

# A Meta-analysis of Longevity Estimates of Mosquito Vectors of Disease: Supplementary Material

Ben Lambert, Ace North, Charles Godfray

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## S1 MRR experiments

### S1.1 Data

The MRR database in Guerra *et al.* (2014) contains 393 individual time-series, along with meta-data for a range of factors for each experiment (for example, species, geography, and date of study). We cleaned the data, making a number of amendments to it (see Section S1.2), and transformed the data into a form amenable for our statistical model. We removed time-series with fewer than six separate recapture observations, resulting in 238 time series. For the species-level analyses, we required at least two time series per species, resulting in loss of six series, meaning that the data used in the Bayesian hierarchical analysis comprised 232 individual time series (see Section S4 for a list of the studies included). Tables 1 and 2 summarise the data used in the Bayesian hierarchical analysis. This data encompassed time-series from MRR experiments across 33 different species and three genera: *Aedes* (91 separate time-series), *Anopheles* (94), and *Culex* (47), and spanning a wide geographical range (Fig. S1).

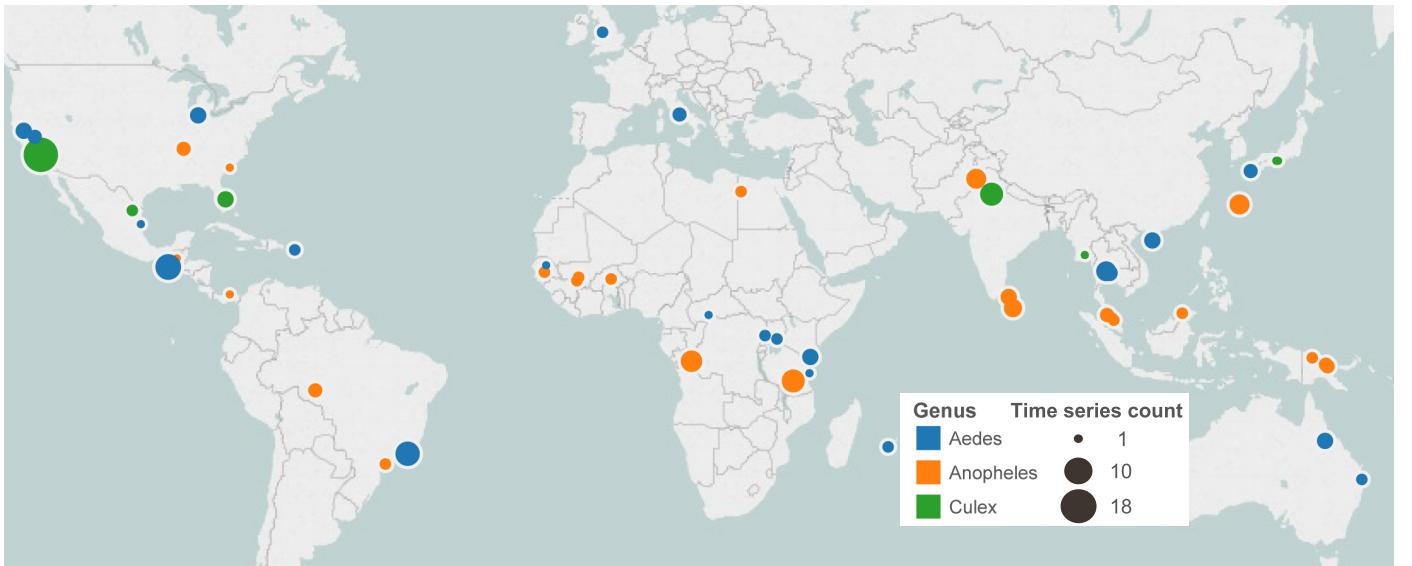
### S1.2 Amendments by MRR ID

This section describes the amendments made by MRR ID (the unique identifier that Guerra *et al.* (2014) use for each MRR record). Where there was ambiguity in the data, we attempted to consult the original publication. The amendments to the dataset are described below:

- 69 and 70: Since the release was not disaggregated by sex, the recapture data were aggregated across both males and females, resulting in a single time series in each case.
- 482: There are actually two series (one with captured mosquitoes, the other with young reared) in the paper (Rawlings *et al.*, 1981), whereas the database contains only one recapture series. In this analysis, both time series are included.
- 483: There are three studies in the paper (Rawlings *et al.*, 1981), (by dye colour there is one for ‘M&Y’, another for white, and a third for green), whereas the database only contains one release series. In this analysis, we analyse all three time series.
- 578: A null observation was removed on day 12, since isn’t present in the original paper (Eyles *et al.*, 1943a).
- 585: It is not clear from the original paper (Smith *et al.*, 1941) whether the missing recapture observations on certain days are because no mosquitoes were found on those days, or because no efforts were made to recapture them on those days. We have assumed that the number recaptured were as stated in the database on those days (missing, because no recapture efforts were made on those days).
- 586: It was unclear from database whether the missing observations are due to lack of recapture, or no effort. Have assumed that zero mosquitoes were captured on these days as seems most likely (the paper could not be accessed).
- 342: Changed number of released from 6,000 to 12,000 following the original publication (Bryan *et al.*, 1991).
- 246: Moved the observations from captures to recaptures following the original publication (Arredondo-Jiménez *et al.*, 1998).
- 55: Corrected a mistake in release data; the actual number released is 739, not 749 (Midega *et al.*, 2007).
- 478-481: All four of these series give releases not disaggregated by gender, whereas the recaptures are split this way. Have combined the recapture series to yield a single release-recapture series in each case.
- 154: Moved captured male series to recaptured following original paper (Tsuda *et al.*, 2001).

- 334: Data starts on day 3, thus have added this number of days to our time variable in this case.

The R file `s_clean_data.R` attached cleans the data, makes the above amendments and outputs the data in a form amenable for estimation using Stan (Carpenter *et al.*, 2016).



**Figure S1: The location and number of separate time-series for the MRR studies included in this analysis.** The area of each circle indicates the number of time-series at each study site. The colour shows the genus of the mosquitoes in each study.

### S1.3 Statistical model

Data for a typical MRR experiment consists of a single release of  $N_R$  marked mosquitoes followed by a series of marked mosquito recaptures on subsequent days (Fig. S3 shows three such example series). We model the number  $y(t)$  of marked mosquitoes recaptured on day  $t$  using a negative binomial sampling model,

$$y(t) \sim \text{NB} ((N_R - Y(t-1))S(t)\psi, \kappa), \quad (1)$$

where  $Y(t-1)$  is the cumulative number of mosquitoes caught on all days before  $t$ ,  $S(t)$  is the probability that an individual mosquito survives and remains in the study area until time  $t$ ,  $\psi$  is the daily recapture probability for an individual mosquito which is assumed constant through time, and  $\kappa$  is the time-independent

Data characteristic	Count
Species	33
Genera	3
<i>Anopheles</i>	94
<i>Aedes</i>	91
<i>Culex</i>	47
Female-only MRR	179
Male-only MRR	35
Mixed sex MRR	18
Pre-release blood-feeding only MRR	71
Pre-release sugar-feeding only MRR	41
Pre-release both blood- and sugar-feeding MRR	4
Pre-release neither blood- and sugar-feeding MRR	116
MRR time-series	232

Table 1: **Summary of variables across all MRR time-series.** For the ‘Species’ and ‘Genera’ rows, the counts represent the number of distinct entries in the database; otherwise the counts represent the number of time series.

Data characteristic	Min	Mean	Median	Max	Standard deviation
Study duration, days	6.0	11.8	10.0	71.0	4.7
Number of days on which collections took place	6.0	10.1	9.0	47	9.1
Number of separate release days	1.0	1.9	1.0	23	3.0
Number released	66	4,929	1,297	86,200	12,043
Number recaptured	2	163	63	4,090	399
Recapture percentage	0%	8.6%	5.2%	57.1%	10.04%
Age at release, days	0	1.8	0	13	2.8

Table 2: **Summary of data from individual MRR time-series.**



Figure S2: **The number of MRR time-series by date and sex of released mosquitoes.** The numbers represent by-decade totals of the 232 time-series we used in the main analysis.

shape parameter of the negative binomial distribution that controls the extent of variance in recapture rate likely due mostly to environmental heterogeneity. We chose a parameterisation of the negative binomial such that its mean is given by  $\mu(t) = (N_R - Y(t-1))S(t)\psi$ , and its variance by  $\sigma(t)^2 = \mu(t) + \frac{\mu(t)^2}{\kappa}$ .

For some MRR experiments, there were a number of releases ( $q \geq 2$ ) of marked mosquitoes throughout the duration of the study. In contrast to single releases, with multiple releases over time, it is not in general possible to determine the particular release to which a recaptured mosquito belongs. To avoid the complication of directly inferring this quantity, we choose to represent previous recaptures probabilistically. This results in a slightly different mean to that of the single release model,

$$\mu(t) = N_{Released}(1 - \psi)^{t-1}S(t)\psi, \quad (2)$$

where the factor of  $(1 - \psi)^{t-1}$  represents the probability that a mosquito is *not* recaptured on a previous day. Where experiments consisted of two or more releases occurring at distinct points in time we assumed that recaptures of individual mosquitoes from either batch were independent of one another, although with the same sampling parameters ( $\psi$  and  $\kappa$ ). This results in an overall mean composed of the sum of those from all  $q$  releases,

$$\mu(t) = \mu_1(t) + \dots + \mu_q(t). \quad (3)$$

The simplest assumption is that death and dispersal rates are independent of



Figure S3: **Example MRR time-series for three different studies from the Guerra *et al.* (2014) database.** In all the above experiments there was a single release of a batch of marked mosquitoes.

mosquito age, giving an exponential ‘survival’ function,

$$S(t) = e^{-\lambda t}, \quad (4)$$

where  $\lambda$  is the sum of the rates of death and dispersal from the study area. To estimate the lifespan of mosquitoes we use this model, partly because of the limited evidence we determine in favour of senescence (Figs. 8 and 9).

We assume that the number of mosquitoes recaptured on one day is independent of the number recaptured on any other day, apart from their joint dependence on  $\lambda$ ,  $\psi$  and  $\kappa$ . This results in a likelihood of the data of the form,

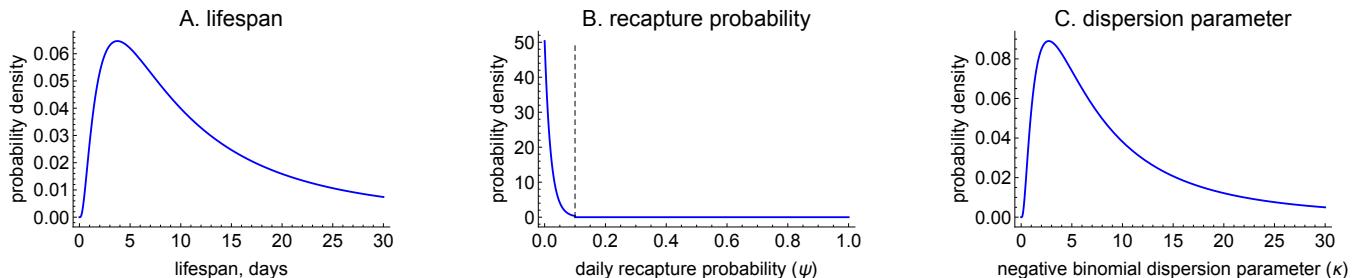
$$\mathcal{L}(y(t_1), y(t_2), \dots, y(t_R) | \lambda, \psi, \kappa) = \prod_{i=1}^R p(y(t_i) | \psi, \lambda, \kappa), \quad (5)$$

where  $R$  is the number of individual days where collections took place, and  $p(y(t_i) | \psi, \lambda, \kappa)$  is the probability of recapturing  $y(t_i)$  mosquitoes on day  $t_i$  determined from a negative binomial distribution with parameters  $\mu = e^{-\lambda t} \psi$ , and  $\kappa$ .

## S1.4 Individual time-series estimates

We first treat each time-series separately, and estimate individual  $(\lambda, \psi, \kappa)$  parameters of the statistical model (described in the previous section) for each time-series. To use a Bayesian methodology we must specify priors on this set of parameters. Here we choose to specify independent priors on each parameter of the form:  $\lambda \sim \mathcal{N}(-2.32, 1)$ ,  $\psi \sim \exp(50)$  (with  $\psi$  constrained to be less than 0.1, a threshold below which the majority of daily recapture probabilities in the data are observed) and  $\kappa \sim \text{log-normal}(2, 1)$ . This prior on the rate parameter of the exponential distribution ( $\lambda$ ) corresponds to a wide range of possible lifespans (Fig. S4A), with

a mean of 10 days. It was necessary to use an informative prior on  $\psi$  to bound it to sensible values and to prevent the correlation of estimates with  $\lambda$  leading to unreasonably short estimates of  $\lambda$ ; the prior on  $\kappa$  is fairly uninformative and allows a wide range of values (Fig. S4B,C).



**Figure S4: The prior probability distributions used for lifespan (A), recapture probability (B) and dispersal parameter (C) in the individual time-series analysis for the MRR studies.** Note: the prior for the recapture probability was truncated at  $\psi = 0.1$  since most MRR day one recapture fractions were significantly below this threshold.

### S1.5 Estimating lifespan at the species, genus and overall groupings

We synthesise information from across all MRR experiments to produce more robust estimates of mosquito lifespan than can be obtained from considering the individual time-series separately. However there exists considerable heterogeneity across the experiments. This heterogeneity has two sources. There is that arising from variability in experimental methodology. There is also variability from actual differences in lifespan across the different mosquito cohorts; for example due to genetic differences between mosquito populations or due to climatic differences. Because of this heterogeneity we use a Bayesian hierarchical model which is akin to a ‘random effects’ model in classical statistics. This type of model assumes that there is random variation in parameters at the individual time-series level, although each of the parameters is drawn from a common ‘population-level’ distribution. In our case we separately estimate three different model groupings where the population-level distributions correspond to the species, genus and overall (across all studies) levels respectively (Fig. S5). This allows us to estimate average mosquito lifespan for a given species or genus, or alternatively across all time-series, by independent sampling from the posterior predictive distribution from which the individual  $\lambda_i$  are drawn.



**Figure S5: A representation of the hierarchical Bayesian model, for the constant mortality model case when considering the species-level grouping.** Here ‘pdf’ indicates ‘probability density function’, and  $\lambda_i$ ,  $\psi_i$ , and  $\kappa_i$  represent the force of mortality for the exponential distribution, daily recapture probability and over-dispersion parameter of the negative binomial distribution for time-series  $i$  in the dataset;  $\mu_i(t) = \psi_i e^{-\lambda_i t}$  is the mean number of mosquitoes recaptured on day  $t$ .

Whilst we assume that the variation in mosquito mortality across experiments is random in nature, we recognise that there may exist systematic sources of variation that we do not include in our model. To account for this potential source of bias we examined how the individual estimates of lifespan correlated with experimental covariates (trapping method and number or density of traps). The data on trapping method in the Guerra et al., (2014) database is less reliable than other data entries because published MRR studies may use multiple trapping methods and typically do not disaggregate captures by method. When we examined the correlation of trapping method with lifespan estimates, however, we did not find systematic variation by method (data not shown). We determined a positive correlation between trapping density and lifespan estimates (Fig. S24), which indicates the impact of mosquito dispersal on estimated lifespan.

A Bayesian framework requires that we incorporate our pre-analysis beliefs into our estimates through the use of priors for all parameters in a particular model.

In our hierarchical model we are required to specify prior distributions at two levels of the analysis. The first of these links the individual time-series estimates with the overarching group-level distributions. The parameters of these group-level distributions are then set prior distributions (Fig. S5). As an example, we suppose that the rate parameter  $\lambda_i$  of our exponential survival model in experiment  $i$  is given by:

$$\lambda_i = \exp(c_i + \delta_{\text{genus}[i]}^m \text{sex}_i^m + \delta_{\text{genus}[i]}^{\text{mix}} \text{sex}_i^{\text{mix}} +) \quad (6)$$

$$\delta_{\text{genus}[i]}^{\text{sugar}} \text{sugar}_i + \delta_{\text{genus}[i]}^{\text{blood}} \text{blood}_i), \quad (7)$$

where  $\delta_{\text{genus}[i]}^m$  measures a genus-specific effect of male-only releases ( $\text{sex}_i^m = 1$ ) versus female-only ( $\text{sex}_i^m = 0$ );  $\delta_{\text{genus}[i]}^{\text{mix}}$  is the analogous effect for mixed releases versus female-only;  $\delta_{\text{genus}[i]}^{\text{sugar}}$  is the analogous effect for mosquitoes that were sugar-fed prior to release versus those that were not fed; and  $\delta_{\text{genus}[i]}^{\text{blood}}$  is the analogous effect for mosquitoes that were blood-fed prior to release versus those that were not fed. The parameter  $c_i$  is modelled hierarchically, being drawn from a group-level distribution assumed to be normal,

$$c_i \sim \mathcal{N}(\mu_\lambda, \sigma) \quad (8)$$

We then specify priors on these group-level parameters,  $\mu_\lambda \sim \mathcal{N}(-2.32, 1)$  and  $\sigma \sim \text{log-normal}(-3, 1)$ . On all  $\delta$  parameters, except  $\delta_{\text{genus}[i]}^{\text{mix}}$ , we specify standard normal priors. We specify a uniform prior on  $\delta_{\text{genus}[i]}^{\text{mix}} \sim U(0, \delta_{\text{genus}[i]}^m)$  so that the effect of mixed releases lies between the female-only release effect (0) and the male-only release effect ( $\delta_{\text{genus}[i]}^m$ ).

The relatively complex nature of priors in hierarchical models make it important to determine their influence on inferences. We chose the above – somewhat uninformative – priors to allow a range of mosquito lifespans in order to minimise their effect on the estimates we report (Fig. S6). We also chose to set hierarchical priors on the remaining parameters in our models –  $\psi$  the probability of daily recapture, and  $\kappa$  the ‘over-dispersion’ parameter of a negative binomial distribution. For  $\psi$  we chose an informative prior that placed all probability mass  $\psi \leq 10\%$ , since in most experiments the fraction of mosquitoes captured was significantly below this value. For  $\kappa$  we chose a fairly wide prior that had most of its probability mass below  $\kappa = 20$  (Fig. S7). In all cases the hierarchical priors were chosen to have similar implications on lifespan, recapture probability and over-dispersion at the individual time-series level as for the non-hierarchical analysis described previously.

## S1.6 Testing for age-dependent mortality in wild mosquitoes

Previous work has found evidence of age-dependent mortality in lab populations (Styer *et al.*, 2007; Dawes *et al.*, 2009), and less-commonly in wild mosquitoes (Clements & Paterson, 1981). Furthermore, recent modelling work has examined the implications of departures from a constant risk of mortality (Styer *et al.*, 2007; Hancock *et al.*, 2009; Novoseltsev *et al.*, 2012). To determine whether senescence occurs in wild mosquitoes we re-estimate our model using survival functions,  $S(t)$ , that allow for a rate of mortality that can vary with age. Specifically, we re-estimate our model using five other models that were previously used in the literature (see Table 3 for a description of these). Each of these models makes different assumptions about how the rate of death and dispersal varies with age, but all can be represented by a general form,

$$S(t) = e^{-\int_0^t \lambda(\tau) d\tau}. \quad (9)$$

where we constrain the parameters of our models to preclude the possibility of a hazard that decreases with age ( $\frac{d\lambda(t)}{dt} \geq 0$ ). Whilst this could occur if older mosquitoes disperse less than younger mosquitoes, it is unlikely this would outweigh any declines in survival associated with old age.

The parameters of the survival function of each model were assigned hierarchical priors that allowed considerable variation in mosquito lifespan (see Fig. S6). Otherwise the statistical model we used remained the same as for the constant mortality case. In testing for age-dependent mortality, we did not account for sex or pre-release feeding effects due to the complexity of including these elements in more complex survival models.

## S1.7 Model estimation by MCMC

The likelihood and priors we use result in posterior distributions whose analytic form cannot be calculated with existent computational methods. Instead we use Markov Chain Monte Carlo (MCMC) methods to sample from each posterior distribution. We used *Stan* software (Carpenter *et al.*, 2016) that implements an efficient MCMC algorithm known as NUTS (Hoffman & Gelman, 2014).

To judge convergence of the sampling algorithm to the posterior density, we calculated  $\hat{R}$  across all Markov chains – a ratio that compares the between-chain variation to that within each chain that is commonly used to measure convergence in MCMC (Gelman & Rubin, 1992). For each class of model, we used the following MCMC parameters,

- Individual lifespan models (Section S1.4): 12 independent chains with 1000 iterations per chain,

Survival function	Hazard rate	Interpretation	Mean time spent in study area, $\bar{T}$	Papers assuming this function
Exponential	$\lambda$	Constant mortality risk	$\frac{1}{\lambda}$	Ross (1910); Anderson & May (1992); Smith & McKenzie (2004)
Gompertz	$\alpha e^{\beta t}$	Mortality increases with age at an ever-increasing rate	$\frac{e^{\frac{\alpha}{\beta}} \Gamma(0, \frac{\alpha}{\beta})}{\beta}$	Clements & Paterson (1981); Styer <i>et al.</i> (2007); Novoseltsev <i>et al.</i> (2012)
Weibull	$\alpha t^\beta; \beta \geq 1$	Mortality increases with age at an ever-increasing rate	$\alpha^{-\frac{1}{\beta}} \Gamma(1 + \frac{1}{\beta})$	Hancock <i>et al.</i> (2009); and Carey (2001) considering general insect demography
Gompertz-Makeham	$\alpha e^{\beta t} + c$	Two additive mortality risks: one that increases with age, and another that is age-independent	No simple analytic form	Styer <i>et al.</i> (2007)
Logistic	$\frac{\alpha e^{\beta t}}{1 + \frac{\alpha s}{b}(e^{\beta t} - 1)}$	Mortality risk increases with age, although at a declining rate	No simple analytic form	Styer <i>et al.</i> (2007); Novoseltsev <i>et al.</i> (2012)
Logistic-Makeham	$\frac{\alpha e^{\beta t}}{1 + \frac{\alpha s}{b}(e^{\beta t} - 1)} + c$	Two separate additive mortality risks: an age-dependent risk of the same form as the logistic model, and a constant hazard	No simple analytic form	Styer <i>et al.</i> (2007); Bellan (2010)

Table 3: A description of the survival functions used in this study, arranged in rough order of model complexity (simple-complex from top-bottom.) All parameters are defined to be non-negative.  $\Gamma(\theta)$  and  $\Gamma(\theta_1, \theta_2)$  refer to the Euler gamma function, and incomplete gamma function respectively. The ‘mean time spent in study area’ is an estimate of the combined effects of mosquito mortality and dispersal from the area of the study where collections take place, since our data does not provide spatially-resolved data.

Survival function	time-series-level priors	Group-level priors
Exponential	$c \sim \mathcal{N}(\mu_\lambda, \sigma)$	$\mu_\lambda \sim N(-2.32, 1), \sigma \sim \text{log-normal}(-3, 1)$
Gompertz	$\alpha, \beta \sim \text{log-normal}(\mu_{\alpha \beta}, 0.2)$	$\mu_\alpha \sim N(-3, 1), \mu_\beta \sim N(-3, 1.1)$
Weibull	$\alpha, (\beta - 1) \sim \text{log-normal}(\mu_{\alpha \beta}, 0.2)$	$\mu_\alpha \sim N(-4.8, 1.75), \mu_\beta \sim N(-4, 2)$
Gompertz-Makeham	$\alpha, \beta, c \sim \text{log-normal}(\mu_{\alpha \beta c}, 0.2)$	$\mu_\alpha \sim N(-3, 1), \mu_\beta \sim N(-3, 0.5), \mu_c \sim N(-4.5, 0.5)$
Logistic	$\alpha, \beta, s \sim \text{log-normal}(\mu_{\alpha \beta s}, 0.2)$	$\mu_\alpha \sim N(-2.8, 1), \mu_\beta \sim N(-3, 1), \mu_s \sim N(-3, 1)$
Logistic-Makeham	$\alpha, \beta, s, c \sim \text{log-normal}(\mu_{\alpha \beta s c}, 0.2)$	$\mu_\alpha \sim N(-3.2, 1), \mu_\beta \sim N(-3.2, 1), \mu_s \sim N(-3, 0.5), \mu_c \sim N(-4, 0.5)$

Table 4: **The priors used on parameters of each different survival model.**

For the exponential model the ‘group-level’ priors were the same for the genus and ‘overall’ models that were also estimated. The exponential model was the only model that was simple enough to allow the scale parameter of the log-normal ( $\sigma$ ) to be estimated by the data. The notation  $\alpha, \beta \sim \text{log-normal}(\mu_{\alpha|\beta}, 0.2)$  means that  $\alpha$  and  $\beta$  were assigned independent log-normal priors with location parameters  $\mu_\alpha$  and  $\mu_\beta$  respectively, and a scale parameter of 0.2 in both cases.

- Hierarchical lifespan estimates (Section S1.5): 12 independent chains with 15,000 iterations per chain,
- Age-dependent analysis (Section S1.6): 12 independent chains with 3000 iterations per chain.

In all cases, we discarded the first half of these iterations as warm-up (Gelman *et al.*, 2014). At the end of all runs for lifespan estimation,  $\hat{R} < 1.1$  for all model parameters. For the age-dependent cases, there remained a handful of parameters where  $\hat{R} > 1.1$  after running simulations for 3000 iterations but this did not affect our inferences, since repeated runs demonstrated the same pattern. We also ensured that across each MCMC run the number of divergent iterations (that can bias the MCMC away from the true posterior density) was minimal. In the majority of cases, the number of divergent iterations was far fewer than 1% of the total number of samples.

