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Where did the nets go? Tracing long-lasting insecticidal net migration on Bioko Island

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Abstract

Background Long-lasting insecticidal nets (LLINs) are commonly distributed through mass distribution campaigns (MDCs). MDCs are often followed by substantial loss of LLINs, affecting coverage. Here, data from an MDC and a malaria indicator survey (MIS) on Bioko Island were used to characterize LLIN mobility.

Methods Between October 2014 and July 2015, an MDC reached most of the households of the island. All nets distributed were marked with a unique code corresponding to the community where they were distributed. An MIS conducted in August and September 2015 allowed to measure LLIN loss and mobility by verifying the number of existing nets and the community code. Multivariate models were used to identify factors associated with households with LLINs with mismatched codes. A source-sink analysis measuring risk gradient between the source community and the sink household was used to assess the overall effect of migrating nets.

Results The MIS revealed that of the 11,599 LLINs distributed to surveyed households, 7274 (62.7%) were observed during the MIS, indicating that 37.3% were no longer present. Among the 7,274 surviving nets, community codes were registered only for 3,413 (46.9%), and 551 of these (16.1%) revealed a mismatched code. Having open eaves was significantly associated with the presence of mismatched LLINs in households (aOR: 1.61; 95% CI 1.35–1.93, $p < 0.001$). The source sink analysis showed that while the majority of LLINs migrated from lower to higher risk areas (62.3%), almost a third migrated in the opposite direction.

Conclusion While redistribution had a positive impact on some communities by serving populations at higher risk of transmission, many households in high-risk areas lost their nets to areas with lower risk. This, coupled with the significant LLIN loss post-MDC, pointed to critical inefficiencies and prompted a shift in LLIN distribution strategy from MDC to demand-driven fixed distribution points.

Keywords Malaria, LLIN distribution, LLIN migration, Bioko Island

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Background

Over the past two decades, interventions targeting malaria vectors have been scaled up, leading to significant declines in global malaria morbidity and mortality [1]. One of the most widely implemented vector control strategies is the distribution of long-lasting insecticidal nets (LLINs), with approximately 181 million LLINs delivered to malaria endemic regions in 2024 [1]. Since LLINs are designed to retain their insecticidal properties for at least three years, mass distribution campaigns (MDCs) have been recommended to coincide with this timeframe [1, 2]. However, LLIN durability is often compromised under real-world conditions due to wear and tear, improper handling, and environmental factors [3–6]. Moreover, many LLINs are discarded and a significant proportion is given away or relocated between households and communities [7].

LLINs protect users from mosquito bites by creating a physical barrier and by killing or deterring mosquitoes that land on the net [2, 8–10], thus providing a household and community-level effect [11]. LLIN use is highly associated with individual access [12–14]. Periodic MDCs are expected to guarantee high LLIN coverage of access and use [14], but studies analyzing post-MDC data reveal a significant and rapid decrease in LLIN access [3, 15]. Some possible reasons for this lack of retention of distributed nets include poor knowledge of the health risks posed by malaria and low perception of the protective benefits of LLINs [16–18].

Since 2015, vector control on Bioko Island has relied heavily on LLINs and indoor residual spraying (IRS). Two island-wide MDCs took place in 2015 and 2018, respectively, observing the 3-year interval recommendation. These were door-to-door MDCs, meaning that campaign field workers targeted every active household on the island to provide enough LLINs to serve all residents. The LLINs distributed were PermaNet 3.0 (Adiwara) in 2015 and Olyset Plus (Sumitomo Chemical) in 2018. Each campaign successfully reached around 90% of the island population, with 149 thousand and 156 thousand LLINs distributed to 60,810 and 63,149 households in 2015 and 2018, respectively [15]. Both MDCs were resource intensive, with around 90 field workers deployed for almost 150 workdays. However, between a third to almost half the nets were lost between 3 and 5 months after each distribution and numbers continued to decline in subsequent years [15]. Thus, Bioko presents an example where the gap between access and use is substantial despite having guaranteed access, suggesting behavioral factors are at play [15, 19]. These persistent challenges prompted a critical evaluation of distribution strategies, including a shift from door-to-door MDCs toward fixed distribution points [15].

In this paper, LLIN loss and migration between communities after MDCs were quantified. During the 2015 MDC, LLINs were tagged with a code specific to the community where they were distributed, with the aim of tracking their location at the time of the 2015 malaria indicator survey (MIS). The numbers of LLINs in surveyed households were compared to the numbers delivered during the MDC and inspected for their community code. Factors potentially involved in driving LLIN movement were explored. Crucially, by estimating the malaria risk gradient between source and destination communities of households, it was possible to assess whether informal redistribution directed nets toward or away from higher malaria risk communities, a question with direct implications for evaluating and planning LLIN distribution strategies.

Methods

Study design

This was an observational analytical study integrating data from the 2015 MDC and MIS on Bioko Island to evaluate LLIN loss and migration patterns. Here, LLIN loss is defined as nets no longer observed at the surveyed household where they had been distributed during MDC, and LLIN migration as nets originally distributed elsewhere during MCD and reallocated to the surveyed household.

