Genetic elimination of field-cage populations of Mediterranean fruit flies

Philip T. Leftwich1,2, Martha Koukidou1, Polychronis Rempoulakis3,4,5, Hong-Fei Gong1, Antigoni Zacharopoulou4, Guoliang Fu1, Tracey Chapman2, Aris Economopoulos3, John Vontas3 and Luke Alphey1,5,6

1Oxitec Limited, 71 Innovation Drive, Milton Park, Oxford OX14 4RQ, UK
2School of Biological Sciences, University of East Anglia, Norwich Research Park, Norwich, Norfolk NR4 7TJ, UK
3Faculty of Biotechnology and Applied Biology, Department of Biology, University of Crete, Heraklion, Crete, Greece
4Department of Biology, Division of Genetics, Cell and Developmental Biology, University of Patras, Patras, Greece
5Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK
6The Pirbright Institute, Ash Road, Woking GU24 0NF, UK

The Mediterranean fruit fly (medfly, Ceratitis capitata Wiedemann) is a pest of over 300 fruits, vegetables and nuts. The sterile insect technique (SIT) is a control measure used to reduce the reproductive potential of populations through the mass release of sterilized male insects that mate with wild females. However, SIT flies can display poor field performance, due to the effects of mass-rearing and of the irradiation process used for sterilization. The development of female-lethal RIDL (release of insects carrying a dominant lethal) strains for medfly can overcome many of the problems of SIT associated with irradiation. Here, we present life-history characterizations for two medfly RIDL strains, OX3864A and OX3647Q. Our results show (i) full functionality of RIDL, (ii) equivalency of RIDL and wild-type strains for life-history characteristics, and (iii) a high level of sexual competitiveness against both wild-type and wild-derived males. We also present the first proof-of-principle experiment on the use of RIDL to eliminate medfly populations. Weekly releases of OX3864A males into stable populations of wild-type medfly caused a successive decline in numbers, leading to eradication. The results show that genetic control can provide an effective alternative to SIT for the control of pest insects.

1. Introduction

The Mediterranean fruit fly (medfly, Ceratitis capitata Wiedemann) is a globally distributed agricultural pest, infesting over 300 types of cultivated and wild fruits, vegetables and nuts—the widest known host range of any pest fruit fly [1]. Control methods include the use of baited traps [2,3], insecticides [4], biological control [5] and the sterile insect technique (SIT) [1,6,7]. Of these, SIT has garnered the most attention as an environmentally friendly and species-specific method, successfully implemented against the medfly as well as several other insects [8]. SIT involves the mass release of sterilized insects to disrupt normal mating patterns and induce a high frequency of sterile matings [9]. A potential benefit of SIT is that it can facilitate the establishment of ‘medfly-free zones’, removing the need for costly quarantine measures that become necessary within medfly-infested areas in order to export produce [10,11].

Overall, SIT must be cost-effective in comparison to other control methods [12–15]. Its success depends upon the ability of released sterile males to find a lek, perform courtship, attract wild females, successfully mate, inseminate females and finally to elicit effective female refractoriness to remating [16–18]. The most common mechanism by which sterility is achieved in SIT released...
males is through exposure to ionizing radiation. However, this has well-documented negative impacts on longevity and mating performance [16,19–21].

Release of insects carrying a dominant lethal (RIDL) [22–27] provides an alternative that removes the need to subject insects to ionizing radiation. One version of RIDL, on which we focus here, involves the mass release of male insects carrying a female-specific lethal transgene (fsRIDL) [28–31]. Matings with fsRIDL males by wild females produce no viable female offspring, thereby decreasing the reproductive potential of the wild population. If sufficient numbers of females mate with fsRIDL males over time then the population will collapse. Prototype fsRIDL strains of medfly have already been developed [25,27,28,32–34] giving 100% female-specific lethality at the pre-pupal stage. This lethality can be switched off to enable females to develop normally during mass rearing by providing a chemical repressor (tetracycline) in the diet.

OX3864A and OX3647Q are the leading fsRIDL strains for this important agricultural pest. Here, we describe the development and testing of these two new fsRIDL strains, and also large cage population suppression trials using the OX3864A strain. OX3864A provided repressible, fully penetrant female-specific lethality, together with the expression of a dominant fluorescent marker to facilitate identification. In a series of tests of life history, this strain displayed greater fitness than existing strains used for SIT and exhibited a high level of mating competitiveness. Large cage experiments demonstrated proof-of-principle that periodic release of OX3864A males could eradicate wild-type (wt) medfly populations.

