. vaporariorum* (Westwood) from *S. habrochaites* (CGN1.1561) and identified two QTLs reducing whitefly oviposition rate (*Tv-1* on Chr. 1 and *Tv-2* on Chr. 12) together with two QTLs related to trichome type IV density (*TriIV-1* on Chr. 5 and *TriIV-2* on Chr. 9) and one QTL for trichome type VI density (*TriVI-1* on Chr. 1). After this first study, others have explored different resistance sources and more QTLs were identified. A summary of the QTLs related to whitefly resistance in tomato is given in Table 1. The use of backcross introgression lines (ILs) was also proposed as a method to identify genomic regions important for whitefly resistance. These ILs helped to identify regions and genes involved in traits related to insect resistance, like the production of monoterpenes, sesquiterpenes and acyl sugars [29-32]. However, they failed to identify regions associated to whitefly resistance in terms of adult survival or oviposition rate [33], supporting the observations from the QTL mapping studies that whitefly resistance is polygenic inherited and possibly epistatic interactions play a role as well. Except the QTLs described by Maliepaard *et al.* [28], all other QTLs affecting whitefly oviposition were highly correlated with a reduction in whitefly survival and/or to high densities of trichomes type IV, suggesting that the low oviposition rate is the consequence of a low survival rate [16,33,34]. To study resistance mechanisms affecting whitefly oviposition rate exclusively, we focused on the further characterization of the QTLs identified by Maliepaard *et al.* [28], and determined their role in resistance against *Bemisia tabaci*.

Methods

Plant materials and growing conditions

The study was based on the F₂ offspring population that was created by Maliepaard *et al.* [28], it was obtained by self-pollination of a single F₁ plant that was derived from a cross between *S. lycopersicum* (cv. Moneymaker) and *S. habrochaites* (CGN1.1561). We have sown again individuals of this F₂ population and selected plants that were homozygous for either one or both QTLs associated to a reduction in oviposition rate using Cleaved Amplified Polymorphisms (CAPs) markers (Table 2). The selected F₂, BC₁ and BC₂ plants were backcrossed with *S. lycopersicum* (cv. Moneymaker) for three generations. Plants were chosen containing at least one of the markers flanking the QTLs. The obtained F₂BC₃ and F₂BC₄ families were genotyped and phenotyped for adult survival and oviposition rate. Selected F₂BC₄ plants were selfed to obtain F₂BC₄S₁ plants and F₂BC₄S₂, which were also genotyped and phenotyped. An overview of the material development is shown in Figure 1.

The tomato plants were grown in a greenhouse in Wageningen, The Netherlands (20 ± 2°C, 70% RH, 16/8 h day/night) in 14 cm diameter pots filled with soil compost. The plants were fertilized twice a week with standard fertilizer for tomato and watered once a day. When the plants were five weeks old, they were transferred to an insect proof greenhouse. The greenhouse temperature was increased slowly from 20 to 27°C to allow plants to adapt to the higher temperature (27 ± 2°C, 70% RH, 16/8 h day/night) used during the infestation that took place one week after transfer.

Insect rearing

A non-viruliferous whitefly rearing (*Bemisia tabaci* Group Mediterranean-Middle East-Asia Minor I) was maintained on the susceptible tomato cultivar Moneymaker at Wageningen UR Plant Breeding, Wageningen, The Netherlands. The initial inoculum was obtained from a rearing at the Laboratory of Entomology, Wageningen UR, Wageningen, The Netherlands.

No-choice experiment

Whiteflies (four days old) were anesthetized using CO₂. Five females were selected under a binocular and put in a clip-on cage (2.5 cm diameter and 1.0 cm high). Three cages per plant were attached to the first to third fully expanded leaf counting from the top. Five days after inoculation, the number of living and dead whiteflies was recorded and living whiteflies were removed. The number of eggs was counted, and the Oviposition rate (OR) and Adult survival (AS) were calculated according to Bas *et al.* [36]. In these calculations mortality is assumed constant over time [37]. For the analysis of AS in the F₂BC₃ population, a Kruskal-Wallis analysis of variance

Table 1 Overview of the QTLs found associated to whitefly resistance in tomato

Trait	QTL	Chr.	Resistance donor	% Explained	References
Adult survival (<i>B. tabaci</i>)	<i>Wf-1</i>	2	<i>S. galapagense</i> (PRI95004)	54.1	[16]
	<i>Wf-2</i>	9		14.8	
	<i>Wf-I</i>	1	<i>S. pennellii</i> (LA3791)	12.1	[34]
	<i>Wf-III</i>	3		15.6	
	<i>Wf-IV</i>	4		12.3-30.7	
	<i>Wf-VI</i>	6		10.1	
Oviposition rate (<i>B. tabaci</i>)	<i>Wf-1</i>	2	<i>S. galapagense</i> (PRI95004)	41.7	[16]
	<i>Wf-2</i>	9		11.1	
	<i>R2/9</i>	9	<i>S. habrochaites</i> (LA1777)	55.2	[33]
	<i>R1/10</i>	10		15	
	<i>R3/11a</i>	11		52.9	
	<i>R4/11b</i>	11		43.3	
	<i>Wf-IV</i>	4	<i>S. pennellii</i> (LA3791)	10.3-29.6	[34]
	<i>Wf-VI</i>	6		13.9	
	<i>Wf-X</i>	10		10	
Oviposition rate (<i>T. vaporariorum</i>)	<i>Tv-1</i>	1	<i>S. habrochaites</i> (CGN1.1561)	6.4	[28]
	<i>Tv-2</i>	12		8	
Pre-adult survival (<i>B. tabaci</i>)	<i>Wf-1</i>	2	<i>S. galapagense</i> (PRI95004)	13.3	[16]
Density of trichome type IV	<i>Wf-1</i>	2	<i>S. galapagense</i> (PRI95004)	66.3	[16]
	<i>Wf-2</i>	9		8.7	
	<i>TriIV-1</i>	5	<i>S. habrochaites</i> (CGN1.1561)	n.d.	[28]
	<i>TriIV-2</i>	9		n.d.	
	<i>R2/9</i>	9	<i>S. habrochaites</i> (LA1777)	69.7	[33]
	<i>R1/10</i>	10		22.5	
	<i>R3/11a</i>	11		69	
	<i>R4/11b</i>	11		n.d.	
	<i>TA2A</i>	2	<i>S. pennellii</i> (LA0716)	2.6	[35]
	<i>3A</i>	3		5.1	
	<i>TA4</i>	4		5.2	
	<i>6A</i>	6		4.7	
	<i>7B</i>	7		2.8	
	<i>10A</i>	10		4.6	
	<i>11A</i>	11		8.1	
Density of trichome type VI	<i>TriVI-1</i>	1	<i>S. habrochaites</i> (CGN1.1561)	n.d.	[28]

% Explained = percentage of variance explained by the QTL.

was used [38]. A square root transformation was applied to oviposition rate (OR) prior to the data analysis and analysed by one-way ANOVA followed by a least significant difference (LSD) test.

DNA isolation and genotyping

Genomic DNA was extracted from young leaflets using the micro-prep DNA extraction protocol [39]. The DNA concentration was adjusted to 50 ng/ul. For molecular marker analysis, three types of marker assays were used:

CAPs, a custom made Infinium bead array and KASPar (KBiosciences Competitive Allele-Specific PCR).