Study area

Bioko is the largest island of Equatorial Guinea (EG). It is located in the Bight of Biafra, off the coast of Cameroon (Fig. 1). About 80% of the island population lives in Malabo, the former country capital. Sustained and intensive malaria control initiated in 2004 and implemented through the Bioko Island Malaria Elimination Project (BIMEP) has effectively decreased malaria parasite prevalence, measured annually during MIS, by more than 84% (from 45% at baseline to 7.2% in 2025) [20, 21]. However, challenges remain due to persistent local vector populations and significant malaria importation [22, 23].

Data

The two main data sources used in this study, the 2015 MDC and the 2015 MIS, are described below.

The 2015 MDC took place in nine months, between October 2014 and July 2015 [23, 24], with door-to-door visits reaching 88% of inhabited households (n = 60,810) on Bioko Island. At each visit, data were recorded on the number of residents, the number of existing nets in good condition (i.e. LLINs without any evident tears or wear off), and the number of new LLINs allocated to guarantee individual access to all residents on the basis of one net per two individuals (i.e. universal access). Household

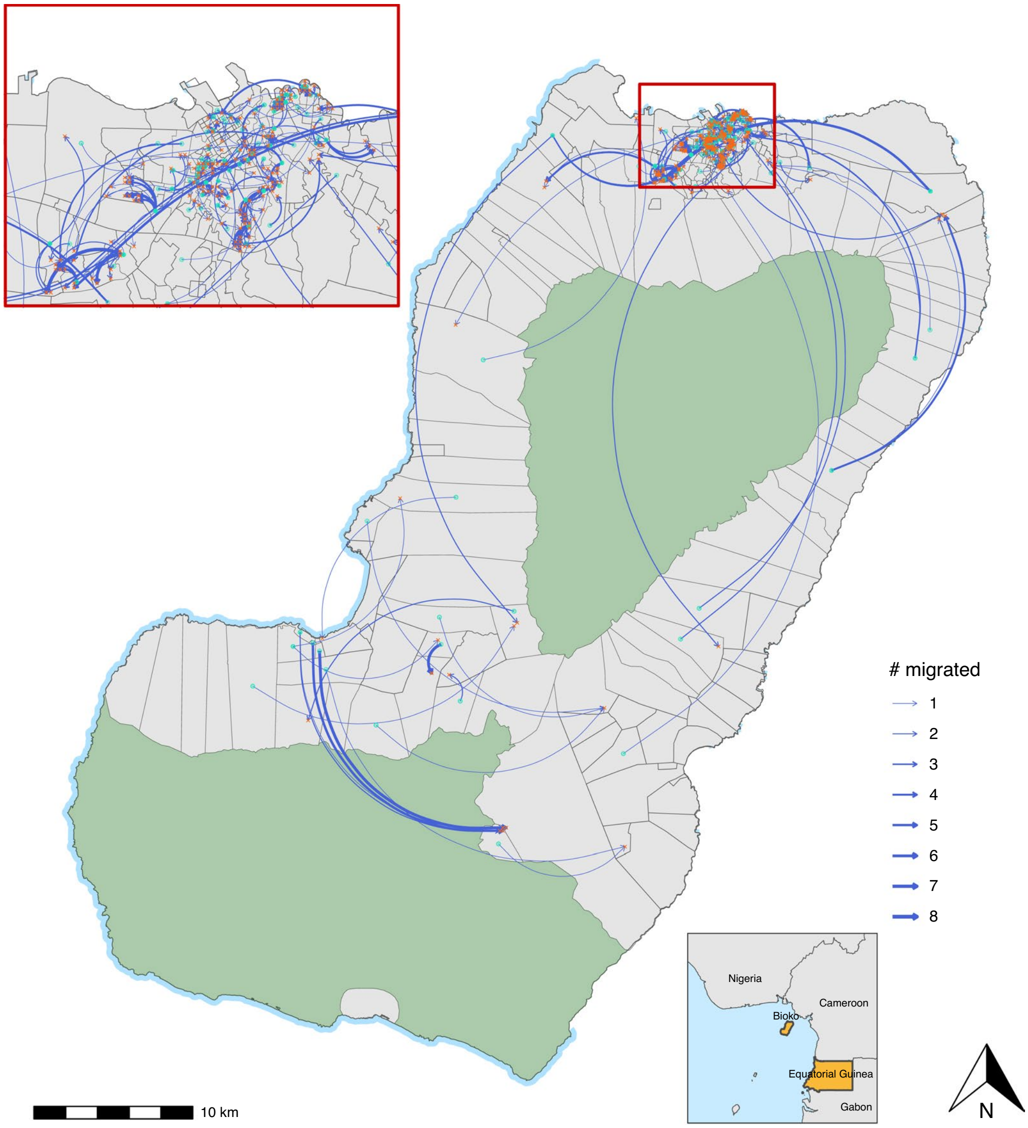

Fig. 1 Post MDC LLIN migration on Bioko Island. Grey polygons represent communities. Green circles represent the centroids of source communities. Orange crosses represent sink households, mapped to their sector (100 × 100 m grid), with 68 sectors having more than one sink household; hence, arrows account for as many as eight mismatched LLINs. Blue arrows connect sources to sinks, and their thickness illustrates the quantity of LLINs that migrated. The map inset at the top left demarcates urban Malabo to help illustrate the many LLINs migrating between urban communities. The smaller inset at the bottom right shows the location of Bioko Island relative to mainland EG and other countries in the Gulf of Guinea

data were linked to a unique household identifier within a spatial decision support system (SDSS) described elsewhere [24, 25]. In addition, all LLINs delivered were tagged with a unique code corresponding to the community to which the household belonged. The code was handwritten in situ using an indelible ink marker.