2. Material and methods

(a) Medfly stocks

We used the TOLIMAN medfly strain as the wt background for the construction of both transgenic lines and for all subsequent testing of life-history traits prior to the experiments in Crete. TOLIMAN is a wt strain originating from Guatemala; it has been maintained at Oxitec (Oxford, UK) since 2004. tsl is the genetic sexing strain T(Y;5)101 called also Vienna-8 (without the pericentric inversion D53), introgressed into the TOLIMAN wt [35]. Genetic sexing in tsl is usually achieved by heat stress through exposure of eggs to 34°C for 24 h, though female survival may still be compromised by temperatures above 23°C. A wp marker is closely linked to tsl and is usually used to detect females [35–37]. OX3864A and OX3647Q are the newly developed RIDL strains tested in this study. Both are engineered to carry DsRed2 fluorescent markers [38] and use the tetracycline-repressible transactivator (TIA), which functions as both the transactivator and lethal effector via a positive feedback loop as described below [27].

(b) Germ line transformation with OX3864 and OX3647 constructs

Germline transformation of medfly with the OX3864 and OX3647 constructs was carried out using a piggyBac transposon vector, by standard micro-injection [39]. Two hundred and thirty pre-blastoderm medfly embryos were microinjected with OX3864, and 2700 with OX3647.

(c) Insect rearing at Oxitec

Adult fly colonies were kept at 21°C (tsl female survival is compromised at higher temperatures), 50% RH and a 13L:11D cycle. Adults were fed on a diet of yeast hydrolysate and sucrose (1:4 ratio by mass). Water was supplied through damp cotton wicks. Newly hatched larvae were transferred to larval medium, consisting of standard yeast–wheat germ–glucose–agar diet. For ‘on-tet’ rearing, suppressing transgene expression, this was supplemented with tetracycline hydrochloride to a final concentration of 100 μg ml−1. Densities of approximately 1 larva per 0.5 g of diet were used throughout. Pupae were kept between 18 and 25°C (depending on requirements) until eclosion.

(d) Insect rearing at the University of Crete

Insects were reared as above, except that experiments were conducted at 25°C, and the larval diet comprised 550 ml distilled water, 162 g sugar, 81 g brewer’s yeast, 6 g citric acid, 5 g sodium benzoate and 242 g wheat bran. For ‘on-tet’ rearing, this diet was supplemented with tetracycline hydrochloride to a final concentration of 100 μg ml−1.

(e) Tests for longevity

Longevity tests were performed at 21°C and RH 50% in six replicate plastic cages (9 × 9 × 9 cm), each containing 30 males and 30 females of the same genotype (1 insect/8.1 cm² cage surface). Three of the cages were randomly assigned to a stress test of no food and no water. This was done to assess relative measures of nutrient reserves available at eclosion, an important indicator of potential longevity under release conditions. The remaining cages had an ad libitum supply of food and water. Cages were monitored on a daily basis; dead adults were removed and sexed, until all flies were dead, in line with FAO/IAEA/USDA guidelines [40].

(f) Lifetime female fertility and egg hatching rates

From the non-stressed cages described above, eggs were collected over 24-h periods and counted under a dissecting microscope. The egg samples were then incubated on wet Whatman filter paper (Fisher Scientific) and sealed into a Petri dish with parafilm (200 eggs per Petri dish, 600 eggs per line in total). Seventy-two hours after egg collection, Petri dishes were unsealed and examined under a dissection microscope in order to count the number of empty versus unhatched egg casings.

(g) Adult eclosion rates

Three hundred pupae from each line were kept singly and monitored for eclosion. Adults were checked for sex and visible deformity before recording. Unclosed or partially eclosed pupae casings were counted and then discarded.

(h) Mating competition and remating tests

Competitive mating tests, in which the OX3864A and OX3647Q strains competed against wt males for access to wt females, were carried out according to FAO/IAEA/USDA guidelines [40]. Adult OX3864A, OX3647Q and TOLIMAN wt were obtained from larvae reared ‘off-tet’ at low density (1 larva/0.5 g medium). Field cages (1.25 m tall with a base of 0.5 m²) were constructed inside a greenhouse at the Zoology Department, Oxford University (Oxford, UK), with small orange trees (approx. 1 m in height) placed inside. Experiments took place during August (sunrise 06.00) using natural light and a stable temperature and humidity (25°C, 50% RH). Thirty males from either OX3864A or OX3647Q were placed together with 30 wt males at 06.30, and 30 females were introduced 30 min later.

