Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

A functional durability framework for insecticide-treated nets (ITNs): integrating fabric and insecticide durability through mathematical modelling of longitudinal field data from Tanzania

Sarah J Moore

smoore@ihi.or.tz

Ifakara Health Institute

Dennis J Massue

National Institute for Medical Research

Watson S Ntabaliba

Ifakara Health Institute

Olivier J T Briet

European Centre for Disease Prevention and Control

Thomas A Smith

Swiss Tropical and Public Health Institute

Research Article

Keywords: Insecticide Treated Nets (ITN), durability, physical integrity, insecticidal activity, mosquito, Anopheles, mortality, feeding inhibition, bioassay, Ifakara Ambient Chamber Test (I-ACT), mathematical modelling

Posted Date: July 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10026662/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

A functional durability framework for insecticide-treated nets (ITNs): integrating fabric and insecticide durability through mathematical modelling of longitudinal field data from Tanzania

Sarah J Moore[1,2,3,4§*], Dennis J Massue[1,2,5,6*], Watson S Ntabaliba[3], Olivier J.T Briet[1,2,7]and Thomas A Smith[1,2]

[1] Swiss Tropical and Public Health Institute, Kreuzstrasse 2 4123 Allschwil Switzerland

[2] University of Basel Petersplatz 1 4003 Basel Switzerland

[3] Vector Control Product Testing Unit, Environmental and Ecological Sciences, Ifakara Health Institute Bagamoyo Pwani Tanzania

[4] Nelson Mandela African Institute of Science and Technology Tengeru Arusha Tanzania

[5] National Institute for Medical Research Amani Research Centre P. O. Box 81 Muheza Tanga Tanzania

[6] University of Dar es Salaam Mbeya College of Health and Allied Sciences, Mbeya, Tanzania

[7] European Centre for Disease Prevention and Control Solna Sweden

§Corresponding author

*Contributed equally

SJM: smoore@ihi.or.tz

DJM: dennisjoram@gmail.com

WSN: wntabaliba@ihi.or.tz

OJTB: o.briet@gmail.com

TAS: thomas-a.smith@unibas.ch

Abstract

Background

Insecticide-treated nets (ITNs) are assumed to remain functional for three-years. However, products within the same class differ in fabric durability and persistence of bioavailable insecticide. Understanding the relative contributions of both factors to ITN efficacy under real-use conditions is essential for optimising product design.

Methods

Physical and chemical decay were assessed using pyrethroid ITNs collected from a three-year longitudinal field trial in Tanzania. The effects of insecticide content, hole location, and holed surface area on 24h-mortality and blood-feeding of laboratory-reared pyrethroid-susceptible *Anopheles gambiae* sensu stricto mosquitoes were evaluated using the Ifakara Ambient Chamber Test (I-ACT) bioassay. Entomological effects were analysed using a differential equation model for mosquito mortality and feeding, with a hyperbolic function for holed area and a saturating function for insecticide content, allowing separation of barrier and insecticidal effects.

Results

Fabric integrity and insecticide content declined over time, with marked variation between brands. Approximately 50% of fabric damage occurred in the bottom quadrant

that was typically tucked under mattresses and contributed minimally to mosquito entry. As nets aged, increasing holed area led to higher blood-feeding success among attacking mosquitoes, driven primarily by large holes in lower side panels above the mattress, representing 27% of holed surface area accessible to mosquitoes.

Despite this, residual insecticidal activity remained sufficient to maintain low mosquito survival. The model showed excellent fit and enabled independent estimation of barrier and insecticidal effects. Differences in mosquito mortality between brands were largely explained by linear scaling of insecticide concentration, with a shared parameter describing the concentration required to achieve half-maximal effect. Overall, estimated entomological effectiveness declined only modestly with net age.

Conclusion

Functional durability of ITNs can be understood as the outcome of two analytically separable processes: physical degradation of the fabric and loss of bioavailable insecticide. I-ACT enabled precise measurement of both effects. Even heavily damaged nets retained substantial effectiveness when insecticidal activity remained high and nets continued to be used.

This framework provides a practical means for comparing ITN products and strengthening durability monitoring. Future ITN design should prioritise insecticidal performance to kill mosquitoes, while recognising that fabric construction influences both fabric durability and user acceptability. These fabric related characteristics are

important to maximise retention, sustained use and ensure cost-effective public health impact.

Keywords

Insecticide Treated Nets (ITN), durability, physical integrity, insecticidal activity, mosquito, *Anopheles,* mortality, feeding inhibition, bioassay, Ifakara Ambient Chamber Test (I-ACT), mathematical modelling

Background

Insecticide Treated nets (ITNs) are the primary preventative intervention against malaria in Africa. However, in 2024, only 54% of the population at risk had access to an ITN within their household, just 1% higher than in 2015 (1), and well below the target of at least 80% access in endemic areas (2). Achieving the "Global Technical Strategy (GTS) For Malaria 2016–2030" (3) targets of 90% reduction in malaria between 2015 and 2030 will require annual funding for malaria control to more than double, from $3.9 to $9.3 billion (1). It therefore remains incumbent upon the malaria control community to use available investments wisely to maximise population access to effective ITNs.

ITNs lose effectiveness from the moment of distribution through becoming physically damaged and through loss of insecticide. Physical deterioration is important because holes allow mosquitoes to enter ITNs and feed on the occupants (4, 5), which discourages use of ITNs and leads to them being discarded or repurposed (6-8). Although ITN replacement strategies assume a three-year lifespan, most nets last around two years in practice (9), contributing to persistent gaps in population access (10).

Continuous distribution of longer lasting ITNs will improve the likelihood of achieving ITN coverage targets set by the GTS (10-12), and longer lasting ITNs are more cost effective (13, 14) and avert more malaria cases (15, 16). While recent ITN research and development efforts have focused largely on new active ingredients (AI) to address insecticide resistance (17), improving both chemical durability and fabric integrity is also likely to substantially enhance public health impact (18, 19).

World Health Organisation guidance recommends monitoring ITN survivorship (attrition), fabric integrity, and insecticidal activity (20). These methods are designed to rapidly assess ITN presence and the amount of damage on the nets, distinguishing between damage in different parts of the net using the approximated holed surface area. This is important because holes in different places could easily have different effects on mosquito mortality and blood-feeding (21). However, the relative contribution of hole size, hole location and residual insecticide content to entomological efficacy remains insufficiently understood. Conventional durability monitoring approaches treat physical and chemical residual as separate endpoints, offering limited insight into how these interact to influence overall ITN performance under real-world conditions.

This study uses data from a randomised controlled trial conducted across eight epidemiologically and ecologically distinct districts in Tanzania, in which three pyrethroid ITN products (PermaNet 2.0 (2012 version), Olyset, and NetProtect) were distributed and followed for three years (13). At 10, 22 and 36 months post-deployment, sample nets were collected to assess (1) physical integrity through measuring hole size and location, (2) whole-net residual insecticide content, and (3) entomological efficacy using the Ifakara Ambient Chamber Test (I-ACT) (22). We examined how locations of the holes and chemical content were associated with mosquito mortality and blood-feeding. The bioassay results were used to estimate parameters of the model of Chitnis *et al* (23), and how both the deterioration of active ingredients and the physical integrity of ITNs in the field modify the impact on malaria transmission.

Methods

ITNs

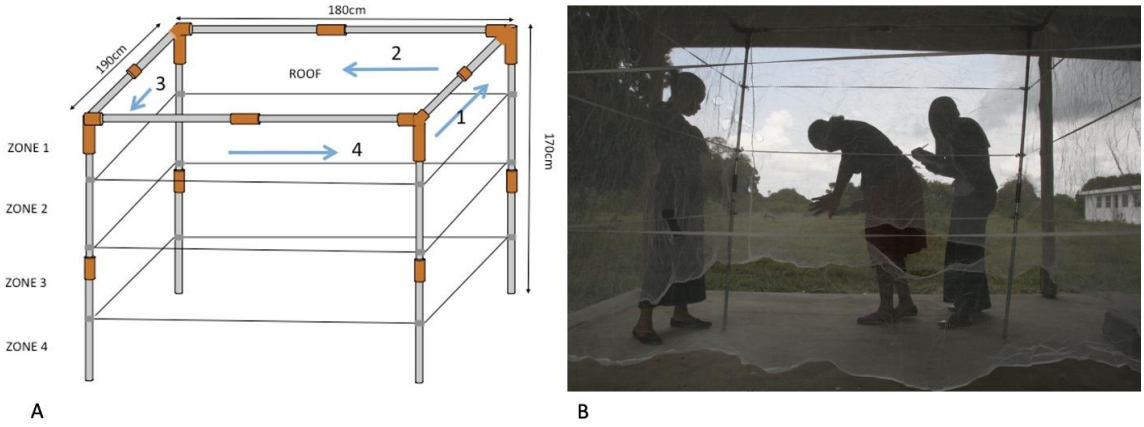
At each of the three time points, 48 each of Olyset (permethrin incorporated into polyethylene fibres at 1000 mg/m^2), PermaNet 2.0 (manufactured 2012, deltamethrin coated on polyester fibres at 55 mg/m^2) and NetProtect ITNs (deltamethrin incorporated into polyethylene fibres at 63 mg/m^2) were randomly sampled from all nets collected in the trial (24). All nets were rectangular, white, double sized (190 cm length × 180 cm width × 150 cm height).