The Stan scripts for the lifespan estimation (i.e. those using an exponential survival model) for the MRR analyses are provided below. The script for the individual time series analysis (Section S1.4):

```
data {
  // Single release parameters
  int<lower=0> N; // number of observations
```

```

int<lower=0> K; // number of groups
int Y[N]; // observations for the releases
int S[K]; // time series lengths
vector[N] t; // time observations (days)
int Pos[K]; // starting position of each dataset

// Multiple release parameters
int RelFreq[K]; // frequency of releases in each study
// starting position of releases in each study
// in RelNumber
int PosRel[K];
int<lower=0> NReleases; // total number of releases
// numbers released in each study
vector[NReleases] RelNumber;
// time of each release in each study
vector[NReleases] RelTime;

real Age[K];
}

parameters {
real<lower=0.3, upper=20> kappa[K];
real<lower=0> cDecay[K];
real<lower=0, upper=1> psi[K];
}

model {
// Likelihood
for (i in 1:K) {
real lambda[S[i]];

if (RelFreq[i]< 2) // Single release
{
    real numberCaught;
    numberCaught = 0;
    for (j in 1:S[i])
    {
        lambda[j]= (psi[i] *
                    (RelNumber[PosRel[i]] - numberCaught) *
                    exp(-cDecay[i] * (t[Pos[i] + j - 1] + Age[i])));
}
}
}
}

```

```

//1e-5 to prevent loc=0
Y[Pos[i] + j - 1] ~ neg_binomial_2(
    lambda[j] + 1e-5, kappa[i]);
numberCaught = numberCaught + Y[Pos[i] + j - 1];
}
} else // Multiple release
{
    for (j in 1:S[i])
    {
        real lambdaTemp;
        lambdaTemp = 0;
        for (kk in 1:RelFreq[i])
        {
            if (t[Pos[i] + j - 1] > RelTime[PosRel[i]+kk-1])
            {
                lambdaTemp = (
                    lambdaTemp +
                    RelNumber[PosRel[i] + kk - 1] *
                    ((1 - psi[i])^(t[Pos[i] + j - 1] -
                    RelTime[PosRel[i]+kk-1]-1)) *
                    psi[i] * exp(-cDecay[i] *
                    (t[Pos[i] + j - 1] -
                    RelTime[PosRel[i]+kk-1] + Age[i]))
                );
            }
        }
        lambda[j] = lambdaTemp;
        Y[Pos[i] + j - 1] ~ neg_binomial_2(lambda[j]+1e-5, kappa[i]);
    }
}

// Priors
for (i in 1:K)
{
    cDecay[i] ~ lognormal(-2.32, 1);
    kappa[i] ~ lognormal(2, 1);
    psi[i] ~ exponential(50);
}
}

```

```

generated quantities {
  vector[K] lifespans;
  for(i in 1:K)
    lifespans[i] = 1 / cDecay[i];
}

```

The script for the hierarchical lifespan estimation (Section S1.5) is shown below:

```

data {
  // Single release parameters
  int<lower=0> N; // number of observations
  int<lower=0> K; // number of groups
  int Y[N]; // observations
  int S[K]; // group sizes
  vector[N] t; // time observations (days)
  int Pos[K]; // starting position of each dataset

  // Multiple release parameters
  int RelFreq[K]; // release frequency in each study
  int PosRel[K]; // starting position of releases in each study
  int<lower=0> NReleases; // release frequencies
  vector[NReleases] RelNumber; // numbers released
  vector[NReleases] RelTime; // release times

  int<lower=0> nSpecies; // number of individual species
  int SpeciesIndex[K]; // species index of each study

  real Age[K];
  int SexM[K];
  int SexMix[K];
  int Genus[K];
  int Blood[K];
  int Sugar[K];
}

transformed data{
  int SpeciesToGenus[nSpecies];
  for(i in 1:K){
    SpeciesToGenus[SpeciesIndex[i]] = Genus[i];
  }
}

```

```

}

parameters {
real<lower=0.3,upper=100> kappa[K];
real a[nSpecies];
real<lower=0> p[nSpecies];
real<lower=0> r[nSpecies];
real cDecay[K];
real<lower=0,upper=0.1> psi[K];
real<lower=0> sigma_a[nSpecies];
real delta_M[3];
real delta_Blood[3];
real delta_Sugar[3];
real<lower=0, upper=1> u_mixed[3];
}

transformed parameters{
real delta_Mixed[3];
for(i in 1:3)
  delta_Mixed[i] = u_mixed[i] * delta_M[i];
}

model {
for (i in 1:K) {
  real lambda[S[i]];
  real decay_temp = exp(cDecay[i]+delta_M[Genus[i]] * SexM[i] +
    delta_Mixed[Genus[i]] * SexMix[i] + delta_Sugar[Genus[i]] *
    Sugar[i] + delta_Blood[Genus[i]] * Blood[i]);

  if (RelFreq[i]< 2) // Single release
  {
    real R_times_psi;
    real numberCaught;
    numberCaught = 0;
    R_times_psi = psi[i];
    for (j in 1:S[i])
    {
      lambda[j]= R_times_psi *
        (RelNumber[PosRel[i]]-numberCaught) *
        exp(-decay_temp * (t[Pos[i] + j - 1] + Age[i]));
    }
  }
}
}

```

```

Y[Pos[i] + j - 1] ~ neg_binomial_2(lambda[j] + 1e-5,
                                      kappa[i]);
numberCaught = numberCaught + Y[Pos[i] + j - 1];
}
}
else // Multiple release
{
  for (j in 1:S[i])
  {
    real lambdaTemp;
    lambdaTemp = 0;
    for (kk in 1:RelFreq[i])
    {
      if (t[Pos[i] + j - 1] > RelTime[PosRel[i] + kk - 1])
      {
        lambdaTemp = (lambdaTemp +
                      RelNumber[PosRel[i] + kk - 1] *
                      ((1-psi[i])^(t[Pos[i] + j - 1] -
                                   RelTime[PosRel[i] + kk - 1] - 1)) *
                      psi[i] * exp(-decay_temp *
                                    (t[Pos[i] + j - 1] -
                                     RelTime[PosRel[i] + kk - 1] + Age[i])));
      };
    }
    lambda[j] = lambdaTemp;
    Y[Pos[i] + j - 1] ~ neg_binomial_2(lambda[j] + 1e-5,
                                         kappa[i]);
  }
}

// Priors
for (i in 1:K)
{
  int speciesTemp;
  speciesTemp = SpeciesIndex[i];
  cDecay[i] ~ normal(a[speciesTemp], sigma_a[speciesTemp]);
  kappa[i] ~ exponential(p[speciesTemp]);
  psi[i] ~ exponential(r[speciesTemp]);
}

```

```

}

a ~ normal(-2.32, 1);
sigma_a ~ lognormal(-3, 1);
p ~ lognormal(1.5, 1);
r ~ gamma(100, 2);
delta_M ~ normal(0, 1);
delta_Blood ~ normal(0, 1);
delta_Sugar ~ normal(0, 1);
}

generated quantities{
real overallcDecay[nSpecies];
real overallFLife[nSpecies];
real overallMLife[nSpecies];
real overallMixedLife[nSpecies];
real overallFBloodLife[nSpecies];
real overallFBothLife[nSpecies];
real overallFSugarLife[nSpecies];
real overallMSugarLife[nSpecies];

for(i in 1:nSpecies){
    overallcDecay[i] = normal_rng(a[i], sigma_a[i]);
    overallFLife[i] = 1 / exp(overallcDecay[i]);
    overallMLife[i] = 1 / exp(overallcDecay[i] +
                                delta_M[SpeciesToGenus[i]]);
    overallMixedLife[i] = 1 / exp(overallcDecay[i] +
                                delta_Mixed[SpeciesToGenus[i]]);
    overallFBloodLife[i] = 1 / exp(overallcDecay[i] +
                                delta_Blood[SpeciesToGenus[i]]);
    overallFSugarLife[i] = 1 / exp(overallcDecay[i] +
                                delta_Sugar[SpeciesToGenus[i]]);
    overallFBothLife[i] = 1 / exp(overallcDecay[i] +
                                delta_Sugar[SpeciesToGenus[i]] +
                                delta_Blood[SpeciesToGenus[i]]);
    overallMSugarLife[i] = 1 / exp(overallcDecay[i] +
                                delta_M[SpeciesToGenus[i]] +
                                delta_Sugar[SpeciesToGenus[i]]);
}
}

```

## S1.8 K-Fold cross validation

One way to estimate a model's out-of-sample predictive capability is to use the Akaike Information Criterion that explicitly penalises a model in accordance to its complexity (typically indexed by its number of free parameters) to correct for model over-fit. The way in which this correction takes places however, is fairly heuristic, and less appropriate for hierarchical models. An alternative method, common in the machine learning literature, is known as 'cross-validation' (see for example, Kohavi *et al.* (1995)). Here to estimate out of sample predictive capability, the original data set is partitioned into training and test sets. The model is then fitted to the training set, and its predictive performance measured on the independent test set.

We use cross-validation to compare the predictive power of the species, genus and overall models, and later to determine whether age-dependent mortality occurs. In particular, we use K-Fold cross validation where we repeatedly partition our dataset into a test set composed of a number of individual time-series, and a training set of the remainder (see for example, Marsland (2015)). We then use the fitted model to measure the predictive performance on the test set. The particular measure we use is the expected log point-wise predictive density (elpd)(Vehtari *et al.*, 2015) which sums the predictive performance for each data point averaged across all posterior samples.

Since the models are hierarchical we must specify how to draw parameters for a given test sample time-series. Here we chose to draw values of the individual time-series parameters as samples from the population distribution that corresponds to that particular sample's respective grouping. So if the particular test sample time-series pertains to *Ae. aegypti* (and we are using the species-level model) then we draw independent samples for the statistical model's parameters from the estimated *Ae. aegypti* population distribution,

$$\theta_i \sim p(\theta^{\text{Ae. aegypti}} | \text{data}), \quad (10)$$

where  $\theta_i$  is the value of the parameters used in test time-series  $i$ , and  $p(\theta^{\text{Ae. aegypti}} | \text{data})$  is the overall posterior distribution across all *Ae. aegypti* experiments.

## S1.9 Model checking

To check the fit of the model to the data, we simulated from the posterior predictive distribution for each data point within each time series of recapture observations (see Figures S8, S9 & S10 and the attached file, `mrr_ppcs_all.pdf` for the full graphs). In the majority of cases, the data lay within the 95% predictive intervals indicating that the model was a good fit to the data.

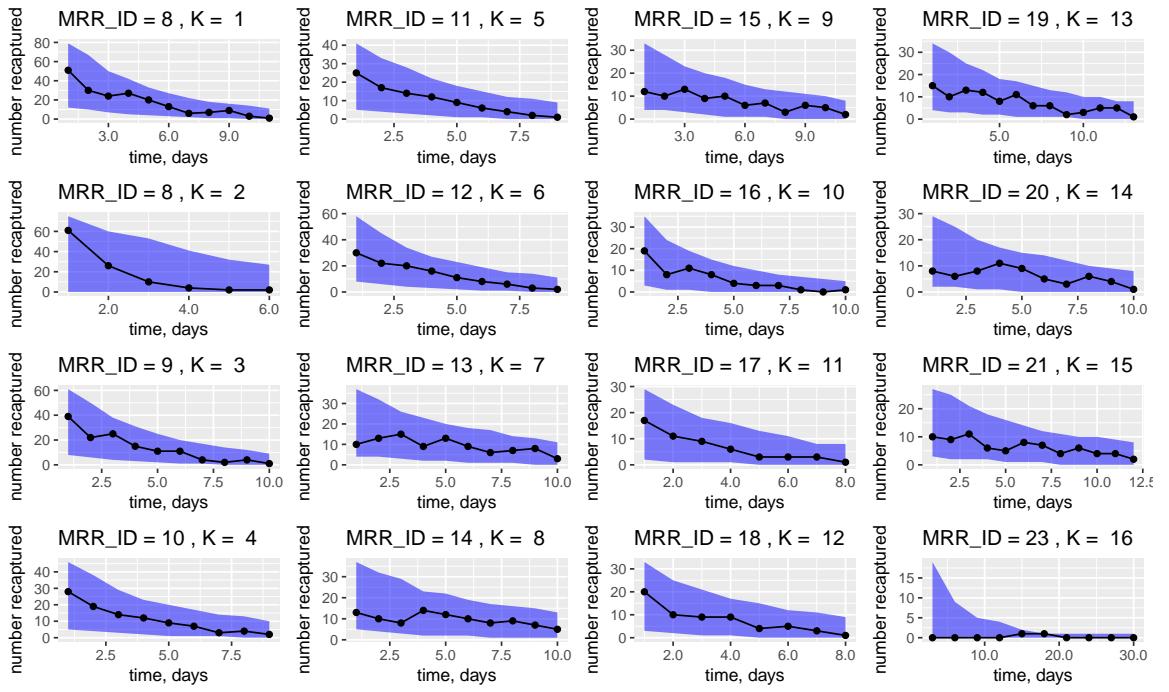


Figure S8: The numbers of mosquitoes recaptured (black lines) versus the 95% central posterior interval of the posterior predictive distribution (blue shading) for a selection of the time series. For the rest of the posterior predictive checks for the MRR models, see the file referenced in the text.

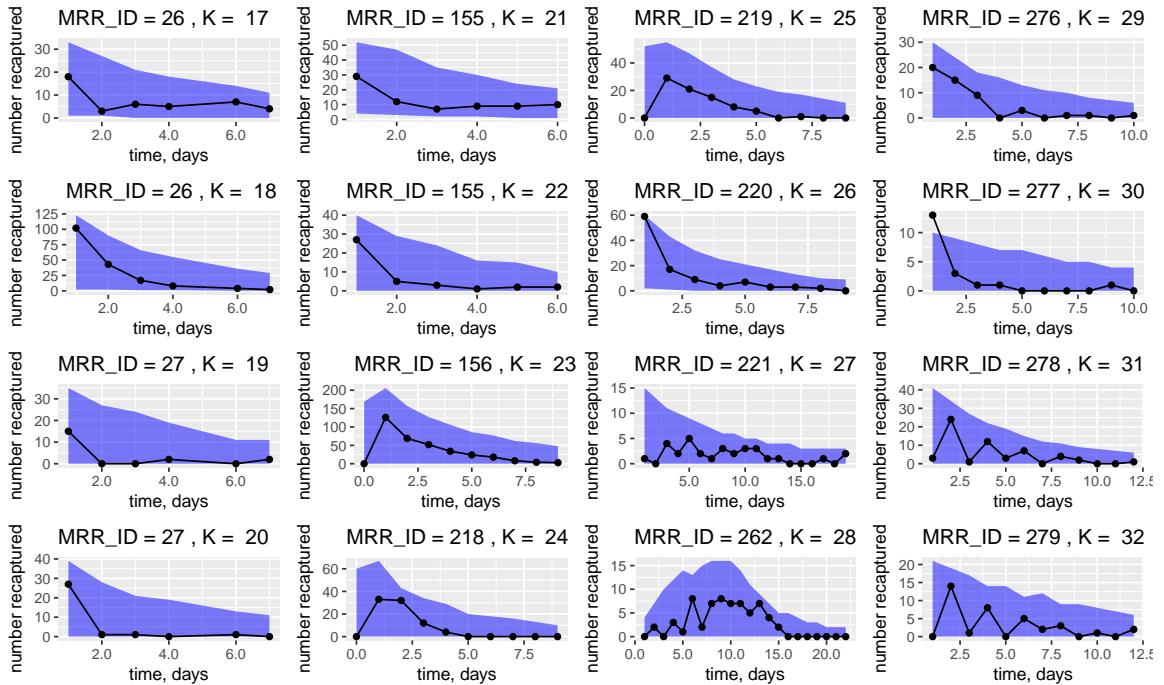


Figure S9: The numbers of mosquitoes recaptured (black lines) versus the 95% central posterior interval of the posterior predictive distribution (blue shading) for a selection of the time series. For the rest of the posterior predictive checks for the MRR models, see the file referenced in the text.

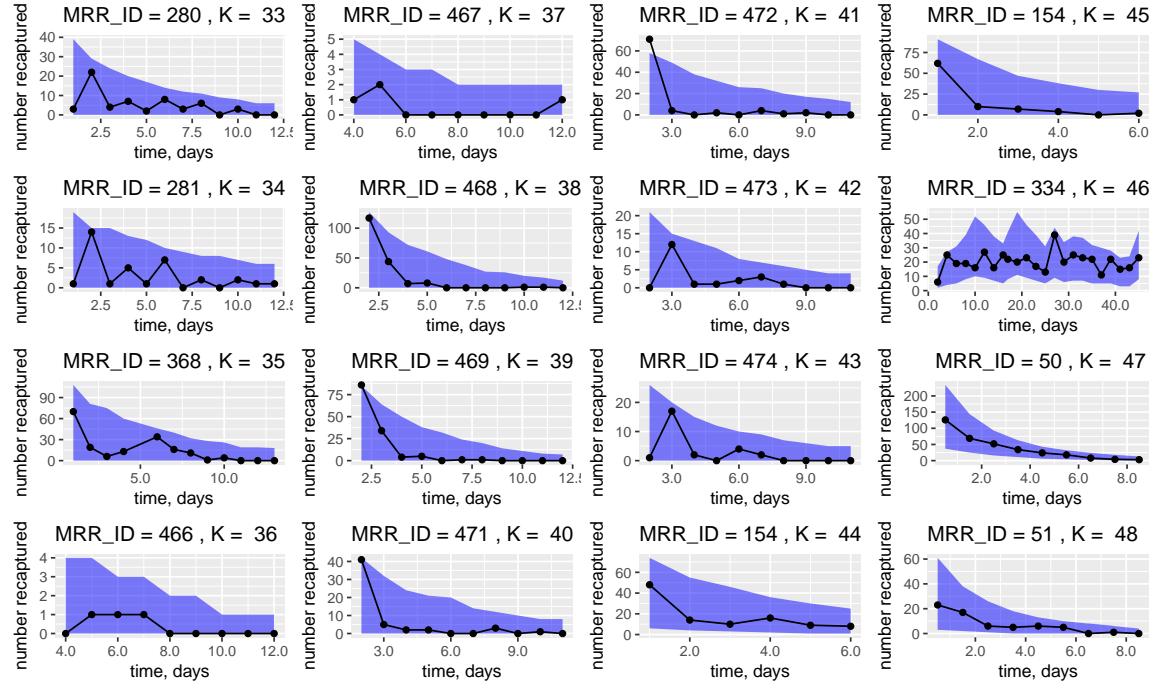
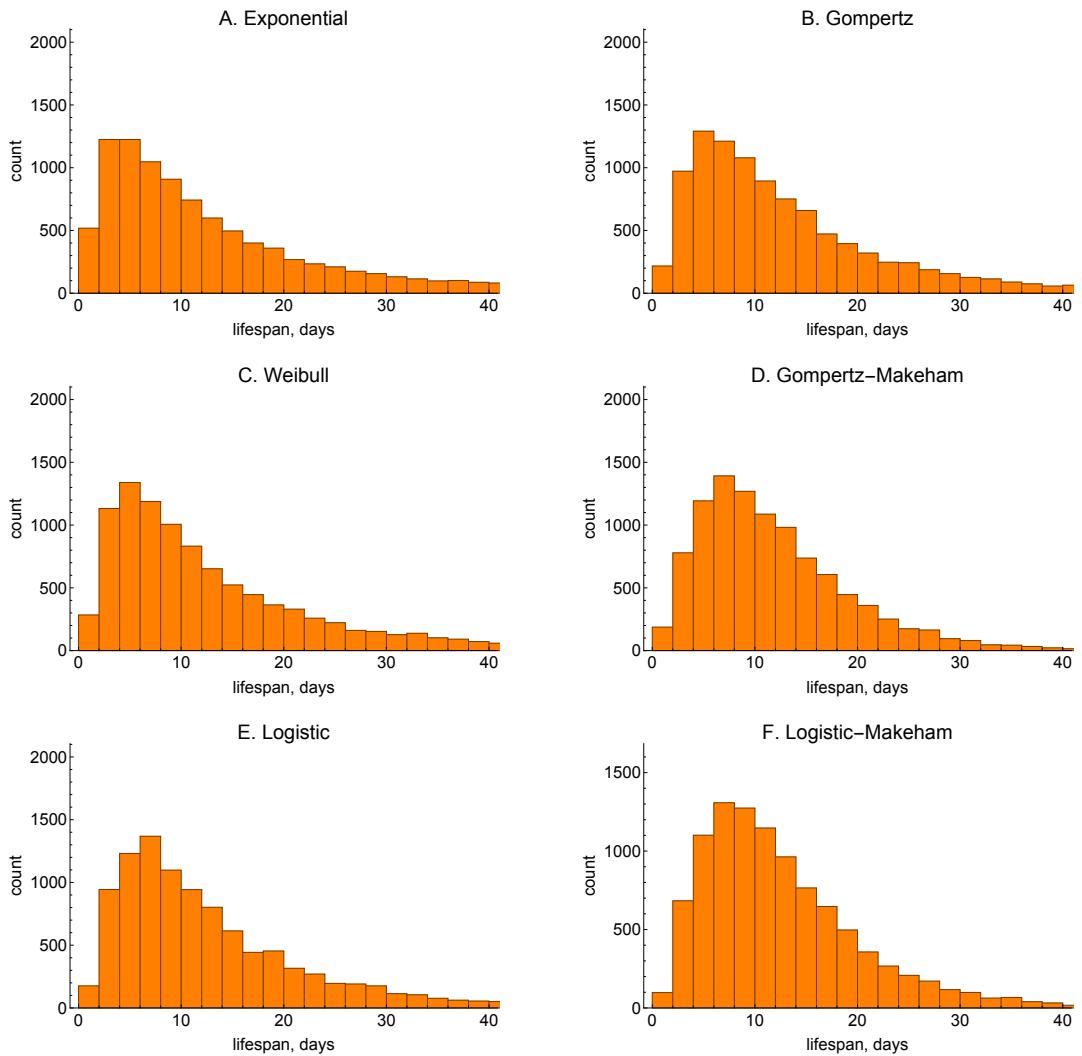


Figure S10: The numbers of mosquitoes recaptured (black lines) versus the 95% central posterior interval of the posterior predictive distribution (blue shading) for a selection of the time series. For the rest of the posterior predictive checks for the MRR models, see the file referenced in the text.



**Figure S6: Samples from the prior predictive distribution of mean lifespan across the six models of mosquito mortality introduced in Table 3.** In all cases 10,000 samples were generated using the priors indicated in Table 4, resulting in distributions with a mean close to 10 days.



Figure S7: **Samples from the priors for daily recapture probability ( $\psi$ ) and over-dispersion parameter ( $\kappa$ ).** In both panels, 10,000 samples were generated using the following hierarchical priors: for the individual time series parameters,  $\psi_i \sim \exp(r)$  (with  $\psi$  constrained to be less than 0.1 - encompassing the upper limit of day one recapture fractions observed in most data series) and  $\kappa_i \sim \exp(p)$ ; for the top-level parameters:  $r \sim \text{gamma}(100, 2)$  and  $p \sim \text{log-normal}(1.5, 1)$ .

## S2 Dissection based estimates

### S2.1 Collection of dissection data

A comprehensive search of the literature using Google Scholar ([scholar.google.co.uk](https://scholar.google.co.uk)) was performed using various combinations of the following keywords: dissection, mosquito, parity, parous, age, and physiological age. No constraints were placed on publication date, location or type. This list was supplemented with a number of author-specific searches for those individuals most prevalent in the literature. In particular we searched for all articles authored by: Charlwood, Muller, Schlein, Samarawickrema, Reisen, Detinova, Polodova, Gillies, and Wilkes. An additional list of potential articles was provided by doing a forward article search on some of the most highly-cited articles in the database: Polovodova (1949); Detinova *et al.* (1962); Gillies & Wilkes (1965); Clements & Paterson (1981). The list of results was then filtered manually by examining the titles and abstracts to produce a candidate list of the articles most likely to contain data on the physiological age of dissected mosquitoes caught in the wild, as determined by the Polovodova (1949) method.

A relational database was used to store the raw data from the actual experiments, along with the meta-data associated with each of the experiments. In many of the published articles wild mosquitoes were caught and dissected over a period of time, and the raw data thus consists of snapshots of the age structure of the population at regular intervals in time. In the cases where the data was more sparse (fewer than ten individuals, on average, per date), we aggregated across dates and recorded this as a single entry; otherwise we recorded the snapshots of the population at each different date. We record separate series for each species that was captured, or for those that were recorded at separate capture locations (potentially with an alternative collection method), and do not aggregate over these datasets.

For each individual series we recorded the following meta-data: genus, species, collection method, whether or not insecticide was mentioned as being used during or shortly before the time of mosquito collections, and the start and end dates of the experiment. At the article level we recorded the following meta-data: author, year, title, country, location (within country), start and end date, whether insecticide was used during any of the experimental replicates, whether a mrr experiment occurred alongside the dissection study, and the collection location (indoor or outdoor). At either the individual series or article levels we record additional meta-data describing the nature of data collection, for example explaining where the data was contained within the article, whether it was obtained by digitising graphs, and the number of separate dated series. For those few cases ( $n = 16$  series) where the data was obtained by digitising graphs, we used the WebPlotDigitizer

online tool (Rohatgi, 2017).

The data collection method resulted in 568 separate dissection series, across 72 published articles (see Section S5 for a list of the studies included in our final dataset). The published datasets cover the period from 1960-2015 with comparable numbers of studies across each decade (Fig. S11). The statistical approach applied to the data relies on the assumption that there is a constant rate of recruitment into the adult population (see Section S2.2). If populations fluctuate strongly from month-to-month this assumption will likely be violated. To try to mitigate against such a risk, we aggregate the data across all dates to obtain a single series for each identifier, resulting in 201 such series. To obtain a reasonable level of accuracy on estimates we remove all those individual (aggregated) series where there are fewer than 100 mosquitoes in total in the series. Finally we remove data for any species where there was only one series resulting in 131 series across four genera (*Anopheles*, *Culex*, *Aedes*, and *Mansonia*) and 25 species (Table S5). These studies are distributed across a wide range of geographies (Fig. S12). The raw data for the dissection analysis are shown in Figures S13, S14 and S15.