The basic sequence of courtship and copulation is well characterized in the medfly and follows a distinct sequence of male behaviour patterns, consisting of ‘pheromone calling’ and rapid wing vibrations [41]. After courting, the male will leap onto the female and if successful intromission occurs, the pair...
will generally remain still for the duration of copulation, typically 90–195 min [42]. Mating pairs were removed from cages following intromission, and carefully introduced into horizontally placed 1.5-ml eppendorfs. Copulation initiation time was recorded and copulations were scored as successful only if the pair mated for more than 30 min after transfer to the eppendorf. Short copulations (less than 15 min) were eliminated from the data as they often fail to result in sperm transfer [42]. The mating experiments ended 9 h after initiation (16:00) or whenever all females had copulated, whichever was sooner. The identity of the mating males was determined by scoring for the presence of the DsRed2 fluorescent marker under a fluorescence microscope. Tests were performed with 10 replicates for each line; 167 and 237 couples were assessed for OX3864A and OX3647Q, respectively.

To test the ability of males to induce refractoriness to remating in females, we separated the mated females into two groups of 40 based on their initial mating choice (wt or fslRIDL male) then re-exposed them to equal numbers of wt and fslRIDL males on the following day. This process was repeated with the OX3647Q experiment and run for 3 days, with cages scored for matings for 9 h daily. Mating pairs were removed during mating as described above and the males again genotyped by screening fluorescence. For mating competitiveness tests with wild-derived flies, pupae were recovered from infested oranges gathered from insecticide-free orchards in Heraklion province, Crete. Wild-derived adults were separated by sex immediately after eclosion and left at 25 °C, 50% RH for 10–13 days to reach sexual maturity. All flies were allowed to adjust to natural light and temperature conditions of the glasshouse for a minimum of 24 h prior to the start of the experiment. Experiments began 1 h after sunrise and lasted for a minimum of 9 h. Mating tests were performed in greenhouse facilities at the University of Crete. OX3864A mating competition tests were performed in seven replicates with 89 pairs assessed.

(i) Caged suppression of stable wild-type populations

Stable populations of wt medfly were established in four large field cages with two cages chosen at random to be ‘treatment’ cages into which, in addition to the normal number of pupae added to the cages, approximately 1500 RIDL males per week were released. This protocol was based on that of Valdez et al. [30]. The greenhouse-based field cages measured 8 m² and were housed at the University of Crete, Heraklion, using natural light and a stable temperature and humidity (ca 25 °C, 50% RH). Each cage contained a 1.5 m high lemon tree, three food and light and a stable temperature and humidity (ca 8 °C, 50% RH). The number of pupae that were returned to this cage (using the coefficient 0.76) was therefore 96 (126 × 0.76). This methodology allowed for a dynamic pupal return that was dependent on egg production and pupal survival and reflected the number of eggs laid and the action of RIDL on female larval survival.

(j) Statistical analysis

Longevity was compared using Cox’s model of Proportional Hazards. Comparisons of fecundity and fertility were made using repeated measures ANOVA analysis on (i) total daily egg production per cage, (ii) the estimated mean daily egg production per female and (iii) egg-first instar larva hatch rate. A Greenhouse–Geisser correction was used for egg production per female, to correct for violations of sphericity in the repeated measures design. Comparisons of the eclosion rates and male proportions among lines were made using ANOVA with a Tukey HSD post hoc test. For repeated measures analyses, pairwise comparisons were made following Bonferroni correction. Net reproductive rate per female ($\lambda$) and average generation time ($G$) (spanning the peak of female fertility from one generation to the next) were calculated. From these estimates, an index of fitness ($r$) value for comparison of the potential population growth rate of each line was calculated by adapting the Euler equation [43]. Pairwise comparisons of each relative sterility index (RSI) to wild-derived or wt flies were performed using $t$-tests. Proportions were first arcsine transformed for analysis. Comparisons of remating rates were performed using Fisher’s exact tests. The Cox’s Proportional Hazards model was run in R [44], all other tests were performed using SPSSv14 (SPSS Inc., Chicago, IL, USA).