For CAPs the PCR reactions were carried out in a final volume of 20 μ l, containing 50 ng of genomic DNA, 0.04 μ l of DreamTaq polymerase (Fermentas), 2 μ l 10X DreamTaq buffer (Fermentas), 0.4 μ l of dNTP (5 mM) and 1 μ M of each primer (20 pmol). The cycling profile was: 94°C for 3 min, followed by 30 cycles at 94°C for 30 s, 55°C for 30 s, and 72°C for 1 min, and a final extension step at 72°C for 10 min. Aliquots (5 μ l) of the

Table 2 Primers for CAPs analysis

Marker name	Chr.	Primer sequence	Restriction enzyme
TG59	1	AACTCTACGCTGCACTGCTG CTGAAGCTCCACCTTGAGGTG	Hpa II
TG17	1	GGTCTTCCCTTCGTATTTCAT GTTATTCCGGTCTTGTCTTCACG	HpyCH4 IV
CD2	12	CAGCTGCAACTCCACTACCA GGGCTGAAGAACTGCACTC	Mwo I
TG68	12	TTTGATTACACTGCCTTACATA CATGTCAAGGGGATTGAACA	Dde I

amplified products were digested for at least one hour at 37°C in a final volume of 15 µl with 0.5 µl of the appropriate restriction enzyme, using the buffer recommended by the supplier. Amplification and digestion products were analysed by agarose gel electrophoresis (1.5% TBE, agarose) and visualized by GelRed® staining. In Table 2 the primer sequences and the restriction enzymes used are shown.

For genome wide SNP marker analysis, an Infinium bead array was used [40]. On this array, 5528 tomato SNPs were present. Marker analysis was carried out by

Service XS Leiden, The Netherlands, according to the Illumina® Infinium HD Ultra Assay protocol (www.illumina.com). After removing missing data and monomorphic markers, 1166 SNP markers were used in the analysis. For fine mapping of the target regions, we developed KASPar assays based on SNP markers that were on the array. The chromosomal positions are according to International Tomato Annotation Group (ITAG) Release 2, official annotations on the SL2.31 version of the tomato genome [41] (www.solgenomics.net). The sequences flanking the SNPs can be found on <http://www.plantbreeding.wur.nl/Publications/SNP/4072SNP-Sequences.xlsx> [39]. The KASPar assays were run by the van Haeringen lab (VHL), Wageningen, the Netherlands.

Trichome description

Trichomes present on the abaxial side of the leaf were classified according to type [42]. For an estimation of trichome density, the abaxial part of three leaflets was observed under a binocular microscope and a visual scale was used to describe it. The scale used was adapted from Simmons and Gurr [43] and consisted of four categories: 3, Abundant (>5 per mm²); 2, sparse (5–1 per mm²); 1, very sparse (<1 per mm²), and 0, absent.

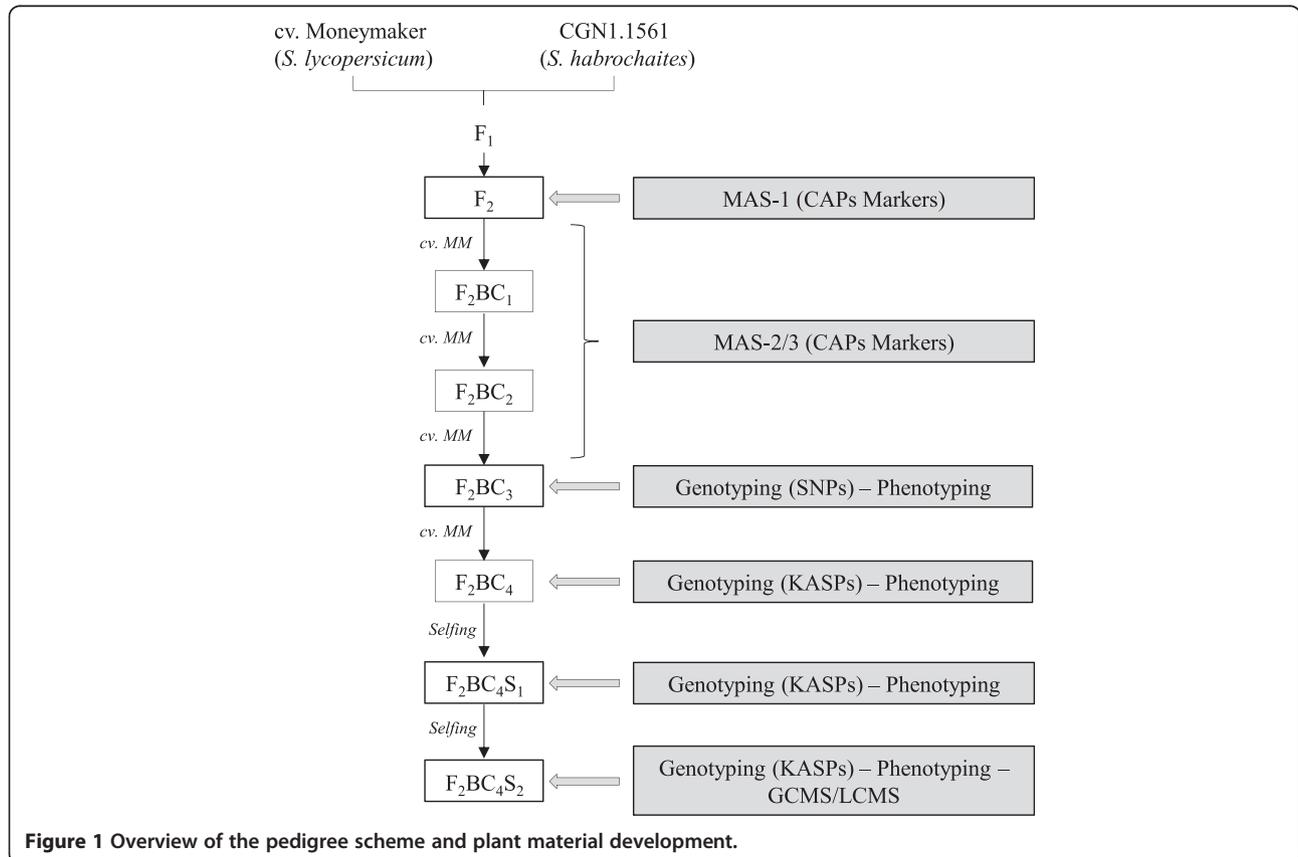


Figure 1 Overview of the pedigree scheme and plant material development.

GC-MS analysis

The $F_2BC_4S_2$ plant were analysed for the presence and concentration of methylketones. From each plant one complete leaf (second fully expanded leaf from the top of the plant) was cut, placed immediately into an aluminium envelope and frozen in liquid nitrogen. Each sample was ground to a freeze-dried powder and stored at -80°C until processing. Three biological replicas were used for the analysis. Each replica consisted on the mix of 5 plants per recombinant class. Per replica, 400 mg of leaf powder was put into a reaction tube with 3 ml of anhydrous dichloromethane ($>99.8\%$, Sigma-Aldrich) as solvent and $0.75\ \mu\text{g}$ per ml heptadecanoic acid methyl ester was added as internal standard. The samples were homogenized using a vortex and centrifuged at 1500 rpm for 10 min. The supernatant was filtered through a soft glass column (Pasteur capillary pipette), which contained 1 cm of silanized glass wool fibres and 2 cm sodium sulphate (Na_2SO_4) powder as filter. Samples were injected using a 7683 series B injector (Agilent Technologies) into a 7890 A GC (Agilent Technologies) coupled to a 5975 C MSD (Agilent Technologies). Chromatography was performed using a Zb-5MS column (Phenomenex, 30 m, 0.25 mm inner diameter, and 0.25 μm film thickness) with 5 m retention gap. Injection temperature was 250°C , and temperature of column was programmed at 45°C for 1 min, increased by $10^\circ\text{C}\ \text{min}^{-1}$ to 300°C , and kept at 300°C for 7 min. Column flow was set at $1\ \text{ml}\ \text{min}^{-1}$, using Helium as carrier. The column effluent was ionised and mass spectra was obtained from 35–400 m/z . MetAlign metabolomics software package (www.metalign.nl) was used to perform peak alignment and noise reduction, and MSClust software package (www.metalign.nl) was used for data reduction by clustering several peaks into putative metabolites. Putative metabolites were identified corresponding the obtained mass spectra to the NIST library (National Institute of Standards and Technology, Gaithersburgh, MD, USA), the Wiley online library, and the Wageningen Natural compounds spectral library. Prior to statistical analysis, the metabolites were Log transformed and auto scaled to the mean. To select metabolite compounds putatively related to whitefly preference a t-test, followed by False Discovery Rate correction [44].