Assessment of physical integrity

Each ITN was hung over a 190 × 180 × 170 cm collapsible bed net frame with elastic guides, which divided the frame into four zones of 42cm width (Figure 1). The number, size and location of holes by zone and roof were recorded. Each hole was assumed to be circular and assigned one of four size categories (size 1: <2 cm, size 2: 2–10 cm, size 3: 10–25 cm, size 4: >25 cm) (25). For each net, the proportion of the area holed (h) was calculated as total holed area divided by the total net surface area. Results were summarised using hole surface area (HSA), and nets were classified as good (<79 cm^2); damaged (80–789 cm^2); or too torn (>790 cm^2) (25). In addition, the proportionate hole index (pHI) was calculated as a weighted sum of hole counts by size category using median-area weights of 1, 23, 196 and 576, respectively. pHI was classified as good (<64), damaged (65–642) or too torn (>643) (25). This was done as it is commonly used in durability reports.

Figure 1 Measurement of holed area by zone of net.

A: the rectangular collapsible bed net frame showing the division of the sides into four equal zones of 42.5 cm height. B: a net draped over the frame undergoing hole assessment.



Insecticide Concentrations

Concentrations of permethrin in Olyset nets were determined using gas chromatography with flame ionisation detection. For PermaNet 2.0 and NetProtect, high-performance liquid chromatography with diode array detection was used to determine deltamethrin concentrations (13). For the descriptive analyses, insecticide concentrations were expressed as proportions of the manufacturers' mean target concentrations (Olyset®: permethrin 20 g/kg permethrin; PermaNet 2.0: 1.4 g/kg deltamethrin; NetProtect: 1.8 g/kg deltamethrin).

Mosquitoes

Mosquitoes used for testing bioefficacy were laboratory-reared fully pyrethroid-susceptible nulliparous female *Anopheles gambiae* sensu stricto (Ifakara strain, Njage 1996), 5–8 days old, reared according to standard rearing techniques (26). The larvae were fed with finely ground Tetramin fish food and the emerging adults were maintained on 10% sugar solution. The insectary was maintained between 25–29°C and 70–80% relative humidity. Mosquitoes were selected to ensure fitness from a minimum of three cages by holding a hand close to the cage and aspirating those mosquitoes that were actively probing. The mosquitoes were sugar starved for 6 hours prior to experiments to increase avidity.

Ifakara Ambient Chamber Test (I-ACT) assay methodology

Bioefficacy was assessed using the Ifakara Ambient Chamber Test (I-ACT) system (22) in Bagamoyo, Tanzania. Each of the 48 ITNs per product per year was tested on two separate nights using a randomized balanced semi-factorial design, which also included 236 no-net controls. In each chamber (5 m long, 2 m wide, and 2 m high), a test net was hung from a frame with a human volunteer sleeping underneath. At 21:00hrs, 30 mosquitoes were introduced into each chamber and collected at 06.30hrs. Mosquitoes were first collected from inside the net using a mouth aspirator and then from the floor and chamber walls using 6V mechanical aspirators (27). Mosquitoes were then held under insectary conditions for 24 hours with access to 10% sugar solution, before being scored into four categories: alive unfed, alive fed, dead unfed and dead fed. After each experimental night, chambers were aired and bedsheets washed between replicates to prevent insecticide carry-over.

Model for bioefficacy

Mosquito transitions inside the I-ACT chambers were modelled as a first-order Markov process (i.e. there is no memory) using a competing rates model of Denz *et al* (28) as adapted by Champagne *et al* (29) fitted to the proportions of mosquitoes in each of the four categories:

Feeding occurs with rate:

$$\alpha = \alpha_{\min} + (\alpha_{\max} - \alpha_{\min})(1 - x_1(h)) \quad (1)$$

where $\alpha_{\min}$ is the rate with an intact net, $\alpha_{\max}$ is the rate with no net and $x_1(h)$ is a continuous function of the holed area. Using the notation in Table 1, the effect of the physical integrity of the net, valid for the full range of levels of damage is:

$$x_1 = \left(\frac{\theta_1(1-h)}{\theta_1 + h}\right)^{\theta_2}, \quad (2)$$

which ranges between 0 (completely holed net or no net: $h = 1$) and 1 (intact net: $h = 0$). The parameters θ_1 and θ_2 jointly determine the shape of the relationship between holed area and effect and must be estimated.

Variation in the biological effects of chemical agents (repellent or insecticidal) arise predominantly from differences in detoxification of some common target molecule. It is therefore reasonable to model them in the same way as the kinetics of enzymatic action are modelled using the Michaelis-Menten equation. In this formulation killing occurs with rate:

$$\mu = \mu_0 + \frac{V_{max}[X]}{K + [X]} \quad (3)$$

where μ_0 is the background mosquito mortality rate applicable in the absence of active ingredient (AI); $[X]$ is the effective concentration of AI; V_{max} determines the maximum killing rate, and K is the concentration at which the rate of excess mortality is $V_{max}/2$ and thus measures the resistance level of the mosquito.

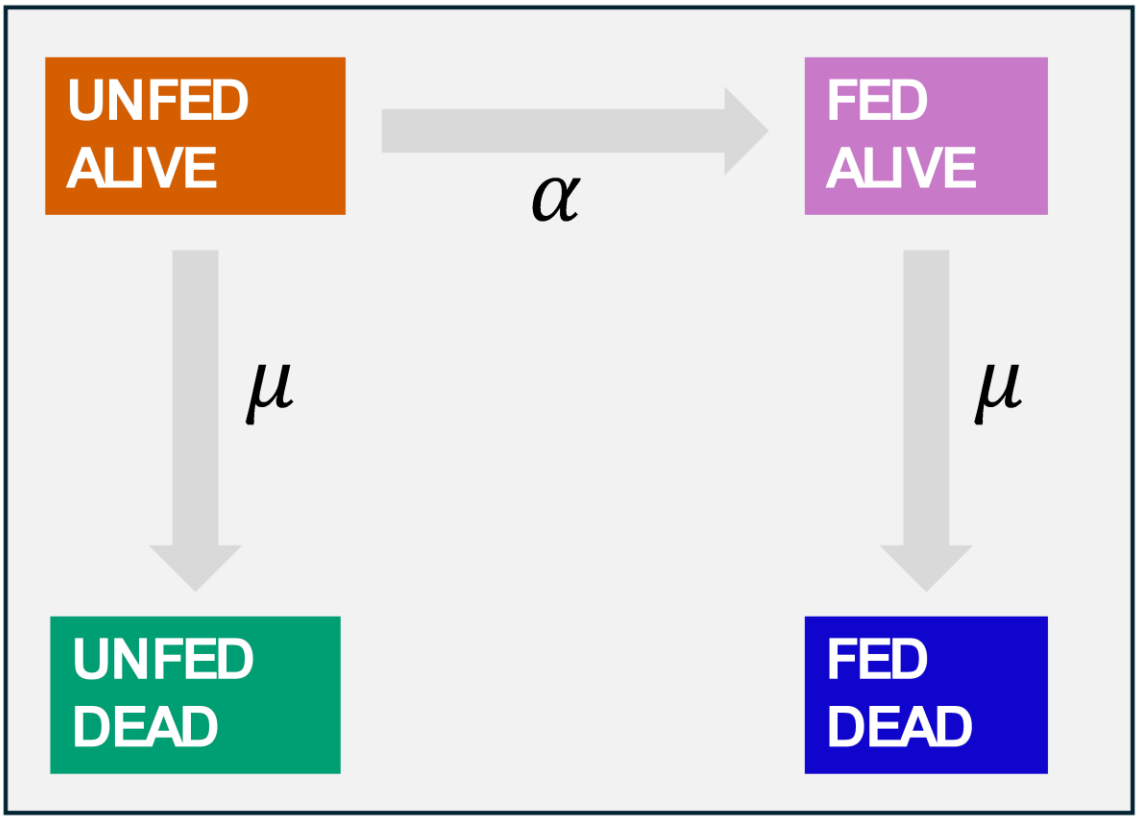
Table 1. Notation

Symbol	***Description***
h	Proportion holed area of net
$[X]$	Effective concentration of AI
x_1	Holed-area specific proportion of maximal barrier effect
x_2	Proportion of mosquitoes killed by AI
θ_1, θ_2	Shape parameters for barrier effect
K	Michaelis constant
p_{UA}	Expected proportion of mosquitoes unfed alive.
p_{UD}	Expected proportion of mosquitoes unfed dead.
p_{FA}	Expected proportion of mosquitoes fed alive.
p_{FD}	Expected proportion of mosquitoes fed dead.
P_{att}	Probability that a mosquito attacks.
P_B	Probability that a mosquito feeds, conditional on attacking.
P_C	Probability that a mosquito escapes, conditional on feeding.

Differences between the two insecticides, permethrin (Olyset) and deltamethrin (PermaNet 2.0 and NetProtect nets) were allowed for by multiplying the concentration of deltamethrin by a scale factor, S, to give the concentration of permethrin that returns the same value of μ.

Figure 2. Modelled processes

Coloured boxes: observed categories of mosquitoes. Greek letters indicate transition rates.