3. Results

(a) Strain development

Repressible female-specific lethality was achieved by introduction of alternatively spliced, sex-specific introns from the medfly and the peach fruit fly $\text{transformer}$ genes ($\text{Cctra}$ and $\text{Bztra}$) in the $\text{tTA}$ open reading frame [28]. Only females produce functional $\text{tTA}$, and this initiates a lethal $\text{tTA}$ positive feedback loop in the absence of tetracycline (figure 1a) [28]. This mechanism functions as both the pre-release genetic sexing and post-release population suppression mechanism. The OX3864A and OX3647Q strains developed and tested here contained potentially significant improvements over previous fslRIDL strains. These include double tet/o$\text{tTA}$ autoloops with two separate $\text{tra}$ introns in the open reading frames, and DsRed2 fluorescent markers for ease of identification (figure 1b,c) [25,28]. $\text{tsf}$ is the genetic sexing strain $\text{T(v)}$[5][101 called also Vienna-8 (without the pericentric inversion D53), introgressed into the TOLIMAN wt [35].

Forty-nine $G_0$ adults were obtained for OX3864 (a survival rate of 21%), and 950 for OX3647 (35% survival). Backcrossing to wt flies yielded multiple transgenic lines (electronic supplementary material, table S2). OX3864A and OX3647Q were selected for further development as they
Figure 1. Life-history traits of fsRIDL strain flies, visualization of RIDL transformation marker and RIDL construct details. (a) Key elements of transgenic constructs: OX3864 and OX3647 use a tetO-tTA positive feedback system to give tetracycline-repressible lethality [26,31], rendered female-specific by addition of two sex-specific alternative splicing introns from two different tephritid species (to avoid repetitive genetic elements and the risk of recombination): Bactrocera zonata, BzTra (GenBank accession: BankIt1696174 BzTra KJ397268), and Ceratitis capitata, CcTra [28]. Only females produce splice variants encoding functional tTA protein. OX3864 and OX3647 differ in the promoter used for DsRed2. OX3864 used HR5 IE1, whereas OX3647 used polyubiquitin. (b) DsRed2 fluorescence renders the RIDL males (middle, OX3647Q; right, OX3864A) easily and reliably distinguishable from wt (left). (c) Same adults as in panel (b), under white light. (d) Survival under stress test conditions, i.e. without food or water post-eclosion. Adult male and female survival data are combined (n = 180). (e) Survival under non-stressed conditions of ad libitum food and water (n = 180), OX3647Q showed significantly reduced survival relative to wt. (f) Female lifetime egg productivity: average production from three cages of 30 females over three weeks. Wt lines produced more eggs than the other three lines; OX3864A produced more eggs than tsl and OX3647Q. (g) Individual female lifetime fecundity: no difference between the strains in the average number of eggs laid per female. (h) Hatching rates of eggs laid by the females in panel (g). tsl and OX3647Q had reduced egg hatch rates relative to wt, OX3864A did not differ from wt. All values are mean (± s.e.) unless otherwise stated.
displayed complete penetrance, full repressibility, pre-pupal female lethality and excellent fluorescence (table 1). After the initial transformations, the ends of the piggyBac transposable elements were removed from the new strains via crossing to strain OX3133, which provides a source of transposase, following the method described by Dafa’alla et al. [45] (electronic supplementary material, figure S1). Homozygous lines of each strain were subsequently derived by inbreeding, with confirmation by PCR. Flanking sequences for each insertion site in these two strains are provided in the electronic supplementary material, figure S1, and the chromosomal insertion site of the OX3864 construct in line OX3864A is shown in the electronic supplementary material, figure S2. Insecticide bioassays were conducted (electronic supplementary material, table S3) in order to determine the resistance status of the OX3864A line. We know of no reason for thinking that the transgene might affect insecticide susceptibility, however we considered it important to assess insecticide susceptibility of the strains to minimize the risk that release might introgress insecticide resistance into wild populations.