Statistical analysis

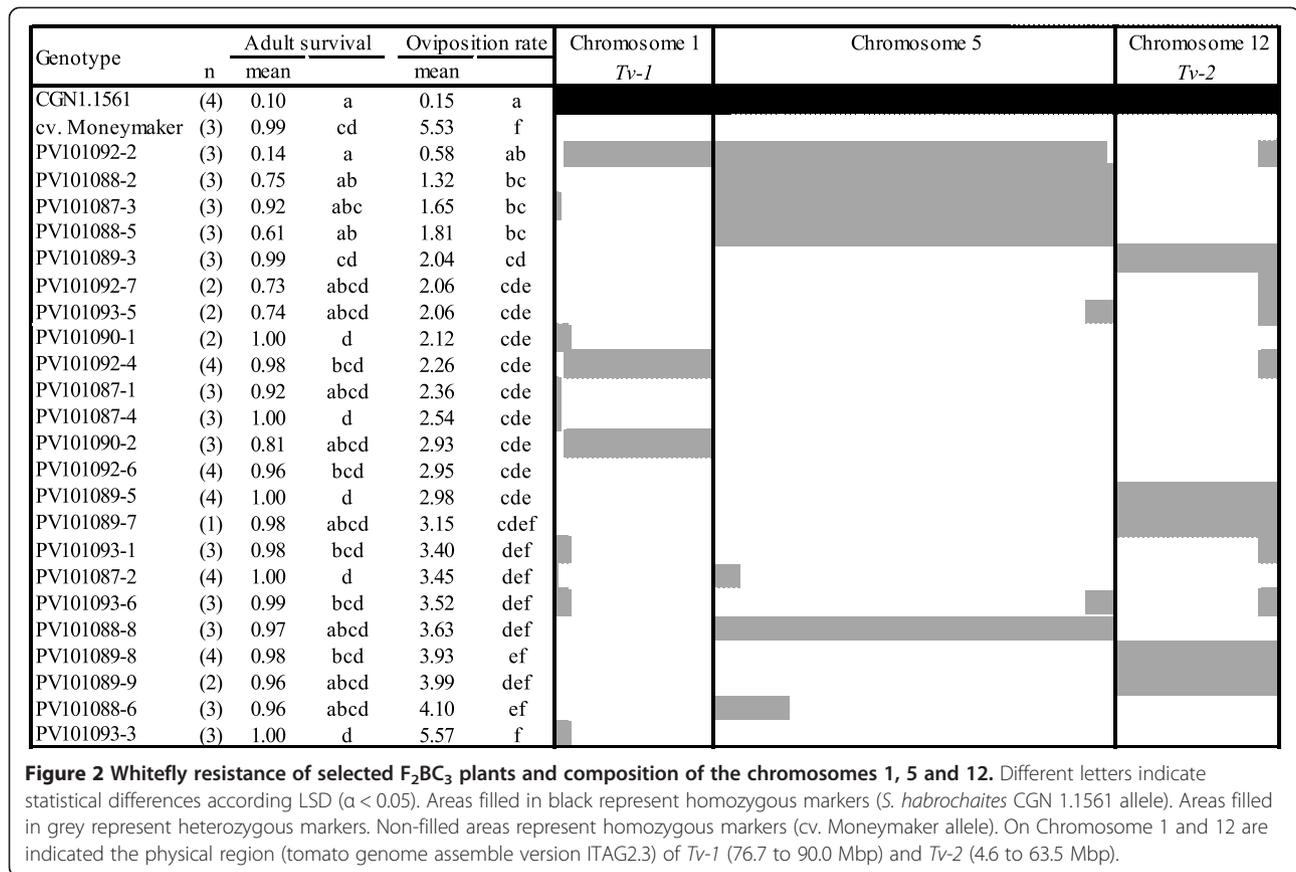
All statistical procedures were performed using the statistical software package GenStat 16th edition. A T-test followed by a False discovery Rate [44] was done per marker to define the region associated to the reduced oviposition rate.

Results

Plant material development started from F_2 plants containing *Tv-1*, *Tv-2* or both using the markers shown in

Table 2. Three successive marker assisted backcrosses were carried out with selection for the presence of at least one of the markers linked to the QTL (Figure 1). Twenty-three F_2BC_3 plants were randomly selected for phenotyping and genotyping to confirm the presence of *Tv-1* and *Tv-2*. As reference lines, we included *S. habrochaites* (CGN1.1561) and *S. lycopersicum* cv. Money-maker. Accession CGN1.1561 showed low values for adult survival (AS, 0.1 ± 0.21 females/day) and oviposition rate (OR, 0.2 ± 0.30 eggs/female/day), and cv. Money-maker showed high values for adult survival (AS, 1.0 ± 0.01 females/day) and oviposition rate (OR, 5.5 ± 0.72 eggs/female/day). Among the twenty-three F_2BC_3 , variation was found for both parameters. For AS, only three F_2BC_3 plants were significantly different from cv. Money-maker (Figure 2). Whereas, for OR a gradient was observed, with fourteen F_2BC_3 plants showing statistically significant lower values than cv. Money-maker (Figure 2). To determine the position and size of the introgressions, the twenty-three F_2BC_3 plants were genotyped using an Infinium bead array [40]. Several plants had an introgression of *Tv-1*, *Tv-2* or parts thereof. None of the plants had the complete *Tv-1* and *Tv-2* region as defined by Maliepaard *et al.* [28] (Figure 2). The four F_2BC_3 plants with the lowest OR (PV101092-2, PV101088-2, PV101087-3 and PV101088-5) shared an introgression on Chr. 5, but had differences in the presence of the regions *Tv-1* and/or *Tv-2*. One plant (PV101088-8) had the same introgression on Chr. 5, but the OR was not significantly different from cv. Money-maker (Figure 2).

To further investigate the effect of the introgression on Chr. 5, five F_2BC_3 plants (PV101092-2, PV101088-2, PV101087-3, PV101093-1, PV101087-2) were selected based on OR, the presence/absence of *Tv-1*, *Tv-2* and the presence of the introgression on Chr. 5. The plants PV101092-2, PV101088-2, PV101087-3, contained the Chr. 5 (61.27 Mbp) introgression, whereas it was smaller in PV101087-2 and not present in PV101093-1. The five plants have varying parts of *Tv-1* and *Tv-2* or lack these completely (PV101088-2, Figure 2). The plants were backcrossed with cv. Money-maker to generate five F_2BC_4 families. All F_2BC_4 plants plus parental plants, CGN1.1561 and cv. Money-maker were genotyped for *Tv-1*, *Tv-2* and the introgression on Chr. 5, and phenotyped for adult survival, oviposition rate, trichome type and trichome density. Figure 3 shows the distribution for AS and OR and the link to the respective F_2BC_3 line. Clear differences were seen between cv. Money-maker and CGN1.1561 for AS ($P < 0.01$) and OR ($P < 0.01$). In the studied F_2BC_4 plants, there was mainly segregation for OR with the parents on the extremes of the distribution. Genotyping showed that from the offspring of PV101088-2 (renamed to PV101392) four of the five sibling plants were heterozygous for the region on Chr. 5.



These plants had an OR level comparable to CGN1.1561, the remaining plant of the five (PV101392-2), lacked the CGN1.1561 allele and had a high OR (Figure 4). To investigate a possible relation between the reduction in OR and the presence of glandular trichomes, the presence/density was determined on the parental lines and the F₂BC₄ plants. Accession CGN1.1561 was the only one with trichomes type IV and VIc, whereas the F₂BC₄ plants and the *cv. Moneymaker* had mainly trichomes type V and VIa. No differences were seen in the density of trichome type VIa among the F₂BC₄ plants and *cv. Moneymaker*.