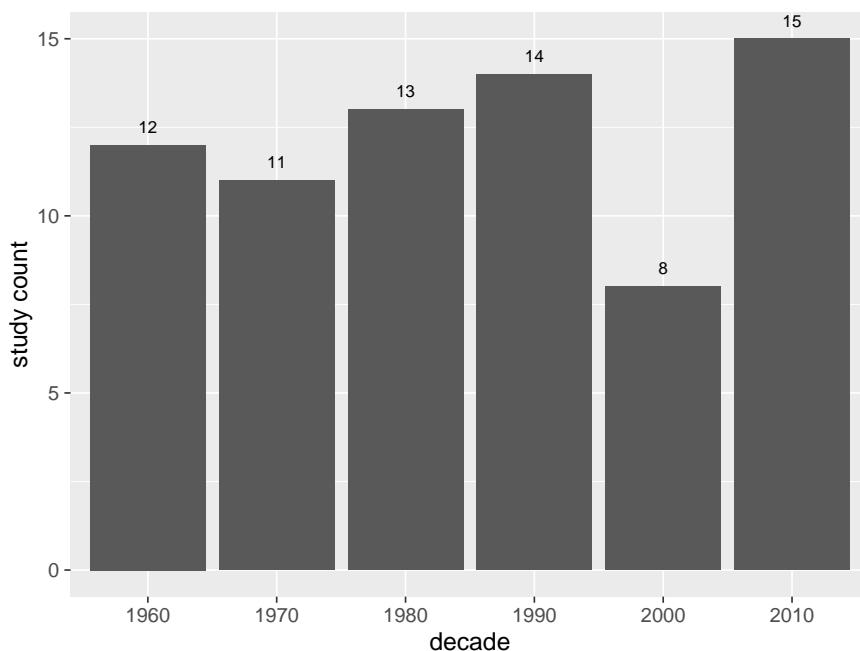


Figure S11: The numbers of published studies that estimate gonotrophic age by dissection across the study period.

Genus	Species	Frequency
<i>Anopheles</i>	<i>gambiae s.l.</i>	19
<i>Culex</i>	<i>quinquefasciatus</i>	12
<i>Anopheles</i>	<i>maculipennis</i>	11
<i>Anopheles</i>	<i>farauti s.l.</i>	10
<i>Anopheles</i>	<i>sergentii</i>	8
<i>Aedes</i>	<i>polynesiensis</i>	8
<i>Culex</i>	<i>pipiens</i>	6
<i>Anopheles</i>	<i>culicifacies</i>	5
<i>Anopheles</i>	<i>darlingi</i>	5
<i>Anopheles</i>	<i>quadrimaculatus</i>	5
<i>Anopheles</i>	<i>stephensi</i>	4
<i>Anopheles</i>	<i>melas</i>	4
<i>Culex</i>	<i>annulirostris</i>	4
<i>Aedes</i>	<i>aegypti</i>	3
<i>Aedes</i>	<i>samoanus</i>	3
<i>Anopheles</i>	<i>minimus</i>	3
<i>Anopheles</i>	<i>rivulorum</i>	3
<i>Culex</i>	<i>thalassius</i>	3
<i>Mansonia</i>	<i>uniformis</i>	3
<i>Anopheles</i>	<i>subpictus</i>	2
<i>Aedes</i>	<i>sollicitans</i>	2
<i>Aedes</i>	<i>vexans</i>	2
<i>Anopheles</i>	<i>bellator</i>	2
<i>Anopheles</i>	<i>cruzii</i>	2
<i>Culex</i>	<i>tritaeniorhynchus</i>	2
<b><i>Anopheles</i></b>		<b>83</b>
<b><i>Culex</i></b>		<b>27</b>
<b><i>Aedes</i></b>		<b>18</b>
<b><i>Mansonia</i></b>		<b>3</b>
<b>Total</b>		<b>131</b>

Table 5: The numbers of dissection series for each species or genus included in the overall dataset.

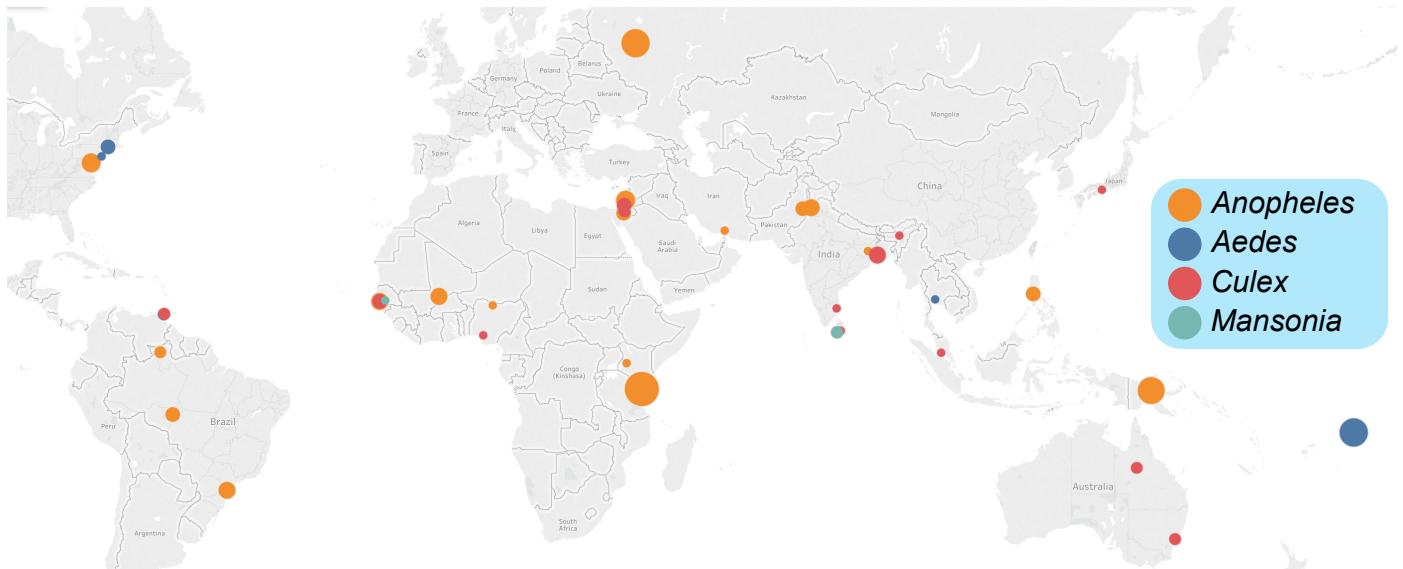


Figure S12: **The geographic location of each of the dissection databases included in the meta-analysis.** The area of the bubbles indicates the number of unique data series available.

## S2.2 Statistical analysis of dissection data

We suppose that the number of individuals recruited into the adult female population is constant over time, meaning that the age-structure of the population is stable. Whilst environmental heterogeneity will naturally lead to variation in adult recruitment over time, we hope that by aggregating data across studies undertaken over a range of dates we may reduce the impact of this effect on our results. Suppose that the probability an individual female mosquito survives until age  $a$  is given by the survival function  $S(a)$ , then the number of individuals in the

Variable	Min	Median	Mean	Max	Standard deviation
Min age of captures, gonotrophic cycles	0	0	0.02	1.00	0.12
Median age of captures, gonotrophic cycles	0	1.00	0.63	2.00	0.62
Mean age of captures, gonotrophic cycles	0.17	0.90	1.00	3.03	0.58
Max age of captures, gonotrophic cycles	1.00	5.00	5.77	13.00	2.94
Number captured	100	565	1,317	14,012	1,885

Table 6: **Summaries of the characteristics of the 131 individual dissection data series that are included in this analysis.** Note when series are censored (see Section S2.2.1) we assume that all mosquitoes dissected over the threshold are of this age when calculating summary statistics.

population surviving to this age is given by,

$$A(a) = A(0)S(a), \quad (11)$$

where  $A(0)$  is the number of female mosquitoes recruited into the population per unit time. Consider one individual experiment where we randomly sample from a wild population that is structured as per eq. (11). In this case the number of individuals sampled at each age is binomially-distributed,

$$X(a) \sim \mathcal{B}(A(a), p(a)), \quad (12)$$

where  $p(a)$  is the probability of recapturing a single mosquito of age  $a$ . In what follows we assume that the probability of capturing a given mosquito is independent of their age, so that  $p(a) = p = \text{const}$ . Since in general  $A(a)$  is large and  $p(a)$  is small, we can approximate the above using a Poisson distribution,

$$X(a) \sim \text{Poisson}(A(a)p). \quad (13)$$

However we believe that the assumption of *independent* captures of individual mosquitoes, which underlies the binomial and Poisson models, is likely suspect for the same reasons as for the MRR analysis (see Section S1.3). As before we choose to specify a negative binomial sampling distribution that allows for non-independent captures,

$$X(a) \sim \text{NB}(A(a)p, \kappa), \quad (14)$$

where we use the parameterisation such that the mean is given by  $A(a)p$ , and the over-dispersion parameter,  $\kappa$ , where as  $\kappa \rightarrow \infty$  the above sampling distribution approaches a Poisson.

In the field, unfortunately, we do not know the number of mosquitoes recruited into the adult population,  $A(a)$ , nor the probability of capturing an individual at a given point in time,  $p$ . Instead we model their product  $\Psi = A(0)p$  (the population of adult female mosquitoes of age zero that can be captured) probabilistically resulting in a model,

$$X(a) \sim \text{NB}(\Psi S(a), \kappa). \quad (15)$$

The resultant likelihood of a data series consisting of counts:  $(y(a_1), y(a_2), \dots, y(a_R))$ , is then calculated by assuming (conditional) independence of the observations,

$$\mathcal{L}(y(a_1), y(a_2), \dots, y(a_R) | S(\cdot), \Psi, \kappa) = \prod_{a=a_1}^{a_R} p(y(a) | S(a), \Psi, \kappa), \quad (16)$$

where  $p(y(a)|S(a), \Psi, \kappa)$  corresponds to the negative binomial probability mass function for a count of  $y(a)$  mosquitoes aged  $a$  as specified in eqn. (15), and  $R$  is the number of separate physiological age classes in which the count was non-zero. Since we do not know  $\Psi$  we must learn it from the data. One approach to estimate this parameter could be use the number of captures of nulliparous mosquitoes,  $X(0)$  in place of  $\Psi$ . We prefer to allow for some uncertainty in this parameter and use the data to estimate its value. However, unfortunately, the negative binomial likelihood allows too much variation in this parameter (because the data are over-dispersed), and instead we specify a likelihood of the form,

$$X(0) \sim \mathcal{N}(\Psi, \sqrt{\Psi}), \quad (17)$$

solely for the first data point  $X(0)$ . The above allows for some freedom in  $\Psi$  whilst ensuring that the parameter's probability mass lies near enough to  $X(0)$  to allow useful model estimates.  $\Psi$  is set a uniform prior over the range  $[0, \frac{3}{2}X(0)]$ .

Since  $S(a)$  is monotonically-decreasing we know that, if recruitment to the adult population is constant, then the numbers of nulliparous individuals should exceed the count in subsequent parity states. However in a number of data series there is a relative dearth of nulliparous mosquitoes versus uniparous individuals. This deficiency has been noted in a previously-published study where the authors hypothesise that it is due to the issue of sampling the nulliparous population, since they are more likely to rest outside, compared with parous individuals (Gillies & Wilkes, 1965). However there is evidence to suggest that, on average, the first gonotrophic cycle is longer than subsequent cycles (see Section S2.5), meaning that a relative surplus of nulliparous mosquitoes may exist in captured samples (Clements & Paterson, 1981).

In our analysis, we chose to remove the counts of nulliparous individuals from the series where the count was low relative to uniparous or higher parity individuals since this may indicate issues with sampling the nulliparous population. Specifically we stipulated that the nulliparous count should exceed 90% of the count for the uniparous individuals. For those cases where this condition was not met we removed the nulliparous observation and analyse the series of counts for all subsequent pars (uniparous and subsequent parous states).

Here we estimate our model with one of six different survival functions (the same as for the MRR case; Table 3), each of which makes different assumptions regarding how the force of mortality is affected by mosquito age. To estimate lifespan at the species, genus and overall groupings we then use a hierarchical Bayesian model of the same mathematical form as for the analysis of MRR experiments (see Section S1.5). However the priors for the analysis of dissection data were modified so that they represented a mean prior lifespan of three gonotrophic cycles, although allowed considerable variation in mean lifespan (Fig. S16). The priors used for the

Survival function	Physiological age series-level priors	Group-level priors
Exponential	$\lambda \sim \text{log-normal}(\mu_\lambda, \sigma)$	$\mu_\lambda \sim N(-1.2, 1), \sigma \sim \text{log-normal}(-2, 1)$
Gompertz	$\alpha, \beta \sim \text{log-normal}(\mu_{\alpha \beta}, 0.2)$	$\mu_\alpha \sim N(-1.5, 1), \mu_\beta \sim N(-2.5, 0.5)$
Weibull	$\alpha, (\beta - 1) \sim \text{log-normal}(\mu_{\alpha \beta}, 0.2)$	$\mu_\alpha \sim N(-2.5, 1), \mu_\beta \sim N(-4, 0.5)$
Gompertz-Makeham	$\alpha, \beta, c \sim \text{log-normal}(\mu_{\alpha \beta c}, 0.2)$	$\mu_\alpha \sim N(-1.4, 1), \mu_\beta \sim N(-3, 0.4), \mu_c \sim N(-4.5, 0.5)$
Logistic	$\alpha, \beta, s \sim \text{log-normal}(\mu_{\alpha \beta s}, 0.2)$	$\mu_\alpha \sim N(-1.4, 1), \mu_\beta \sim N(-2, 1), \mu_s \sim N(-3, 1)$
Logistic-Makeham	$\alpha, \beta, s, c \sim \text{log-normal}(\mu_{\alpha \beta s c}, 0.2)$	$\mu_\alpha \sim N(-3, 1), \mu_\beta \sim N(-1.3, 1), \mu_s \sim N(-2, 0.5), \mu_c \sim N(-4, 0.5)$

Table 7: **The priors used on parameters of each different survival model for the dissection data analysis.** For the exponential model the ‘group-level’ priors were the same for the genus and ‘overall’ models that were also estimated. The exponential model was the only model that was simple enough to allow the scale parameter of the log-normal ( $\sigma$ ) to be estimated by the data. The notation  $\alpha, \beta \sim \text{log-normal}(\mu_{\alpha|\beta}, 0.2)$  means that  $\alpha$  and  $\beta$  were assigned independent log-normal priors with location parameters  $\mu_\alpha$  and  $\mu_\beta$  respectively, and a scale parameter of 0.2 in both cases.

over-dispersion parameter ( $\kappa$ ) for the negative binomial likelihood were the same as for the MRR analysis.

To determine whether mosquitoes experience age-dependent mortality we compared the predictive power of each of the models that incorporate a hazard function that depends on age with that from the exponential model. As for the MRR analysis we also used K-Fold cross-validation to perform this comparison, where the data are randomly partitioned into training and test sets (see Section S1.8). The model is then fitted to each training set and used to predict the data in the independent test set. Since there are fewer series than for the MRR dataset we used two partitions for each species, where each partition was of roughly the same number of individual series.

The estimates of mean mosquito lifespan that we present here (Fig. ??) resulted from the use of the exponential survival model (i.e. no age dependence). This choice was made because we found limited evidence in support of age-dependent mortality (see Section ??). However, since the priors for each of the survival functions were specified to allow for a wide variety of lifespans (Fig. S16) the specific choice of survival function made little difference to resultant estimates (data not shown).

To demonstrate that the results we obtain are not sensitive to the particular form

of hierarchical prior structure chosen we also provide estimates of the lifespan for each series analysed on its own. To do so we assume priors on the rate parameter of the exponential distribution that provides support over a wide range of possible lifespans (Fig. S17A). We also specified a prior on the over-dispersion parameter  $\kappa$  that was comparable to the hierarchical case (Fig. S17B).

As for the MRR analysis we use *Stan* that implements a form of MCMC algorithm known as NUTS (Hoffman & Gelman, 2014) to sample from the posterior. The protocol followed for the MCMC sampling was the same as described in Section S1.7.

### S2.2.1 Analysis of censored data series

In some of the published papers the data are censored above a threshold age,  $a_T$ . In these cases we only know the number,  $y(a_T)$ , of individuals who were captured and dissected with an estimated physiological age that is greater than or equal to the threshold. Since we do not know the estimated physiological age of individual specimens  $i$ , we represent this as a parameter,  $\aleph_i$ , in our statistical model. This means that the joint distribution is a function of  $y(a_T)$  different  $\aleph_i$  parameters. Since these parameters are not directly of interest, and our chosen MCMC engine, Stan (Stan Development Team, 2014), does not directly allow discrete parameters in models, we marginalise these out of the joint distribution. To do this exactly would require an infinite sum over all the possible ages for all  $y(a_T)$  mosquitoes that have been caught whose age exceeds the threshold. Rather than carry out this intractable number of summations we instead make the approximation that all mosquitoes in this group are of the same age  $\aleph_i = \aleph, \forall i \in (1, \dots, y(a_T))$ . We believe this assumption is justifiable, particularly since the numbers of mosquitoes in each subsequent age category is a strongly-decreasing function of age. This means that whilst we do not know with certainty individuals' ages, it is likely that most will be of the threshold age  $a_T$ .

This approximation means that to marginalise the parameter  $\aleph$  out of the joint distribution, we are only required to do a single summation. Specifically if we have  $y(a_T)$  captured individuals of age equal to, or exceeding, some threshold age,  $a_T$ , the probability of these observations is given by,

$$q(y(a_T)|S(\cdot), \Psi, \kappa) = \sum_{\aleph=a_T}^{\infty} p(y(a_T), \aleph|S(\aleph), \Psi, \kappa) \quad (18)$$

$$= \sum_{\aleph=a_T}^{\infty} p(y(a_T)|S(\aleph), \Psi, \kappa) \times p(\aleph) \quad (19)$$

where  $q(y(a_T)|S(\aleph), \Psi, \kappa)$  is the probability of observing  $y(a_T)$  counts for mosquitoes of an age  $\aleph$ . In practice, since we do not believe mosquitoes live

for longer than 20 gonotrophic cycles (the maximum observed in the data was 13), we cut-off the summation at this point, and assume that the discrete prior probability distribution  $p(\aleph)$  is uniform over this range. The overall likelihood for the cases where the series are censored therefore has the form,

$$\mathcal{L}(y(a_1), y(a_2), \dots, y(a_{T-1}), y(a_T) | S(\cdot), \Psi, \kappa) = \left( \prod_{a=a_1}^{a_T-1} p(y(a) | S(a), \Psi, \kappa) \right) q(y(a_T) | S(\aleph), \Psi, \kappa). \quad (20)$$

In practice, the number of mosquitoes captured in those series that are censored represents a small percentage of total captures (the median is approximately 2%), and so the effect of the  $q(\cdot)$  term above is likely minimal on resultant inferences.

### S2.3 Model estimation by MCMC

As for the MRR analysis, we used *Stan* software (Carpenter *et al.*, 2016) to sample from the posterior distributions of model parameters.

To judge convergence of the sampling algorithm to the posterior density, we calculated  $\hat{R}$  across all Markov chains – a ratio that compares the between-chain variation to that within each chain that is commonly used to measure convergence in MCMC (Gelman & Rubin, 1992). For each model, we ran 16 independent Markov chains with 200 iterations per chain, discarding the first half of these iterations as warm-up (Gelman *et al.*, 2014). After running the algorithm for the given number of observations,  $\hat{R} < 1.1$  for all model parameters. We also ensured that across each MCMC run the number of divergent iterations (that can bias the MCMC away from the true posterior density) was minimal. In the majority of cases, the number of divergent iterations was far fewer than 1% of the total number of samples.

The model used to estimate the lifespan in terms of gonotrophic cycles is provided below.

```

data{
int N; // number of obs
int K; // number of time series
int Y[N]; // number captured
int S[K]; // length of each series
int threshold[K]; // age of censoring; if -1 then no censoring
int Pos[K]; // position of start of each series in Y
int species[K]; // index variable of species
int nSpecies; // number of species
}

parameters{
real<lower=0> PopSize[K];
real<lower=0> alpha[K];
real alpha_mean[nSpecies];
real<lower=0> alpha_sigma[nSpecies];
real<lower=0> kappa[K];
real<lower=0> p[nSpecies];
}

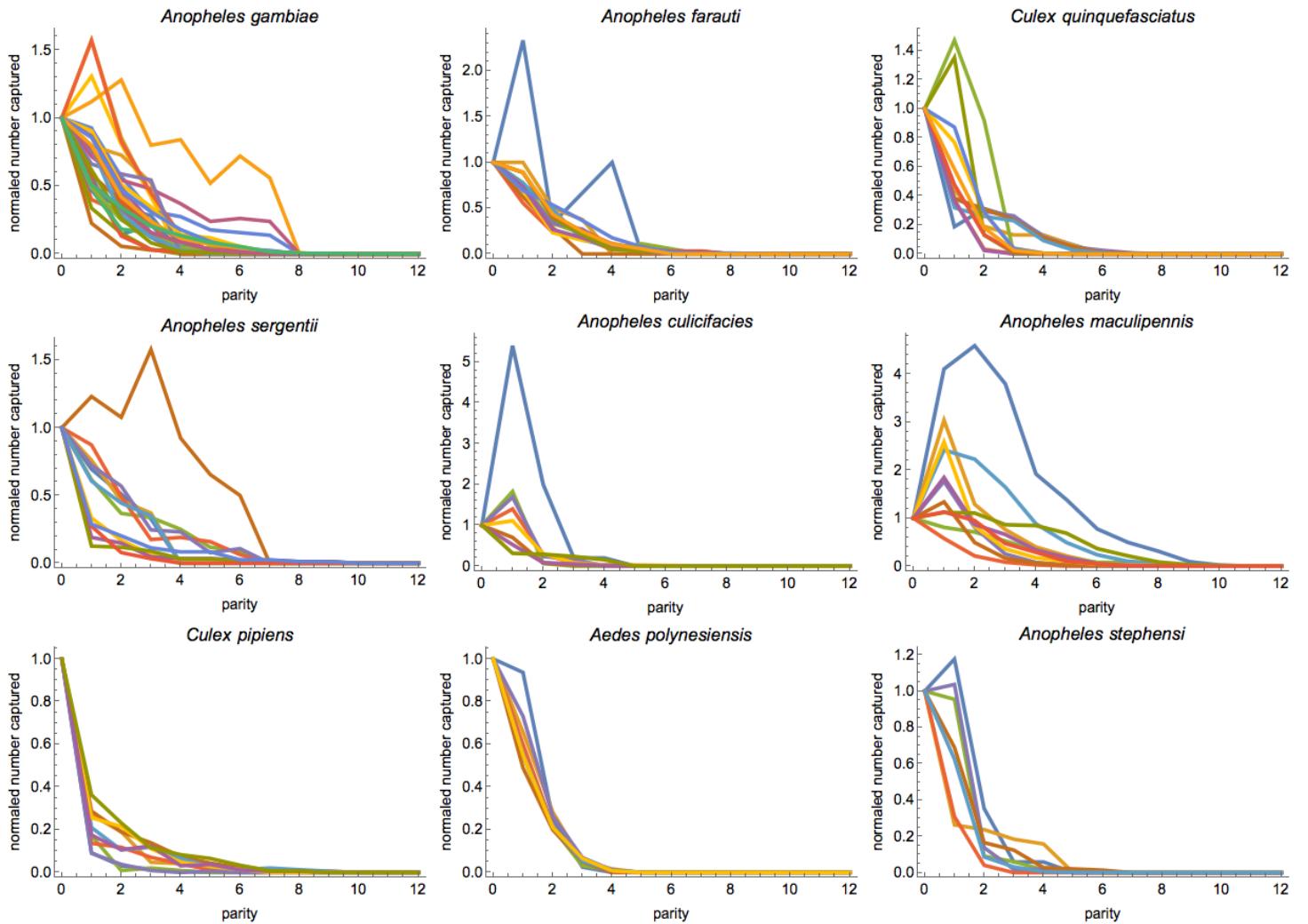
model{
// Likelihood
for(i in 1:K){
  for(t in 2:S[i]){
    // uncensored
    if(threshold[i] < 0)
      Y[Pos[i]+t-1] ~ neg_binomial_2(PopSize[i] *
                                      exp(-alpha[i] * (t-1)), kappa[i]);
    // censoring
    else{
      if((t-1) < threshold[i])
        Y[Pos[i]+t-1] ~ neg_binomial_2(PopSize[i] *
                                      exp(-alpha[i] * (t-1)), kappa[i]);
      else{
        real lLogProb[20];
        for(j in 1:20){
          lLogProb[j] = neg_binomial_2_lpmf(Y[Pos[i]+t-1] | PopSize[i] * exp(-alpha[i] * (t-1)),
                                              kappa[i]);
        }
        target += log_sum_exp(lLogProb);
      }
    }
  }
}
}

// Priors
for(i in 1:K){
  int aSpecies;
  aSpecies = species[i];
  Y[Pos[i]] ~ normal(PopSize[i], sqrt(PopSize[i]));
}

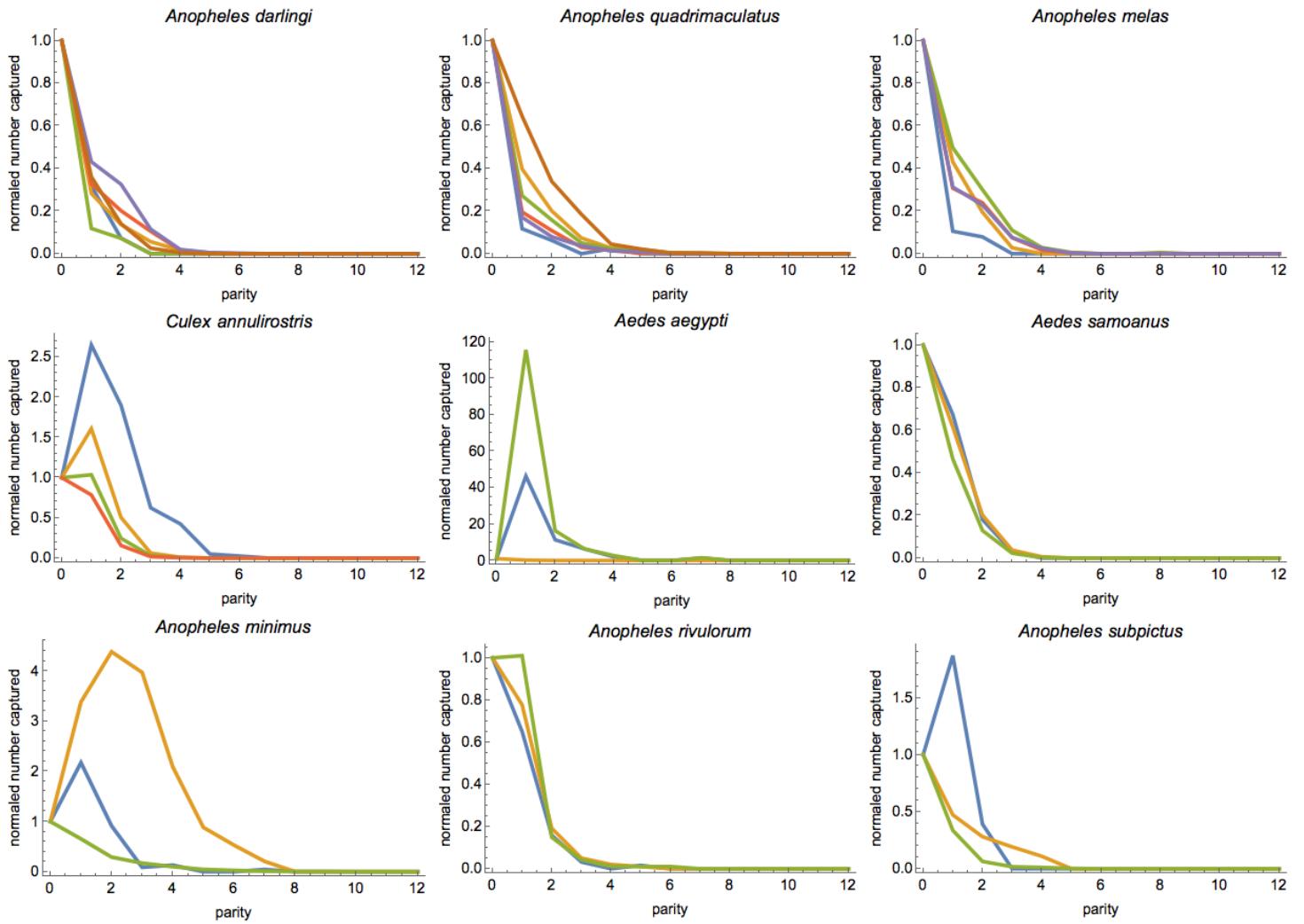
```