(b) Longevity
Flies held under the stress conditions had significantly reduced lifespans compared with those provided with food and water (log rank test $\chi^2 = 1307, p < 0.001$). All stressed flies were dead within 6 days (figure 1d). In the non-stressed cages supplied with food and water, there were significant effects on survival of strain genotype (i.e. RIDL versus wt and tsl; $\chi^2 = 15.6, p < 0.001$; figure 1e). Sex had no significant effect on longevity ($\chi^2 = 0.17, p = 0.68$) and therefore the survival data for both sexes were combined. Under stress conditions, OX3647Q showed significantly higher survival in both sexes in comparison to the wt for either the stressed or non-stressed treatments (stressed treatment: OX3864A $p = 0.53$, $z = 0.53$; OX3647Q $z = 5.92, p < 0.01$). There was no significant difference in the average lifespan of OX3864A and tsl flies in comparison to the wt for either the stressed or non-stressed treatments (stressed treatment: OX3864A $z = 5.19, p = 0.001$; non-stressed treatment: OX3864A $z = 5.2$, $p = 0.01$). There was no significant difference in the average lifespan of OX3864A and OX3647Q in comparison to the wt for either the stressed or non-stressed treatments (stressed treatment: OX3864A $z = 5.19, p = 0.001$; OX3864Q $z = 5.19, p = 0.001$; figure 1f).

(c) Lifetime female fecundity
Percage daily egg production from the non-stressed cages declined significantly over time (repeated measures ANOVA: $F_{1,6,129} = 253.04, p < 0.001$) and there was also a significant effect of strain genotype ($F_{4,8,129} = 5.19, p = 0.008$). Pairwise comparisons with a Bonferroni correction revealed that significantly fewer eggs were produced over the lifetime for both RIDL and tsl lines in comparison to the wt (wt mean lifetime egg production $= 4315 \pm 48.51$; OX3864A $= 3470 \pm 226$, $p < 0.004$; OX3864Q $= 2593 \pm 147$, $p < 0.001$; tsl $= 2465 \pm 93.29$, $p < 0.001$). OX3864Q and OX3864A are independent transgene insertions (electronic supplementary material, figure S1), showing Mendelian inheritance consistent with single transposon insertion.

By recording daily mortality, it was also possible to estimate age-specific egg production per female. Consistent with the above, this showed that fecundity declined significantly with time (repeated measures ANOVA: $F_{1,9,152} = 131.85$, $p < 0.001$).
p < 0.001). However, there was no significant effect of geno- 
type on this decline (F_{5,215.2} = 2.19, p = 0.104, figure 1g). 
Supporting this, a one-way ANOVA on the number of eggs 
laid at peak fecundity (day 10) also revealed no significant 
differences in egg laying per female between the lines (F_{3,8} = 0.29, p = 0.97).

(d) Egg hatching rates
There was a significant effect of age on egg hatching rates 
(repeated measures ANOVA \(F_{3,40} = 207.3, \ p < 0.001\)), as well 
as a significant effect of strain genotype (\(F_{15,40} = 4.52, \ p < 0.001\), figure 1h). Pairwise comparisons with a Bonferroni 
correction showed that OX3647Q and tsl, but not OX3646A, 
had mean percentage egg hatching rates that were signifi-
cantly lower than the wt (wt = 89.56% ± 0.84; OX3647Q = 
79.11% ± 0.84, \(p < 0.001\); tsl = 78.33% ± 0.84, \(p < 0.001\); 
OX3646A = 87.11% ± 0.84, \(p = 0.247\)).

(e) Adult eclosion rates
There was also a significant difference in adult eclosion rates 
between lines (ANOVA: \(F_{3,10} = 9.89, \ p < 0.001\)). A Tukey 
HSD post hoc test revealed that this was mostly attributable 
to a significantly lower adult eclosion rate in OX3647Q in 
comparison to wt (wt = 86.1% ± 0.69; OX3647Q = 75.7% ± 
2.43, \(p < 0.01\); OX3646A = 84.7% ± 0.91, \(p = 0.9\); tsl = 
81.2% ± 1.04, \(p = 0.25\)). There was a significant effect of 
strain genotype on adult sex ratio (\(F_{3,10} = 5.06, \ p = 0.036\), 
attributable to a difference in the sex ratio of males to females 
in OX3647Q but not in the other lines (Tukey HSD post hoc 
tests: \(wt = 47\% ± 1.8\); OX3647Q = 54% ± 1, \(p = 0.035\); 
OX3646A = 55% ± 2.3, \(p = 0.035\); tsl = 50% ± 1.5, \(p = 0.83\)).

(f) Fitness indices
From the individual life-history components, \(R_0\) and \(G\) were 
calculated (electronic supplementary material, table S4), and 
from these estimates an index of fitness (\(r\)) per female was 
than derived. The \(r\) value for the wt was 0.195, which equates 
to each female contributing on average 0.195 females per day 
to the next generation. The other lines had lower fitness indi-
ces (OX3646A: \(r = 0.187\), OX3647Q: \(r = 0.176\), tsl: \(r = 0.165\)).