The model is illustrated graphically in Figure 2. Feeding and killing are treated as competing processes, leading to the dynamics described in the Supplementary Information and to the following expectations for the proportions of mosquitoes in each state at unit time:

$$p_{UA} = \exp\big(-(\mu+\alpha)\big)$$
$$p_{UD} = \frac{\mu}{\mu+\alpha}\Big(1-\exp\big(-(\mu+\alpha)\big)\Big)$$
$$p_{FA} = \exp(-\mu) - \exp\big(-(\mu+\alpha)\big) \quad , \qquad (4)$$
$$p_{FD} = 1-\exp(-\mu) - \frac{\mu}{\mu+\alpha}\Big(1-\exp\big(-(\mu+\alpha)\big)\Big)$$

202 The transition probabilities, P_{att} (probability of attacking), P_B (probability of feeding) and
203 P_C (probability of escaping) are computed as functions of these state probabilities
204 (Supplementary Information 1).

205 The overall proportion of mosquitoes that are killed is equal to:

$$p_{UD} + p_{FD} = 1-\exp(-\mu) \qquad (5)$$

206 of which:

$$x_2 = 1-\exp\big(-(\mu-\mu_0)\big) \qquad (6)$$

207 can be attributed to the AI effect, and the LD50, defined as the concentration at which the
208 AI kills half the mosquitoes is, (by substituting equation 3 into equation 6 and finding $[X]$
209 $x_2 = 0.5$):

$$LD50 = \frac{K\ln(2)}{V_{max} - \ln(2)} \qquad (7)$$

210 Two different variants of this model were fitted. In Model A, all the parameters specified
211 in equations (1-7) are time independent. In Model B, $\boldsymbol{\mu_0}$ and $\boldsymbol{\alpha_{max}}$ vary by time-period.
212 The quantitative results given in the main text refer to Model A. Results for Model B are
213 provided in the Supplementary Information.

214

Data processing and data analysis

All data were recorded on paper data entry forms in the laboratory and double entered by two different individuals into Excel. Data was validated, cleaned and verified using Stata 13.0 software (Stata Corp., College Station, USA).

R Statistical Software (30) was used for data analysis. Graphics were produced using the ggplot2 r package. The model was fitted in `rstan`, treating the observed numbers of mosquitoes in each of the four categories as multinomially distributed, with probabilities corresponding to the proportions of unfed-alive, unfed-dead, fed-dead, and fed alive mosquitoes. Fitted values were obtained by computing the fitted values of p_{UA}, p_{UD}, p_{FA} and p_{FD} separately for each of a set of 4000 samples from the joint posterior distributions of the parameters and taking the medians of these values, for each of the 1,078 multinomial proportions in the dataset.

Results

Physical integrity

The numbers of holes of each size category were over-dispersed, with maximum numbers considerably higher than the means across all size categories and net zones (Table 2). Fewer holes occurred in the roofs of the nets, and there was an increase in the number and size of holes towards the bottom of the sides of the nets. The smallest holes (size 1) contributed little to the holed area. Size categories 2–4 contributed fairly equally to the holed area, although the largest holes (size 4), concentrated mainly in Zones 3 and 4 near the bottom of the net, contributed most of the holed area.

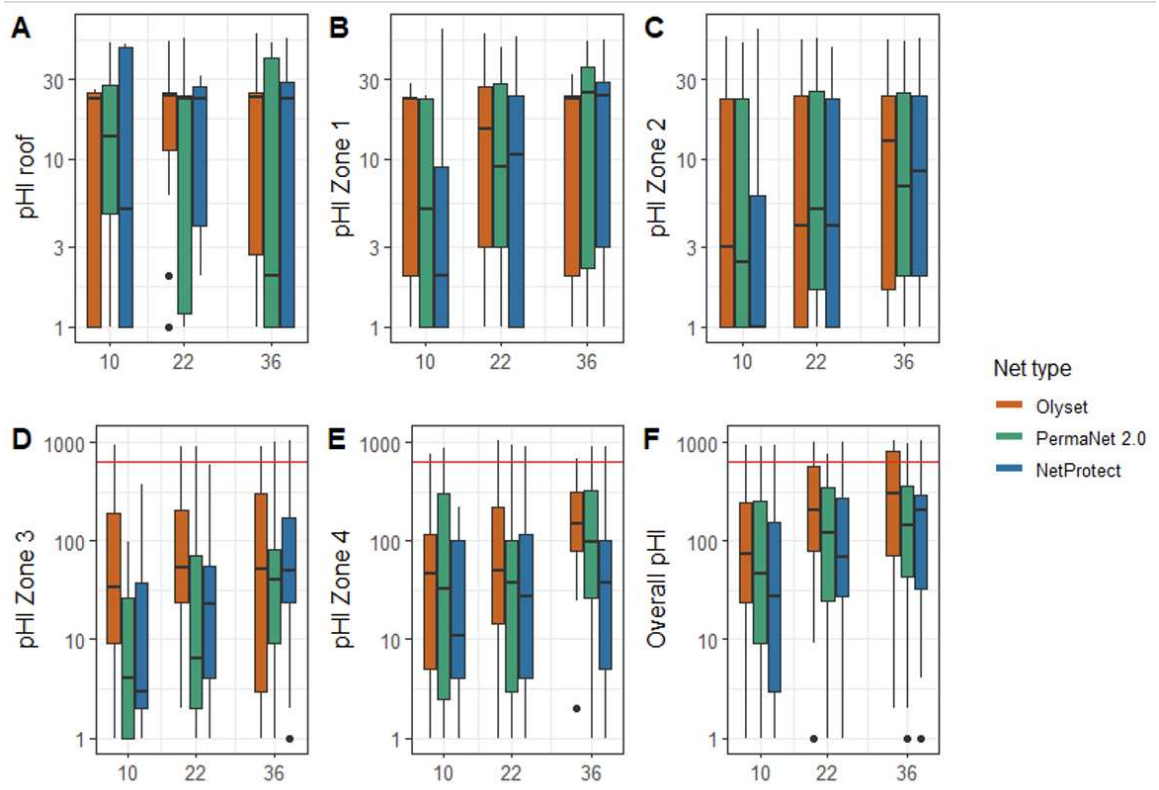
236 **Table 2. Numbers of holes, proportionate hole index (pHI) and holed area (HA) by**

237 **size category and net Zone**

Zone	Size category	Mean number of holes	Maximum number of holes	Mean HA (cm^2)	% of total HA
roof	1	1.46	45	1.5	0.2
	2	0.69	21	7.9	1.2
	3	0.07	3	12.1	1.9
	4	0.02	1	28.1	4.3
	All	**2.24**	**70**	**49.6**	**7.6**
side Zone 1	1	1.66	51	1.7	0.3
	2	0.48	22	5.5	0.9
	3	0.08	2	14.1	2.2
	4	0.04	2	49.9	7.7
	All	**2.26**	**77**	**71.2**	**11.1**
side Zone 2	1	2.19	43	2.2	0.3
	2	0.65	21	7.4	1.2
	3	0.07	3	13.8	2.1
	4	0.02	3	28.1	4.3
	All	**2.93**	**70**	**51.5**	**7.9**
side Zone 3	1	4.71	51	4.7	0.7
	2	1.58	28	18	2.8
	3	0.17	5	32.1	5.0
	4	0.09	4	120.1	18.6
	All	**6.55**	**88**	**174.9**	**27.1**
side Zone 4	1	6.46	58	6.5	1.0
	2	2.23	30	25.4	3.9
	3	0.31	6	56.7	8.8
	4	0.16	5	210.6	32.6
	All	**9.16**	**99**	**299.2**	**46.3**
overall	All	23.15	254	646.3	

Figure 3. pHI by year and net zone

Distributions of pHI for each net type using standard boxplots. The red horizontal line indicates the cut off of pHI=643 used to classify nets as 'too torn'.



Irrespective of net brand, the roof had the least damage (<10%) (Table 2, Figure 3A). Damage was low in the upper half of the side panels (Figure 3BC), but markedly higher in the bottom half of the nets (Figure 3D and E). Zone 4 - the bottom quadrant tucked under the mattress ("tucking zone"), had the greatest damage, accounting for approximately 46% of total damage (Table 2, Figure 3E). Zone 3, located at the bottom of the net above the tucking zone and close to the sleeper had largest holed area accessible to mosquitoes (27%), making this zone the most important for mosquito entry and escape. In the field study, over 94% of households reported tucking the bottom 26–35 cm of the net under the mattress.

This pattern is consistent with repeated tucking contributing to the concentration of damage in the lower quadrant of the net.

Table 3 and Figure 3 summarise net integrity by brand and year. Irrespective of brand, net integrity deteriorated considerably over three years of field use. The median pHI of Olyset net increased from 53 (IQR: 10–249) in year 1 to 564 (IQR: 79–1034) in year 3. Corresponding increases were observed for PermaNet 2.0 24 (IQR:0–223) to 295 (IQR: 41–1053) and NetProtect 23 (IQR: 3–152) to 246 (IQR: 29–1028) (Table 3). Overall pHI was higher for Olyset than the other brands, particularly in Zone 3, and at the 10-month and 22-month time points. Correspondingly, a greater proportion of Olyset nets were classified as "too torn" (Table 3).

Table 3. Proportionate hole index (pHI) by net type and years of field use

Age of net (months)	***Statistic***	***Olyset®***	***PermaNet 2.0***	***NetProtect***
10	Mean (95% CI)	226 (150–302)	211 (122–301)	117 (74–159)
	Median (IQR)	53 (10–249)	24 (0–223)	23 (3–152)
22	Mean (95% CI)	624 (453–795)	619 (422–816)	213 (148–278)
	Median (IQR)	298 (79–990)	198 (24–629)	58 (11–281)
36	Mean (95% CI)	780 (582–978)	587 (449–726)	830 (529–1131)
	Median (IQR)	564 (79–1036)	295 (41–1053)	246 (29–1028)
% by category (all samples)	Good (<64)	31% (n=87)	43% (n=122)	49% (n=140)
	Damaged (65–642)	37% (n=104)	32% (n=91)	33% (n=93)
	Too torn (>643)	32% (n=90)	25% (n=70)	18% (n=50)

CI- confidence interval; IQR- interquartile range

Insecticide Concentrations

There was considerable variation in the total insecticide content between nets and over time (Figure 4a, Table 4). PermaNet 2.0 and NetProtect showed substantial declines in total active ingredient (AI) concentration during use, whereas Olyset exhibited comparatively lower loss of insecticide.