## S2.4 Model checking

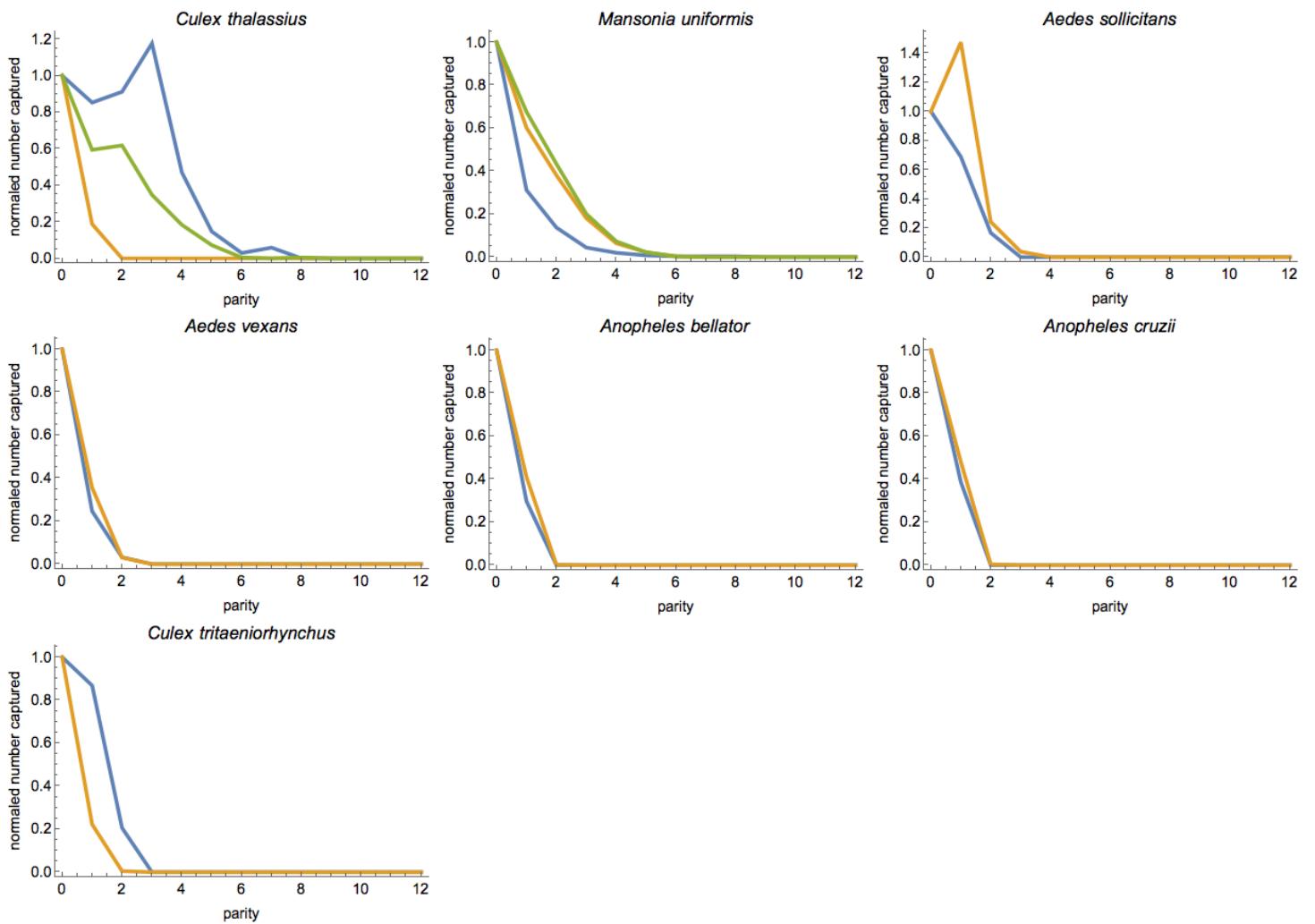
As for the MRR experiments, we simulated from the posterior predictive distribution for each series of dissection data. In the majority of the cases, the capture data lay within the 95% posterior predictive intervals, indicating that our model was a good fit to the data (see Figures S18, S19 & S20 and the attached file, `dissection_ppcs_all.pdf` for the full graphs).



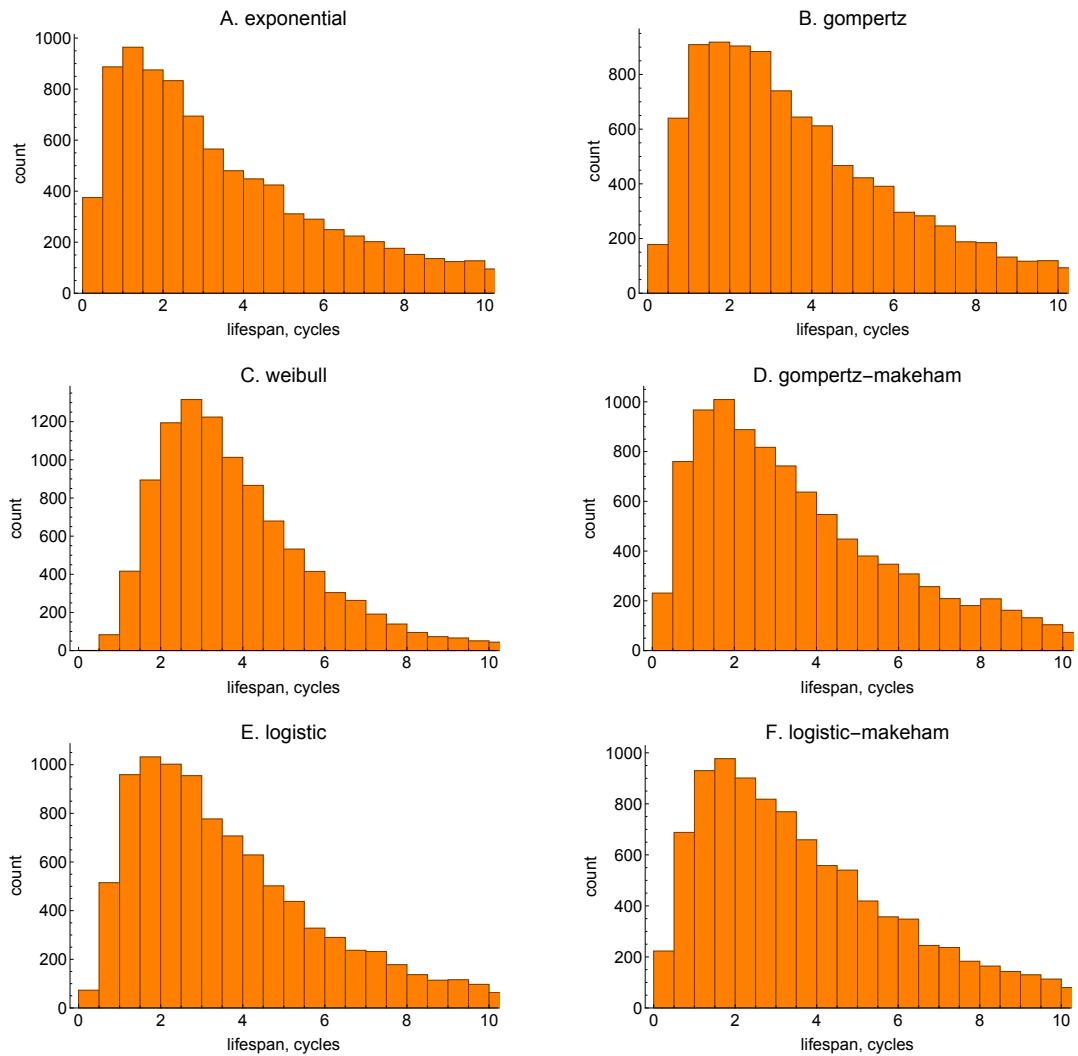
**Figure S13: The normalised physiological age series for nine species in the database.** Each different coloured line represents an individual series. In each case the count for all ages has been normalised by the nulliparous count. In all cases we do not include any data for censored observations (see Section S2.2.1).



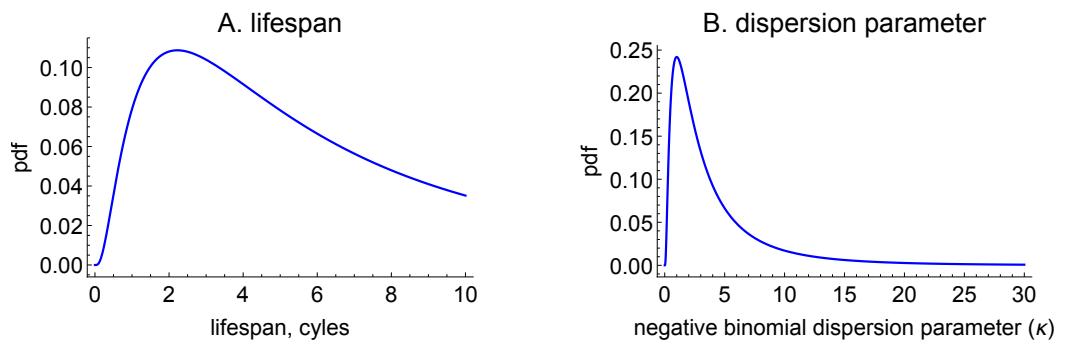
**Figure S14: The normalised physiological age series for nine species in the database.** Each different coloured line represents an individual series. In each case the count for all ages has been normalised by the nulliparous count. In all cases we do not include any data for censored observations (see Section S2.2.1).



**Figure S15: The normalised physiological age series for nine species in the database.** Each different coloured line represents an individual series. In each case the count for all ages has been normalised by the nulliparous count. In all cases we do not include any data for censored observations (see Section S2.2.1).



**Figure S16: The priors over mean lifespan used to analyse the data for each of the hierarchical models.** The distributional form of the priors is given in Table 7. In all cases the plots show data for 10,000 samples from the relevant prior distribution.



**Figure S17: The priors over A. mean lifespan and B. over-dispersion parameter used to analyse the individual dissection series.** The prior on the rate parameter of the exponential distribution was  $\lambda \sim \text{log-normal}(-1.8, 1)$ . The prior on the dispersion parameter was  $\kappa \sim \text{log-normal}(1, 1)$ .

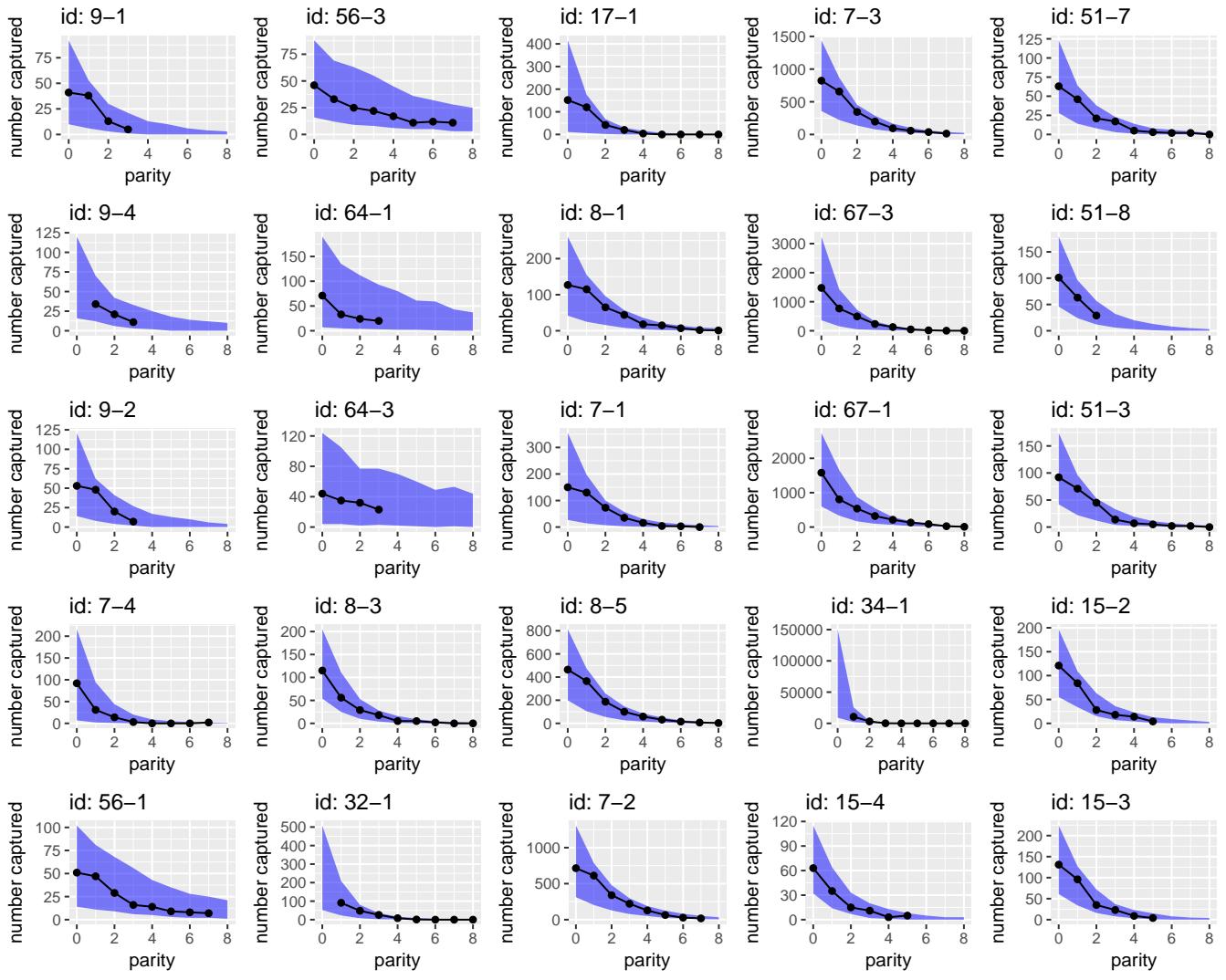


Figure S18: The numbers of mosquitoes recaptured (black lines) versus the 95% central posterior interval of the posterior predictive distribution (blue shading) for a selection of the dissection series. The titles correspond to the unique combination of "identifier - physiological-experiment-id" in the database. For the rest of the posterior predictive checks for the dissection data models, see the file referenced in the text.

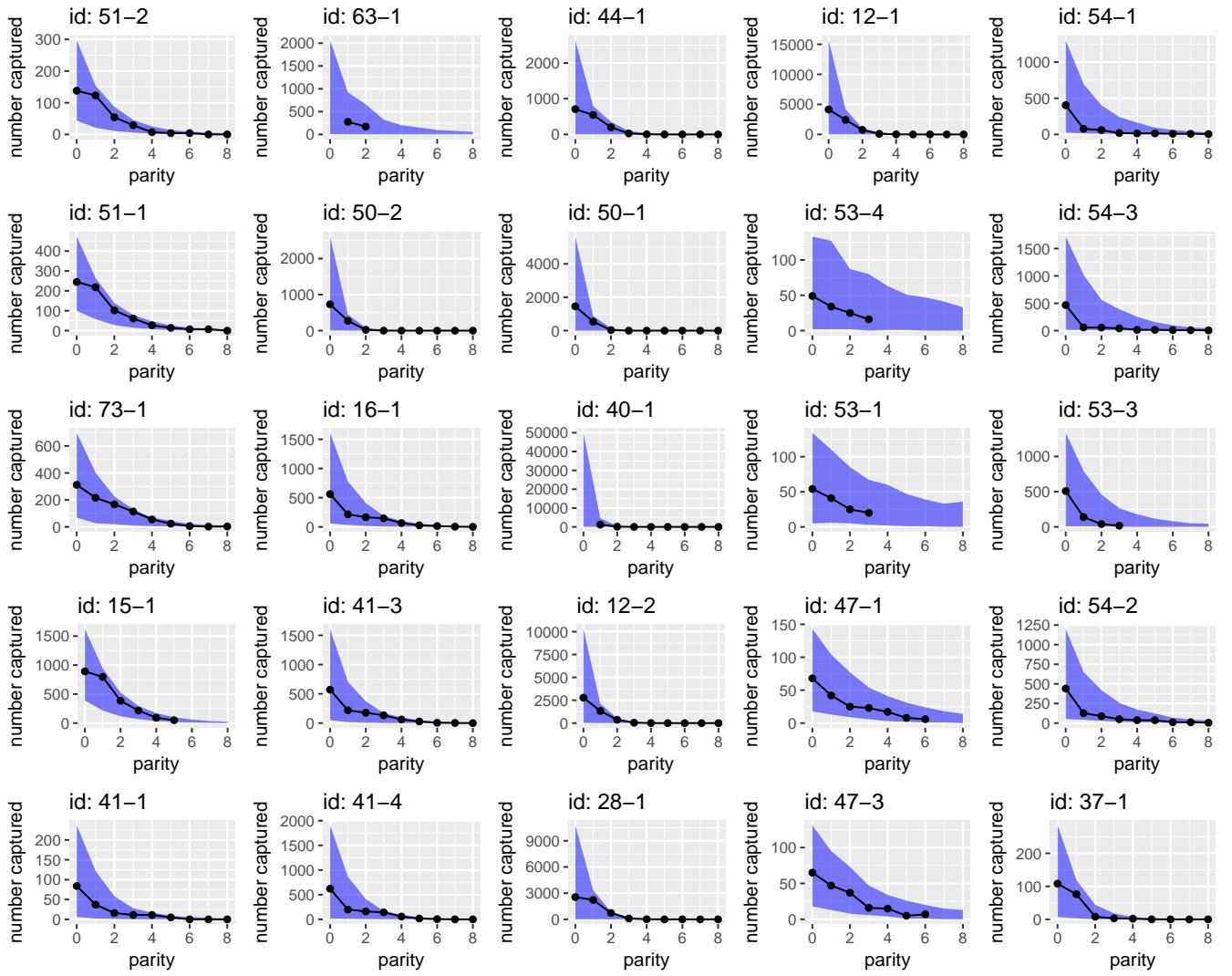


Figure S19: The numbers of mosquitoes recaptured (black lines) versus the 95% central posterior interval of the posterior predictive distribution (blue shading) for a selection of the dissection series. The titles correspond to the unique combination of "identifier - physiological-experiment-id" in the database. For the rest of the posterior predictive checks for the dissection data models, see the file referenced in the text.

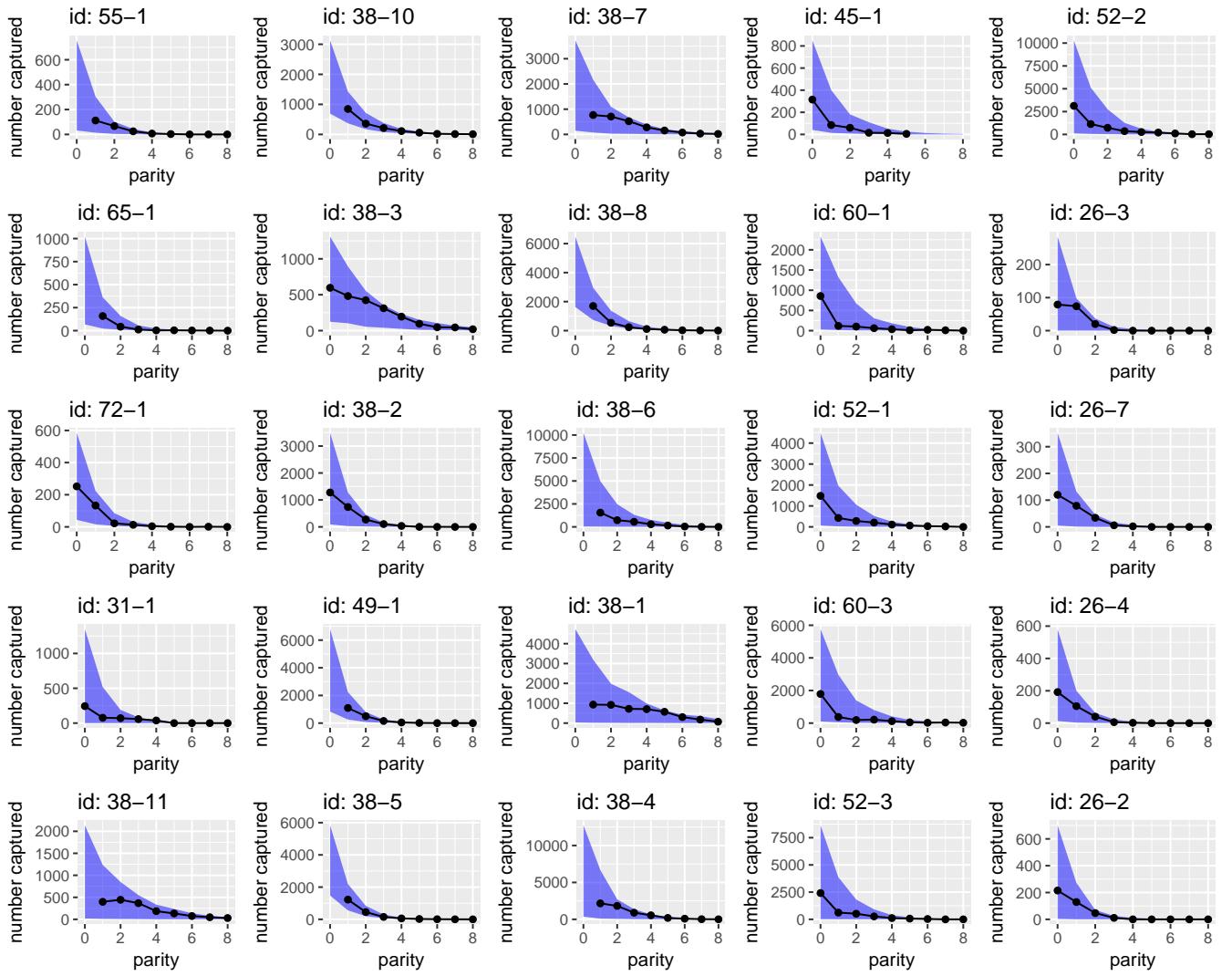


Figure S20: The numbers of mosquitoes recaptured (black lines) versus the 95% central posterior interval of the posterior predictive distribution (blue shading) for a selection of the dissection series. The titles correspond to the unique combination of "identifier - physiological-experiment-id" in the database. For the rest of the posterior predictive checks for the dissection data models, see the file referenced in the text.