(g) Mating competitiveness of OX3864A and OX3647 
males with wild-type TOLIMAN flies
We used the RSI as a measure of male sexual competitiveness 
[46]. RSI ranges between 0 and 1. A RSI of 1 would represent 
100% of matings by transgenic males, a value of 0 would rep-
resent 0% of matings by transgenic males if mating with wt then 
remated with wt \(n = 5\), remated with OX3646A \(n = 3\); OX3647Q: \(x^2 = 0.17, \ p = 0.5\) (males 
that first mated with wt then remated with wt \(n = 6\), remated with OX3647Q \(n = 6\), males that first mated with wt 
then remated with wt \(n = 7\), remated with OX3647Q \(n = 5\)).

For those females that did remate when first mated to a RIDL 
male, no male genotype was preferred (OX3864A: \(x^2 = 0.58, \ p = 0.4\) (males 
that first mated with wt then remated with wt \(n = 3\), remated with OX3646A \(n = 1\); females that 
first mated with wt then remated with wt \(n = 5\), remated with OX3646A \(n = 3\) or OX3647Q: \(x^2 = 1.8, \ p = 0.13\) (test: 
OX3864A: \(x^2 = 0.46, \ p = 0.775\); seven females first mated 
to OX3646A males remated, eight females first mated to wt 
males remated; OX3647Q: \(x^2 = 1.72, \ p = 0.165\). A Tukey 
HSD post hoc test revealed that this was mostly attributable 
to a significantly lower adult eclosion rate in OX3647Q in 
comparison to wt (wt = 89.56% ± 0.84; OX3647Q = 
79.11% ± 0.84, \(p < 0.001\); tsl = 78.33% ± 0.84, \(p < 0.001\); 
OX3646A = 87.11% ± 0.84, \(p = 0.247\)).

The mean RSI value of the OX3864A flies when mating with 
wild-derived medfly from Crete was 0.45 ± 0.13 (\(t\)-test: 
\(t_{12} = -0.9, \ n = 89, \ p = 0.38\), which gave no evidence for a 
difference in mating competitiveness between OX3864A and 
wild-derived males.

(i) Suppression of stable caged populations of wild-
type medfly using OX3864A
Dramatic decreases in weekly egg production were observed 
seven weeks post-RIDL release (PR) in treatment cages, 
compared with a continued stable rate of egg production in 
control cages (figure 2a). This was due to the proportion of 
returned progeny carrying the OX3864A transgene increasing 
in treatment cages, resulting in a rapid decline in the female 
population (figure 2b). Transgene frequency in the treatment 
cage populations was monitored by screening the returning 
pupae (chosen from all the pupae produced at random) 
for the presence of the DsRed2 fluorescent marker. The 
frequency of the transgene in the returning progeny of the 
treatment cages was at 100% by week 8 PR (figure 2c), with 
both cages considered extinct by week 14 PR (extinction 
defined as zero egg production for two consecutive weeks).

4. Discussion
In this study, we investigated the OX3864A and OX3647Q 
homezygous isRIDL lines of the medfly. Both lines had 
higher fitness than the classic genetic sexing strain Vienna-
8, but equal mating competitiveness with the wt TOLIMAN 
strain from which they were derived. In addition, OX3646A 
displayed equal mating competitiveness with wild-derived 
males and proved capable of population suppression in 
proof-of-principle cage trials. By comparison at each stage 
with wt and tsl, it was possible to investigate any impacts 
on performance that arose during strain development.

The lack of a strong effect on female survival in the trans-
genic strains is important as it implies no adverse 'leaky 
expression' of the female-lethal insert at the adult stage. While 
all the non-wild-type strains displayed reduced egg production 
over the course of their lifetime when compared with the wt, the 
magnitude of this effect was greatest for the OX3647Q and 
isl strains, which were significantly less fecund than OX3864A. 
However, analysis of age-specific egg production showed no 
significant differences between any of the strains, indicating 
that differences in egg production over the lifetime of the 
cages were due to minor differences in adult female survival 
rates not previously detected. Pupal to adult eclosion rates 
did not differ significantly between wt, OX3864A or tsl.
However, there was a significant reduction in overall eclosion along with a decreased proportion of female eclosion in OX3647Q. This could indicate incomplete suppression of the fsRIDL transgene at this stage.