The AI concentrations were strongly negatively correlated with the holed area (Spearman rank correlations of -0.47, -0.62, and -0.49 for Olyset®, PermaNet 2.0 and NetProtect respectively, all p-values < 0.001). Thus, nets with greater holed area tended to have lower residual insecticide content, suggesting that physical deterioration and insecticide loss may be linked through shared use-related processes.

Table 4. Measured AI concentrations (g/kg)

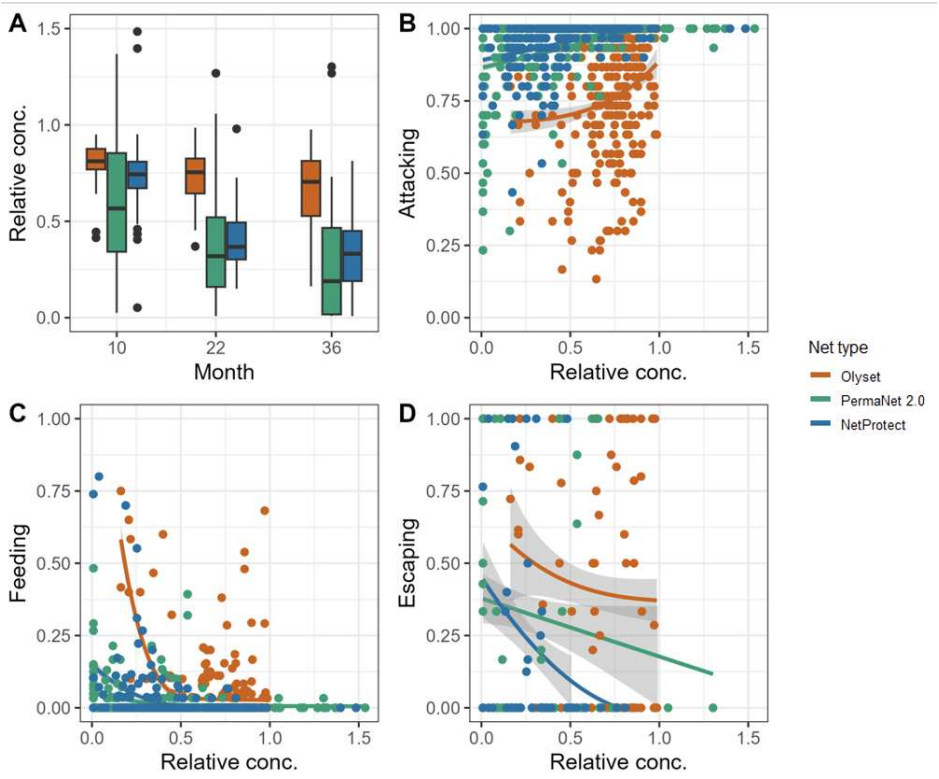
Net type	***Month***	***Median***	***Interquartile range***	***Permethrin equivalent****
Olyset	10	16.5	15.6–17.8	16.5
	22	15.3	13.1–16.8	15.3
	36	14.3	10.7–16.5	14.3
PermaNet	10	0.678	0.407–1.03	529.2
	22	0.38	0.190–0.62	296.6
	36	0.225	0.020–0.555	175.6
NetProtect	10	0.941	0.850–1.02	734.5
	22	0.465	0.382–0.625	363.0
	36	0.420	0.240–0.570	327.9

*The permethrin equivalent for the deltamethrin nets is obtained by multiplying the median concentration by the estimate of the scale-factor, *S*

On average, Olyset nets were associated with lower proportions of mosquitoes attacking (Figure 4B), but greater proportions of those that attacked succeeded in feeding (Figure 4C) and escaping (Figure 4D). Nets with higher concentrations of insecticide had higher proportions of mosquitoes recorded as attacking, but lower proportions feeding and escaping. This reflects the fact that attacking mosquitoes are more likely to be killed upon contact when insecticide levels are high.

Figure 4. Distributions of insecticide concentrations and their entomological effects.

A: Distributions of concentrations (expressed as a proportion of the manufacturer's target concentration for each product) by month of follow-up. B, C, D: entomological outcomes expressed as proportions of mosquitoes reaching each step in the feeding cycle as a proportion of those reaching the previous step. Lines are monotone P-splines (R package spam). The grey shading corresponds to 95% credible intervals.

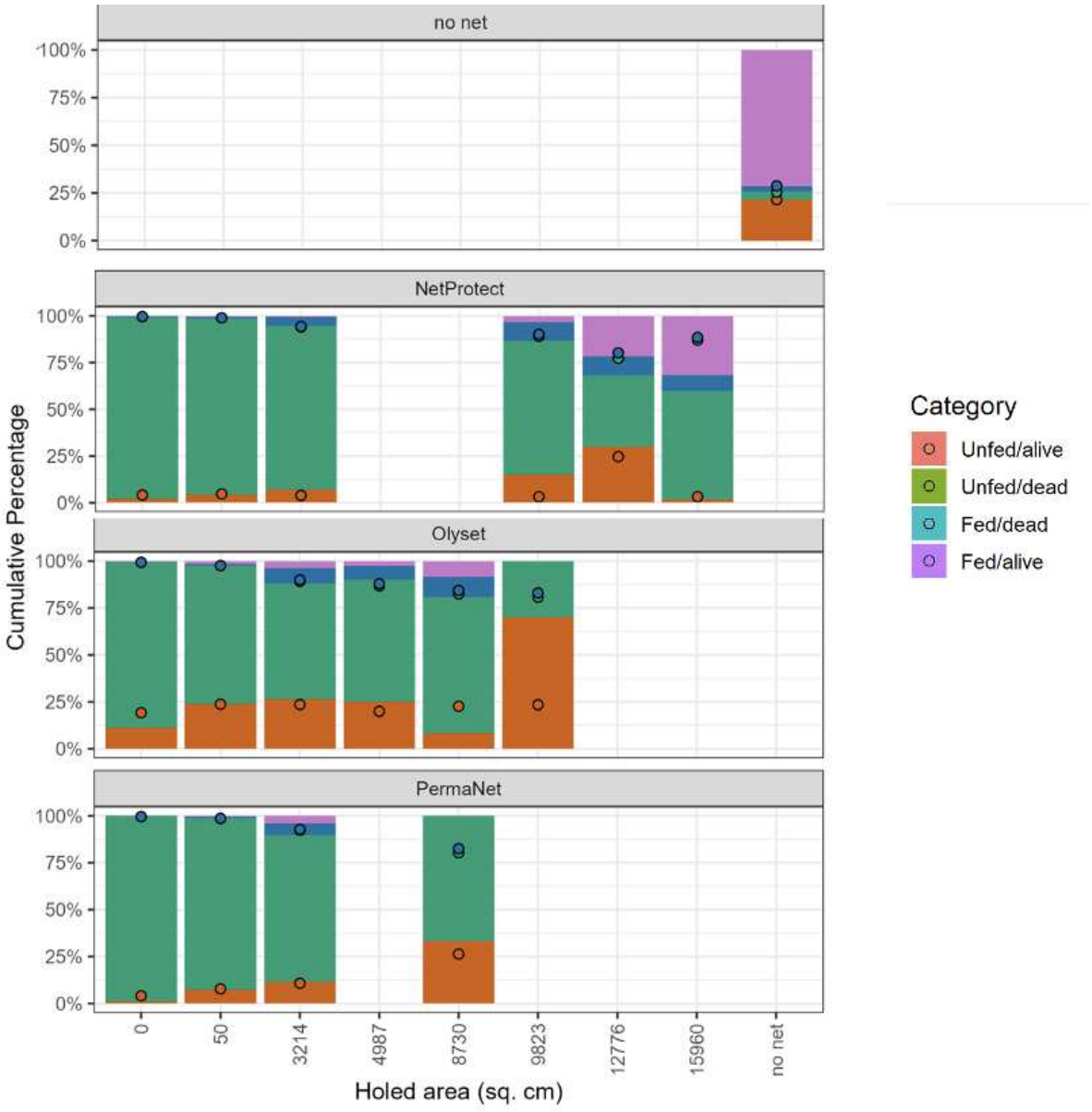


Observed entomological outcomes

The observed proportions of mosquitoes in each of the four outcome categories (unfed alive, unfed dead, fed dead, and fed alive) are shown in Figure 5, stratified by product and holed area.

Figure 5. Proportions of mosquitoes by holed area

Colours correspond to the observed proportions of mosquitoes in each category. Points are the fitted values from the model.