As the offspring of PV101392 showed a low OR and lacked the *Tv-1* and *Tv-2* region (Figure 4), we focussed on the introgression on Chr. 5. To find offspring plants with a smaller introgression on Chr. 5, PV101392-1PV101392-3, PV101392-4 and PV101392-5 were selfed. Of the 275 F₂BC₄S₁ offspring plants, 33 plants out of 61 recombinants were selected based on length differences of the introgressed region, as judged from marker analysis. The genotyping results (grouped by introgression length) and phenotyping results (OR) are shown in Figure 5. With the F₂BC₄S₁ we could narrow down this introgression to a 3.06 Mbp region

between the markers rs2009 (4.76 Mbp) and rs2071 (7.83 Mbp).

To further fine map and confirm the effect of the introgression on Chr. 5, eight F₂BC₄S₁ plants (PV121430-4, PV121430-11, PV121433-30, PV121430-89, PV121432-26, PV121433-29, PV121433-53 and PV121434-57) with a low OR and heterozygous for parts of this region in Chr. 5 were selfed. Of the 295 F₂BC₄S₂, 77 plants out of 154 recombinants were phenotyped based on length differences of the introgressed region, as judged from marker analysis. The results grouped by introgression length are shown in Figure 6. The F₂BC₄S₂ plants with a *S. habrochaites* (CGN 1.1561) introgression on Chr. 5, between the markers rs2009 (4.76 Mbp) and rs2093 (11.8 Mbp), had an OR similar to the low levels of CGN1.1561 and in the case of plants with the *cv. Moneymaker* allele homozygous present, the OR was higher (Figure 6). Some of the F₂BC₄S₂ had a reduced adult survival; however, AS and OR were not strongly correlated ($R = 0.43$) having plants with the introgression on Chr. 5 and with AS levels comparable to those found on *cv. Moneymaker* and with a significant lower OR. In the F₂BC₄S₂, no plants were found with a further smaller introgression.

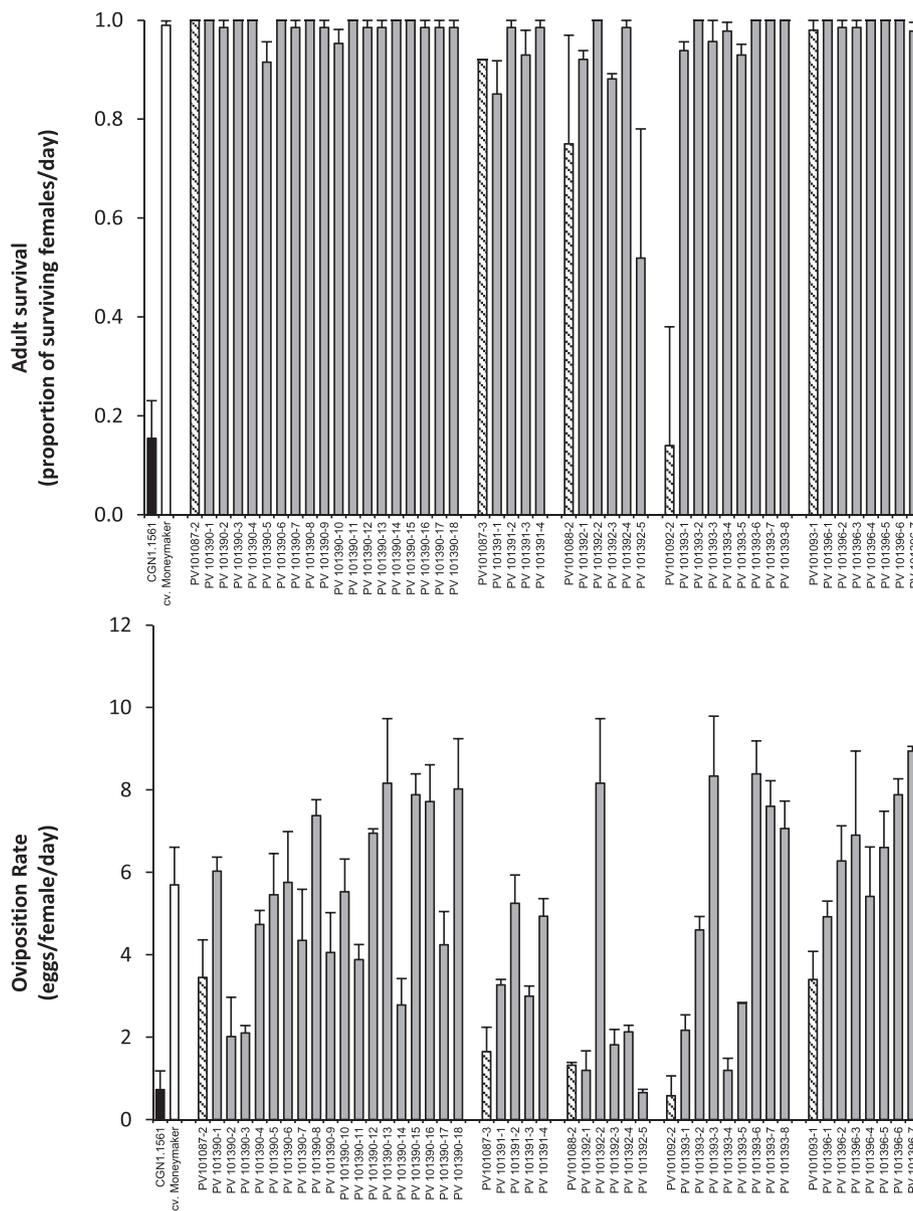


Figure 3 Phenotyping results of the F₂BC₄ plants. The upper panel shows adult survival, the lower panel oviposition rate. Plants are grouped according to family. The first sample of each block is the parent of that family (black stripes). *Solanum habrochaites* (CGN1.1561) is black and cv. Moneymaker is white.

Because CGN1.1561 is member of the group of *S. habrochaites* accessions that accumulate methyl ketones, the F₂BC₄S₂ families were analysed for the presence of those compounds (2-Tridecanone, 2-Undecanone, 2-Pentadecanone and 2-Dodecanone). The accession CGN1.1561 had all these methyl ketones in higher relative abundance compared to cv. Moneymaker and to the F₂BC₄S₂ families (Additional file 1: Table S1). In addition, there were no differences on the relative abundance of these methyl ketones among the F₂BC₄S₂ families and cv. Moneymaker.

Discussion

An introgression on Chromosome 5 (OR-5) reduces whitefly oviposition rate

Using F₂BC₃ plants, we identified a *S. habrochaites* (CGN1.1561) introgression on the short arm of Chr. 5 (hereafter called OR-5), which confers a reduction in *B. tabaci* oviposition rate. By analysing F₂BC₄, F₂BC₄S₁ and F₂BC₄S₂ populations, we could confirm that this introgression of 3.06 Mbp is causing the reduced whitefly oviposition rate. The reduction in oviposition caused by the