Mating competitiveness of both transgenic strains was high, neither strain was significantly different from the wt and there was no evidence for negative impacts of transgenesis as measured by this important parameter. In addition, we found no impairment in the ability of transgenic males to induce female refractoriness to remating. By contrast, previous work has shown that female remating is significantly higher following matings to irradiated (as in SIT) as compared with non-irradiated males [21]. Overcoming this deleterious effect by use of an fsRIDL strain represents a significant improvement.

Those negative effects as were observed (e.g. minor decreases in adult longevity and egg hatching rates) could arise from the presence of the transgene, potentially from insertion effects, but could also be due to inbreeding during...

Figure 2. Changing medfly population dynamics through introduction of OX3864A males into large cages of stable wild-type medfly populations. (a) Average daily egg production for each week in treatment and control cages. Weeks 0 – 8 constituted the population stabilization period (230 pupae added each week). Introductions of 1700 OX3864A pupae into each treatment cage commenced from week 8 onwards, in addition pupal return to each treatment cage was made proportional to the control cages. Six weeks after OX3864A male introductions, there was a clear reduction in egg production in the treatment cages compared with the control cages, continuing until eventual extinction of the wild-type population in both treatment cages (as assessed by two weeks of no egg production) by week 22 (14 weeks post initial RIDL release). The dotted line denotes the average weekly daytime temperature (Celsius) taken from daily midday temperature readings. (b) Numbers of females in treatment and control cages. (c) Proportion of progeny returned to each of the treatment cages from the oviposition traps displaying the DsRed2 fluorescent phenotype. Percentage of returning pupae carrying a copy of the OX3864A transgene reached 100% in both treatment cages by week 17 (11 weeks post-RIDL release).
the construction of the strain [47,48]. Further work could potentially improve the fsRIDL system used here, for example by backcrossing strains to the wt genetic background. This would counter any deleterious effects of inbreeding relative to the wt strain but would not eliminate costs due to the insertion itself. The latter can instead be reduced by the creation and comparison of multiple transgenic lines, as in this study.

Lethality in the OX3864A strain occurs during late larval development. Lethality acting earlier in the life cycle, as has recently been shown in medfly [49] and Anastrepha suspensa [50], could be beneficial for control. Such early-acting lethality might reduce factory production costs, as all larvae in the release generation are male and there are no superfluous female larvae competing for food. However, the first and second instar larvae are much smaller relative to the last instar and consume only a small fraction of the total diet required to produce an adult, producing a minimal effect on rearing costs. The stage at which female killing occurs should also have little impact on the potential for fruit damage and efficacy of control. In all sterile-male strategies, including fsRIDL, wild females mating a released ‘sterile’ male still oviposit in fruit, producing ‘sting’ damage which may allow microbial infection. All sterile-male systems aim rather to provide long-term control and damage reduction by reducing the number of females in subsequent generations. Our results show that the fsRIDL system tested has excellent characteristics for this purpose.

The key finding was that both fsRIDL strains tested here showed good competitiveness in life-history tests in comparison to tsl. Rearing strains at higher temperatures (not permissive to tsl) is predicted to further increase r (fitness measured as population growth rates) through a reduction in the generation time (electronic supplementary material, table S4). OX3864A in particular compared well with the TOLIMAN wt and was selected for the next phase of assessment.

There was no evidence for a difference in mating competitiveness between OX3864A and wild-derived medfly under caged conditions. In these experiments, this strain displayed better mating competitiveness (RSI 0.49 ± 0.13) than recorded with traditional genetic sexing strains such as the tsl line Vienna-8 (RSI 0.3 [51]), and far exceeded the minimum proposed RSI for viable SIT strains in tephritids (0.2 [40]). However, larger scale field trials of mating competitiveness are needed to confirm this for release programmes.