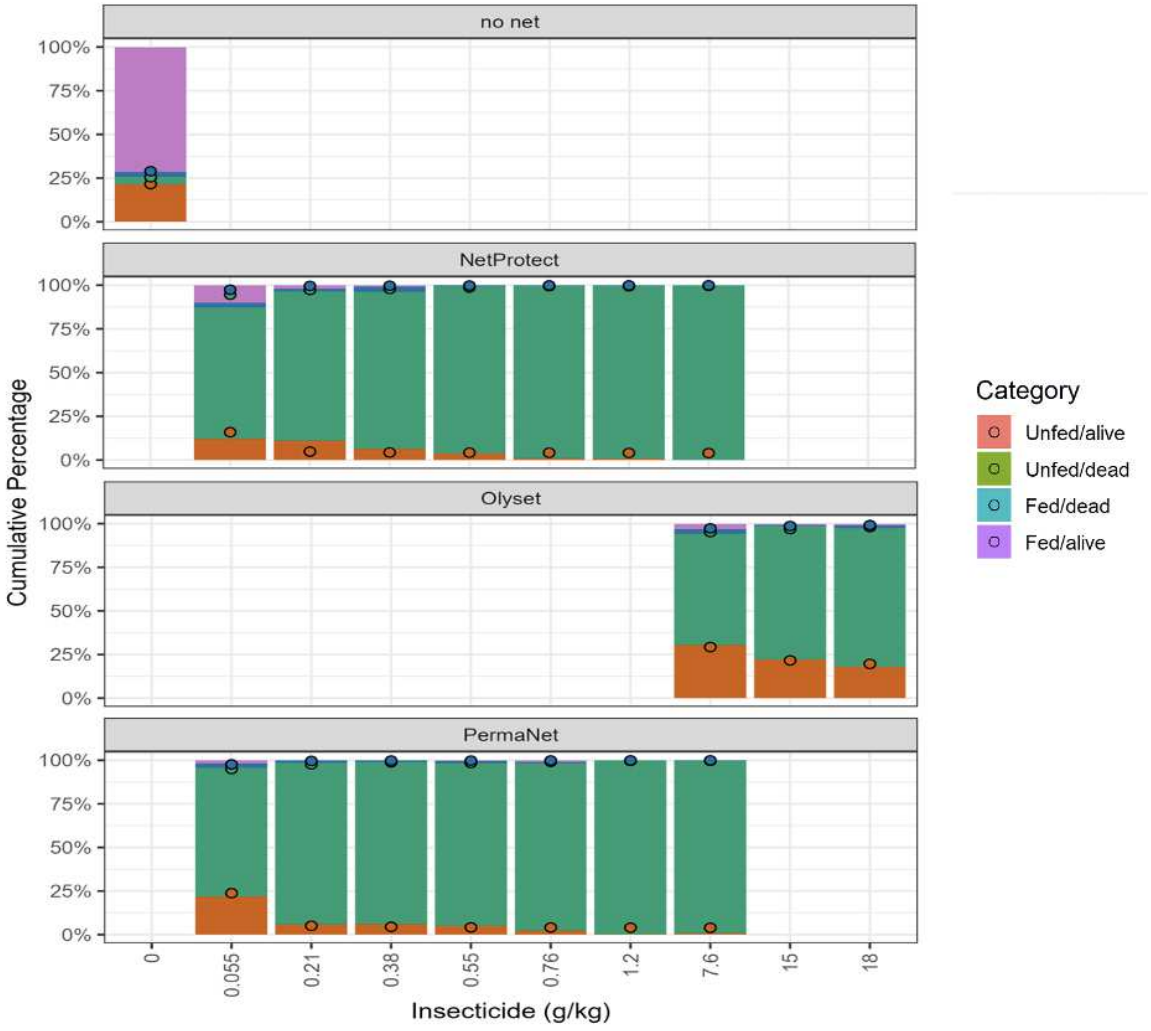
Across all brands most mosquitoes were recovered unfed and dead. As holed area increased, the proportion recovered unfed and alive also increased, suggesting that reduced contact with insecticide-treated surface lowered mortality before feeding inhibition was fully lost. When nets were extensively damaged, a larger proportion of mosquitoes both fed and survived. In the absence of a net, most mosquitoes were recovered fed and alive category. Mosquito survival was similar for PermaNet and NetProtect but was higher for Olyset®.

Effects of insecticide concentrations

Within each net type, mosquito mortality increased with measured insecticide concentration, while the proportion surviving unfed decreased (Figure 6). However, the response curves differed markedly between Olyset and the deltamethrin-treated nets (Figure 6), indicating that ITNs within the same broad pyrethroid class cannot be assumed to have equivalent entomological effects. Olyset contains permethrin, a type I pyrethroid associated with strong irritant and excito-repellent effects, and substantial numbers of mosquitoes remained unfed and alive across much of the tested concentration range. In contrast, PermaNet 2.0 and NetProtect contain deltamethrin, a type II pyrethroid associated with rapid knockdown and mortality. For these nets, mosquito survival remained low across the tested concentrations, with mortality increasing steeply and reaching saturation even at relatively low deltamethrin concentrations (Figure 6).

Figure 6. Data and fitted values by insecticide concentration

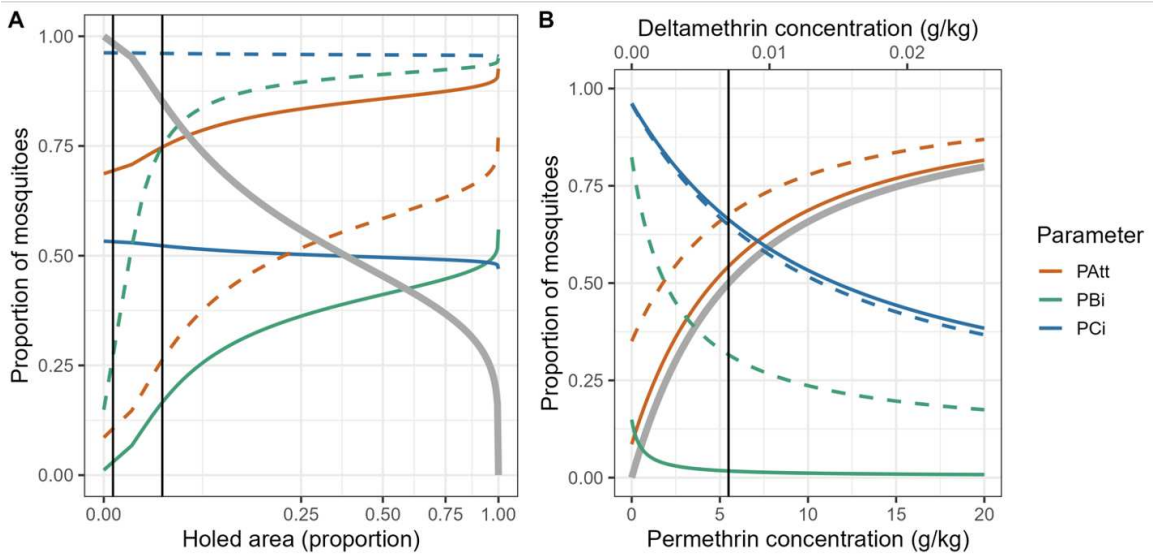
Colours correspond to the observed proportions of mosquitoes in each category. Points are the fitted values from the model. Insecticide concentrations are the measured values.



Entomological effects of holed area

The trends with attacking and escaping are the converse of those fitted for fixed AI concentrations (Figure 7A) and arise because of the negative correlations of pHI with AI concentrations. The quantification of the effect of holed area shows that in the absence of insecticide, most of the effect of holes (especially on the probability of feeding) occurs with only low levels of damage, as measured by *h* area (Figure 7A).

Figure 7. Holed area and AI concentration dependence of estimates of transition probabilities.

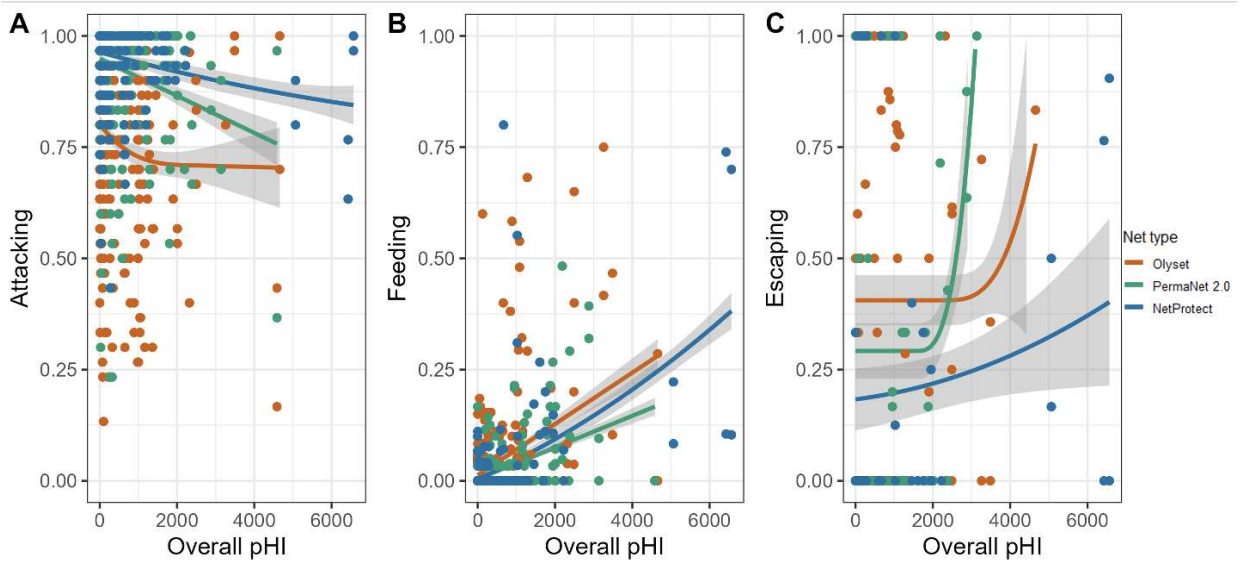


Coloured lines: estimates of transition probabilities (P_{att} : probability of attacking, P_B: probability of feeding, P_C : probability of escaping).
A: Estimates by holed area: dashed lines: no insecticide; continuous lines 10 mg/sq m permethrin. The vertical lines correspond to the cutoffs for 'damaged' and for 'too torn'; grey line: proportion of barrier effect (x_1).
B: Estimates by AI concentration: dashed lines: 5% of net holed; continuous lines: intact nets. The vertical line corresponds to the LD50 of 5.5 g/kg of permethrin. grey line: proportion of mosquitoes killed by AI.