The 2015 annual MIS was carried out in August and September on a representative random sample of the population [26]. Survey responses were linked to the household identifier on the SDSS [24, 25]. Written informed consent to conduct the survey was obtained from the household head or an adult resident. Consenting individuals, or their legal guardians in the case of minors, responded to the survey questionnaire and were tested for malaria infection using a rapid diagnostic test with a nominal level of detection of 100 parasites per microliter of blood (RDT; CareStart G0131 Combo kit, AccessBio Inc., Monmouth, USA). Those who tested positive for malaria received free treatment with artemether-lumefantrine, following national guidelines.

Data collected on housing characteristics and LLINs included the number and condition of observed nets and their tagged community code. However, this protocol was not always followed, and some nets were not directly observed and, hence, their code not registered. In other cases, the handwritten code was hard to read and unambiguous registration was not possible.

Household-level MDC and MIS data were linked using the unique household identifiers on the SDSS. For the analyses of mismatched LLINs, only households where at least one LLIN tag code was recorded were included. LLINs identified as migrating into the household from a different community are hereafter referred to as mismatched or migrating LLINs.

Statistical analyses

To determine the associative relationship between the presence of mismatched LLINs and household characteristics, a multivariate logistic regression was constructed with a binary outcome at the household-level (*i.e.* were any mismatched LLINs recorded at the household?). To account for potential clustering, robust standard errors were applied at community level using the Huber-White sandwich estimator [27]. The variable for urban/rural community designation was dropped from the model due to its close association with district. The multivariate model was constructed from *a priori* associations to LLIN use and access (household size, socio economic status (SES) of household head, education and on-island travel history) [28–30] and statistically supported crude associations with migrating LLINs (Wald test $p < 0.20$; Supplementary Table S1) to avoid excluding potentially important confounders that may become significant after adjustment [31]. All covariates explored are listed and defined in Table 1. While the BIMEP collects regular data on entomological indicators, these were too spatially sparse to include in the model.

Source-sink analysis

Malaria transmission risk was characterized for the community where the LLIN migrated from (source) and for the household where it migrated to (sink). Figure 2 shows a schematic representation of the source-sink analysis for easier interpretation. Two layers of data were used to characterize risk. The first one was malaria parasite prevalence, represented by the *Plasmodium falciparum* parasite rate (*Pf*PR), or the number of people found infected divided by the total number tested with RDT during the MIS, weighted for survey design. *Pf*PR was used as a proxy measure of malaria transmission risk. The second

Table 1 Variables included in the statistical analyses of LLIN migration

Outcome variable	Description
Presence of mismatched LLIN in household	Household community code designation matches/mismatches the recorded community code on the LLIN tag
Risk Factors	**Description**
RDT (+)	Recording of any household member who had a positive RDT result that occurred during the MIS. During the MIS all consenting surveyed household members were tested by RDT
Household size	Categorized grouping of the number of household members, defined as individuals who normally eat and sleep in household over the past 6 months
Change in household size	Observed change in number of household members between MDC and MIS
Change in LLIN quantity	Observed change in number of LLINs between MDC and MIS
Household density (Crowding)	Density of household measured by person per room
Education	Education level of household head measured by the latest completed degree type
LLIN importance	The opinion of interviewee regarding the importance of bednets to prevent malaria
Urban/rural stratum	Household urban/rural stratum determined by the Ministry of Interior demarcation of communities
District	Household location by district determined by the Ministry of Interior demarcation
Household sprayed	Household reported acceptance of IRS in the previous 12 months
Traveled	Reporting of any household member travelling on Bioko Island in the previous 2 months
Socioeconomic Status (SES)	Measurement of socioeconomic status of household by principal component analysis (PCA) scoring based on household assets and utilities; re-categorized into quintiles. Assets included in the PCA are as follows: roof material, wall material, floor material, radio, television, VCR/DVD player, computer, telephone, clock, watch, sofa, table armoire, cabinet, fans, air conditioning, refrigerators, stove, washing machine, car, public/private water source, protected/open water source, electricity source, toilet type, and sanitation mechanism
Open eaves	Household has open eaves

Source-sink analysis

layer was housing characteristics that were deemed conducive to mosquito entry, namely open eaves, unscreened windows, and absence of air-conditioning (AC) [21]. These were used to modify risk under the assumption that they increase indoor mosquito biting at night when LLIN use would have provided protection.

Both layers were processed slightly differently at sources and sinks, as is described below.

Characterizing malaria risk at the source

Given the LLIN codes were specific to the source community, underlying risk at the source was characterized by survey weighted *Pf*PR at the community level. Because the source household was unknown, 2015 housing characteristics for all houses in the source community were extracted from the BIMEP household database [24] and the proportion of houses with open eaves, unscreened windows, and no AC was calculated. This proportion was used to modify the source risk based on evidence that housing characteristics significantly affect malaria risk [21, 32]. The specific threshold values represented arbitrary programmatic approximations rather than precise epidemiological cut-points, and, for the purpose of these analyses, were defined as follows: if the proportion of houses with risk conducive characteristics was $\geq$ 80%, then risk was increased by 50% (*Pf*PR * 1.5); if it was $\geq$ 50% and < 80%, risk was represented by *Pf*PR alone (unmodified); if it was < 50%, risk was decreased by 50% (*Pf*PR * 0.5; Fig. 2).