## S2.5 Data collection of gonotrophic cycle duration

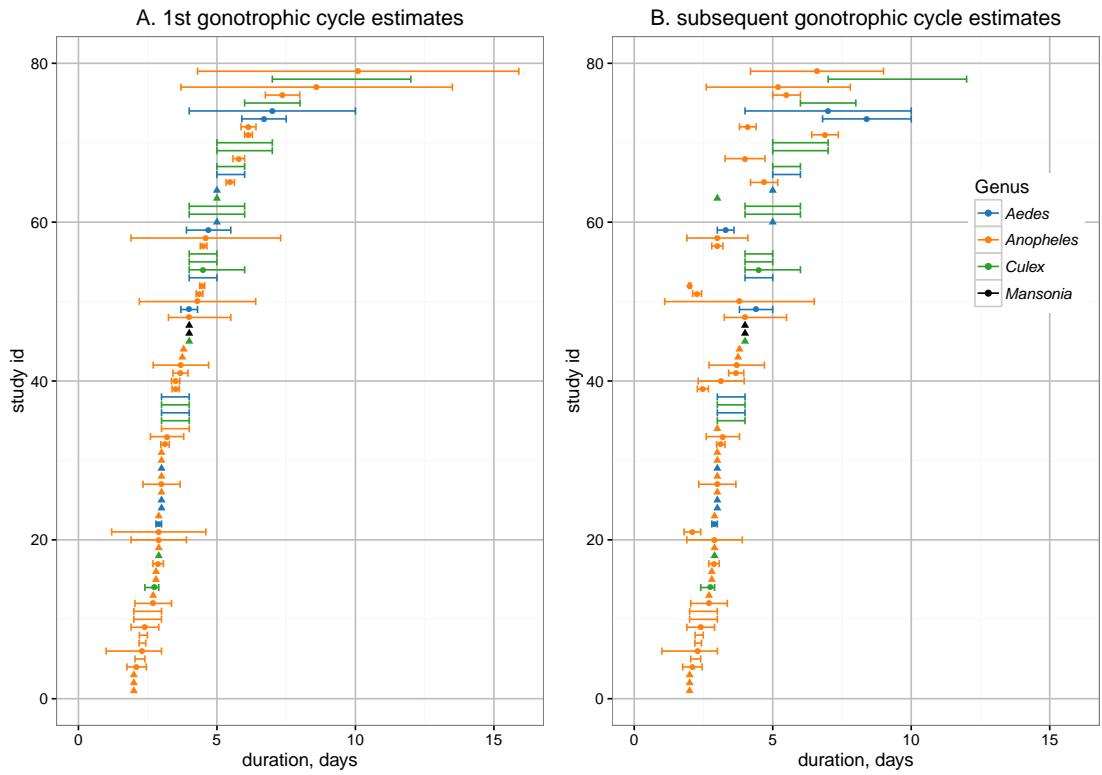
To convert the estimates of lifespan in physiological age into chronological age we require estimates of the duration of the gonotrophic cycle. To determine this characteristic we conducted a meta-analysis of previously-published studies that estimate the duration of the gonotrophic cycle. A search of the literature using Google Scholar ([scholar.google.co.uk](https://scholar.google.co.uk)) was performed using the search term: ‘gonotrophic cycle duration’. The list of articles was then supplemented with a list of references discussed by Silver (2007). Based on the abstracts of the resultant list of published studies we then decided whether to search each article for estimates of the duration of the gonotrophic cycle. Overall 79 separate estimates of this parameter were found across 42 published articles (see Section S6 for a list of the studies included in our dataset). Along with information about the estimates we also recorded study and series meta-data, including the location of the study, the method used for estimation, the species and genus, as well as the temperatures and/or seasons in which the experiments were carried out. The methods used to estimate gonotrophic cycle duration in the literature largely fell into two distinct categories: those based on MRR studies ( $n = 29$ ); and those based on observations of mosquitoes in a laboratory setting ( $n = 42$ ). In the MRR studies estimates are made of the duration of gonotrophic cycles by dissecting recaptured mosquitoes at each time point using the method of Polovodova (1949) to count ovariolar dilations. For the laboratory studies the duration of gonotrophic cycles is determined more directly by observing the time taken for mosquitoes to mate then blood-feed and finally oviposit.

Along with point estimates of the parameter we also collected information about the uncertainty in the estimates (if available). In many articles the duration of the gonotrophic cycle was estimated separately for the first versus subsequent cycles, and these estimates were recorded separately. Raw estimates of gonotrophic cycle duration were obtained for species across four different genera (*Aedes*, *Anopheles*, *Culex* and *Masonia*), although there was a bias towards *Anopheles* with  $n = 47$  estimates out of the total of 79 (Fig. S21).

Since we collected data on the method used to estimate the duration of the gonotrophic cycle we show the raw estimates for the two most common approaches: MRR and laboratory (Fig. S22). From these results it is evident that the estimates from the laboratory studies are, on average, higher than those using the MRR method, (although we wait until Section ?? for a quantitative comparison).

## S2.6 Statistical analysis of gonotrophic cycle data

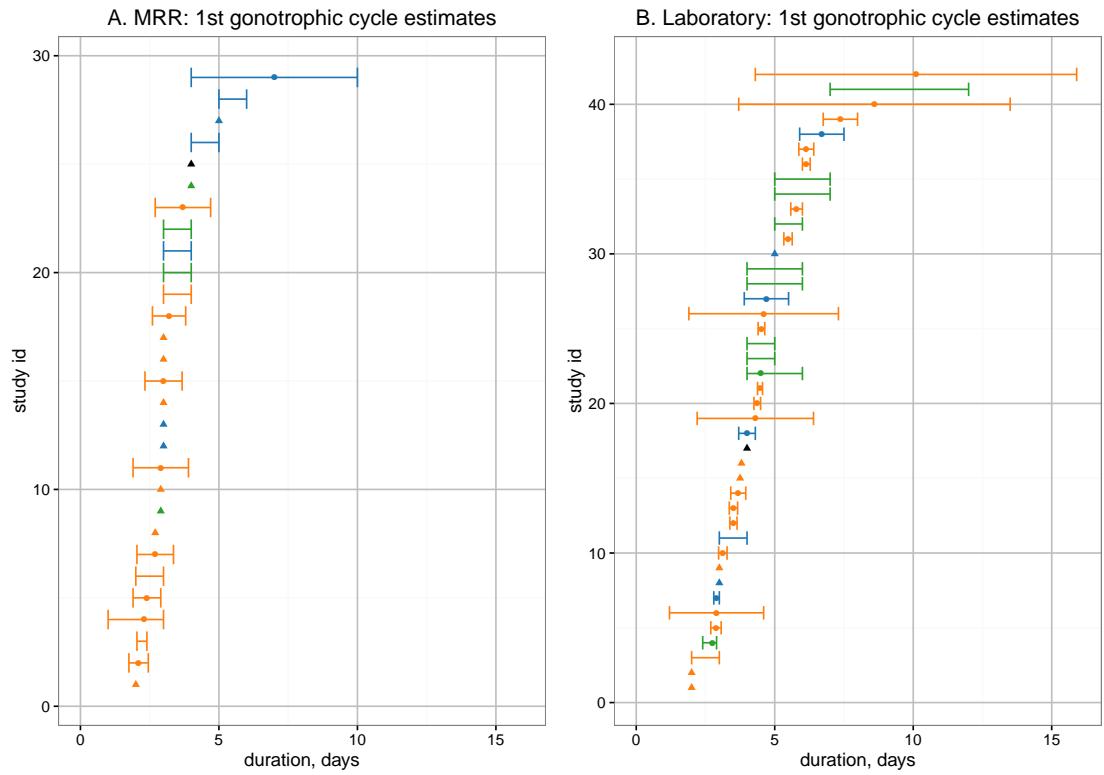
As discussed in Section S2.5, there was considerable study-level heterogeneity in the information provided for the estimates of the gonotrophic cycle duration. A



**Figure S21: Raw gonotrophic cycle duration estimates for A. the 1st cycle and B. subsequent cycles.** The confidence intervals represent a range of uncertainties since they were not available in a standardised form (see Section S2.6 for a discussion of how we handle this issue). If no statement of uncertainty was given in the estimates then we indicate this by a triangle marker. The studies are ordered according to the central estimate of gonotrophic duration.

number of studies ( $n = 24$ ) provided no estimates of uncertainty in gonotrophic cycle duration, whereas the rest gave some indication of confidence or alternatively a range of possible estimates. However the types of uncertainty intervals that were specified varied considerably from study to study, from the vague (but common) ‘4-6 days’ to the more helpful ‘ $5 \pm 1$  day (95% confidence interval)’.

The heterogeneous nature of the gonotrophic cycle estimates requires a method that explicitly accounts for this characteristic of the data. We decided to model the estimates as representing quantiles from an underlying normal distribution that represents uncertainty over possible durations of the gonotrophic cycle. In those circumstances where lower, central and upper bounds were given explicitly the data was fairly symmetric and so we believe assuming the observations come from an unskewed normal distribution is not unreasonable. Explicitly we treated



**Figure S22: Raw gonotrophic cycle duration estimates from A. the MRR and B. from laboratory-based studies.** The confidence intervals represent heterogeneous measures since they were not available in a standardised form (see Section S2.6 for a discussion of how we handle this issue). If no statement of uncertainty was given in the estimates then we indicate this by a triangle marker. The studies are ordered according to the central estimate of gonotrophic duration.

each type of uncertainty interval as follows,

- Simple range, for example, ‘4-6 days’: treat the lower and upper bounds as the 2.5% and 97.5% quantiles of a normal distribution.
- Confidence intervals, ‘ $5 \pm 1$  day (95% confidence interval)’: treat the lower and upper bounds as the relevant quantiles of a normal distribution.
- Point estimates, for example ‘5 days’: treat this as the median of a normal distribution.

The benefit of this approach is that we can convert the quantiles from our normal distribution parameterised by a mean ( $\mu$ ) and standard deviation ( $\sigma$ ) to equivalent

quantiles from a standard normal,

$$Z_{50} = \frac{G_{50} - \mu}{\sigma}, \quad (21)$$

where  $Z_{50}$  and  $G_{50}$  indicate 50% quantiles from a standard normal distribution and a normal distribution respectively. By manipulating the above expression we obtain the following,

$$G_{50} = \sigma Z_{50} + \mu, \quad (22)$$

which forms a straight line in  $(Z, G)$  space with slope  $\sigma$  and y-intercept  $\mu$ . Therefore by plotting the raw observations of  $(Z, G)$  quantiles then estimating a linear regression line we can characterise the underlying  $\mathcal{N}(\mu, \sigma)$  distribution from which we assume they are drawn.

Due to the relative unavailability of estimates for gonotrophic cycle duration across the different genera we generated a single distribution to represent the uncertainty in this parameter by pooling all the data. This was justified because there was not found to be significant variation in the 1st gonotrophic cycle duration (ANOVA:  $F_{3,75} = 2.6, p > 0.05$ ).

## S2.7 Conversion of lifespan from physiological to calendar age

The estimates of lifespan produced from analysing the dissection data are in terms of physiological age (the number of gonotrophic cycles undertaken). To allow comparison with the estimates from the MRR studies (Fig. 2) as well as produce more useful estimates to inform disease transmission dynamical models we convert these estimates to calendar days. To do this we use the estimated parameters of the normal densities that we have assumed represent uncertainty in gonotrophic cycle duration (see Section S2.6) and use them to convert our posterior samples of mean physiological lifespan ( $L_1^p, \dots, L_S^p$ ) to lifespan in calendar ages ( $L_1^c, \dots, L_S^c$ ). To do this we iterate the following for all  $i \in (1, \dots, S)$  posterior samples,

1. Sample  $G_{1i} \sim \mathcal{N}(\mu_{1i}, \sigma_{1i})$ , to obtain a duration for the 1st gonotrophic cycle.
2. Sample  $G_{2i} \sim \mathcal{N}(\mu_{2i}, \sigma_{2i})$ , to obtain a duration for subsequent gonotrophic cycles.
3. If  $L_i^p > 1$ , the mean lifespan is longer than one gonotrophic cycle:  
then  $L_i^c = G_{1i} + G_{2i} \times (L_i^p - 1)$ .

4. Else:

$$\text{then } L_i^c = G_{1i} \times L_i^p.$$

In the using the above methodology to convert from physiological to calendar age we implicitly assume that for each gonotrophic cycle after the first that the cycles are of the same length (we choose one  $G_{2i}$  per sample). However since we allow a different  $G_{2i}$  for each sample we nonetheless believe that the above approach allows for sufficient uncertainty in the estimates of subsequent gonotrophic cycle durations. If instead we believed that significant variation in gonotrophic cycle occurred within a particular mosquito's life (as well as between mosquitoes) then we could draw a new value of  $G_{2i}$  for each subsequent cycle. This produces results with a little more uncertainty than previously (data not shown).

## S3 Results

### S3.1 MRR experiments

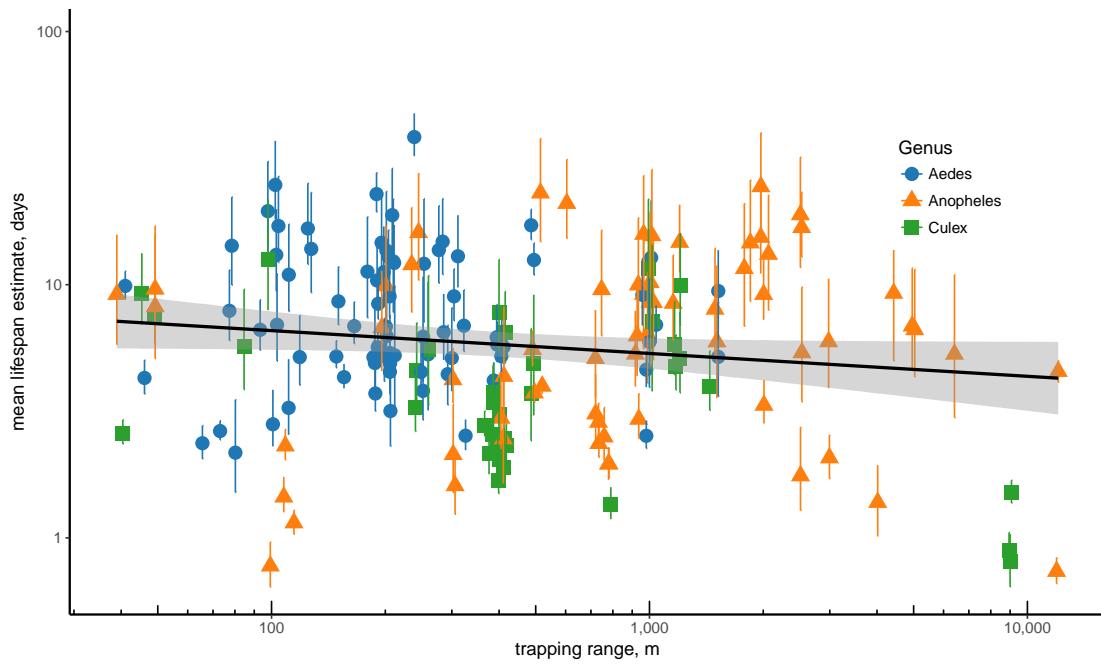
Figures S23, S24 and 4 show the estimates of lifespan versus the trapping range, spatial density and temperature at study location. In these cases, the lifespans shown were obtained from the non-hierarchical model with the exponential survival model.

Fig. ?? shows the lifespans obtained by sex, for each genus and across all studies ("overall") using the hierarchical Bayesian model with exponential survival model. In the genus-level models, the sex-specific effects (male-only, female-only, mixed-releases) were estimated as independent random effects for each genus with standard normal priors. For the overall model, the sex-specific effects were estimated as independent random effects across all studies, with a standard normal prior.

Fig. ?? shows the lifespans obtained for each pre-release feeding category for each genus and across all studies using the hierarchical Bayesian model with exponential survival model. In the genus-level models, the feeding-specific effects (fed nothing, blood-fed-only, sugar-fed-only and fed both) were estimated as independent random effects for each genus with standard normal priors. For the overall model, the feeding-specific effects were estimated as independent random effects across all studies, with a standard normal prior.

Genus	Species	5%	25%	50%	75%	95%	Mean	Std. dev.
<i>Aedes</i>	<i>simpsoni s.l.</i>	6.3	11.3	18.3	31.8	75.0	26.9	29.5
<i>Aedes</i>	<i>communis</i>	10.0	13.2	15.4	18.2	24.3	16.2	5.2
<i>Anopheles</i>	<i>koliensis</i>	6.7	10.5	15.2	24.0	56.5	21.9	25.2
<i>Anopheles</i>	<i>punctulatus</i>	7.2	10.7	15.1	22.8	48.9	20.3	28.6
<i>Aedes</i>	<i>cantans</i>	9.7	12.0	13.9	16.1	20.6	14.4	4.7
<i>Aedes</i>	<i>albopictus</i>	8.0	10.0	11.6	13.7	17.7	12.1	3.4
<i>Anopheles</i>	<i>albimanus</i>	5.9	8.6	11.6	16.9	35.7	15.2	18.7
<i>Anopheles</i>	<i>darlingi</i>	4.9	7.3	10.2	16.0	37.5	14.5	14.8
<i>Anopheles</i>	<i>maculatus</i>	5.7	7.9	10.2	13.7	24.3	12.2	8.7
<i>Anopheles</i>	<i>culicifacies s.l.</i>	4.6	7.3	9.1	11.4	18.2	10.1	6.9
<i>Anopheles</i>	<i>sergenti</i>	3.6	5.9	8.7	13.8	32.6	12.4	13.4
<i>Aedes</i>	<i>triseriatus</i>	5.6	6.6	7.5	8.5	10.7	7.7	1.8
<i>Anopheles</i>	<i>farauti s.l.</i>	4.2	5.4	6.4	7.7	10.5	6.8	2.1
<i>Aedes</i>	<i>africanus</i>	3.4	5.1	6.2	7.8	11.9	7.0	9.3
<i>Aedes</i>	<i>aegypti</i>	2.8	4.5	6.2	8.5	13.9	7.0	3.8
<i>Culex</i>	<i>quinquefasciatus</i>	4.3	5.2	5.9	7.0	9.4	6.3	1.8
<i>Culex</i>	<i>nigripalpus</i>	3.5	4.6	5.8	7.5	11.3	6.4	3.1
<i>Aedes</i>	<i>notoscriptus</i>	2.9	4.0	5.4	8.2	20.2	7.9	9.5
<i>Culex</i>	<i>pipiens</i>	3.4	4.4	5.2	6.4	9.0	5.6	2.0
<i>Anopheles</i>	<i>saperoi</i>	3.5	4.2	4.9	5.8	8.2	5.2	2.0
<i>Anopheles</i>	<i>gambiae s.l.</i>	3.0	3.8	4.4	5.1	6.4	4.5	1.1
<i>Aedes</i>	<i>melanimon</i>	3.3	3.9	4.3	4.8	5.7	4.4	1.0
<i>Anopheles</i>	<i>funestus s.l.</i>	2.9	3.6	4.2	4.8	6.0	4.3	1.0
<i>Anopheles</i>	<i>lesteri</i>	2.4	3.2	3.9	5.0	7.5	4.4	2.1
<i>Anopheles</i>	<i>quadrimaculatus</i>	3.3	3.6	3.9	4.2	4.8	4.0	0.5
<i>Anopheles</i>	<i>pseudopunctipennis s.l.</i>	2.3	2.9	3.5	4.3	6.7	3.8	1.9
<i>Aedes</i>	<i>vexans</i>	1.9	2.3	2.6	3.0	4.1	2.8	1.0
<i>Culex</i>	<i>tarsalis</i>	1.9	2.1	2.3	2.4	2.7	2.3	0.3
<i>Anopheles</i>	<i>vestitipennis</i>	1.3	1.8	2.2	2.9	4.4	2.5	1.2
<i>Anopheles</i>	<i>albitarsis s.l.</i>	1.3	1.6	1.9	2.2	2.9	2.0	1.0
<i>Culex</i>	<i>tritaeniorhynchus</i>	0.7	0.9	1.1	1.2	1.6	1.1	1.0
<i>Anopheles</i>	<i>subpictus s.l.</i>	0.4	0.6	0.8	1.1	2.4	1.1	2.6
<i>Aedes</i>		2.8	4.8	6.9	10.0	17.2	8.1	4.9
<i>Anopheles</i>		1.5	3.0	5.0	8.4	17.8	6.8	6.4
<i>Culex</i>		1.1	1.8	2.5	3.5	5.6	2.9	1.5
<b>Overall</b>		1.4	2.8	4.6	7.5	15.4	6.0	5.2

Table 8: Posterior summaries of mean unfed female mosquito lifespan from the MRR analysis. The 5%, 25%, 50%, 75% and 95% columns indicate the respective quantiles of the posterior distribution for mean lifespan, and the ‘Mean’ and ‘Std. dev.’ columns indicate the posterior mean and standard deviation of mean lifespan.



**Figure S23: Posterior estimates of mean mosquito lifespan for each time-series versus the trapping range.** The markers show the median posterior estimates, with the lower and upper bounds indicating the 25% and 75% quantiles, respectively. The black line shows a linear regression line estimated using the median posterior lifetimes, with the grey shading indicating 95% confidence intervals. All estimates were obtained using the non-hierarchical exponential survival model.

### S3.1.1 Table of estimated lifespans estimated from mark-release-recapture studies

## S3.2 Dissection studies

### S3.2.1 Table of estimated lifespan in terms of gonotrophic cycles and chronological time using dissection data

### S3.2.2 Chronological lifespan estimates

## S3.3 Comparison of LBLs between the MRR and dissection analyses

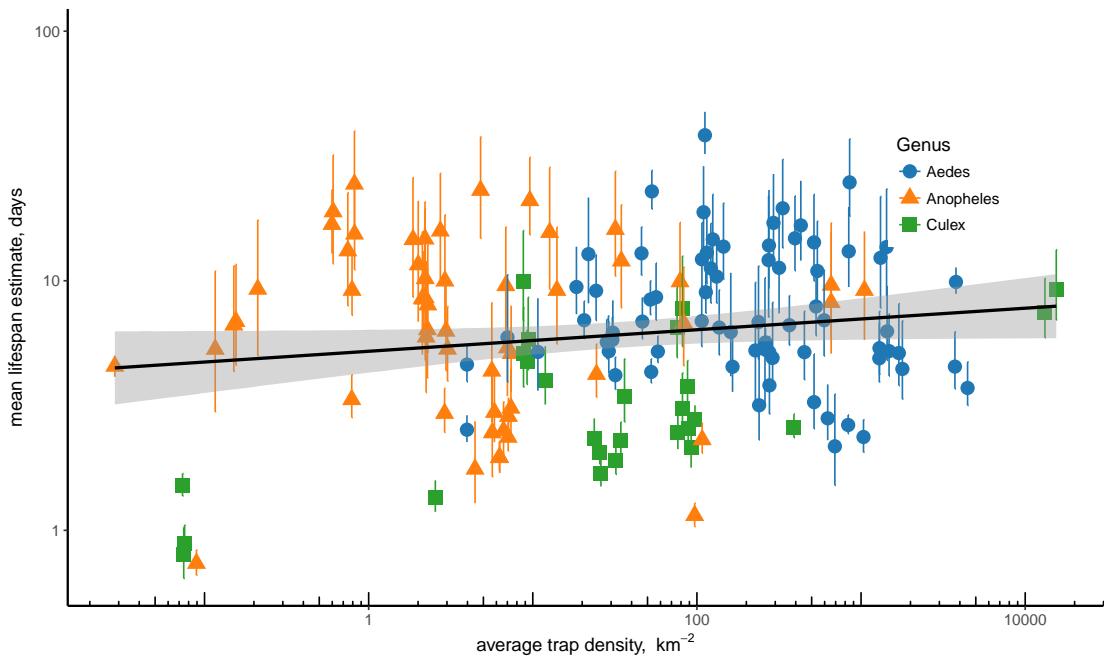
To conduct a comparison between the LBLs from the MRR analysis and from the dissections, we converted the latter lifespans from gonotrophic cycles to chronological age as described in Section S2.7. We conducted ANOVA using the individual

Genus	Species	5%	25%	50%	75%	95%	Mean	Std. dev.
<i>Anopheles</i>	<i>sergentii</i>	1.0	1.9	2.5	3.4	6.2	3.0	2.5
<i>Anopheles</i>	<i>gambiae s.l.</i>	0.7	1.2	1.9	2.9	5.4	2.4	1.9
<i>Culex</i>	<i>thalassius</i>	1.1	1.6	1.8	2.1	2.9	1.9	1.0
<i>Anopheles</i>	<i>farauti s.l.</i>	1.5	1.6	1.7	1.7	1.9	1.7	0.1
<i>Anopheles</i>	<i>minimus</i>	0.7	1.2	1.7	2.2	4.1	2.0	2.2
<i>Anopheles</i>	<i>maculipennis</i>	0.8	1.1	1.4	1.8	2.9	1.6	0.7
<i>Culex</i>	<i>pipiens</i>	1.1	1.3	1.4	1.5	1.7	1.4	0.2
<i>Mansonia</i>	<i>uniformis</i>	0.9	1.1	1.1	1.2	1.4	1.1	0.2
<i>Anopheles</i>	<i>rivulorum</i>	0.8	1.0	1.1	1.1	1.4	1.1	0.2
<i>Anopheles</i>	<i>melas</i>	0.8	1.0	1.0	1.1	1.3	1.0	0.2
<i>Anopheles</i>	<i>culicifacies</i>	0.9	1.0	1.0	1.1	1.2	1.0	0.1
<i>Anopheles</i>	<i>subpictus</i>	0.6	0.9	1.0	1.2	2.1	1.2	2.0
<i>Aedes</i>	<i>aegypti</i>	0.5	0.8	1.0	1.2	2.0	1.2	3.0
<i>Anopheles</i>	<i>quadrimaculatus</i>	0.7	0.9	1.0	1.1	1.3	1.0	0.2
<i>Anopheles</i>	<i>stephensi</i>	0.6	0.8	1.0	1.1	1.6	1.0	0.4
<i>Anopheles</i>	<i>darlingi</i>	0.7	0.8	0.9	1.0	1.3	1.0	0.2
<i>Culex</i>	<i>quinquefasciatus</i>	0.4	0.7	0.9	1.3	2.2	1.1	0.6
<i>Aedes</i>	<i>polynesiensis</i>	0.8	0.9	0.9	0.9	1.0	0.9	0.1
<i>Culex</i>	<i>tritaeniorhynchus</i>	0.3	0.6	0.9	1.3	4.2	2.5	30.8
<i>Culex</i>	<i>annulirostris</i>	0.5	0.8	0.9	1.0	1.4	0.9	0.5
<i>Aedes</i>	<i>samoanus</i>	0.6	0.7	0.8	0.9	1.0	0.8	0.2
<i>Aedes</i>	<i>sollicitans</i>	0.4	0.5	0.6	0.8	1.3	0.7	0.5
<i>Aedes</i>	<i>vexans</i>	0.4	0.5	0.6	0.7	0.9	0.6	0.7
<i>Anopheles</i>	<i>cruzii</i>	0.3	0.5	0.5	0.7	1.1	0.6	0.4
<i>Anopheles</i>	<i>bellator</i>	0.3	0.4	0.5	0.6	1.0	0.6	1.8
<i>Anopheles</i>		0.6	1.0	1.4	1.9	3.2	1.6	0.9
<i>Mansonia</i>		0.9	1.1	1.1	1.2	1.4	1.1	0.2
<i>Culex</i>		0.5	0.8	1.0	1.4	2.3	1.2	0.6
<i>Aedes</i>		0.6	0.7	0.8	0.9	1.1	0.8	0.2
<b>Overall</b>		0.5	0.8	1.2	1.7	2.7	1.3	0.7

Table 9: Posterior summaries of mean mosquito lifespan in terms of gonotrophic cycles from dissection studies. The 5%, 25%, 50%, 75% and 95% columns indicate the respective quantiles of the posterior distribution for mean lifespan, and the ‘Mean’ and ‘Std. dev.’ columns indicate the posterior mean and standard deviation of mean lifespan.