In the presence of insecticide, the level of damage to the net has much less effect on all outcomes. Much more damage is needed to have a substantial impact on the amount of feeding with insecticide-treated nets than with untreated nets (Figure 7A). The measured pHI was positively correlated with feeding success among mosquitoes that attacked (Figure 8B), consistent with the fitted model. It was also negatively correlated with attacking (Figure 8A), and positively correlated with escaping (Figure 8C).

Figure 8. Observed entomological effects by pHI.

Lines are monotone P-splines (R package spam). The grey shading corresponds to 95% credible intervals.



Model fit and interpretation

Model A provided an excellent fit to the data, as demonstrated by the close correspondence between observed and fitted values in Figure 5 and Figure 6. This was achieved despite the relatively small number of parameters estimated (Table 5) and the monotonicity constraints imposed on the relationships shown in Figure 7. This strongly suggests that it accurately captures the mode of action of the nets.

Table 5. Parameter estimates

		Estimate	*95% interval*	*Units*
K	Insecticide sensitivity	19.9	(18.5–21.3)	g permethrin/kg
θ_1	Holed area shape	0.018	(0.007–0.073)	dimensionless
θ_2	Holed area shape	0.193	(0.101–0.562)	dimensionless
$V_{\max}$	Maximum rate of killing	3.19	(3.10–3.28)	night^{-1}
μ_0	Baseline mortality rate	0.282	(0.202–0.362)	night^{-1}
S	AI scale factor	780.6	(681.6–901.3)	dimensionless
$\alpha_{\min}$	Minimum rate of feeding	0.013	(0.010–0.017)	night^{-1}
$\alpha_{\max}$	Maximum rate of feeding	1.46	(1.41–1.51)	night^{-1}

The model resolves ITN performance (conditional on use) into its two separate determinants: physical integrity (holed area), which affects feeding, and AI concentration, which determines the mosquito mortality rate, without requiring any interaction terms. In other words, the barrier effect is neither enhanced nor weakened by insecticide (although insecticide reduces the probability of feeding when nets are damaged). The correlations between these two factors, and the mathematical interplay between them (as detailed in the supplementary information) determine the proportions of mosquitoes recovered in each category.

Analyses of Model B detailed in the Supplementary Information indicated that most mosquito mortality was attributable to the insecticide, while feeding inhibition was driven by the barrier effect with a small contribution from sublethal insecticidal activity in the permethrin arm when nets were damaged. Variation in ITN performance between time periods was small relative to the overall effect of the nets, suggesting that bioassay responses were consistent over time after accounting for changes in insecticide content and holed area with little evidence of additional time-dependent effects.

Importantly, only one parameter, the insecticide scale factor, *S,* varied by net type. The model fitting estimated that the deltamethrin concentrations should be multiplied by a scale-factor of 780.6 (Table 5) to give the permethrin concentration with equivalent effect. After this adjustment, the fitted curves for the two insecticides were identical (Figure 7B).

Although unadjusted deltamethrin concentrations (g/kg) were lower than permethrin concentrations, the adjusted effective concentrations were higher (Table 4). Because most deltamethrin concentrations were well above the LD50 and the insecticidal effects saturated at these levels, reductions in AI during use had little impact on entomological outcomes for the deltamethrin nets.

Discussion

ITN mode of action

ITN procurers recognise that WHO-prequalified pyrethroid ITNs rarely remain effective for the full three-year lifespan assumed in distribution campaigns (31). Even so, they are procured by product class, implying an assumption that all pyrethroid ITNs provide broadly equivalent protection over a similar period (32). Value-based procurement is not yet considered based on individual product performance (33). However, the results of the durability field trial (13) showed that products have different survival under similar user conditions in Tanzania. The current I-ACT study further demonstrates that, under conditions of day-to-day use, different ITN products also accrue damage at different rates, and differ in the rates at which insecticidal activity declines. Despite these differences, pyrethroid ITNs with similar physical integrity and equivalent insecticide concentrations showed comparable functional performance against pyrethroid-resistant mosquitoes in this study, provided the nets remain in use. Olyset is a permethrin incorporated net that appears to function primarily by reducing host availability with lower pre-and post-prandial killing effect than the two deltamethrin nets. In contrast, the deltamethrin nets caused high pre-prandial mortality and slightly more post prandial mortality, even up to three years of field use. The entomological effects of Olyset were slightly less than those of the deltamethrin nets, although all three products remained highly effective against pyrethroid-susceptible mosquitoes. However, this cannot be assumed to be the case for resistant mosquitoes, which are widespread throughout sub-Saharan Africa. Sustained malaria control will therefore require continued investment in new insecticides and formulations that remain both durable under field conditions and effective against pyrethroid-resistant mosquitoes.

Effects of holes

Increasing holed surface area was associated with higher mosquito blood feeding (Figure 7) but had minimal impact on mosquito mortality, as demonstrated by the excellent fit of the mathematical model that treated mortality as a function of AI concentration only. This is consistent with findings from a review of experimental hut studies comparing holed and intact pyrethroid ITNs, which showed increased blood feeding in huts with holed nets, as expected, but little or no difference in mosquito mortality between treated nets with and without holes (4). A separate study examining the effect of holed surface area on ITN efficacy found that personal protection from both ITNs and untreated nets decreased exponentially as holed surface area increased, without evidence for a clear threshold beyond which nets became ineffective (5). The authors also demonstrated that the insecticidal effect of ITNs was lower among resistant mosquitoes than in susceptible mosquitoes, but holed surface area had little or no impact on mosquito mortality (5).

More recent experimental hut trials in Tanzania using resistant mosquito populations and comparing pyrethroid-only ITNs with dual-active ingredient nets similarly found no relationship between mortality or blood feeding and the size or number of holes in field-aged ITNs (34). These findings suggest that ITNs containing insecticides to which the vector population remains susceptible can continue to provide community-level effects even when damaged (35). However, clinical evidence indicates that nets in good condition provide greater protection than severely damaged nets (16). Moreover, people are far more likely to discard badly damaged ITNs (6, 8) and ITN use is the strongest predictor of malaria prevention impact (7).

Hole location (zone) also had limited influence on entomological outcomes in this experiment. This contrasts with findings from a videography study demonstrating that mosquitoes preferentially entered ITNs through the roof (21). The reasons for this discrepancy are unclear but may reflect differences in experimental design (I-ACT versus experimental huts), net condition (field aged nets in the current study had relatively little damage in the roof and upper panels unlike the deliberately damaged nets in the videography study), or mosquito resistance profiles (susceptible mosquitoes in the present study versus resistant populations in the videography experiment).

Several studies have highlighted the importance of holes in the upper part of the net, where mosquitoes are attracted by host odour plumes (36-42). However, mosquitoes are more likely to exit from side holes (21) which may explain why most of the effect on transmission was contributed by large holes (size 3 or 4) in Zone 3 of the net – the area identified in (21) as the most important location for mosquito exit after feeding.

Effects of insecticide concentration

The results also demonstrate that the I-ACT can measure the chemical performance of ITNs by assessing effects on mosquito mortality. Insecticide concentration in the fabric was strongly associated with entomological outcomes, indicating that chemical content provides a meaningful proxy for functional efficacy. Dose-response curves and LD50 values were estimated for both permethrin and deltamethrin with a single parameter describing the concentration at which the half-maximal insecticidal effect is achieved. This linear scaling of insecticide concentrations accounts for the

The I-ACT system does not estimate deterrence from entering a room, nor the proportion of mosquitoes that exit a house after entry. Being a closed system, it may measure higher mortality than in real rooms from which the mosquitoes can escape. However, the finding of similar non-monotonic relationships of P_{att} with AI concentration in open (experimental hut) systems (7) suggests that the bias is likely to be small.

Model fit and applications

The model proposed here to analyse the data simultaneously meets several objectives. It is supported by the known biology and consistent with known relationships (e.g., holes in nets are predicted to lead to increases in mosquitoes feeding inside them, and the direct effects of insecticides are expected to decrease as insecticide concentration wanes). At the same time, it gives an excellent fit to the data.

These criteria are met for the whole parameter space. The model is much more parsimonious than previously used logistic regressions used to analyse experimental hut data on effects of decay of ITNs (5, 7, 43) (see supplementary information).

Models with more parameters than necessary are likely to overfit, mistaking noise for signal. Parsimonious models generally provide more precise predictions and generalizations to out-of-sample scenarios.

The model could be used to parameterise generally applicable transmission models for chemically and physically decayed nets (7), although extension to different mosquito strains and ITN brands will be required. It will also be important to assess the extent to which parameters estimated in the I-ACT system apply to other settings including alternative bioassays including experimental huts, as well different kinds of houses.