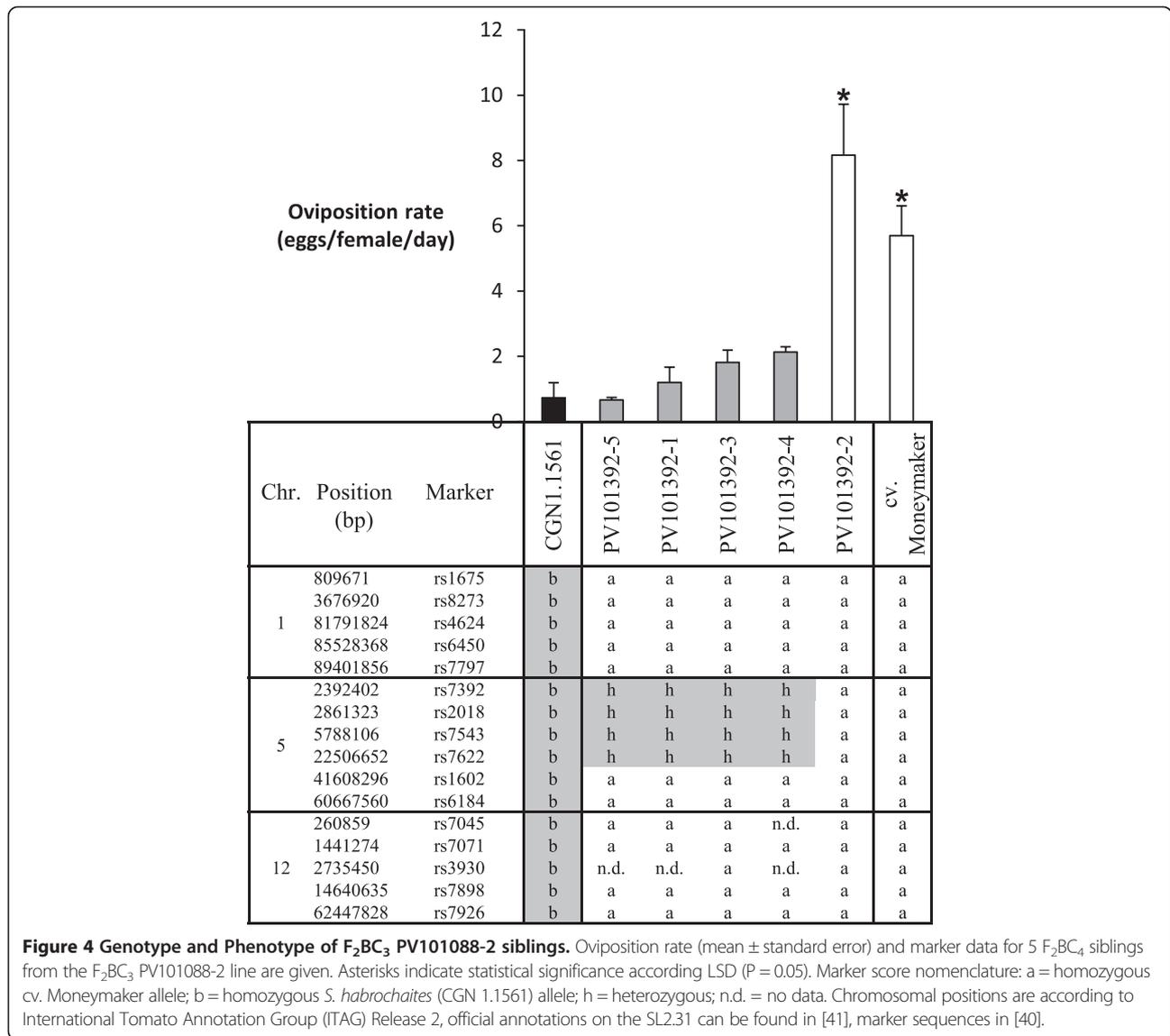


Figure 4 Genotype and Phenotype of F₂BC₃ PV101088-2 siblings. Oviposition rate (mean ± standard error) and marker data for 5 F₂BC₄ siblings from the F₂BC₃ PV101088-2 line are given. Asterisks indicate statistical significance according LSD (P = 0.05). Marker score nomenclature: a = homozygous cv. Moneymaker allele; b = homozygous *S. habrochaites* (CGN 1.1561) allele; h = heterozygous; n.d. = no data. Chromosomal positions are according to International Tomato Annotation Group (ITAG) Release 2, official annotations on the SL2.31 can be found in [41], marker sequences in [40].

presence of *OR-5* is independent of adult survival and the presence of trichome type IV. Plants were found on which all whiteflies were alive but a reduction in oviposition was observed (Figure 3) and none of the plants had the sticky trichomes type IV. The plants homozygous for the *S. habrochaites* (CGN1.1561) allele in the F₂BC₄S₂ had a higher OR compared to plants heterozygous for this allele. This effect of over dominance might indicate an interaction between the *S. habrochaites* (CGN1.1561) and the *S. lycopersicum* allele. It would also implicate that the high level of resistance in terms of low AS and OR found in CGN1.1561 is the result of epistatic interaction between different genes. In the F₂BC₃ population only one plant had the *OR-5* region but with OR levels similar to cv. Moneymaker. This result may be explained in several ways. First, there is the chance of a double recombination in the *OR-5* region. However, no double

recombination event was detected in this plant with the Infinium bead array. Secondly, there is the possibility of an epistatic effect between *OR-5* and a locus different from *Tv-1* or *Tv-2*. Finally, there is always the possibility of a phenotyping artefact.

Selection of the chromosome 5 region

For the selection of the F₂BC₃ plants, we used markers that are linked to the loci *Tv-1* and *Tv-2* loci, which are located on Chr. 1 and 12 respectively. It is therefore remarkable that we ended up with an introgression on Chr. 5, which had never actively been selected for. This may be explained by starting with F₂ plants containing the introgression on Chr. 5 either homozygous or heterozygous (3 out of 4 plants have the introgression). The chance that plants in the F₂BC₃ still possess the introgression is 1 out of 4 or 8, which is more or less the