Genus	Species	5%	25%	50%	75%	95%	Mean	Std. dev.
<i>Anopheles</i>	<i>sergentii</i>	4.2	7.6	10.1	13.6	24.6	11.9	9.7
<i>Anopheles</i>	<i>gambiae s.l.</i>	2.8	5.2	7.6	11.4	21.6	9.5	7.4
<i>Culex</i>	<i>thalassius</i>	4.6	6.3	7.4	8.6	12.0	7.9	4.1
<i>Anopheles</i>	<i>farauti s.l.</i>	5.9	6.5	6.9	7.3	8.0	6.9	0.7
<i>Anopheles</i>	<i>minimus</i>	3.1	5.2	6.9	9.0	16.4	8.1	9.4
<i>Anopheles</i>	<i>maculipennis</i>	3.3	4.8	5.9	7.5	11.4	6.5	2.7
<i>Culex</i>	<i>pipiens</i>	4.6	5.3	5.7	6.2	6.9	5.8	0.8
<i>Mansonia</i>	<i>uniformis</i>	3.8	4.4	4.8	5.2	6.0	4.8	0.8
<i>Anopheles</i>	<i>rivulorum</i>	3.4	4.0	4.5	4.9	5.9	4.5	0.8
<i>Anopheles</i>	<i>melas</i>	3.3	3.9	4.3	4.8	5.5	4.4	0.7
<i>Anopheles</i>	<i>culicifacies</i>	3.4	4.0	4.3	4.7	5.4	4.4	0.6
<i>Aedes</i>	<i>aegypti</i>	2.1	3.5	4.3	5.0	7.9	5.0	11.5
<i>Anopheles</i>	<i>subpictus</i>	2.6	3.6	4.3	5.1	8.3	5.0	7.7
<i>Anopheles</i>	<i>quadrimaculatus</i>	2.9	3.6	4.1	4.7	5.6	4.2	0.9
<i>Anopheles</i>	<i>stephensi</i>	2.4	3.4	4.1	4.9	6.9	4.3	1.8
<i>Culex</i>	<i>quinquefasciatus</i>	1.7	2.8	4.0	5.5	9.0	4.5	2.5
<i>Anopheles</i>	<i>darlingi</i>	2.7	3.5	3.9	4.5	5.5	4.0	1.0
<i>Aedes</i>	<i>polynesiensis</i>	3.1	3.5	3.8	4.1	4.5	3.8	0.5
<i>Culex</i>	<i>tritaeniorhynchus</i>	1.3	2.6	3.8	5.7	16.8	9.8	123.0
<i>Culex</i>	<i>annulirostris</i>	2.3	3.1	3.7	4.4	5.9	3.9	1.8
<i>Aedes</i>	<i>samoanus</i>	2.6	3.0	3.3	3.7	4.4	3.4	0.9
<i>Aedes</i>	<i>sollicitans</i>	1.5	2.2	2.7	3.3	5.4	3.0	2.0
<i>Aedes</i>	<i>vexans</i>	1.7	2.1	2.5	2.9	3.9	2.7	2.7
<i>Anopheles</i>	<i>cruzii</i>	1.4	1.9	2.3	2.9	4.6	2.6	1.5
<i>Anopheles</i>	<i>bellator</i>	1.2	1.7	2.0	2.5	4.3	2.5	7.2
<i>Anopheles</i>		2.5	4.1	5.7	7.9	12.7	6.4	3.4
<i>Mansonia</i>		3.7	4.4	4.8	5.1	5.9	4.8	0.8
<i>Culex</i>		2.1	3.2	4.4	5.9	9.5	4.9	2.4
<i>Aedes</i>		2.4	3.1	3.5	3.9	4.7	3.5	0.7
<b>Overall</b>		2.2	3.5	5.1	6.8	10.7	5.5	2.7

Table 10: Posterior summaries of mean mosquito lifespan in terms of chronological time from dissection studies. The 5%, 25%, 50%, 75% and 95% columns indicate the respective quantiles of the posterior distribution for mean lifespan, and the ‘Mean’ and ‘Std. dev.’ columns indicate the posterior mean and standard deviation of mean lifespan.



**Figure S24: Posterior estimates of mean mosquito lifespan for each time-series versus the trap density.** The markers show the median posterior estimates, with the lower and upper bounds indicating the 25% and 75% quantiles, respectively. The trap density was estimated assuming traps were contained within a circular area with radius equal to the trapping range. The black line shows a linear regression line estimated using the median posterior lifetimes, with the grey shading indicating 95% confidence intervals. All estimates were obtained using the non-hierarchical exponential survival model.

time series estimates of LBL for each of the 10 species with estimates from both MRR- and dissection-based analysis. The results of this analysis are shown in Table 11.

### S3.4 EIPs of vector species of malaria, dengue fever, chikungunya and Zika

The following anopheline species were identified as vector species of malaria,

- **Africa:** *A. gambiae s.l.*, *A. funestus* and *A. melas* (Sinka *et al.*, 2012), and *A. rivulorum* (Wilkes *et al.*, 1996).
- **Americas:** *A. albimanus*, *A. albitalis*, *A. darlingi*, *A. pseudopunctipennis* and *A. quadrimaculatus* (Sinka *et al.*, 2012); *A. bellator* (Forattini *et al.*,

species	df <sub>1</sub>	df <sub>2</sub>	F	p
<i>Ae. aegypti</i>	1	55	2.2	0.14
<i>A. darlingi</i>	1	6	114.8	0.00
<i>An. farauti s.l.</i>	1	14	0.9	0.35
<i>A. gambiae s.l.</i>	1	37	3.9	0.06
<i>Cx. pipiens</i>	1	13	0.6	0.47
<i>A. quadrimaculatus</i>	1	8	2.4	0.16
<i>Cx. quinquefasciatus</i>	1	13	2.2	0.17
<i>A. serpentii</i>	1	8	0.4	0.55
<i>Cx. tritaeniorhynchus</i>	1	5	3.5	0.12
<i>Ae. vexans</i>	1	2	1.2	0.39

Table 11: The results of comparisons between LBLs for those species with data for MRRs and dissection-based studies. The ANOVA tests were conducted using LBLs estimated at the time-series level.

1999; Lorenz *et al.*, 2012); *A. cruzii* (Lorenz *et al.*, 2012); and *A. vestitipennis* (Sinka *et al.*, 2010).

- **Europe and the Middle-East:** *A. serpentii* (Sinka *et al.*, 2012); and *A. maculipennis* (?).
- **Asia:** *A. farauti s.l.*, *A. koliensis*, *A. lesteri*, *A. maculatus*, *A. minimus*, *A. punctulatus*, *A. stephensi* and *A. subpictus s.l.* (Sinka *et al.*, 2012); and *A. culicifacies* (?).

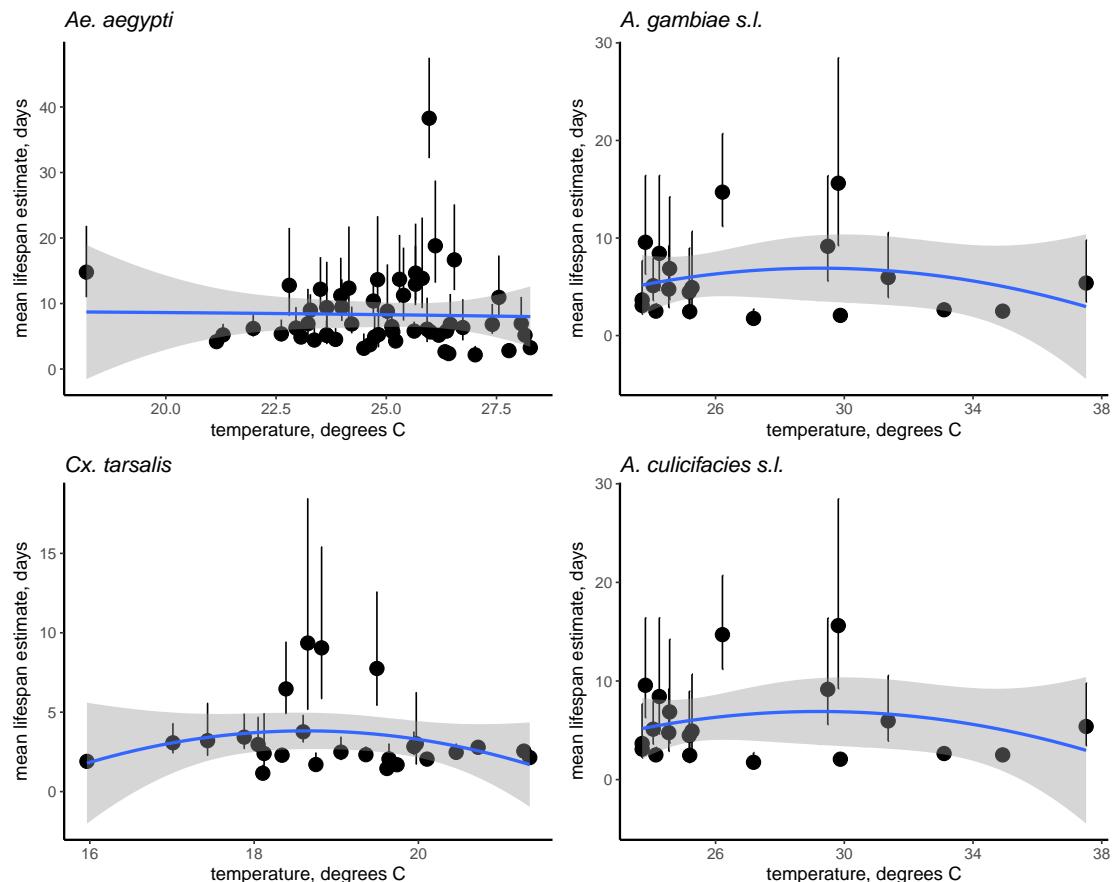
For dengue fever, chikungunya and Zika, the main vector species are *Ae. aegypti* and *Ae. albopictus* (Kraemer *et al.*, 2015; ?; ?).

### S3.5 The statistical power of MRR studies

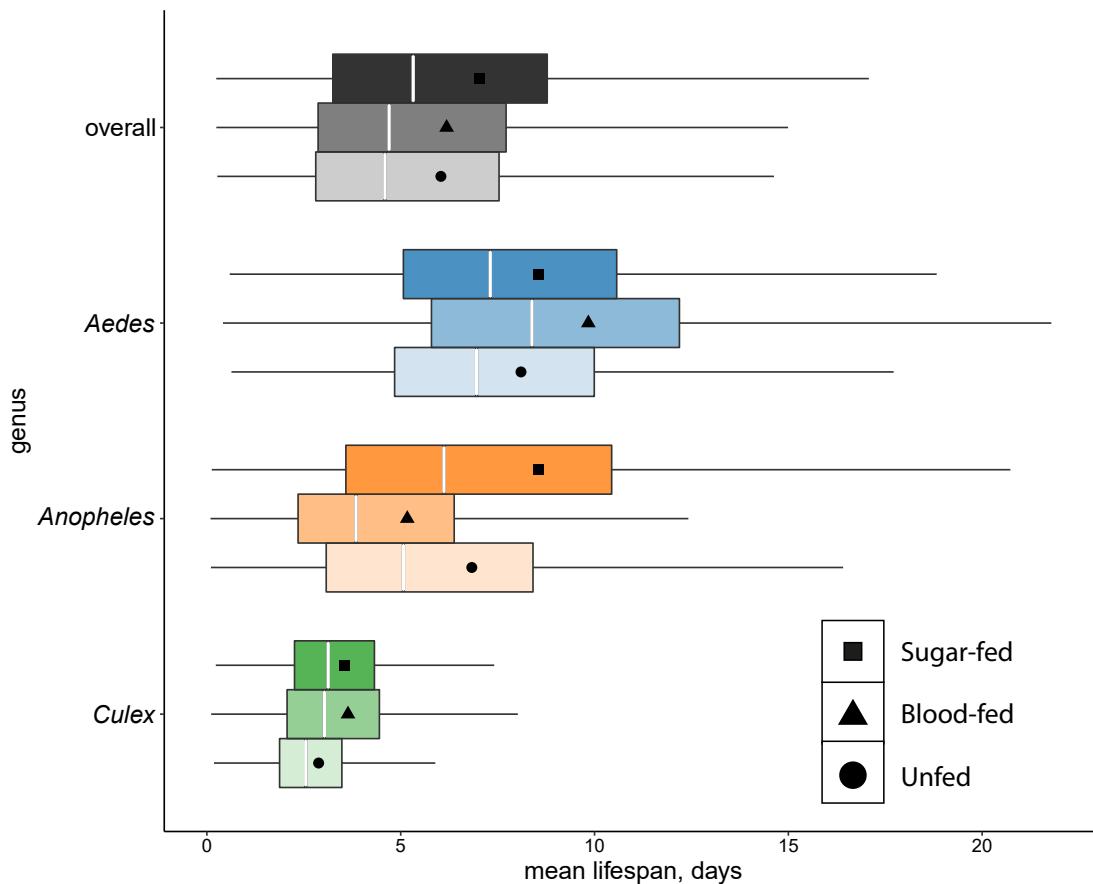
Consider an ideal MRR experiment, where the assumptions of no emigration and harmless marking are fully satisfied. With these data, how accurately can we estimate mosquito lifespan? To address this question we generated artificial MRR data and attempted to estimate the (known) parameters by maximum likelihood (a ‘Monte Carlo’ analysis). Specifically, we simulated releases of  $N$  mosquitoes that are monitored for  $m$  days in each case, and determined how statistical power to estimate lifespan depends on these two parameters (Fig. S27). In order to focus on estimating lifespan, we assumed the mosquitoes experience constant mortality, and recaptures follow the negative binomial sampling model (eqn. 1) where the recapture probability parameters ( $\psi$  and  $\kappa$ ) were the averages of those estimated for the actual data.

Unsurprisingly, the error in predicting lifespan declines as the duration of study is increased (Fig. S27A). However once a study length is much longer than the lifespan of the majority of mosquitoes, the predictive power cannot be improved by extending the study duration. The effect of increasing release size (while holding study length constant) is similarly a case of diminishing returns (Fig. S27B). For the parameters we use, there are significant gains in accuracy from releasing 1,000 rather than 100 mosquitoes, but modest gains from releasing 10,000 rather than 1000 mosquitoes.

We also conducted a power analysis for the detection of senescence in MRR experiments (Fig. S28). Here we calculated the power of a maximum likelihood estimator of the ‘senescence parameter’  $\beta$  of the Gompertz survival function (see Table 3) for case study populations with three different levels of senescence (Fig. S28A.). These indicate that the power to detect senescence is strongly dependent on study length (Fig. S28B.), but is insensitive to release size (Fig. S28C.). Clements & Paterson (1981) conducted a meta-analysis of MRR and dissection-based experiments and found evidence of senescence that is, at least, qualitatively similar in magnitude to that of the ‘mild’ case considered above. For this case detecting senescence with a power of 80% requires a study length of at least 18 days. Since the median study length for experiments included in our analysis was 10 days (Table 1) this could partly explain our failure to detect senescence at the species level.



**Figure S25: Posterior estimates of mean mosquito lifespan for each time-series versus the average monthly temperature for the four species with the most data.** The markers show the median posterior estimates, with the lower and upper bounds indicating the 25% and 75% quantiles, respectively. The black line shows a regression line with linear and quadratic terms estimated using the median posterior lifetimes, with the grey shading indicating 95% confidence intervals. All estimates of lifespan were obtained using the non-hierarchical exponential survival model.



**Figure S26: Posterior estimates of female mosquito mean lifespan according to pre-release feeding status across species, genus and overall groupings as determined from the MRR data.** The lifespans shown are for mosquitoes that were not fed with sugar or blood (for females) before release. The middle line in each box shows the median estimates and the solid dot indicates the mean. The left and right box edges show the 25%, and 75% posterior quantiles respectively. The whiskers show the range of the data, excluding points lying more than 1.5 times the interquartile range away from each edge of the box. The numbers before the start of the left whisker indicate the number of individual time-series within each species. All estimates were obtained using the hierarchical exponential survival model.

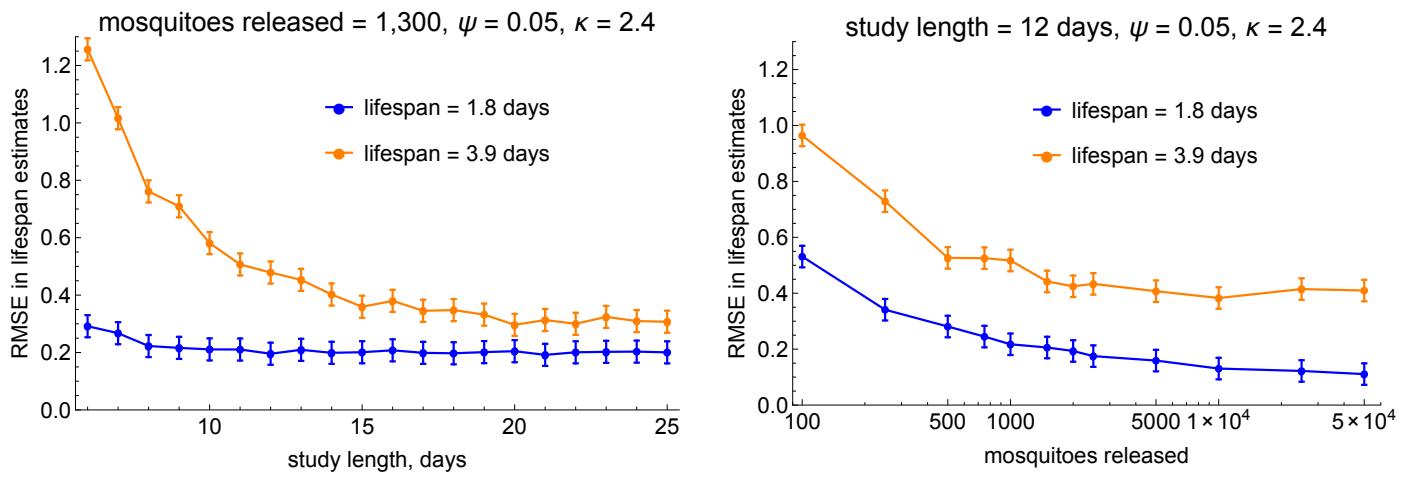
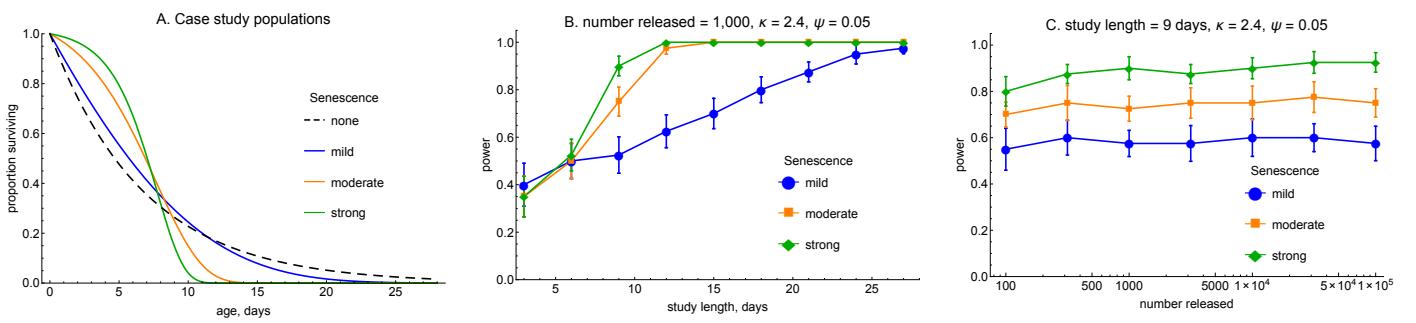
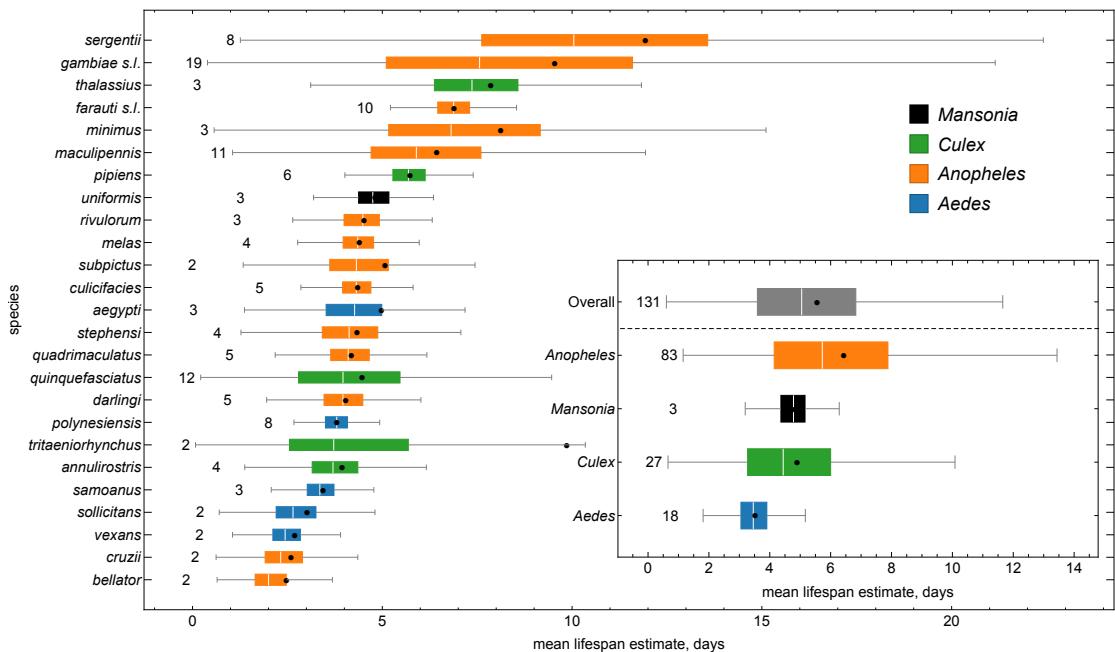


Figure S27: **The average error in predicting mean lifespan as a function of study length (left) and number of released mosquitoes (right) in a Monte Carlo analysis.** For each parameter set we generated 400 simulated data series using the negative binomial sampling model with an exponential survival function as described in the text, and estimated the mean lifespan using maximum likelihood. The error bars show the standard deviation in the prediction error.



**Figure S28: The statistical power to detect senescence for A. three case study populations as a function of B. study length and C. number released.** For each parameter set we generated 500 simulated data series using the negative binomial sampling model with a gompertz hazard function ( $\lambda(t) = \alpha e^{\beta t}$ ), and estimated the  $\beta$  parameter using maximum likelihood and tested the null hypothesis  $\beta = 0$  (constant mortality risk) against the alternative  $\beta > 0$  using an likelihood ratio test with a 5% test size. The error bars show the standard deviation in the power for each parameter set. The recapture probability parameters ( $\psi$  and  $\kappa$ ) used were the averages of those estimated for the actual data.



**Figure S29: Posterior estimates of female mosquito mean chronological lifespan across species, genus and overall groupings as determined from the dissection data.** The lifespans shown are for mosquitoes that were not fed with sugar or blood (for females) before release. The middle line in each box shows the median estimates and the solid dot indicates the mean. The left and right box edges show the 25%, and 75% posterior quantiles respectively. The whiskers show the range of the data, excluding points lying more than 1.5 times the interquartile range away from each edge of the box. The numbers before the start of the left whisker indicate the number of individual time-series within each species. All estimates were obtained using the hierarchical exponential survival model.

## S4 Studies included in the MRR meta-analysis

The following is the subset of studies from the original Guerra *et al.* (2014) database which were used in the MRR meta-analysis of Chapter ??: Marini *et al.* (2010); Baber *et al.* (2010); Lacroix *et al.* (2009); Maciel-de Freitas *et al.* (2008); Midega *et al.* (2007); Maciel-De-Freitas *et al.* (2007); Elizondo-Quiroga *et al.* (2006); Ba *et al.* (2005); Fabian *et al.* (2005); La Corte Dos Santos *et al.* (2004); Watson *et al.* (2000); Harrington *et al.* (2001); Tsuda *et al.* (2001); Muir & Kay (1998); Touré *et al.* (1998); Quinones *et al.* (1997); Costantini *et al.* (1996); Trpis *et al.* (1995); Jensen & Washino (1994); Fernandez-Salas *et al.* (1994); Jaal & MacDonald (1992); Rodriguez *et al.* (1992); Chiang *et al.* (1991); Jensen & Washino (1991); Eldridge & Reeves (1990); Macdonald *et al.* (1968); Pumpuni & Walker (1989); Charlwood & Bryan (1987); Charlwood & Alecrim (1989); Birley & Charlwood (1989); Arredondo-Jiménez *et al.* (1998); Hii *et al.* (1990); Renshaw *et al.* (1994); Milby & Reisen (1989); Maciel-de Freitas *et al.* (2007); Loong *et al.* (1990); Nelson & Milby (1980); Maciel-de Freitas *et al.* (2006); McDonald (1977); Curtis & Rawlings (1980); Rawlings & Davidson (1982); Conway *et al.* (1974); Reisen *et al.* (1979); Nelson *et al.* (1978); Rawlings *et al.* (1981); Sempala (1981); Takagi *et al.* (1995); Buei *et al.* (1980); Eyles *et al.* (1943a); Ordóñez González *et al.* (2001); Pant & Yasuno (1973); Charlwood *et al.* (1988); Reisen *et al.* (1982); Nayar *et al.* (1980); Carnevale *et al.* (1979); Eyles *et al.* (1946); Reisen *et al.* (1984); Charlwood *et al.* (1986); Trpis & Hausermann (1975); Lutwama & Mukwaya (1994); Wada *et al.* (1969); Takken *et al.* (1998); Abdel-Malek *et al.* (1966); Valerio *et al.* (2012); Zetek (1915); Takagi *et al.* (1995); Yasuno *et al.* (1975); Eyles *et al.* (1943b); Germain *et al.* (1974).