The same model could be used to compare a wider range of ITN brands and classes on a common scale. By linking it to data on attrition, net use over time, house entry, insecticide content, and physical damage, it may be used to make improved predictions of the likely impact of different ITN products on malaria transmission. In addition, predictions of likely lifetime impact of new ITN products may be possible using artificially aged nets that replicate reductions in chemical content and physical damage, allowing much of this analysis to be conducted during pre-market product evaluation of new products.

Performance targets for ITNs

The observed differences in functional efficacy between pyrethroid ITN brands underlines the importance of durability assessments within prequalification processes and as part of routine surveillance to ensure that the most long-lasting and effective ITNs are procured for programme use. Both physical damage and insecticide content influence the entomological performance of ITNs. Recent research has focused on incorporating new insecticide classes into ITNs to overcome insecticide resistance. These chemistries can substantially increase mortality of resistant mosquitoes and have demonstrated clear public health impact (44, 45).

Our analyses for the effects of residual insecticide content (chemical durability) on mortality and of physical damage on blood feeding could be used to define performance targets for aged nets, alongside metrics such as the resistance to damage (RD) score [34] that predict net retention. The I-ACT provides an efficient system for assessing mortality and rather than assessing chemical retention in isolation, future durability assessments could establish threshold concentrations associated with acceptable entomological performance, enabling prediction of when field-aged nets are likely to lose functional efficacy. This approach would support the development of chemical durability benchmarks for ITNs (complementary to the RD score for physical durability) to provide a practical tool for product evaluation, prequalification, and optimisation of net formulations. A comprehensive evaluation would also consider deterrence and the fate of deterred mosquitoes, effects which are outside the scope of the present analysis.

Although both fabric integrity and insecticidal content influence ITN impact, we find that even severely damaged nets may retain substantial entomological efficacy when insecticidal activity remains high. However, physical integrity of ITNs matters for reasons beyond its directly measurable entomological effect. In many settings, the median lifespan of ITNs in use is approximately two years (9). Public health impact declines as the number of nets remaining in use decreases (46) reducing community-level protection (47).

As nets accumulate damage during routine use, they are often discarded once they are no longer perceived as protective (48-51). This perception is understandable: holes allow mosquitoes to enter more easily, particularly in areas of insecticide resistance. Although mosquitoes that enter a damaged ITN may still be killed by the insecticide and contribute to community protection, they may first bite, disturb or infect the sleeper.

Therefore, holes may thus matter more to users than to mosquitoes. As ITNs increasingly incorporate more complex and costly insecticides, maximising their public health value with depend not only on maintaining sufficient insecticidal activity, but also on keeping nets acceptable and in use for as long as possible [33]. Future ITN design and evaluation must therefore prioritise not only insecticidal performance, but also the fabric durability and user acceptability needed to keep nets in use.

Conclusion

There is a need for a functional durability framework that integrates fabric integrity and insecticide content, enabling evidence-based comparisons of ITN products to guide design, durability monitoring, and procurement decisions.

Functional durability of ITNs can be understood as the interaction of two analytically separable processes: physical degradation of the fabric and loss of bioavailable insecticide. Using the I-ACT, we could precisely measure both of these effects. Conditional on holed area, variation in efficacy between products was largely explained by differences in insecticide concentration, using a shared parameter describing the concentration required to achieve half-maximal insecticidal effect. Even heavily damaged nets retained substantial effectiveness when insecticidal activity remained high and nets continued to be used.

These findings support a practical framework integrating fabric integrity and insecticide content enabling more meaningful comparison between ITN products and supporting interpretation of product performance as part of durability monitoring. Future ITN

543 design, and procurement should prioritise not only insecticidal performance, but also the
544 fabric durability important to improve user acceptability and retention needed to increase
545 long-term public health impact and maximise cost effectiveness.

Abbreviations

AI: Active Ingredient;

GTS: Global Technical Strategy For Malaria 2016–2030;

HSA hole surface area;

IACT: Ifakara Ambient Chamber Test;

ITN: insecticide treated net;

MCMC: Markov chain Monte Carlo;

pHI: proportionate hole index;

Declarations

Ethics approval and consent to participate

Ethical approval was given from Ifakara Health Institute in Tanzania (Reference number-IHI/IRB/No: 19-2013) and the National Institute for Medical Research (NIMR) (Ref: NIMR/HQ/R.8a/Vol. IX/150 and NIMR/HQ/R.8c/Vol. I/285). All volunteers participated in the I-ACT bioassays provided written informed consent prior to enrolment.

Consent for publication

All authors consent to the publication of this manuscript. Permission to publish was obtained from the Tanzania NIMR (Ref No. BD.242/437/01C/214).

Availability of data and materials

The data underlying the results presented in the study are available from Norwegian Centre for Research Data (NSD), Access to the data sets must be requested from NSD using this order form: https://nsd.no/nsd/english/order.html and referring to the project ID no. NSD2695 and project name "The useful life of bednets for malaria control in Tanzania: Attrition, Bioefficacy, Chemistry, Durability and insecticide Resistance", project no. 220757. Code used in this manuscript is available in the Supplementary materials.

Competing interests

The authors SJM, and WN, conduct product evaluation for a number of vector control product manufacturers. The other authors declare that they have no competing interests.

Funding

Research Council of Norway 970141 669 https://www.forskningsradet.no/en. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Authors' contributions

Conceived and designed the experiment DJM, SJM, OJTB. Performed the experiments DJM, WN. Analysed the data TAS. Wrote the manuscript TAS, SJM and DJM. All authors read and approved the final manuscript. The views expressed are those of OJTB and do not represent ECDC's official position of the European Centre for Disease Prevention and Control. Chat GPT 5.3 was used to edit the final draft of the manuscript to improve clarity.

Acknowledgements

The authors would like to thank all members of the VCPTU who contributed technical assistance for the study, in particular data collections; This paper is published with the permission of the Director-General of the National Institute for Medical Research (NIMR) in Tanzania.

References

1. WHO. The World Malaria Report 2025. Geneva: World Health Organization; 2025.

2. WHO. WHO Guidelines for malaria WHO/UCN/GMP/2023. Geneva: World Health Organisation; 2023.

3. WHO. Global technical strategy for malaria 2016-2030. Geneva: World Health Organisation; 2015.

4. Irish SR. The behaviour of mosquitoes in relation to humans under holed bednets: the evidence from experimental huts. Mem Inst Oswaldo Cruz. 2014;109(7):905-11.

5. Randriamaherijaona S, Briët OJ, Boyer S, Bouraima A, N'Guessan R, Rogier C, et al. Do holes in long-lasting insecticidal nets compromise their efficacy against pyrethroid resistant *Anopheles gambiae* and *Culex quinquefasciatus*? Results from a release-recapture study in experimental huts. Mal J. 2015;14(332).

6. Smith T, Denz A, Ombok M, Bayoh N, Koenker H, Chitnis N, et al. Incidence and consequences of damage to insecticide-treated mosquito nets in Kenya. Malar J. 2021;20(1):476.

7. Briet O, Koenker H, Norris L, Wiegand R, Vanden Eng J, Thackeray A, et al. Attrition, physical integrity and insecticidal activity of long-lasting insecticidal nets in sub-Saharan Africa and modelling of their impact on vectorial capacity. Malaria Journal. 2020;19(1):310.

8. Mvungi NJ, Odufuwa OG, Ruzige PD, Muganga JB, Mmasi DJ, Machange JJ, et al. Fabric integrity, net type and risk index predict attrition of insecticide-treated nets: evidence from a community durability trial of pyrethroid-piperonyl butoxide (PBO) nets in Tanzania. Malar J. 2025.

9. Bertozzi-Villa A, Bever CA, Koenker H, Weiss DJ, Vargas-Ruiz C, Nandi AK, et al. Maps and metrics of insecticide-treated net access, use, and nets-per-capita in Africa from 2000-2020. Nature Communications. 2021;12(1):3589.

10. Koenker H, Yukich J, Erskine M, Opoku R, Sternberg E, Kilian A. How many mosquito nets are needed to maintain universal coverage: an update. Malaria Journal. 2023;22(1):200.

11. Scates S, Finn TP, Wisniewski J, Dadi D, Mandike R, Khamis M, et al. Costs of insecticide-treated bed net distribution systems in sub-Saharan Africa. Mal J. 2020;19(105).

12. Wisniewski J, Acosta A, Kolaczinski J, Koenker H, Yukich J. Systematic review and meta-analysis of the cost and cost-effectiveness of distributing insecticide-treated nets for the prevention of malaria. Acta Trop. 2020;202:105229.

13. Lorenz LM, Bradley J, Yukich J, Massue DJ, Mageni Mboma Z, Pigeon O, et al. Comparative functional survival and equivalent annual cost of 3 long-lasting insecticidal net (LLIN) products in Tanzania: A randomised trial with 3-year follow up. PLOS Medicine. 2020;17(9):e1003248.

14. Eigbiremolen G, Jimoh B, Obodoechi DN, Oluwagbemiga AO, Iwegbu A, Ogunmola S, et al. Costs of single-phase door-to-door insecticide-treated net mass distribution campaigns in Nigeria: a case study in Ondo and Anambra states. Malaria Journal. 2026.

15. Floyd J, Trett A, Golumbeanu M, Champagne C, Ward A, Pothin E, et al. Deriving Greater Value from Malaria Bed Nets through Extending Net Retention: A Modelling Study. medRxiv. 2025:2025.08.02.25332507.