Importantly, we have shown that weekly releases of OX3864A males caused rapid, replicated population collapse in stable caged populations. This provides good evidence for the efficacy of fsRIDL. It is conceivable that additional mechanisms besides female lethality could contribute to RIDL population elimination—however, a direct effect of the transgene on egg laying is unlikely to form part of this response because no females survive. Introggression into the target population of maladaptive alleles from the OX3864A strain could occur over time via surviving males. However, this would not be sufficient to contribute significantly to the rapid, massive and sudden population suppression observed in these experiments. This trial used the TOLIMAN wt strain, rather than wild-derived flies (the logistics of establishing new artificially reared populations of wild-derived flies were prohibitive). However, our results suggest that OX3864A would be similarly effective against wild flies. Therefore, fsRIDL appears to present a cheap and effective alternative to the irradiated tsl strains currently employed in SIT control programmes (‘on-tet’ rearing may be achieved with an incremental cost of ca 1% of the larval diet; electronic supplementary material, table S5). Approval for field studies will be needed in order to make final conclusions. However, we have provided evidence that OX3864A could be used as an effective population control method for the Mediterranean fruit fly.

Acknowledgements. We thank the Vontas laboratory for the use of equipment and facilities, Pedro Rendón and others at USDA for the tsl and wt strains, and colleagues at Oxitec for technical assistance at various stages, particularly Dr S. Scalf for her invaluable help with molecular analysis of strains. We are also grateful to all of the above for support and advice. P.T.L., M.K., H.F.G., G.F. and L.A. designed research; P.T.L., M.K., P.R., G.F. and J.V. performed research; J.V. and A.E. provided advice; P.T.L. analysed data; A.Z. contributed analytical tools; and P.T.L., L.A. and T.C. wrote the paper. L.A., M.K., H.F.G. and G.F. are employees of Oxitec Ltd., a company developing genetics-based control methods against insects of agricultural and medical significance and have employment and equity interest in Oxitec. Oxitec Ltd. and the University of Oxford hold intellectual property related to the subject matter of this paper. The genetically modified line OX3864A used in the study contains patented technology owned by Oxitec Ltd. and the University of Oxford. All other authors declare no conflict of interest.

Data accessibility. All datasets supporting this article have been uploaded either as part of the electronic supplementary material or can be found at the Dryad data repository (doi:10.5061/dryad.6sm71).

Funding statement. This work was funded in part through a NERC open CASE PhD studentship to T.C. and to Oxitec Ltd. P.T.L. received financial support from Oxitec through the NERC open CASE studentship scheme.

References

1. USDA. 2006 California county agricultural commissioners’ data 2005. p. 80. Sacramento, CA: United States Department of Agriculture, National Agricultural Statistics Service.

2. Ben Jemaa JM, Bachrouch O, Allimi E, Dhouibim MH. 2010 Field evaluation of Mediterranean fruit fly mass trapping with Tripack® as alternative to Malathion bait-spraying in citrus orchards. Span. J. Agric. Res. 8, 400–408. (doi:10.5424/sjar/2010082-1187)

3. Avery JW, Chambers DL, Cunningham RT, Leonhardt BA. 1994 Use of cerulean and triudeme in Mediterranean fruit-fly (Diptera, Tephritidae) mass-trapping tests. J. Entomol. Sci. 29, 543–556.

4. Alemamy A, Gonzalez A, Juan A, Tur C. 2008 Evaluation of a chemosterilization strategy against Ceratitis capitata (Diptera: Tephritidae) in Mallorca island (Spain). J. Appl. Entomol. 132, 746–752. (doi:10.1111/j.1439-0418.2008.01376.x)

5. Heudrich DH, Goeden RD. 1996 Issues concerning the eradication or establishment and biological control of the Mediterranean fruit fly, Ceratitis capitata (Wiedemann) (Diptera: Tephritidae), in California. Biol. Control 6, 412–421. (doi:10.1006/bcon.1996.0054)

6. Eckerlen W, Munford J. 2001 Economic evaluation of three alternative methods for control of the Mediterranean fruit fly (Diptera:Tephritidae) in Israel, Jordan, Lebanon, Syrian Arab Republic and territories under the jurisdiction of the Palestinian Authority. Vienna, Austria: IAEA.

7. Jackson DS, Lee BG. 1985 Medfly Mediterranean fruit fly Ceratitis capitata in California 1980–1982. Bull. Entomol. Soc. Am. 31, 29–37.

8. Hendrichs J, Ortiz G, Liedo P, Schwarz A. 1983 Six years of successful medfly program in Mexico and Guatemala. In Fruit flies of economic importance. Proc. CEC/IOBC Int. Symp., November 1982 (ed. R Cavallo), pp. 353–365. Rotterdam, The Netherlands: A.A. Balkema.

9. Knipling EF. 1955 Possibilities of insect control or eradication through the use of sexually sterile males. J. Econ. Entomol. 48, 459–462.