Characterizing risk at the sink

For sinks, survey weighted *Pf*PR at the 1 × 1 km area where the sink house is located [24] was deemed a representative metric of underlying risk around the household. Data on household characteristics for the sink household were obtained from the MIS and modified risk was calculated based on the same evidence as above [21, 32]. The risk modification was applied as follows: if the house had open eaves, unscreened windows and no AC, risk was increased by 50% (*Pf*PR * 1.5); if the house had either one of closed eaves, screened windows or AC, risk was expressed as the area-level *Pf*PR alone (unmodified); if the house had two or more of closed eaves, screened windows or AC, risk was reduced by 50% (*Pf*PR * 0.5; Fig. 2).

Estimating direction and magnitude of risk gradient from source to sink

A risk gradient between sources and sinks was estimated by subtracting risk at the sink from risk at the source. The magnitude of the effect was expressed as the difference in risk. Three approaches were adopted for estimating the risk gradient: the difference between *Pf*PR at the sink and *Pf*PR at the source, the difference between the modified risk at both sink and source, and the difference between the modified risk at the sink and *Pf*PR at the source (Fig. 2). For all three, a positive gradient (*i.e.* risk was higher at the sink) would translate into a beneficial effect of LLIN migration, while a negative gradient (*i.e.* risk was higher at the source) would imply a detrimental effect. In the context of LLIN migration, a positive gradient would mean potentially more overall impact of the intervention given nets migrated to an area with higher risk of malaria transmission. The last two approaches assumed that housing characteristics are an important consideration, recognizing that it is not the same giving away an LLIN if you lived in a house very conducive to mosquito entry than if your house provided barriers against mosquito entry. With this assumption, comparing the risk gradient between modified risk in both source and sink would be ideal, but given the uncertainty generated by not having recorded the specific household at the source, the conservative scenario of estimating the risk gradient with modified risk only at the sink was considered (since the household characteristics were always available at the sink). Therefore, it should be noted that the risk gradient analysis introduced an asymmetry: *Pf*PR and housing characteristics at sink households were directly observed, whereas community-level averages were used as proxies for estimating risk at sources. The three approaches were used as a sensitivity analysis given the assumptions and the asymmetry introduced.

All analyses were conducted in R v4.5.3 [33].

(See figure on next page.)

Fig. 2 Schematic representation of the source-sink analysis and the three approaches to estimate risk gradient. Top (**A**, **B**, and **C**) and bottom (**D**, **E**, and **F**) panels represent each approach under two different scenarios assuming a theoretical source community (represented by the irregular polygons) and a sink household (circled in blue) within a 1 × 1 km area. Arrows indicate direction of LLIN migration. Communities and areas are filled in various shades of orange according to the level of risk indicated in the labels. Risk is determined by *Pf*PR at community (panels **A**, **C**, **D**, and **F**) and area-level (panels **A** and **D**), and by modified risk based on household characteristics (panels B and E at both community and area-level, and **C** and **F** at area-level). For simplicity, household characteristics are illustrated as houses with open eaves and no window screening (no rendering for AC). Orange bars illustrate the magnitude and direction of the gradient: top panels have a positive gradient, while bottom panels have a negative gradient. From these two examples, the reader can infer additional scenarios of various magnitudes and directions of the gradient