16. Lukole EA, Cook J, Mosha JF, Mallya E, Aziz T, Kulkarni MA, et al. Will a lack of fabric durability be their downfall? Impact of textile durability on the efficacy of three types of dual-active-ingredient long-lasting insecticidal nets: a secondary analysis on malaria prevalence and incidence from a cluster-randomized trial in north-west Tanzania. Malar J. 2024;23(1):199.

17. Hemingway J, Shretta R, Wells TNC, Bell D, DjimdÈ AA, Achee N, et al. Tools and Strategies for Malaria Control and Elimination: What Do We Need to Achieve a Grand Convergence in Malaria? PLoS Biol. 2016;14(3):e1002380.

18. Lindsay SW, Thomas MB, Kleinschmidt I. Threats to the effectiveness of insecticide-treated bednets for malaria control: thinking beyond insecticide resistance. Lancet Glob Health. 2021;9(9):e1325-e31.

19. PATH. New Nets Project: Evidence of effectiveness and cost-effectiveness of dual-AI ITNs from the observational pilot studies—final report. Seattle; 2023.

20. WHO. Long-term community studies for ITNs https://extranet.who.int/prequal/sites/default/files/document_files/IG_ITN_LTCS_v0_Aug_2025.pdf. Geneva: World Health Organisation; 2025.

21. Parker JE, Kakiila C, Nelwin K, Kröner C, Logan R, Ismael H, et al. Video tracked *Anopheles arabiensis* entry and exit behaviour at washed and damaged pyrethroid-treated bed nets. R Soc Open Sci 2024;11.

22. Massue DJ, Lorenz LM, Moore JD, Ntabaliba WS, Ackerman S, Mboma ZM, et al. Comparing the new Ifakara Ambient Chamber Test with WHO cone and tunnel tests for bioefficacy and non-inferiority testing of insecticide-treated nets. Malaria Journal. 2019;18(1):153.

23. Chitnis N, Smith T, Steketee R. A mathematical model for the dynamics of malaria in mosquitoes feeding on a heterogeneous host population. Journal of biological dynamics. 2008;2(3):259-85.

24. Lorenz LM, Overgaard HJ, Massue DJ, Mageni ZD, Bradley J, Moore JD, et al. Investigating mosquito net durability for malaria control in Tanzania - attrition, bioefficacy, chemistry, degradation and insecticide resistance (ABCDR): study protocol. BMC Public Health. 2014;14(1):1266.

25. WHO. Vector Control Technical Expert Group Report to MPAC September 2013 Estimating functional survival of long-lasting insecticidal nets from field data. Geneva: World Health Organisation; 2013.

26. MR4. Methods in *Anopheles* Research Manual 2015 edition2016.

27. Vazquez-Prokopec G. A New, Cost-Effective, Battery-Powered Aspirator for Adult Mosquito Collections. J Med Entomol. 2009;46(6):1256-9.

28. Denz A, Njoroge MM, Tambwe MM, Champagne C, Okumu F, van Loon JJA, et al. Predicting the impact of outdoor vector control interventions on malaria transmission intensity from semi-field studies. Parasites & Vectors. 2021;14(1):64.

29. Champagne C, Lemant J, Assenga A, Kibondo U, Lekundayo R, Mbuba E, et al. Cascades of effectiveness of next-generation insecticide-treated nets against malaria, from entomological trials to real-life conditions. Nature Communications. 2025;16(1):16.

30. R Core Team. R: A Language and Environment for Statistical Computing. . Vienna, Austria: R Foundation for Statistical Computing; 2023.

31. The Global Fund, editor 2024 ITN Buyer & Seller Summit2024 2024/12/09: The Global Fund – Procurement & Supply Management.

32. The Global Fund. Pooled Procurement Mechanism Insecticide Treated Nets reference prices table [Data table]. Q2 2025 https://www.theglobalfund.org/media/1ekjul0n/psm_llinreferenceprices_table_en.pdf 2025.

33. McCoy A, Thomsen E, Spiers A, Worrall E. Analysis of insecticide-treated bednet market dynamics between 2004-2021 and monetary value of additional bednet longevity. Cost Eff Resour Alloc. 2026;24(1).

34. Martin JL, Messenger LA, Rowland M, Mosha FW, Bernard E, Kisamo M, et al. Bio-efficacy of field aged novel class of long-lasting insecticidal nets, against pyrethroid-resistant malaria vectors in Tanzania: A series of experimental hut trials. PLOS Global Public Health. 2024;4(10):e0002586.

35. Lukole E, Cook J, Mosha JF, Messenger LA, Rowland M, Kleinschmidt I, et al. Protective efficacy of holed and aging PBO-pyrethroid synergist-treated nets on malaria infection prevalence in north-western Tanzania. PLOS Global Public Health. 2022;2(10):e0000453.

36. Sutcliffe JF, Yin S. Effects of indoor air movement and ambient temperature on mosquito (*Anopheles gambiae*) behaviour around bed nets: implications for malaria prevention initiatives. Malar J. 2021;20(1):427.

37. Sutcliffe J, Ji X, Yin S. How many holes is too many? A prototype tool for estimating mosquito entry risk into damaged bed nets. Malaria Journal. 2017;16(1):304.

38. Sutcliffe JF, Colborn KL. Video studies of passage by *Anopheles gambiae* mosquitoes through holes in a simulated bed net: effects of hole size, hole orientation and net environment. Mal J. 2015;14(199).

39. Jones J, Murray GPD, McCall PJ. A minimal 3D model of mosquito flight behaviour around the human baited bed net. Malar J. 2021;20(1):24.

40. Murray GPD, Lissenden N, Jones J, Voloshin V, Toé KH, Sherrard-Smith E, et al. Barrier bednets target malaria vectors and expand the range of usable insecticides. Nat Microbiol. 2020;5(1):40-7.

41. Parker JEA, Angarita Jaimes NC, Gleave K, Mashauri F, Abe M, Martine J, et al. Host-seeking activity of a Tanzanian population of *Anopheles arabiensis* at an insecticide treated bed net. Malaria Journal. 2017;16(1):270.

42. Angarita-Jaimes NC, Parker JE, Abe M, Mashauri F, Martine J, Towers CE, et al. A novel video-tracking system to quantify the behaviour of nocturnal mosquitoes attacking human hosts in the field. J R Soc Interface. 2016;13(117).

43. Briët OJT, Impoinvil DE, Chitnis N, Pothin E, Lemoine JF, Frederic J, et al. Models of effectiveness of interventions against malaria transmitted by *Anopheles albimanus*. Malaria Journal. 2019;18(1):263.

44. Accrombessi M, Cook J, Dangbenon E, Yovogan B, Akpovi H, Sovi A, et al. Efficacy of pyriproxyfen-pyrethroid long-lasting insecticidal nets (LLINs) and chlorfenapyr-pyrethroid LLINs compared with pyrethroid-only LLINs for malaria control in Benin: a cluster-randomised, superiority trial. Lancet. 2023;401(10375):435-46.

45. Mosha JF, Kulkarni MA, Lukole E, Matowo NS, Pitt C, Messenger LA, et al. Effectiveness and cost-effectiveness against malaria of three types of dual-active-ingredient long-lasting insecticidal nets (LLINs) compared with pyrethroid-only LLINs in Tanzania: a four-arm, cluster-randomised trial. The Lancet. 2022;399(10331):1227-41.

46. Mosha JF, Matowo NS, Kulkarni MA, Messenger LA, Lukole E, Mallya E, et al. Effectiveness of long-lasting insecticidal nets with pyriproxyfen-pyrethroid, chlorfenapyr-pyrethroid, or piperonyl butoxide-pyrethroid versus pyrethroid only against malaria in Tanzania: final-year results of a four-arm, single-blind, cluster-randomised trial. Lancet Infect Dis. 2023.

47. Accrombessi M, Cook J, Dangbenon E, Sovi A, Yovogan B, Assongba L, et al. Effectiveness of pyriproxyfen-pyrethroid and chlorfenapyr-pyrethroid long-lasting insecticidal nets (LLINs) compared with pyrethroid-only LLINs for malaria control in the third year post-distribution: a secondary analysis of a cluster-randomised controlled trial in Benin. The Lancet Infectious Diseases. 2024.

48. Kilian A. How long does a long-lasting insecticidal net last in the field? Public Health Journal. 2010;21:43-7.

49. Kilian A, Byamukama W, Pigeon O, Atieli F, Duchon S, Phan C. Long-term field performance of a polyester-based long-lasting insecticidal mosquito net in rural Uganda. Malaria journal. 2008;7:49.

50. Kilian A, Byamukama W, Pigeon O, Gimnig J, Atieli F, Koekemoer L, et al. Evidence for a useful life of more than three years for a polyester-based long-lasting insecticidal mosquito net in Western Uganda. Malaria journal. 2011;10:299.

51. Loll D, Berthe S, Faye SL, Wone I, Koenker H, Arnold B, et al. User-determined end of net life in Senegal: a qualitative assessment of decision-making related to the retirement of expired nets. Malaria journal. 2013;12:337.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 4.MassueIACTnetdecaymodelsupplementaryinformation.docx
- 5.MassueIACTnetdecaymodelsupplementaryinformationdata.csv
- 5.MassueIACTnetdecaymodelsupplementaryinformationmodelcode.stan
- 5.MassueIACTnetdecaymodelsupplementaryinformationmodelcode.r