## S5 Studies included in the dissection study meta-analysis

The following is a list of studies included in the dissection study meta-analysis of Chapter ??: Catangui *et al.* (1971); Charlwood & Wilkes (1979); Chang *et al.* (1991); Charlwood *et al.* (2000); Edalat *et al.* (2015); de Barros *et al.* (2011); Lines *et al.* (1991a); Magesa *et al.* (1991); Lines *et al.* (1991b); Forattini *et al.* (1996); Samarawickrema (1967, 1968); de Barros *et al.* (2007); Charlwood *et al.* (1985a); Chandra *et al.* (1996); Hoc & Wilkes (1995); Vythilingam *et al.* (1997); Russell (1986); Chadee & Ritchie (2010); Ebsary & Crans (1977); Charlwood (1980); Shriram & Krishnamoorthy (2011); Mahmood & Reisen (1981); Samarawickrema *et al.* (1987); Uttah *et al.* (2013); Ramaiah & Das (1992); Buei & Ito (1982); Chadee *et al.* (1995); Chandra (2008); Foll & Pant (1966); Kanda *et al.* (1975); Mala *et al.* (2014); Shalaby *et al.* (1962); World Health Organisation *et al.* (1960); Reisen *et al.*

(1980); Detinova *et al.* (1962); Smith & Kurtz (1994); Jayanetti *et al.* (1987); Ch *et al.* (2013); Pant *et al.* (1962); Ghosh *et al.* (2010); Mahanta *et al.* (1999); Schlein & Müller (2012); Penilla *et al.* (2002); Schlein & Müller (2015); Snow & Boreham (1978); Detinova (1968); Nathan (1981); Charlwood *et al.* (1985b); Schlein & Müller (2008); Beier *et al.* (2012); Müller & Schlein (2005); Surendran *et al.* (2006); Müller *et al.* (2010); Mendis *et al.* (1998); Wilkes *et al.* (1996); Chatterjee & Chandra (2000); Müller *et al.* (2010); Tuchinda *et al.* (1969); Chan *et al.* (1971); Aigbodion *et al.* (2011); Qualls *et al.* (2015); Reisen *et al.* (1981); Gillies & Wilkes (1972, 1965); Kay (1979); Hitchcock Jr (1968).

## S6 Studies included in the gonotrophic cycle duration meta-analysis

The following is a list of studies included in the gonotrophic study meta-analysis of Chapter ??: Gillies & Wilkes (1965); Sheppard *et al.* (1969); de Meillon *et al.* (1967); Pant & Yasuno (1973); Germain *et al.* (1974); Lowe *et al.* (1973); Fernandez-Salas *et al.* (1994); Buei *et al.* (1980); Rawlings & Curtis (1982); Mori *et al.* (1977); Sempala (1981); Reisen *et al.* (1983); Birley & Charlwood (1989); Suzuki (1978); Charlwood & Bryan (1987); Charlwood *et al.* (1986); Charlwood & Wilkes (1979); Charlwood *et al.* (1995); Chang *et al.* (1991); Edalat *et al.* (2015); de Barros *et al.* (2011); Samarawickrema (1968, 1967); Charlwood *et al.* (1985a); Chandra *et al.* (1996); Russell (1986); Chadee & Ritchie (2010); Mahmood & Reisen (1981); Ahumada *et al.* (2004); Kenawy (1991); Rajagopalan (1980); Chandra (2008); Scholl *et al.* (1979); Mala *et al.* (2014); Afrane *et al.* (2005); Gillies (1953); Quinones *et al.* (1997); Rúa *et al.* (2005); Delatte *et al.* (2009); Arredondo-Jiménez *et al.* (1998); Wong *et al.* (2014); Ijumba *et al.* (2002).

## References

- Abdel-Malek, Albert A, Abdel-Aal, MA, *et al.* 1966. Study of the dispersion and flight range of *Anopheles sergentii* Theo in Siwa Oasis using radioactive isotopes as markers. *Bulletin of the World Health Organisation*, **35**, 968–973.
- Afrane, Yaw A, Lawson, Bernard W, Githeko, Andrew K, & Yan, Guiyun. 2005. Effects of microclimatic changes caused by land use and land cover on duration of gonotrophic cycles of *Anopheles gambiae* (Diptera: Culicidae) in western Kenya highlands. *Journal of Medical Entomology*, **42**(6), 974–980.
- Ahumada, Jorge A, Lapointe, Dennis, & Samuel, Michael D. 2004. Modeling the population dynamics of *Culex quinquefasciatus* (Diptera: Culicidae), along an

- elevational gradient in Hawaii. *Journal of Medical Entomology*, **41**(6), 1157–1170.
- Aigbodion, FI, Uyi, OO, Akintelu, OH, & Salau, LA. 2011. Pelagia Research Library. *European Journal of Experimental Biology*, **1**(4), 173–180.
- Anderson, Roy M, & May, Robert M. 1992. *Infectious diseases of humans: dynamics and control*. Vol. 28. Wiley Online Library.
- Arredondo-Jiménez, Juan I, Rodríguez, Mario H, & Washino, Robert K. 1998. Gonotrophic cycle and survivorship of *Anopheles vestitipennis* (Diptera: Culicidae) in two different ecological areas of southern Mexico. *Journal of Medical Entomology*, **35**(6), 937–942.
- Ba, Yamar, Diallo, Diawo, Kebe, Cheikh Mouhamed Fadel, Dia, Ibrahima, & Diallo, Mawlouth. 2005. Aspects of bioecology of two Rift Valley fever virus vectors in Senegal (West Africa): *Aedes vexans* and *Culex poicilipes* (Diptera: Culicidae). *Journal of Medical Entomology*, **42**(5), 739–750.
- Baber, Ibrahima, Keita, Moussa, Sogoba, Nafomon, Konate, Mamadou, Doumbia, Seydou, Traore, Sekou F, Ribeiro, Jose MC, Manoukis, Nicholas C, et al. 2010. Population size and migration of *Anopheles gambiae* in the Bancoumana Region of Mali and their significance for efficient vector control. *PLoS One*, **5**(4), e10270.
- Beier, John C, Müller, Günter C, Gu, Weidong, Arheart, Kristopher L, & Schlein, Yosef. 2012. Attractive toxic sugar bait (ATSB) methods decimate populations of *Anopheles* malaria vectors in arid environments regardless of the local availability of favoured sugar-source blossoms. *Malaria Journal*, **11**(1), 31.
- Bellan, Steve E. 2010. The importance of age dependent mortality and the extrinsic incubation period in models of mosquito-borne disease transmission and control. *PLoS One*, **5**(4), e10165.
- Birley, MH, & Charlwood, JD. 1989. The effect of moonlight and other factors on the oviposition cycle of malaria vectors in Madang, Papua New Guinea. *Annals of Tropical Medicine & Parasitology*, **83**(4), 415–422.
- Bryan, JH, Foley, DH, Geary, M, & Carven, CTJ. 1991. Anopheles annulipes Walker (Diptera: Culicidae) at Griffith, New South Wales. 3. Dispersal of two sibling species. *Australian Journal of Entomology*, **30**(2), 119–121.
- Buei, K, Ito, S, Nakamura, H, & Yoshida, M. 1980. Field studies on the gonotrophic cycle of *Culex tritaeniorhynchus*. *Medical Entomology and Zoology*, **31**(1), 57–62.

- Buei, Kazuo, & Ito, Sumiyo. 1982. The age-composition of field populations and the survival rates in *Culex tritaeniorhynchus* Giles. *Medical Entomology and Zoology*, **33**(1), 21–25.
- Carey, James R. 2001. Insect biodemography. *Annual Review of Entomology*, **46**(1), 79–110.
- Carnevale, Pierre, Bosseno, Marie-France, Molinier, Michel, Lancien, Jeannick, Le Pont, François, & Zoulani, Albert. 1979. Etude du cycle gonotrophique d'*Anopheles gambiae* (Diptera, Culicidae) (Giles, 1902) en zone de forêt dégradée d'Afrique Centrale. *Cahiers Orstom. Série Entomologie Médicale et Parasitologie*, **17**, 55–75.
- Carpenter, Bob, Gelman, Andrew, Hoffman, Matt, Lee, Daniel, Goodrich, Ben, Betancourt, Michael, Brubaker, Michael A, Guo, Jiqiang, Li, Peter, & Riddell, Allen. 2016. Stan: A probabilistic programming language. *Journal of Statistical Software*.
- Catangui, FP, et al. 1971. Studies on the gonotrophic cycle of *Anopheles minimus flavirostris* and the application of physiological age grading technique on the same species. *Southeast Asian Journal of Tropical Medicine and Public Health*, **2**(3), 384–92.
- Ch, Goutam, Paramanik, Manas, Mondal, Samir Kumar, Ghosh, Arup Kumar, et al. 2013. Comparative Studies of Different Indices Related to Filarial Vector of a Rural and an Urban Area of West Bengal, India. *Tropical Medicine & Surgery*.
- Chadee, Dave D, & Ritchie, Scott A. 2010. Oviposition behaviour and parity rates of *Aedes aegypti* collected in sticky traps in Trinidad, West Indies. *Acta Tropica*, **116**(3), 212–216.
- Chadee, Dave D, Ganesh, R, Hingwan, JO, & Tikasingh, Elisha S. 1995. Seasonal abundance, biting cycle and parity of the mosquito Haemagogus leucocelaenus in Trinidad, west indies. *Medical and Veterinary Entomology*, **9**(4), 372–376.
- Chan, Kai-Lok, et al. 1971. Life table studies of *Aedes albopictus* (Skuse). *Sterility principles for insect control or eradication*, 131–144.
- Chandra, G, Seal, B, & Hati, AK. 1996. Age composition of the filarial vector *Culex quinquefasciatus* (Diptera: Culicidae) in Calcutta, India. *Bulletin of Entomological Research*, **86**(3), 223–226.

- Chandra, Goutam. 2008. Age composition of incriminated malaria vector in a rural foothills in West Bengal, India. *Indian Journal of Medical Research*, **127**(6), 607.
- Chang, Moh-Seng, Chan, Kai-Lok, Ho, Beng-Chuan, & Hawley, William A. 1991. Comparative transmission potential of three *Mansonia spp.* (Diptera: Culicidae) for filariasis in Sarawak, Malaysia. *Bulletin of Entomological Research*, **81**(4), 437–444.
- Charlwood, Jacques D, & Alecrim, WA. 1989. Capture-recapture studies with the South American malaria vector *Anopheles darlingi*, Root. *Annals of Tropical Medicine & Parasitology*, **83**(6), 569–576.
- Charlwood, JD. 1980. Observations on the bionomics of *Anopheles darlingi* Root (Diptera: Culicidae) from Brazil. *Bulletin of Entomological Research*, **70**(4), 685–692.
- Charlwood, JD, & Bryan, JH. 1987. A mark?recapture experiment with the filariasis vector *Anopheles punctulatus* in Papua New Guinea. *Annals of Tropical Medicine & Parasitology*, **81**(4), 429–436.
- Charlwood, JD, & Wilkes, TJ. 1979. Studies on the age-composition of samples of *Anopheles darlingi* Root (Diptera: Culicidae) in Brazil. *Bulletin of Entomological Research*, **69**(02), 337–342.
- Charlwood, JD, Birley, MH, Dagoro, H, Paru, R, & Holmes, PR. 1985a. Assessing survival rates of *Anopheles farauti* (diptera: Culicidae) from Papua New Guinea. *The Journal of Animal Ecology*, 1003–1016.
- Charlwood, JD, Dagoro, H, & Paru, R. 1985b. Blood-feeding and resting behaviour in the *Anopheles punctulatus* Dönitz complex (Diptera: Culicidae) from coastal Papua New Guinea. *Bulletin of Entomological Research*, **75**(3), 463–476.
- Charlwood, JD, Graves, PM, & Birley, MH. 1986. Capture-recapture studies with mosquitoes of the group of *Anopheles punctulatus* Dönitz (Diptera: Culicidae) from Papua New Guinea. *Bulletin of Entomological Research*, **76**(2), 211–227.
- Charlwood, JD, Graves, PM, & Marshall, TF de C. 1988. Evidence for a memorized home range in *Anopheles farauti* females from Papua New Guinea. *Medical and Veterinary Entomology*, **2**(2), 101–108.
- Charlwood, JD, Kihonda, J, Sama, S, Billingsley, PF, Hadji, H, Verhave, JP, Lyimo, E, Lutikhuizen, PC, & Smith, T. 1995. The rise and fall of *Anopheles arabiensis* (Diptera: Culicidae) in a Tanzanian village. *Bulletin of Entomological Research*, **85**(1), 37–44.

- Charlwood, JD, Vij, R, & Billingsley, PF. 2000. Dry season refugia of malaria-transmitting mosquitoes in a dry savannah zone of east Africa. *The American Journal of Tropical Medicine and Hygiene*, **62**(6), 726–732.
- Chatterjee, Soumendranath, & Chandra, Goutam. 2000. Role of *Anopheles subpictus* as a primary vector of malaria in an area in India. *Japanese Journal of Tropical Medicine and Hygiene*, **28**(3), 177–181.
- Chiang, GL, Loong, KP, Chan, ST, Eng, KL, & Yap, HH. 1991. Capture-recapture studies with *Anopheles maculatus Theobald* (Diptera: Culicidae) the vector of malaria in peninsular Malaysia. *Southeast Asian Journal of Tropical Medicine and Public Health*, **22**, 643–647.
- Clements, AN, & Paterson, GD. 1981. The analysis of mortality and survival rates in wild populations of mosquitoes. *Journal of Applied Ecology*, 373–399.
- Conway, GR, Trpis, M, & McClelland, GAH. 1974. Population parameters of the mosquito *Aedes aegypti* (L.) estimated by mark-release-recapture in a suburban habitat in Tanzania. *The Journal of Animal Ecology*, 289–304.
- Costantini, Carlo, LI, Song-Gang, Torre, Alessandra Della, Sagnon, N'Fale, Coluzzi, Mario, & Taylor, Charles E. 1996. Density, survival and dispersal of *Anopheles gambiae* complex mosquitoes in a West African Sudan savanna village. *Medical and Veterinary Entomology*, **10**(3), 203–219.
- Curtis, CF, & Rawlings, P. 1980. A preliminary study of dispersal and survival of *Anopheles culicifacies* in relation to the possibility of inhibiting the spread of insecticide resistance. *Ecological Entomology*, **5**(1), 11–17.
- Dawes, Emma J, Churcher, Thomas S, Zhuang, Shijie, Sinden, Robert E, & Basáñez, María-Gloria. 2009. *Anopheles* mortality is both age-and *Plasmodium*-density dependent: implications for malaria transmission. *Malaria Journal*, **8**(1), 228.
- de Barros, Fábio Saito Monteiro, Arruda, Mércia Eliane, Vasconcelos, Simão D, Luitgards-Moura, José Francisco, Confalonieri, Ulisses, Rosa-Freitas, Maria Goreti, Tsouris, Pantelis, Lima-Camara, Tamara Nunes, & Honório, Nildimar Alves. 2007. Parity and age composition for *Anopheles darlingi* Root (Diptera: Culicidae) and *Anopheles albitalis* Lynch-Arribálzaga (Diptera: Culicidae) of the northern Amazon Basin, Brazil. *Journal of Vector Ecology*, **32**(1), 54–68.
- de Barros, Fabio Saito Monteiro, Honorio, Nildimar Alves, & Arruda, Mer- cia Eliane. 2011. Survivorship of *Anopheles darlingi* (Diptera: Culicidae) in

relation with malaria incidence in the Brazilian Amazon. *PLoS One*, **6**(8), e22388.

de Meillon, Botha, Sebastian, Anthony, & Khan, ZH. 1967. Time of arrival of gravid *Culex pipiens fatigans* at an oviposition site, the oviposition cycle and the relationship between time of feeding and time of oviposition. *Bulletin of the World Health Organisation*, **36**(1), 39.

Delatte, Hélène, Gimonneau, Geoffrey, Triboire, Aurélie, & Fontenille, Didier. 2009. Influence of temperature on immature development, survival, longevity, fecundity, and gonotrophic cycles of *Aedes albopictus*, vector of chikungunya and dengue in the Indian Ocean. *Journal of Medical Entomology*, **46**(1), 33–41.

Detinova, Tatjana Sergeevna, et al. 1962. Age grouping methods in Diptera of medical importance with special reference to some vectors of malaria. *Monograph series World Health Organisation*.

Detinova, TS. 1968. Age structure of insect populations of medical importance. *Annual Review of Entomology*, **13**(1), 427–450.

Ebsary, BA, & Crans, WJ. 1977. The biting activity of *Aedes sollicitans* in New Jersey. *Mosquito News*.

Edalat, Hamideh, Moosa-Kazemi, Seyed Hassan, Abolghasemi, Esmail, & Khairandish, Sedigheh. 2015. Vectorial capacity and age determination of *Anopheles stephensi Liston* (Diptera: Culicidae), during the malaria transmission in Southern Iran. *Journal of Entomology and Zoology Studies*, **3**(1), 256–263.

Eldridge, BF, & Reeves, WC. 1990. Daily survivorship of adult *Aedes communis* in a high mountain environment in California. *Journal of the American Mosquito Control Association*, **6**(4), 662–666.

Elizondo-Quiroga, Armando, Flores-Suarez, Adriana, Elizondo-Quiroga, Darwin, Ponce-Garcia, Gustavo, Blitvich, Bradley J, Contreras-Cordero, Juan Francisco, Gonzalez-Rojas, Jose Ignacio, Mercado-Hernandez, Roberto, Beaty, Barry J, & Fernandez-Salas, Ildefonso. 2006. Gonotrophic cycle and survivorship of *Culex quinquefasciatus* (Diptera: Culicidae) using sticky ovitraps in Monterrey, north-eastern Mexico. *Journal of the American Mosquito Control Association*, **22**(1), 10–14.

Eyles, DE, Bishop, LK, et al. 1943a. An Experiment on the Range of Dispersion of *Anopheles quadrimaculatus*. *American Journal of Hygiene*, **37**(3).

- Eyles, Don E, Cox, Wm W, et al. 1943b. The Measurement of a Population of *Anopheles quadrimaculatus* Say. *Journal of the National Malaria Society*, **2**(2).
- Eyles, Don E, Sabrosky, Curtis W, Russell, John C, et al. 1946. *Long-range dispersal of Anopheles quadrimaculatus*. US Government Printing Office.
- Fabian, Mashauri M, Toma, Takako, Tsuzuki, Ataru, Saita, Susumu, & Miyagi, Ichiro. 2005. Mark-release-recapture experiments with *Anopheles saperoi* (Diptera: Culicidae) in the Yona Forest, northern Okinawa, Japan. *Southeast Asian Journal of Tropical Medicine and Public Health*, **36**(1), 54.
- Fernandez-Salas, Ildefonso, Rodriguez, Mario Henry, & Roberts, Donald R. 1994. Gonotrophic cycle and survivorship of *Anopheles pseudopunctipennis* (Diptera: Culicidae) in the Tapachula foothills of southern Mexico. *Journal of Medical Entomology*, **31**(3), 340–347.
- Foll, CV, & Pant, CP. 1966. The conditions of malaria transmission in Katsina Province, Northern Nigeria, and a discussion of the effects of dichlorvos application. *Bulletin of the World Health Organisation*, **34**(3), 395.
- Forattini, Oswaldo Paulo, Kakitani, Iná, Massad, Eduardo, & Marucci, Daniel. 1996. Studies on mosquitoes (Diptera: Culicidae) and anthropic environment: 11-Biting activity and blood-seeking parity of *Anopheles* (Kerteszia) in South-Eastern Brazil. *Revista de Saude Publica*, **30**, 107–114.
- Forattini, Oswaldo Paulo, Kakitani, Iná, Santos, Roseli La Corte dos, Ueno, Hélène Mariko, & Kobayashi, Keilla Miki. 1999. Role of *Anopheles* (Kerteszia) *bel-lator* as malaria vector in southeastern Brazil (Diptera: Culicidae). *Memórias do Instituto Oswaldo Cruz*, **94**(6), 715–718.
- Gelman, Andrew, & Rubin, Donald B. 1992. Inference from iterative simulation using multiple sequences. *Statistical Science*, 457–472.
- Gelman, Andrew, Carlin, John B, Stern, Hal S, & Rubin, Donald B. 2014. *Bayesian data analysis*. Vol. 2. Taylor & Francis.
- Germain, Max, Hervé, Jean-Pierre, & Geoffroy, Bernard. 1974. Evaluation de la durée du cycle trophogénique d'*Aedes africanus* (Théobald), vecteur potentiel de fièvre jaune, dans une galerie forestière du sud de la République Centrafricaine. *Cahiers ORSTOM. Série Entomologie Médicale et Parasitologie*, **12**(2), 127–133.
- Ghosh, Anupam, Mandal, Samir, & Chandra, Goutam. 2010. Seasonal distribution, parity, resting, host-seeking behavior and association of malarial parasites of *Anopheles stephensi* Liston in Kolkata, West Bengal. *Entomological Research*, **40**(1), 46–54.

- Gillies, MT. 1953. The duration of the gonotrophic cycle in *Anopheles gambiae* and *Anopheles funestus*, with a note on the efficiency of hand catching. *East African Medical Journal*, **30**(4).
- Gillies, MT, & Wilkes, TJ. 1965. A study of the age-composition of populations of *Anopheles gambiae* Giles and *A. funestus* Giles in North-Eastern Tanzania. *Bulletin of Entomological Research*, **56**(02), 237–262.
- Gillies, MT, & Wilkes, TJ. 1972. The range of attraction of animal baits and carbon dioxide for mosquitoes. Studies in a freshwater area of West Africa. *Bulletin of Entomological Research*, **61**(3), 389–404.
- Guerra, Carlos A, Reiner, Robert C, Perkins, AT, Lindsay, Steve W, Midega, J, Brady, Oliver J, Barker, Christopher M, Reisen, William K, Harrington, Laura C, Takken, Willem, et al. 2014. A global assembly of adult female mosquito mark-release-recapture data to inform the control of mosquito-borne pathogens. *Parasite & Vectors*, **7**(1), 276.
- Hancock, PA, Thomas, MB, & Godfray, HCJ. 2009. An age-structured model to evaluate the potential of novel malaria-control interventions: a case study of fungal biopesticide sprays. *Proceedings of the Royal Society of London B: Biological Sciences*, **276**(1654), 71–80.
- Harrington, Laura C, Buonaccorsi, John P, Edman, John D, Costero, Adriana, Kittayapong, Pattamaporn, Clark, Gary G, & Scott, Thomas W. 2001. Analysis of survival of young and old *Aedes aegypti* (Diptera: Culicidae) from Puerto Rico and Thailand. *Journal of Medical Entomology*, **38**(4), 537–547.
- Hii, JK, Birley, MH, & Sang, VY. 1990. Estimation of survival rate and oviposition interval of *Anopheles balabacensis* mosquitoes from mark-recapture experiments in Sabah, Malaysia. *Medical and Veterinary Entomology*, **4**(2), 135–140.
- Hitchcock Jr, James G. 1968. Age composition of a natural population of *Anopheles quadrimaculatus* Say (Diptera: Culicidae) in Maryland, USA. *Journal of Medical Entomology*, **5**(1), 125–134.
- Hoc, TQ, & Wilkes, TJ. 1995. The ovariole structure of *Anopheles gambiae* (Diptera: Culicidae) and its use in determining physiological age. *Bulletin of Entomological Research*, **85**(01), 59–69.
- Hoffman, Matthew D, & Gelman, Andrew. 2014. The No-U-turn sampler: adaptively setting path lengths in Hamiltonian Monte Carlo. *Journal of Machine Learning Research*, **15**(1), 1593–1623.

- Ijumba, JN, Mosha, FW, & Lindsay, SW. 2002. Malaria transmission risk variations derived from different agricultural practices in an irrigated area of northern Tanzania. *Medical and Veterinary Entomology*, **16**(1), 28–38.
- Jaal, Z, & MacDonald, WW. 1992. A mark-release-recapture experiment with *Anopheles lesteri paraliae* in northwest Peninsular Malaysia. *Annals of Tropical Medicine & Parasitology*, **86**(4), 419–424.
- Jayanetti, SR, Wijesundera, Manel de S, & Amaresinghe, FP. 1987. A Study on the Bionomics of Indoor Resting Mosquitoes in Kandy.
- Jensen, Truls, & Washino, Robert K. 1991. An assessment of the biological capacity of a Sacramento Valley population of *Aedes melanimon* to vector arboviruses. *The American Journal of Tropical Medicine and Hygiene*, **44**(4), 355–363.
- Jensen, Truls, & Washino, Robert K. 1994. Comparison of recapture patterns of marked and released *Aedes vexans* and *Ae. melanimon* (Diptera: Culicidae) in the Sacramento Valley of California. *Journal of Medical Entomology*, **31**(4), 607–610.
- Kanda, T, Joo, CY, & Choi, DW. 1975. Epidemiological studies on Malayan filariasis in an inland area in Kyungpook, Korea, 2: The periodicity of the microfilariae and the bionomics of the vector [Brugia malayi, *Anopheles sinensis*]. *Mosquito News*.
- Kay, BH. 1979. Age structure of populations of *Culex annulirostris* (Diptera: Culicidae) at Kowanyama and Charleville, Queensland. *Journal of Medical Entomology*, **16**(4), 309–316.
- Kenawy, Mohamed A. 1991. Development and survival of *Anopheles pharoensis* and *An. multicolor* from Faiyum, Egypt. *J Am Mosq Control Assoc*, **7**(4), 551–5.
- Kohavi, Ron, et al. 1995. A study of cross-validation and bootstrap for accuracy estimation and model selection. *Pages 1137–1145 of: Ijcai*, vol. 14.
- Kraemer, Moritz UG, Sinka, Marianne E, Duda, Kirsten A, Mylne, Adrian QN, Shearer, Freya M, Barker, Christopher M, Moore, Chester G, Carvalho, Roberta G, Coelho, Giovanini E, Van Bortel, Wim, et al. 2015. The global distribution of the arbovirus vectors *Aedes aegypti* and *Ae. albopictus*. *eLife*, **4**, e08347.
- La Corte Dos Santos, Roseli, Forattini, Oswaldo Paulo, & Burattini, Marcelo Nascimento. 2004. *Anopheles albitalis* sl (Diptera: Culicidae) survivorship and density in a rice irrigation area of the State of São Paulo, Brazil. *Journal of Medical Entomology*, **41**(5), 997–1000.