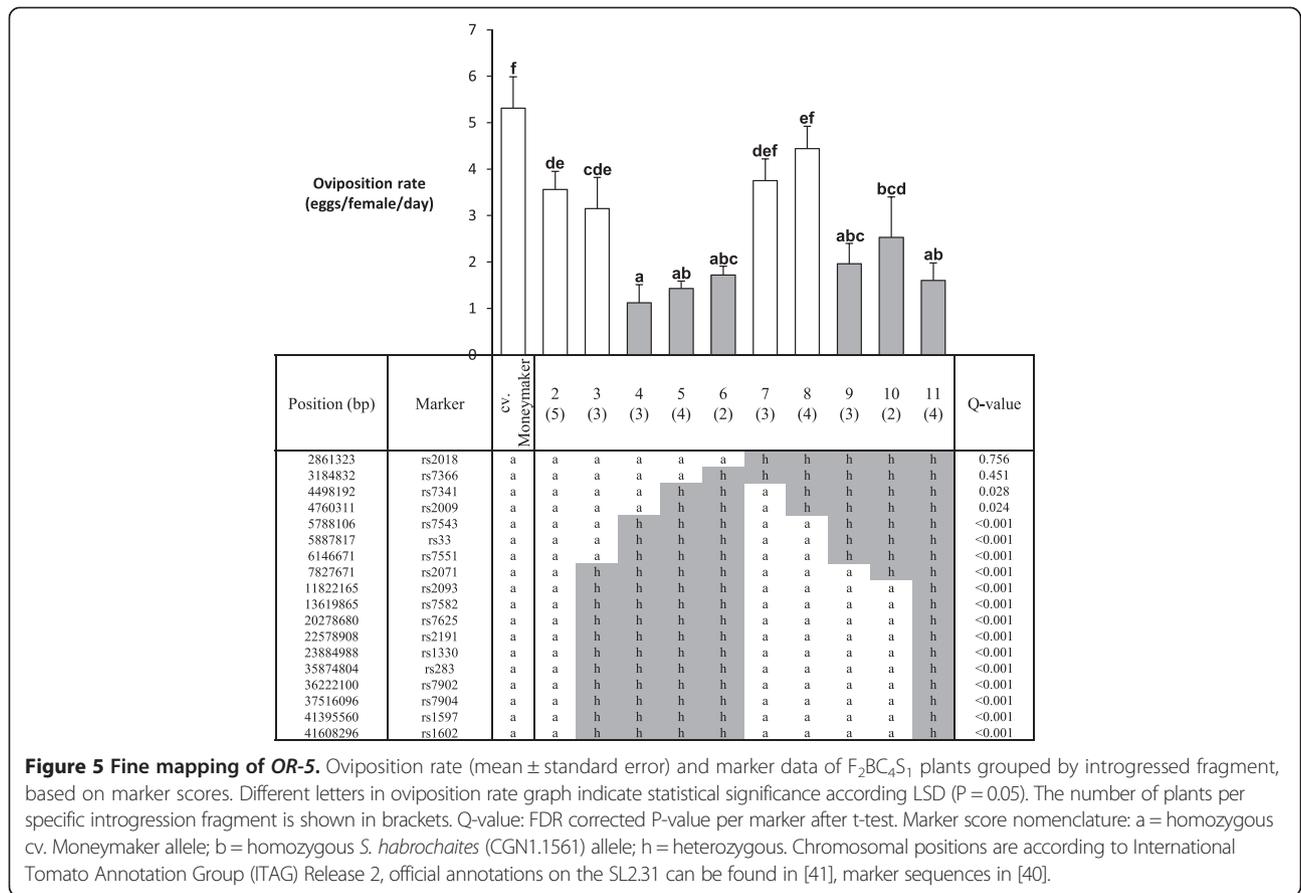


Figure 5 Fine mapping of OR-5. Oviposition rate (mean ± standard error) and marker data of F₂BC₄S₁ plants grouped by introgressed fragment, based on marker scores. Different letters in oviposition rate graph indicate statistical significance according LSD (P = 0.05). The number of plants per specific introgression fragment is shown in brackets. Q-value: FDR corrected P-value per marker after t-test. Marker score nomenclature: a = homozygous cv. Moneymaker allele; b = homozygous *S. habrochaites* (CGN1.1561) allele; h = heterozygous. Chromosomal positions are according to International Tomato Annotation Group (ITAG) Release 2, official annotations on the SL2.31 can be found in [41], marker sequences in [40].

number of Chromosome 5 containing F₂BC₃ plants that we found. The fact that Maliepaard *et al.* [28] did not detect the QTL for OR could be caused by the different whitefly species used (*T. vaporariorum* vs. *B. tabaci*). Different insect species or biotypes may react differently to the same host plant or odour blend, resulting in different behaviour. For example, glucosinolates can confer resistance to some insects, whereas they can be used as host and strong oviposition cues for others [45]. In the case of whiteflies, differences were seen when compared the feeding behaviour of the Q and the B-biotype on the same host plant [46]. Also, tomato plants carrying the *Mil-2* gene were in general more resistance to the Q-biotype than to the B-biotype [47].

Nature of the resistance provided by OR-5

Several QTLs related to whitefly resistance have been identified on Chr. 5 (Table 1). Maliepaard *et al.* [28] found in the region of OR-5 a QTL (*TriIV-1*) that increases the density of trichomes type IV. However, we did not detect any type IV trichomes on the F₂BC₄ plants containing the OR-5 introgression. In a backcross population of potato ((*S. tuberosum* × *S. berthaultii*) × *S. berthaultii*) a region on Chr. 5 was associated with a reduction in the oviposition rate and leaf consumption by

the Colorado potato beetle (*Leptinotarsa decemlineata*) [48]. This region also had a large effect on the density of the glandular secretory type B trichome (LOD: 19.17, explaining 35.6% of the variance), furthermore differences in the sucrose ester levels and in the presence of droplet (exudate) on the tip of the trichomes were associated with this region on Chr. 5 [48]. For *S. pennellii*, two QTLs were described on Chr. 5 that are involved in acyl sugar metabolism, one (*TA5*) related to the total accumulation of acyl sugars and another (5) related to the proportion of 7-methyloctanonate and 9-methyldecanonate fatty acids that are incorporated into acyl sugars [49,50]. To check if acyl sugars were related to the reduction in oviposition rate an LC-MS chromatography analysis was done on the F₂BC₄S₂ plants [14]. No differences were found among the F₂BC₄S₂ plants on the levels of acyls sugars, pointing to a different mechanism of resistance in this plant material specifically affecting whitefly oviposition rate (data not shown). As the parental accession CGN1.1561 accumulates methyl ketones, we also analysed the offspring for the presence of 2-Tridecanone, 2-Undecanone, 2-Pentadecanone and 2-Dodecanone. None of these compounds was detected at elevated levels in the offspring, excluding the option that these methyl ketones may explain the observed reduction in oviposition rate. On the 3.06

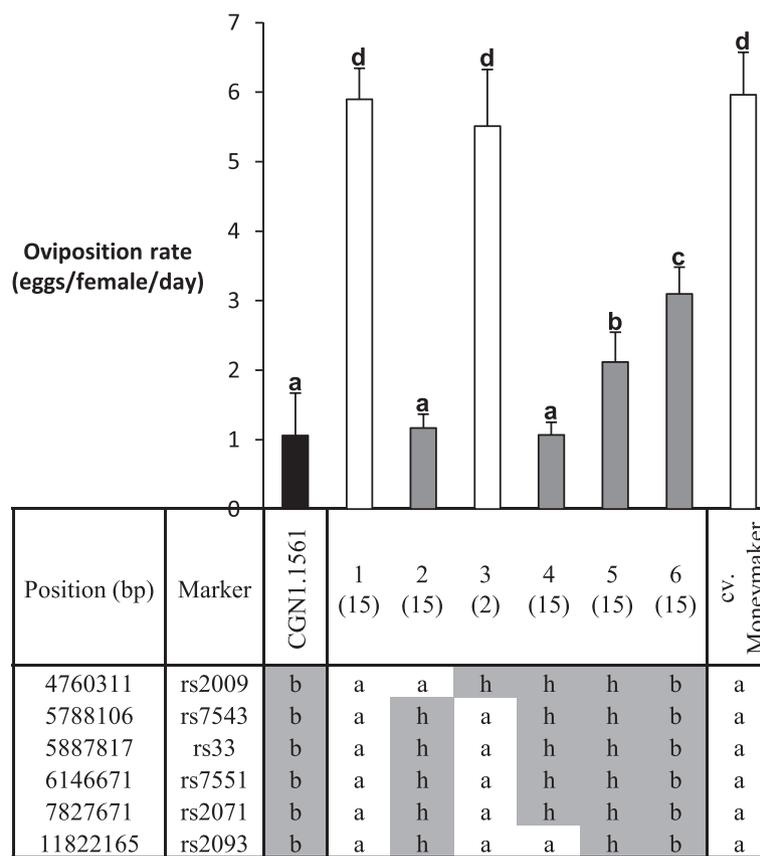


Figure 6 Corroboration of role of OR-5. Oviposition rate (mean ± standard error) and marker data of F₂BC₄S₂ plants grouped by introgressed fragment, based on marker scores. Different letters in oviposition rate graph indicate statistical significance according LSD (P = 0.05). The number of plants per specific introgression fragment is shown in brackets. Marker score nomenclature: a = homozygous cv. Moneymaker allele; b = homozygous *S. habrochaites* (CGN 1.1561) allele; h = heterozygous. Chromosomal positions are according to International Tomato Annotation Group (ITAG) Release 2, official annotations on the SL2.31 can be found in [41], marker sequences in [40].

Mbp introgression of *OR-5* are 258 annotated genes including R-genes, transcription factors, genes involved in acyl sugar and terpenoid metabolism which can be considered as candidate genes for reduced oviposition. To reduce the list of candidate genes and find the gene(s) responsible for the lower OR further fine mapping and functional analysis, including more detailed metabolomics is needed. However, considering the lack of recombinants found in the F₂BC₄S₁ and F₂BC₄S₂ populations between the markers rs-7543 (5.79 Mbp) and rs-7551 (6.15 Mbp), it might be difficult to reduce the size of the introgression.