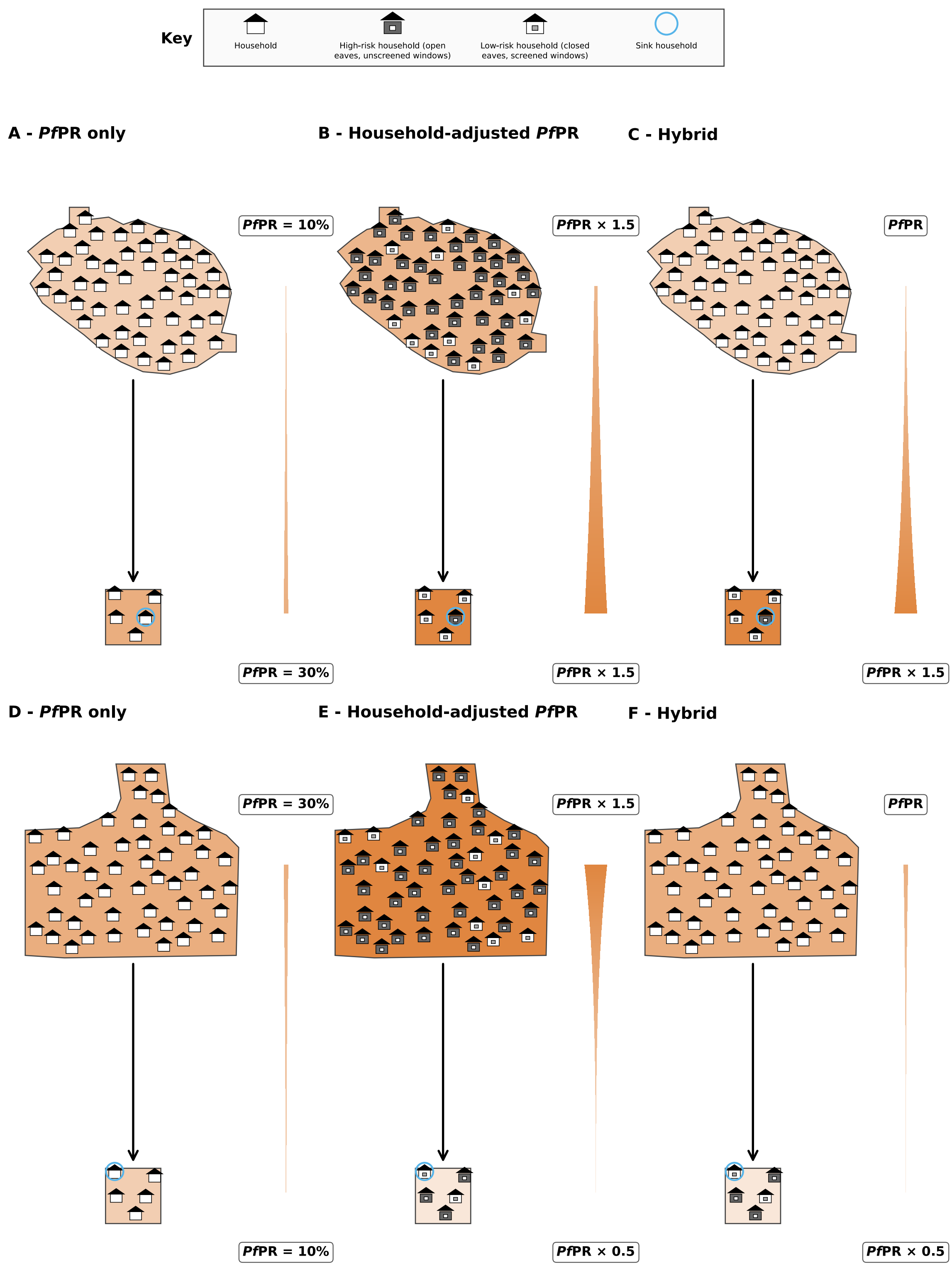

Fig. 2 (See legend on previous page.)

Results

LLIN survival based on MDC data and tag code availability

A total of 11,599 LLINs were distributed during the MDC to 17,047 individuals in 5,101 surveyed houses in the MIS. During the MIS, only 7,274 (62.7%) LLINS were observed. Among those, for 3,861 (53.1%) from 3,434

(67.3%) households, the tag code was not registered. The remaining 3,413 LLINs (46.9%) from 1,668 (32.7%) households could be traced. Among these 1,668 households, in 1,450 (86.9%) residents had lived there for at least one year.

LLIN migration patterns

The majority of LLINs with a tag code (2,862/3,413; 83.9%) matched the community where they were surveyed (*i.e.* did not migrate to a different community), whilst 551 (16.1%) from 294 (17.6%) households were mismatched (*i.e.* did migrate to a sink household in a different community; Fig. 1). Among the 294 sink households, 130 (44.2%) received one and 164 (55.8%) received two or more LLINs, including five households where mismatched LLINs originated from two different communities, and one household where they were sourced from three different communities. Most LLIN migration occurred between communities in the same district (501 out of 551; 90.9%), and most of these (450 out of 501; 89.8%) migrated within Malabo district. Time since MDC showed that most households with mismatched nets were surveyed four months or more after MDC (Supplementary Table S1).

Multivariate analysis

Among the 1668 households where at least one LLIN tag code was recorded, 260 were excluded due to missing covariate values (259 with missing education level and one with unknown travel status), leaving 1408 households in the final model. When stratifying by time interval from MDC to MIS, the majority of households included in the model were surveyed 4 + months post-distribution (961/1,408), with observations concentrated in Malabo (n = 842) and Baney (n = 119) districts. Time since MDC was therefore excluded from the multivariate model to avoid collinearity with the district covariate. In addition, MDC dates were not recorded for 139 households, which would have introduced additional unnecessary data loss. To reduce collinearity, the urban/rural stratification was also excluded as a variable because most urban communities are in Malabo district.

After adjusting for other covariates, households with open eaves were significantly associated with increase in adjusted odds (aOR) of having a migrating LLIN (aOR: 1.61; 95% CI: 1.35–1.93, $p < 0.001$) (Fig. 3). Households where their head had an undergraduate education had 71% higher odds of having a migrating LLIN compared to non-college educated household heads, though this effect was borderline significant (aOR: 1.71; 95% CI 1.00–2.94; $p = 0.05$). Households in districts outside of Malabo were less likely to have a reallocated LLIN compared to households in Malabo (Baney aOR: 0.18; 95% CI 0.08–0.38; $p < 0.001$; Luba aOR: 0.26; 95% CI 0.11–0.64; $p = 0.003$; Riaba aOR: 0.46; 95% CI 0.22 0.96; $p = 0.04$). Education at postgraduate level, household size increase, household size of 8 or more members, and all remaining covariates were not significantly associated with the presence of mismatched LLINs in the model.