- Lacroix, R, Delatte, Hélène, Hue, T, & Reiter, P. 2009. Dispersal and survival of male and female *Aedes albopictus* (Diptera: Culicidae) on Reunion Island. *Journal of Medical Entomology*, **46**(5), 1117–1124.
- Lines, JD, Wilkes, TJ, & Lyimo, EO. 1991a. Human malaria infectiousness measured by age-specific sporozoite rates in *Anopheles gambiae* in Tanzania. *Parasitology*, **102**(2), 167–177.
- Lines, JD, Curtis, CF, Wilkes, TJ, & Njunwa, KJ. 1991b. Monitoring human-biting mosquitoes (Diptera: Culicidae) in Tanzania with light-traps hung beside mosquito nets. *Bulletin of Entomological Research*, **81**(1), 77–84.
- Loong, KP, Chiang, GL, Eng, KL, Chan, Seng Thim, Yap, HH, et al. 1990. Survival and feeding behaviour of Malaysian strain of *Anopheles maculatus Theobald* (Diptera: Culicidae) and their role in malaria transmission. *Tropical Biomedicine*, **7**(1), 71–76.
- Lorenz, Camila, Marques, Tatiani Cristina, Sallum, Maria Anice Mureb, & Suesdek, Lincoln. 2012. Morphometrical diagnosis of the malaria vectors *Anopheles cruzii*, *An. homunculus* and *An. bellator*. *Parasites & Vectors*, **5**(1), 257.
- Lowe, RE, Ford, HR, Smittle, BJ, Weidhaas, DE, et al. 1973. Reproductive behaviour of *Culex pipiens quinquefasciatus* released into a natural population. *Mosquito News*, **33**(2), 221–7.
- Lutwama, JJ, & Mukwaya, LG. 1994. Mark-release-recapture studies on three anthropophilic populations of *Aedes* (*Stegomyia*) *simpsoni* complex (Diptera: Culicidae) in Uganda. *Bulletin of Entomological Research*, **84**(4), 521–527.
- Macdonald, WW, Sebastian, A, & Tun, Maung Maung. 1968. A mark-release-recapture experiment with *Culex pipiens fatigans* in the village of Okpo, Burma. *Annals of Tropical Medicine & Parasitology*, **62**(2), 200–209.
- Maciel-de Freitas, R, Codeco, CT, & Lourenço-de Oliveira, R. 2007. Body size-associated survival and dispersal rates of *Aedes aegypti* in Rio de Janeiro. *Medical and Veterinary Entomology*, **21**(3), 284–292.
- Maciel-de Freitas, Rafael, Neto, Roman Brocki, Gonçalves, Jaylei Monteiro, Codeço, Claudia Torres, & Lourenço-de Oliveira, Ricardo. 2006. Movement of dengue vectors between the human modified environment and an urban forest in Rio de Janeiro. *Journal of Medical Entomology*, **43**(6), 1112–1120.
- Maciel-De-Freitas, Rafael, Codeco, Claudia Torres, & Lourenco-De-Oliveira, Ricardo. 2007. Daily survival rates and dispersal of *Aedes aegypti* females in Rio

de Janeiro, Brazil. *The American Journal of Tropical Medicine and Hygiene*, **76**(4), 659–665.

Maciel-de Freitas, Rafael, Eiras, Álvaro E, & Lourenço-de Oliveira, Ricardo. 2008. Calculating the survival rate and estimated population density of gravid *Aedes aegypti* (Diptera, Culicidae) in Rio de Janeiro, Brazil. *Cadernos de Saúde Pública*, **24**(12), 2747–2754.

Magesa, SM, Wilkes, TJ, Mnzava, AEP, Njunwa, KJ, Myamba, J, Kivuyo, MDP, Hill, N, Lines, JD, & Curtis, CF. 1991. Trial of pyrethroid impregnated bednets in an area of Tanzania holoendemic for malaria Part 2. Effects on the malaria vector population. *Acta Tropica*, **49**(2), 97–108.

Mahanta, B, Handique, R, Dutta, P, Narain, K, & Mahanta, J. 1999. Temporal variations in biting density and rhythm of *Culex quinquefasciatus* in tea agro-ecosystem of Assam, India.

Mahmood, Farida, & Reisen, William K. 1981. Duration of the gonotrophic cycles of *Anopheles culicifacies Giles* and *Anopheles stephensi Liston*, with observations on reproductive activity and survivorship during winter in Punjab province, Pakistan. *Mosquito News*.

Mala, Albert O, Irungu, Lucy W, Mitaki, Elizabeth K, Shililu, Josephat I, Mbogo, Charles M, Njagi, Joseph K, & Githure, John I. 2014. Gonotrophic cycle duration, fecundity and parity of *Anopheles gambiae* complex mosquitoes during an extended period of dry weather in a semi arid area in Baringo County, Kenya. *International Journal of Mosquito Research*, **1**(2), 28–34.

Marini, F, Caputo, B, Pombi, M, Tarsitani, G, & Della Torre, A. 2010. Study of *Aedes albopictus* dispersal in Rome, Italy, using sticky traps in mark–release–recapture experiments. *Medical and Veterinary Entomology*, **24**(4), 361–368.

Marsland, Stephen. 2015. *Machine learning: an algorithmic perspective*. CRC press.

McDonald, PT. 1977. Population characteristics of domestic *Aedes aegypti* (Diptera: Culicidae) in villages on the Kenya Coast I. Adult survivorship and population size. *Journal of Medical Entomology*, **14**(1), 42–48.

Mendis, C, Thompson, R, Begtrup, K, Cuamba, N, & Dgedge, M. 1998. Cordon sanitaire or laissez faire: differential dispersal of young and old females of the malaria vector *Anopheles funestus* Giles (Diptera: Culicidae) in southern Mozambique. *African Entomology*, **6**(1).

- Midega, Janet T, Mbogo, Charles M, Mwambi, Henr, Wilson, Michael D, Ojwang, Gordo, Mwangangi, Joseph M, Nzovu, Joseph G, Githure, John I, Yan, Guiyu, & Beier, John C. 2007. Estimating dispersal and survival of *Anopheles gambiae* and *Anopheles funestus* along the Kenyan coast by using mark–release–recapture methods. *Journal of Medical Entomology*, **44**(6), 923–929.
- Milby, MM, & Reisen, WK. 1989. Estimation of vectorial capacity: vector survivorship. *Bulletin of the Society of Vector Ecology*, **14**(1), 47–54.
- Mori, A, Wada, Y, et al. 1977. The gonotrophic cycle of *Aedes albopictus* in the field. *Tropical Medicine*, **19**(3/4), 141–146.
- Muir, Lynda E, & Kay, Brian H. 1998. *Aedes aegypti* survival and dispersal estimated by mark-release-recapture in northern Australia. *The American Journal of Tropical Medicine and Hygiene*, **58**(3), 277–282.
- Müller, G, & Schlein, Y. 2005. Plant tissues: the frugal diet of mosquitoes in adverse conditions. *Medical and Veterinary Entomology*, **19**(4), 413–422.
- Müller, Günter C, Beier, John C, Traore, Sekou F, Toure, Mahamoudou B, Traore, Mohamed M, Bah, Sekou, Doumbia, Seydou, & Schlein, Yosef. 2010. Successful field trial of attractive toxic sugar bait (ATSB) plant-spraying methods against malaria vectors in the *Anopheles gambiae* complex in Mali, West Africa. *Malaria Journal*, **9**(1), 210.
- Nathan, Michael B. 1981. Bancroftian filariasis in coastal North Trinidad, West Indies: intensity of transmission by *Culex quinquefasciatus*. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **75**(5), 721–730.
- Nayar, JK, Provost, MW, & Hansen, CW. 1980. Quantitative bionomics of *Culex nigripalpus* (Diptera: Culicidae) populations in Florida: 2. Distribution, dispersal and survival patterns. *Journal of Medical Entomology*, **17**(1), 40–50.
- Nelson, RL, & Milby, MM. 1980. Dispersal and survival of field and laboratory strains of *Culex tarsalis* (Diptera: Culicidae). *Journal of Medical Entomology*, **17**(2), 146–150.
- Nelson, RL, Milby, MM, Reeves, WC, & Fine, PEM. 1978. Estimates of survival, population size, and emergence of *Culex tarsalis* at an isolated site. *Annals of the Entomological Society of America*, **71**(5), 801–808.
- Novoseltsev, Vasiliy N, Michalski, Anatoli I, Novoseltseva, Janna A, Yashin, Anatoliy I, Carey, James R, & Ellis, Alicia M. 2012. An age-structured extension to the vectorial capacity model. *PLoS One*, **7**(6).

- Ordóñez González, José Genaro, Mercado Hernández, Roberto, Flores Suárez, Adriana Elizabeth, & Fernández Salas, Ildefonso. 2001. The use of sticky ovitraps to estimate dispersal of *Aedes aegypti* in northeastern Mexico. *Journal of the American Mosquito Control Association*, **17**(2), 93–97.
- Pant, Chandra Prakash, World Health Organisation, *et al.* 1962. Distribution of anophelines in relation to altitude in Nepal.
- Pant, CP, & Yasuno, M. 1973. Field studies on the gonotrophic cycle of *Aedes aegypti* in Bangkok, Thailand. *Journal of Medical Entomology*, **10**(2), 219–223.
- Penilla, RP, Rodriguez, MH, Lopez, AD, Viader-Salvadó, JM, & Sanchez, CN. 2002. Pteridine concentrations differ between insectary-reared and field-collected *Anopheles albimanus* mosquitoes of the same physiological age. *Medical and Veterinary Entomology*, **16**(3), 225–234.
- Polovodova, VP. 1949. The determination of the physiological age of female *Anopheles* by the number of gonotrophic cycles completed. *Meditinskaia Parazitologija Parazitar Bolezni*, **18**, 352–355.
- Pumpuni, CB, & Walker, ED. 1989. Population size and survivorship of adult *Aedes triseriatus* in a scrap tireyard in northern Indiana. *Journal of the American Mosquito Control Association*, **5**(2), 166–172.
- Qualls, Whitney A, Müller, Günter C, Traore, Sekou F, Traore, Mohamed M, Arheart, Kristopher L, Doumbia, Seydou, Schlein, Yosef, Kravchenko, Vasiliy D, Xue, Rui-De, & Beier, John C. 2015. Indoor use of attractive toxic sugar bait (ATSB) to effectively control malaria vectors in Mali, West Africa. *Malaria Journal*, **14**(1), 301.
- Quinones, ML, Lines, JD, Thomson, MC, Jawara, M, Morris, J, & Greenwood, BM. 1997. *Anopheles gambiae* gonotrophic cycle duration, biting and exiting behaviour unaffected by permethrin-impregnated bednets in The Gambia. *Medical and Veterinary Entomology*, **11**(1), 71–78.
- Rajagopalan, PK. 1980. Population dynamics of culex pipiens fatigans, the filariasis vector, in pondicherry: influence of climate and environment. *Pages 745–52 of: Proceedings of the Indian National Sciences Academy*, vol. 46.
- Ramaiah, KD, & Das, PK. 1992. Non-involvement of nulliparous females in the transmission of bancroftian filariasis. *Acta Tropica*, **52**(2-3), 149–153.
- Rawlings, P, & Curtis, Chris F. 1982. Tests for the existence of genetic variability in the tendency of *Anopheles culicifacies* species B to rest in houses and to bite man. *Bulletin of the World Health Organisation*, **60**(3), 427.

- Rawlings, P, & Davidson, G. 1982. The dispersal and survival of *Anopheles culicifacies Giles* (Diptera: Culicidae) in a Sri Lankan village under malathion spraying. *Bulletin of Entomological Research*, **72**(1), 139–144.
- Rawlings, P, Curtis, CF, Wickramasinghe, MB, & Lines, J. 1981. The influence of age and season on dispersal and recapture of *Anopheles culicifacies* in Sri Lanka. *Ecological Entomology*, **6**(3), 307–319.
- Reisen, William K, Mahmood, Farida, & Parveen, Tauheeda. 1979. *Anopheles subpictus Grassi*: observations on survivorship and population size using mark-release-recapture and dissection methods. *Researches on Population Ecology*, **21**(1), 12–29.
- Reisen, William K, Mahmood, Farida, & Parveen, Tauheeda. 1980. *Anopheles culicifacies Giles*: a release-recapture experiment with cohorts of known age with implications for malaria epidemiology and genetical control in Pakistan. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, **74**(3), 307–317.
- Reisen, William K, Mahmood, Farida, & Azra, Khawar. 1981. *Anopheles culicifacies giles*: Adult ecological parameters measured in rural punjab province, pakistan using capture-mark-release-recapture and dissection methods, with comparative observations on An. stephensi liston and An. subpictus grassi. *Researches on Population Ecology*, **23**(1), 39–60.
- Reisen, William K, Milby, Marilyn M, Reeves, William C, Meyer, Richard P, & Bock, Martha E. 1983. Population ecology of *Culex tarsalis* (Diptera: Culicidae) in a foothill environment of Kern County, California: temporal changes in female relative abundance, reproductive status, and survivorship. *Annals of the Entomological Society of America*, **76**(4), 800–808.
- Reisen, WK, Sakai, RK, Baker, RH, Azra, K, Niaz, S, et al. 1982. *Anopheles culicifacies*: observations on population ecology and reproductive behavior. *Mosquito News*, **42**(1), 93–101.
- Reisen, WK, Yoshimura, G, Reeves, WC, Milby, MM, & Meyer, RP. 1984. The impact of aerial applications of ultra-low volume adulticides on *Culex tarsalis* populations (Diptera: Culicidae) in Kern County, California, USA, 1982. *Journal of Medical Entomology*, **21**(5), 573–585.
- Renshaw, M, Service, MW, & Birley, MH. 1994. Host finding, feeding patterns and evidence for a memorized home range of the mosquito Aedes cantans. *Medical and Veterinary Entomology*, **8**(2), 187–193.

- Rodriguez, Mario H, Bown, David N, Arredondo-Jimenez, Juan I, Villarreal, Cuauhtemoc, Loyola, Enrique G, & Frederickson, Christian E. 1992. Gonotrophic cycle and survivorship of *Anopheles albimanus* (Diptera: Culicidae) in southern Mexico. *Journal of Medical Entomology*, **29**(3), 395–399.
- Rohatgi, Ankit. 2017 (January). *WebPlotDigitizer*.
- Ross, Ronald. 1910. *The prevention of malaria*. Dutton.
- Rúa, Guillermo L, Quiñones, Martha L, Vélez, Iván D, Zuluaga, Juan S, Rojas, William, Poveda, Germán, & Ruiz, Daniel. 2005. Laboratory estimation of the effects of increasing temperatures on the duration of gonotrophic cycle of *Anopheles albimanus* (Diptera: Culicidae). *Memorias Do Instituto Oswaldo Cruz*, **100**(5), 515–520.
- Russell, Richard C. 1986. *Culex annulirostris Skuse* (Diptera: Culicidae) at Appin, NSW? bionomics and behaviour. *Austral Entomology*, **25**(2), 103–109.
- Samarawickrema, WA. 1967. A study of the age-composition of natural populations of *Culex pipiens fatigans* Wiedemann in relation to the transmission of filariasis due to *Wuchereria bancrofti* (Cobbold) in Ceylon. *Bulletin of the World Health Organisation*, **37**(1), 117.
- Samarawickrema, WA. 1968. Biting cycles and parity of the mosquito *Mansonia* (*Mansonioides*) uniformis (Theo.) in Ceylon. *Bulletin of Entomological research*, **58**(02), 299–314.
- Samarawickrema, WA, Sone, Fola, & Cummings, RF. 1987. Seasonal abundance, diel biting activity and parity of *Aedes polynesiensis marks* and *A. samoanus* (Grünberg) (Diptera: Culicidae) in Samoa. *Bulletin of Entomological Research*, **77**(2), 191–200.
- Schlein, Yosef, & Müller, Gunter C. 2008. An approach to mosquito control: Using the dominant attraction of flowering Tamarix jordanis trees against *Culex pipiens*. *Journal of Medical Entomology*, **45**(3), 384–390.
- Schlein, Yosef, & Müller, Günter C. 2012. Diurnal resting behavior of adult *Culex pipiens* in an arid habitat in Israel and possible control measurements with toxic sugar baits. *Acta Tropica*, **124**(1), 48–53.
- Schlein, Yosef, & Müller, Günter C. 2015. Decrease of larval and subsequent adult *Anopheles sergentii* populations following feeding of adult mosquitoes from *Bacillus sphaericus*-containing attractive sugar baits. *Parasites & Vectors*, **8**(1), 244.

- Scholl, PJ, Porter, CHARLES H, & Defoliart, GENE R. 1979. *Aedes triseriatus*: persistence of nulliparous females under field conditions. *Mosquito News*, **39**, 368–371.
- Sempala, SDK. 1981. The ecology of *Aedes (Stegomyia) africanus* (Theobald) in a tropical forest in Uganda: mark-release-recapture studies on a female adult population. *International Journal of Tropical Insect Science*, **1**(3), 211–224.
- Shalaby, AM, World Health Organisation, *et al.* 1962. Studies on the age composition of *Anopheles Culicifacies Giles* at different phases of the development of resistance to DDT in Panchmahals district of Gujarat State, India.
- Sheppard, PM, Macdonald, WW, Tonn, RJ, & Grab, B. 1969. The dynamics of an adult population of *Aedes aegypti* in relation to dengue haemorrhagic fever in Bangkok. *The Journal of Animal Ecology*, 661–702.
- Shriram, AN, & Krishnamoorthy, K. 2011. Population dynamics, age composition and survival of *Downsiomyia nivea* in relation to transmission of diurnally subperiodic filariasis. *Journal of Asia-Pacific Entomology*, **14**(1), 34–40.
- Silver, John B. 2007. *Mosquito ecology: field sampling methods*. Springer Science & Business Media.
- Sinka, Marianne E, Bangs, Michael J, Manguin, Sylvie, Coetzee, Maureen, Mbogo, Charles M, Hemingway, Janet, Patil, Anand P, Temperley, Will H, Gething, Peter W, Kabaria, Caroline W, Okara, Robi M, Boekel, Thomas Van, Godfray, H Charles J, Harbach, Ralph E, & Hay, Simon I. 2010. The dominant *Anopheles* vectors of human malaria in Africa, Europe and the Middle East: occurrence data, distribution maps and bionomic précis. *Parasites & Vectors*, **3**(1), 117.
- Sinka, Marianne E, Bangs, Michael J, Manguin, Sylvie, Rubio-Palis, Yasmin, Chareonviriyaphap, Theeraphap, Coetzee, Maureen, Mbogo, Charles M, Hemingway, Janet, Patil, Anand P, Temperley, William H, *et al.* 2012. A global map of dominant malaria vectors. *Parasites & Vectors*, **5**(1), 1.
- Smith, David L, & McKenzie, F Ellis. 2004. Statics and dynamics of malaria infection in *Anopheles* mosquitoes. *Malaria Journal*, **3**(1), 13.
- Smith, Gordon E, Watson, Robert B, & Cromwell, Robert L. 1941. Observations on the flight range of *Anopheles quadrimaculatus*, Say. *American Journal of Epidemiology*, **34**(2), 102–113.
- Smith, Stephen M, & Kurtz, RM. 1994. The age structure of a population of *Aedes provocans* (Diptera: Culicidae) in southwestern Ontario. *Great Lakes Entomologist*, **27**(2), 113.

- Snow, WF, & Boreham, PFL. 1978. The host-feeding patterns of some culicine mosquitoes (Diptera: Culicidae) in The Gambia. *Bulletin of Entomological Research*, **68**(4), 695–706.
- Stan Development Team. 2014. *Stan: A C++ Library for Probability and Sampling, Version 2.5.0*.
- Styer, Linda M, Carey, James R, Wang, Jane-Ling, & Scott, Thomas W. 2007. Mosquitoes do senesce: departure from the paradigm of constant mortality. *The American Journal of Tropical Medicine and Hygiene*, **76**(1), 111–117.
- Surendran, SN, Ramasamy, MS, De Silva, BGDNK, & Ramasamy, R. 2006. *Anopheles culicifacies* sibling species B and E in Sri Lanka differ in longevity and in their susceptibility to malaria parasite infection and common insecticides. *Medical and Veterinary Entomology*, **20**(1), 153–156.
- Suzuki, Takeshi. 1978. Preliminary studies on blood meal interval of *Aedes polynesiensis* in the field. *Medical Entomology and Zoology*, **29**(2), 169–174.
- Takagi, Masahiro, Tsuda, Yoshio, Suzuki, Akemi, & Wada, Yoshito. 1995. Movement of individually marked *Aedes albopictus* females in Nagasaki, Japan. *Tropical Medicine*, **37**(2), 79–85.
- Takken, W, Charlwood, JD, Billingsley, PF, & Gort, G. 1998. Dispersal and survival of *Anopheles funestus* and *A. gambiae* sl (Diptera: Culicidae) during the rainy season in southeast Tanzania. *Bulletin of Entomological Research*, **88**(5), 561–566.
- Touré, Yeya T, Dolo, Guimogo, Petrarca, Vincenzo, Dao, Adama, Carnahan, John, & Taylor, Charles E. 1998. Mark–release–recapture experiments with *Anopheles gambiae* sl in Banambani Village, Mali, to determine population size and structure. *Medical and Veterinary Entomology*, **12**(1), 74–83.
- Trpis, Milan, & Hausermann, Walter. 1975. Demonstration of differential domesticity of *Aedes aegypti* (L.) (Diptera, Culicidae) in Africa by mark-release-recapture. *Bulletin of Entomological Research*, **65**(2), 199–208.
- Trpis, Milan, Häusermann, Walter, & Craig Jr, George B. 1995. Estimates of population size, dispersal, and longevity of domestic *Aedes aegypti* aegypti (Diptera: Culicidae) by mark–release–recapture in the village of Shauri Moyo in eastern Kenya. *Journal of Medical Entomology*, **32**(1), 27–33.
- Tsuda, Yoshio, Takagi, M, Wang, S, Wang, Z, & Tang, L. 2001. Movement of *Aedes aegypti* (Diptera: Culicidae) released in a small isolated village on Hainan Island, China. *Journal of Medical Entomology*, **38**(1), 93–98.

- Tuchinda, P, Kitaoka, Masami, Ogata, Takayuki, & Kurihara, T. 1969. On the diurnal rhythmus of biting behavior of *Aedes aegypti* in relation to the age and to the hemorrhagic fever in Bangkok, 1964. *Japanese Journal of Tropical Medicine*, **10**(1), 1–6.
- Uttah, Emmanuel C, Iboh, Cletus I, Ajang, Raymond, Osim, SE, & Etta, Hannah. 2013. Physiological age composition of female anopheline mosquitoes in an area endemic for malaria and filariasis. *International Journal of Scientific and Research Publications*, **3**(7), 1–4.
- Valerio, Laura, Facchinelli, Luca, Ramsey, Janine M, & Scott, Thomas W. 2012. Dispersal of male *Aedes aegypti* in a coastal village in southern Mexico. *The American Journal of Tropical Medicine and Hygiene*, **86**(4), 665–676.
- Vehtari, Aki, Gelman, Andrew, & Gabry, Jonah. 2015. Efficient implementation of leave-one-out cross-validation and WAIC for evaluating fitted Bayesian models. *arXiv preprint arXiv:1507.04544*.
- Vythilingam, Indra, Oda, Kazumasa, Mahadevan, S, Abdullah, Ghani, Thim, Chan Seng, Hong, Choo Choon, Vijayamalar, B, Sinniah, Mangalam, & Igarashi, Akira. 1997. Abundance, parity, and Japanese encephalitis virus infection of mosquitoes (Diptera: Culicidae) in Sepang District, Malaysia. *Journal of Medical Entomology*, **34**(3), 257–262.
- Wada, Yoshito, Kawai, Senji, Oda, Tsutomu, Miyagi, Ichiro, Suenaga, Osamu, Nishigaki, Jojiro, Omori, Nanzaburo, Takahashi, Katsumi, Matsuo, Reizo, Itoh, Tatsuya, et al. 1969. Dispersal experiment of *Culex tritaeniorhynchus* in Nagasaki area (Preliminary report). *Tropical Medicine*, **11**(1), 37–44.
- Watson, Tonya M, Saul, Allan, & Kay, Brian H. 2000. *Aedes notoscriptus* (Diptera: Culicidae) survival and dispersal estimated by mark-release-recapture in Brisbane, Queensland, Australia. *Journal of Medical Entomology*, **37**(3), 380–384.
- Wilkes, TJ, Matola, YG, & Charlwood, JD. 1996. *Anopheles rivulorum*, a vector of human malaria in Africa. *Medical and Veterinary Entomology*, **10**(1), 108–110.
- Wong, Jacklyn, Astete, Helvio, Morrison, Amy C, & Scott, Thomas W. 2014. Sampling considerations for designing *Aedes aegypti* (Diptera: Culicidae) oviposition studies in Iquitos, Peru: substrate preference, diurnal periodicity, and gonotrophic cycle length. *Journal of Medical Entomology*, **48**(1), 45–52.
- World Health Organisation, et al. 1960. Preliminary appraisal on the use of age-grouping methods in anopheline mosquitos.

Yasuno, M, Rajagopalan, PK, Laüreque, GC, *et al.* 1975. Migration patterns of *Culex fatigans* around Delhi, India. *Tropical Medicine*, **17**(2), 91–96.

Zetek, James. 1915. Behavior of *Anopheles albimanus* Wiede and *tarsimaculata Goeldi*. *Annals of the Entomological Society of America*, **8**(3), 221–271.