Perspectives of OR-5 for breeding whitefly resistant varieties

Since the late nineties of the 20th century, the efforts to get whitefly resistant tomatoes have increased considerably, but so far they have been unsuccessful [4]. The screening of genetic resources for novel whitefly resistance mechanisms has increased, going from distant wild relatives of tomato (i.e. *S. pennellii*, *S. habrochaites*) to in depth studies of several accessions of closely related species (i.e. *S.*

galapagense, *S. pimpinellifolium*) [7-9,11,13,14]. These efforts have led to the identification of specific secondary metabolites conferring resistance to whiteflies (methyl ketones, sesquiterpenes, and acyl sugars) [12,15,51], the identification of QTLs related to resistance [16,28,33], and in some cases to the genes involved in the synthesis of resistance related metabolites [17,19,20,30,31]. The identification of *OR-5*, affecting specifically whitefly oviposition rate and independent of the presence of trichome type IV, opens new opportunities for breeding. The *OR-5* region is expected to reduce population development of *B. tabaci* strongly. As the reduction in oviposition is not linked to the sticky trichomes type I and IV, and the known negative effect of this type of resistance on parasitoids and predators [43,52-54], it can be expected that this resistance will be very suitable in combination with biological control. On varieties containing the *OR-5* region the *B. tabaci* population development will be slowed down giving the natural enemies ample opportunity to keep the population below threshold levels or even to remove developing whiteflies. Therefore, the gene will in particular be useful in protected tomato production

conditions (greenhouse cultivation). For open field production, the resistances based on trichomes type I and IV will be more suitable [16].

Conclusions

We identified a region at the top of Chr. 5 (OR-5), which is associated with a reduction in the oviposition rate of *B. tabaci*. This reduction was independent of the presence of the QTLs *Tv-1* and *Tv-2* that were identified previously [28], as well as of the presence of trichomes type IV. The OR-5 locus will provide new opportunities for resistance breeding against whiteflies, which is especially relevant in greenhouse cultivation.

Additional file

Additional file 1: Table S1 GC-MS analysis of the relative abundance (average \pm standard error) of methyl ketone per F₂BC₄S₂ family.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The project was conceived by AFL, BV and SvH. AFL performed the experiments and data analysis. AFL and FRGMD performed the crossings and population developments. AFL and RM performed the GC-MS experiment and data analysis. AFL, BV, RM, RGFV and SvH have been involved in the writing of the manuscript. All authors read and approved the final manuscript.

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References

- Martin JH, Mound LA: An annotated check list of the world's whiteflies (Insecta: Hemiptera: Aleyrodidae). *Zootaxa* 2007, **1492**:1–84.
- Brown JK, Bird J: Whitefly-transmitted geminiviruses and associated disorders in the Americas and the Caribbean Basin. *Plant Dis* 1992, **76**(3):220–225.
- Byrne DN, Bellows TS Jr: *Whitefly biology*. *Annu Rev Entomol* 1991, **36**:431–457.
- Broekgaarden C, Snoeren TAL, Dicke M, Vosman B: Exploiting natural variation to identify insect-resistance genes. *Plant Biotech J* 2011, **9**(8):819–825.
- Schoonhoven LM, van Loon JJA, Dicke M: *Insect-plant Biology*. Oxford: Oxford University Press; 2005.
- Heinz KM, Zalom FG: Variation in trichome-based resistance to *Bemisia argentifolii* (Homoptera: Aleyrodidae) oviposition on tomato. *J Econ Entomol* 1995, **88**(5):1494–1502.
- Muigai SG, Schuster DJ, Snyder JC, Scott JW, Bassett MJ, McAuslane HJ: Mechanisms of resistance in *Lycopersicon* germplasm to the whitefly *Bemisia argentifolii*. *Phytoparasitica* 2002, **30**(4):347–360.
- Freitas J, Maluf W, das Graças Cardoso M, Gomes LA, Bearzotti E: Inheritance of foliar zingiberene contents and their relationship to trichome densities and whitefly resistance in tomatoes. *Euphytica* 2002, **127**(2):275–287.
- Muigai SG, Bassett MJ, Schuster DJ, Scott JW: Greenhouse and field screening of wild *Lycopersicon* germplasm for resistance to the whitefly *Bemisia argentifolii*. *Phytoparasitica* 2003, **31**(1):27–38.
- Fernández-Muñoz R, Salinas M, Álvarez M, Cuartero J: Inheritance of resistance to two-spotted spider mite and glandular leaf trichomes in wild tomato *Lycopersicon pimpinellifolium* (Jusl.) Mill. *J Am Soc Hortic Sci* 2003, **128**(2):188–195.
- Baldin ELL, Vendramim JD, Lourenção AL: Resistance of tomato genotypes to the whitefly *Bemisia tabaci* (Gennadius) biotype B (Hemiptera: Aleyrodidae). *Neotrop Entomol* 2005, **34**(3):435–441.
- Rodríguez-López MJ, Garzo E, Bonani JP, Fereres A, Fernandez-Munoz R, Moriones E: Whitefly resistance traits derived from the wild tomato *Solanum pimpinellifolium* affect the preference and feeding behavior of *Bemisia tabaci* and reduce the spread of Tomato yellow leaf curl virus. *Phytopathology* 2011, **101**(10):1191–1201.
- Firdaus S, Heusden A, Hidayati N, Supena E, Visser R, Vosman B: Resistance to *Bemisia tabaci* in tomato wild relatives. *Euphytica* 2012, **187**(1):31–45.
- Lucatti AF, Van Heusden AW, De Vos RCH, Visser RGF, Vosman B: Differences in insect resistance between tomato species endemic to the Galapagos Islands. *BMC Evol Biol* 2013, **13**:175.
- Rodríguez-López MJ, Garzo E, Bonani JP, Fernández-Muñoz R, Moriones E, Fereres A: Acylsucrose-producing tomato plants forces *Bemisia tabaci* to shift its preferred settling and feeding site. *PLoS ONE* 2012, **7**(3):e33064.
- Firdaus S, Heusden AW, Hidayati N, Supena E, Mumm R, Vos RCH, Visser RGF, Vosman B: Identification and QTL mapping of whitefly resistance components in *Solanum galapagense*. *Theor Appl Genet* 2013, **126**(6):1487–1501.
- Bleeker PM, Mirabella R, Diergaarde PJ, VanDoorn A, Tissier A, Kant MR, Prins M, De Vos M, Haring MA, Schuurink RC: Improved herbivore resistance in cultivated tomato with the sesquiterpene biosynthetic pathway from a wild relative. *Proc Natl Acad Sci U S A* 2012, **109**(49):20124–20129.
- Antonius G: Production and quantification of methyl ketones in wild tomato accessions. *J Environ Sci Health* 2001, **36**:835–848.
- Ben-Israel I, Yu G, Austin MB, Bhuiyan N, Auldridge M, Nguyen T, Schauvinhold I, Noel JP, Pichersky E, Fridman E: Multiple biochemical and morphological factors underlie the production of methylketones in tomato trichomes. *Plant Physiol* 2009, **151**:1952–1964.
- Fridman E, Wang J, Iijima Y, Froehlich JE, Gang DR, Ohlrogge J, Pichersky E: Metabolic, genomic, and biochemical analyses of glandular trichomes from the wild tomato species *Lycopersicon hirsutum* identify a key enzyme in the biosynthesis of methylketones. *Plant Cell* 2005, **17**:1252–1267.
- Leckie BM, Jong DM, Mutschler MA: Quantitative trait loci increasing acylsugars in tomato breeding lines and their impacts on silverleaf whiteflies. *Mol Breeding* 2012, **30**:1621–1634.
- Milligan SB, Bodeau J, Yaghoobi J, Kaloshian I, Zabel P, Williamson VM: The root-knot nematode resistance gene *Mi* from tomato is a member of leucine zipper, nucleotide binding, leucine-rich repeat family of plant genes. *Plant Cell* 1998, **10**:1307–1319.
- Kaloshian I, Lange WH, Williamson VM: An aphid-resistance locus is tightly linked to the nematode-resistance gene, *Mi*, in tomato. *Proc Natl Acad Sci U S A* 1995, **92**:622–625.
- Rossi M, Goggin FL, Milligan SB, Kaloshian I, Ullman DE, Williamson VM: The nematode resistance gene *Mi* of tomato confers resistance against the potato aphid. *Proc Natl Acad Sci U S A* 1998, **95**:9750–9754.
- Nombela G, Williamson VM, Muñoz M: The root-knot nematode resistance gene *Mi-1.2* of tomato is responsible for resistance against the whitefly *Bemisia tabaci*. *MPMI* 2003, **16**:645–649.
- Casteel CL, Walling LL, Paine TD: Behavior and biology of the tomato psyllid, *Bactericera cockerelli*, in response to the *Mi-1.2* gene. *Entomol Exper Appl* 2006, **121**:67–72.
- Nombela G, Beitia F, Muñoz M: Variation in tomato host response to *Bemisia tabaci* (Hemiptera: Aleyrodidae) in relation to acyl sugar content and presence of the nematode and potato aphid resistance gene *Mi*. *Bull Entomol Res* 2000, **90**:161–167.