Source-sink risk gradient findings

The results of the three approaches to define risk gradients between sources and sinks are shown in Figs. 4 and 5. When estimating the risk gradient simply through *Pf*PR at both source and sink, almost the same amount of LLINs migrated towards the worsening as towards the improving direction (244; 44.3%, and 236; 42.8%, respectively) with a small number of nets migrating between sources and sinks with no appreciable difference in risk (71; 12.9%). When estimating the risk gradient by modified *Pf*PR at both sources and sinks, however, the majority of LLINs migrated towards higher risk (400; 72.6%), 126 (22.9%) migrated towards lower risk, and only 25 (4.5%) showed no difference in risk at source and sink. When the risk gradient was estimated only by modifying *Pf*PR at the sink, the balance leaned also towards improving, with 295 (53.5%) LLINs migrating towards sinks with higher risk, 217 (39.4%) to lower risk sinks, and 39 (7.1%) migrating between sources and sinks with similar risk. Importantly, for 355 mismatched LLINs (64.4%), the risk gradient direction was consistent between the three approaches. Of these, 115 migrated towards lower risk sinks (32.4%), 221 towards higher risk sinks (62.3%), and 19 migrated between sources and sinks with similar risk (5.4%).

When looking at the distribution of the risk gradient magnitude by each approach, if using *Pf*PR only or modified only at the sinks, the net effect of LLIN migration was virtually nil (median = 0%, IQR [−1.6–1.8%] and median = 0.6%, IQR [−1.8–4.4%], respectively). When assessing the gradient estimated through modified risk at both sources and sinks, an overall beneficial effect resulting from net migration was evident (median = 4.2%, IQR [0–8.0%]; Fig. 6).

Discussion

This paper documents LLIN migration on Bioko Island shortly after the 2015 MDC and explores the household factors associated with this migration. Undergraduate level of education of the household head showed a 71% increase in the odds of the presence of mismatched LLINs in the household, though this effect was borderline significant. Higher level of education of the household head aligns with LLIN use having been strongly associated with the education level of the household head in other settings [31, 34], and probably reflects

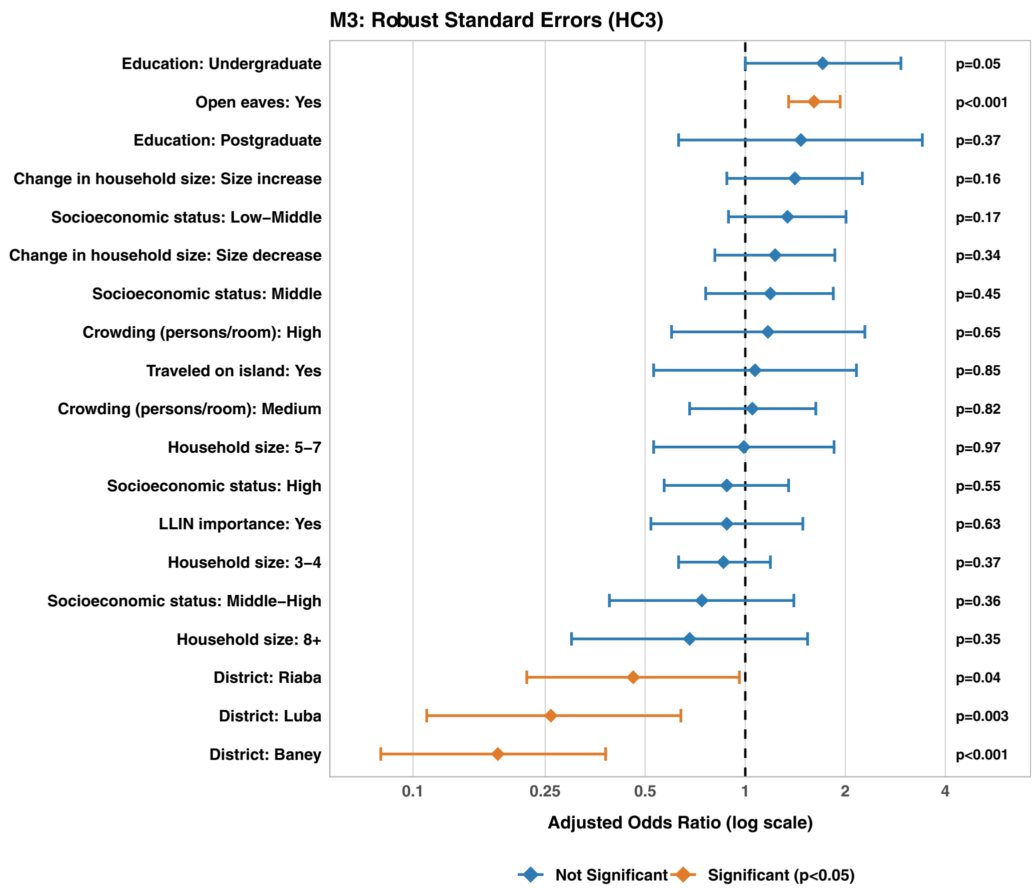

Fig. 3 Adjusted odds ratios from the multivariate logistic regression model for factors associated with the presence of mismatched LLINs among 1,408 of the 1,668 households where at least one LLIN code was recorded, after excluding 260 households with missing covariate values. Points represent mean estimates plotted on a log scale with horizontal whisker lines indicating 95% confidence intervals. Orange points and whiskers indicate statistically significant associations ($p < 0.05$), and blue represent non-significant associations. The vertical dashed line at OR = 1 represents no association. Reference categories (not shown) are as follows: 1–2 people (household size), no change (change in household size), low household density (crowding), non-college education (education), LLINs not believed to be protective against malaria (LLIN importance), did not travel within Bioko (traveled on island), low SES quintile (socioeconomic status), closed eaves (open eaves), and Malabo district (district)