28. Maliepaard C, Bas NJ, Van Heusden S, Kos J, Pet G, Verkerk R, Vrieland R, Zabel P, Lindhout P: **Mapping of QTLs for glandular trichome densities and *Trialeurodes vaporariorum* (greenhouse whitefly) resistance in an F₂ from *Lycopersicon esculentum* X *Lycopersicon hirsutum* f. *glabratum*.** *Heredity* 1995, **75**(4):425–433.
29. Schillmiller A, Shi F, Kim J, Charbonneau AL, Holmes D, Daniel Jones A, Last RL: **Mass spectrometry screening reveals widespread diversity in trichome specialized metabolites of tomato chromosomal substitution lines.** *Plant J* 2010, **62**(3):391–403.
30. Schillmiller AL, Charbonneau AL, Last RL: **Identification of a BAHD acetyltransferase that produces protective acyl sugars in tomato trichomes.** *Proc Natl Acad Sci U S A* 2012, **109**(40):16377–16382.
31. Schillmiller AL, Schauvinhold I, Larson M, Xu R, Charbonneau AL, Schmidt A, Wilkerson C, Last RL, Pichersky E: **Monoterpenes in the glandular trichomes of tomato are synthesized from a neryl diphosphate precursor rather than geranyl diphosphate.** *Proc Natl Acad Sci U S A* 2009, **106**(26):10865–10870.
32. Van der Hoeven RS, Monforte AJ, Breeden D, Tanksley SD, Steffens JC: **Genetic control and evolution of sesquiterpene biosynthesis in *Lycopersicon esculentum* and *L. hirsutum*.** *Plant Cell* 2000, **12**(11):2283–2294.
33. Momotaz A, Scott JW, Schuster DJ: **Identification of quantitative trait loci conferring resistance to *Bemisia tabaci* in an F₂ population of *Solanum lycopersicum* x *Solanum habrochaites* accession LA1777.** *J Am Soc Hortic Sci* 2010, **135**(2):134–142.
34. Van den Elsen F: *Resistance Mechanisms against Bemisia tabaci in Wild Relatives of Tomato*. Wageningen, The Netherlands: Thesis Wageningen University; 2013.
35. Blauth SL, Churchill GA, Mutschler MA: **Identification of quantitative trait loci associated with acylsugar accumulation using intraspecific populations of the wild tomato, *Lycopersicon pennellii*.** *Theor Appl Genet* 1998, **96**(3–4):458–467.
36. Bas N, Mollema C, Lindhout P: **Resistance in *Lycopersicon hirsutum* f. *glabratum* to the greenhouse whitefly (*Trialeurodes vaporariorum*) increases with plant age.** *Euphytica* 1992, **64**(3):189–195.
37. Van Giessen WA, Mollema C, Eelsey KD: **Design and use of a simulation model to evaluate germoplasm for antibiotic resistance to the greenhouse whitefly (*Trialeurodes vaporariorum*) and the sweetpotato whitefly (*Bemisia tabaci*).** *Entomol Exp Appl* 1995, **76**:271–286.
38. Zar JH: *Biostatistical Analysis*. Upper Saddle River, NJ: Pearson Education International; 2010.
39. Fulton T, Chunwongse J, Tanksley S: **Microprep protocol for extraction of DNA from tomato and other herbaceous plants.** *Plant Mol Biol Rep* 1995, **13**(3):207–209.
40. Viquez-Zamora M, Vosman B, van de Geest H, Bovy A, Visser R, Finkers R, van Heusden A: **Tomato breeding in the genomics era: insights from a SNP array.** *BMC Genomics* 2013, **14**(1):354.
41. Consortium TG: **The tomato genome sequence provides insights into fleshy fruit evolution.** *Nature* 2012, **485**(7400):635–641.
42. Channarayappa C, Shivashankar G, Muniyappa V, Frist RH: **Resistance of *Lycopersicon* species to *Bemisia tabaci*, a tomato leaf curl virus vector.** *Can J Bot* 1992, **70**(11):2184–2192.
43. Simmons AT, Gurr GM: **Trichomes of *Lycopersicon* species and their hybrids: effects on pests and natural enemies.** *Agric For Entomol* 2005, **7**(4):265–276.
44. Benjamini Y, Hochberg Y: **Controlling the false discovery rate: A practical and powerful approach to multiple testing.** *J R Stat Soc* 1995, **57**(1):289–300.
45. Hopkins RJ, van Dam NM, van Loon JJA: **Role of glucosinolates in insect-plant relationships and multitrophic interactions.** *Annu Rev Entomol* 2009, **54**(1):57–83.
46. Jiang YX, Lei H, Collar JL, Martin B, Muniz M, Fereres A: **Probing and feeding behavior of two distinct biotypes of *Bemisia tabaci* (Homoptera: Aleyrodidae) on tomato plants.** *J Econ Entomol* 1999, **92**(2):357–366.
47. Nombela G, Beitia F, Muñiz M: **A differential interaction study of *Bemisia tabaci* Q-biotype on commercial tomato varieties bearing or not bearing the *Mi* resistance gene, and comparative host responses with the B-biotype.** *Entomol Exp Appl* 2001, **98**(3):339–344.
48. Bonierbale MW, Plaisted RL, Pineda O, Tanksley SD: **QTL analysis of trichome-mediated insect resistance in potato.** *Theor Appl Genet* 1994, **87**(8):973–987.
49. Mutschler MA, Doerge RW, Liu SC, Kuai JP, Liedl BE, Shapiro JA: **QTL analysis of pest resistance in the wild tomato *Lycopersicon pennellii*: QTLs controlling acylsugar level and composition.** *Theor Appl Genet* 1996, **92**(6):709–718.
50. Blauth SL, Steffens JC, Churchill GA, Mutschler MA: **Identification of QTLs controlling acylsugar fatty acid composition in an intraspecific population of *Lycopersicon pennellii* (Corr.) D'Arcy.** *Theor Appl Genet* 1999, **99**(1–2):373–381.
51. Bleeker PM, Diergaarde PJ, Ament K, Schütz S, John B, Dijkink J, Hiemstra H, De Gelder R, De Both MTJ, Sabelis MW, Haring MA, Schuurink RC: **Tomato-produced 7-epizingiberene and R-curcumene act as repellents to whiteflies.** *Phytochemistry* 2011, **72**(1):68–73.
52. Farrar RR, Kennedy GG, Kashyap RK: **Influence of life history differences of two tachinid parasitoids of *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) on their interactions with glandular trichome/methyl ketone-based insect resistance in tomato.** *J Chem Ecol* 1992, **18**:499–515.
53. Kashyap RK, Kennedy GG, Farrar RR: **Mortality and inhibition of *Helicoverpa zea* Egg parasitism rates by *Trichogramma* in relation to trichome/methyl ketone-mediated insect resistance of *Lycopersicon hirsutum* f. *glabratum*, accession PI 134417.** *J Chem Ecol* 1991, **17**:2381–2395.
54. Kennedy GG: **Tomato, pests, parasitoids, and predators: Tritrophic interactions involving the genus *Lycopersicon*.** *Ann Rev Entomol* 2003, **48**:51–72.

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