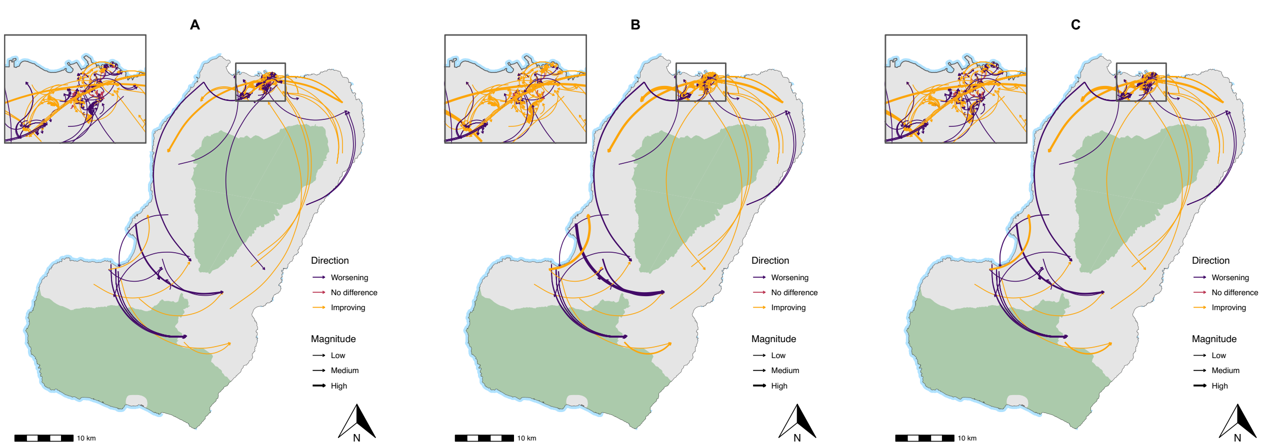

Fig. 4 Risk gradient between sources and sinks of LLINs on Bioko Island. The gradient was estimated as the difference between *Pf*PR at the sink and at the source (**A**), the difference between the modified risk at both sink and source (**B**), and the difference between the modified risk at the sink and *Pf*PR at the source (**C**). Arrows indicate direction plotted from the centroid of the source community to the centroid of the sector of the sink household. The color of the arrows indicates the direction of the gradient and the width its magnitude. The map inset demarcates urban Malabo

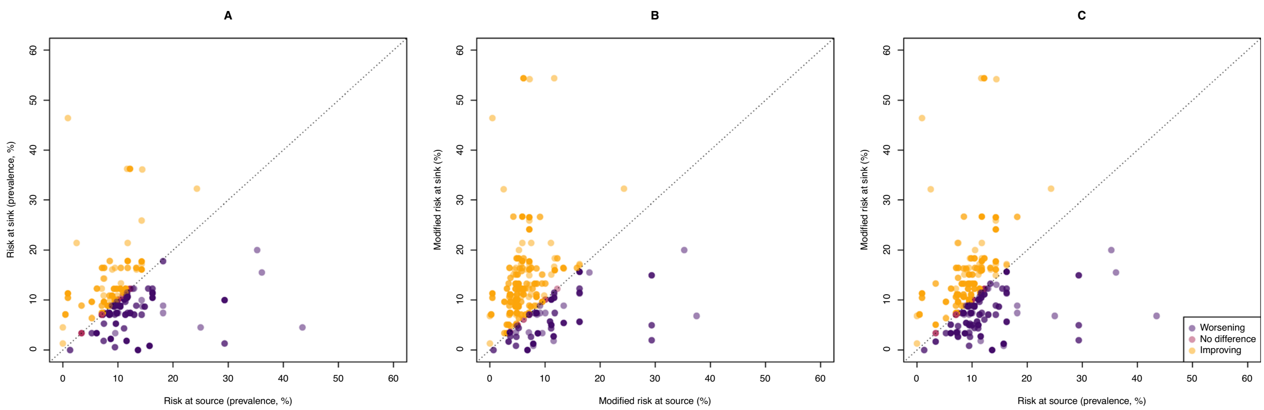

Fig. 5 Relationship between risk at the sources and sinks of LLINs on Bioko Island. Risk was determined by the difference between *Pf*PR at the sink and at the source (**A**), the difference between the modified risk at both sink and source (**B**), and the difference between the modified risk at the sink and *Pf*PR at the source (**C**). The diagonal dotted line represents no difference

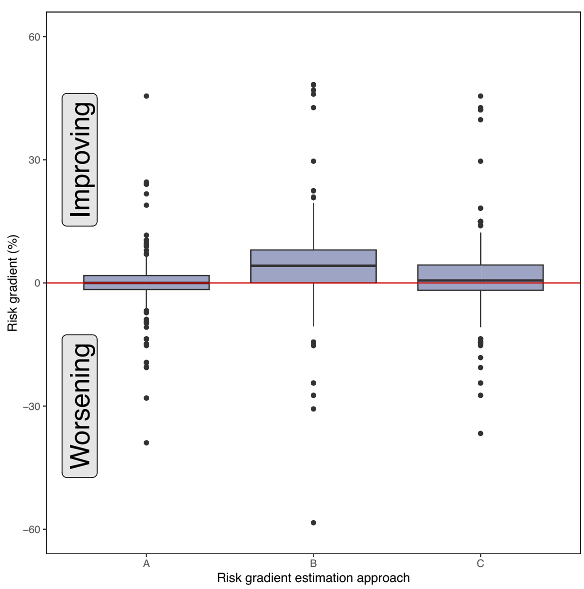

Fig. 6 Distribution of risk gradient (%) by each approach. In (**A**), the risk gradient was expressed as the difference between *Pf*PR at the sink and at the source; in (**B**), as the difference between the modified risk at both sink and source; in (**C**) as the difference between the modified risk at the sink and *Pf*PR at the source. The red horizontal line represents no difference between an overall improving or worsening effect

greater awareness of risk. SES was not a significant covariate in the multivariate model, but the presence of open eaves was significantly associated with the presence of mismatched LLINs, increasing the odds by 61% compared to households with closed eaves. This suggests that probably a combination of the nuisance and the perception of risk caused by mosquitoes biting indoors is an important factor for the demand of LLINs. From a programmatic perspective, this indicates that housing characteristics visible during routine surveillance, such as open eaves, could serve as markers to identify households that may benefit the most from targeted LLIN replenishment and behavior change communication.

Most migrating nets were found in urban Malabo and the odds of finding a mismatched LLIN in the other districts was significantly lower. Further, more LLIN movement occurred between urban communities, which could possibly be driven by household member migration, proximity and better-established social networks within the urban center. This aligns with observations in other settings, where LLIN migration has been associated with community-level connections and familial ties [35]. Critically, evidence of this informal reallocation of LLINs further supported the redefinition of the LLIN distribution strategy on Bioko from MDC to fixed distribution points, which was initiated in 2021 in urban Malabo but has since expanded to serve the whole island [15]. The concentration of net migration within Malabo observed in this analysis provided early evidence supporting this geographic prioritization.

The multivariate model had some limitations. Cluster-robust standard errors were applied to account for potential within-community correlation, though residual clustering beyond the community level cannot be excluded. Potential bias may have been introduced by the significant lack of tag codes registered during the survey for 53.1% of LLINs, particularly since this may not have been entirely random (Supplementary Table S2). However, given this happened during survey registration of the codes after nets had migrated, this was not correlated with net migration nor age of the nets. Other LLIN distribution channels are present on

Bioko, such as through the ANC visits, schools and private sector, which may have added to the lack of LLIN tag code registration in some of the observed nets.

One unique feature of these analyses was the ability to characterize risk at both the source community and the destination household of the migrating nets. This allowed the estimation of the risk gradient between sources and sinks to better understand the overall effect of LLIN movement (Fig. 2). The inability to identify specific source households introduced uncertainty in source risk estimates, and future distributions that tag nets at the household level should allow more precise source-sink comparisons. This also precluded the ability to track LLIN movement within communities, which could be substantial. With these caveats in mind, the source-sink analysis revealed that the majority of mismatched LLINs (62.3%) flowed toward higher-risk areas regardless of the method used for assigning risk. When risk was modified by housing characteristics conducive to mosquito entry at both source and sink, almost three quarters of nets (72.6%) flowed toward higher risk areas, which aligns with the finding of open eaves being a very significant factor associated with net migration. However, a considerable proportion of mismatched nets moved in the other direction, from higher to lower risk areas, representing a worsening effect (Fig. 6). These observations have direct implications for LLIN distribution planning and point to a loss of resources to net migration, and also support the shift in strategy from MDCs to fixed distribution points [15] because a demand-driven approach assumes those who make the effort to obtain LLINs from a distribution facility are more appreciative of their protective value and more likely to keep and use them. No strategy is perfect, and inevitably LLINs will continue migrating among the population. The key insight is that informal redistribution, when it occurs, appears to generally follow a rational pattern toward higher risk households. The fixed-point distribution model leverages this behavior rather than fighting against it, while freeing the substantial resources invested in MDC that can be redirected to complementary malaria control strategies.

To the authors' knowledge, this is the first report of LLIN migration at this level of spatial granularity. While the findings may be specific to the context of Bioko Island, they point to the need to adapt LLIN distribution strategies according to behavioral and programmatic needs. Importantly, BIMEP data show that between 2023 and 2025, the total number of LLINs distributed through fixed distribution points was 144,000, a number very close to that of nets distributed in both the 2015 and 2018 MDC [15]. This is to say that the new strategy secured a similar number of nets to the population with significantly less resources invested. While precise cost comparisons are beyond the scope of this analysis, the reduction from approximately 90 field workers over 150 workdays for each MDC to a smaller, continuously operating fixed-point system represents substantial savings in personnel, logistics, and coordination. Programs in similar contexts, particularly urban settings with high population density, established social networks, and strong baseline coverage, may achieve comparable efficiency by transitioning to demand-driven distribution models. In rural or dispersed populations with weaker infrastructure and lower baseline coverage, the trade-offs may differ and operational research could inform context-specific strategies.

Mismatched LLINs represented 16.1% of all nets with registered codes, considerably higher than LLIN redistribution reported in other countries [35]. In addition, 4,325 of the 11,599 LLINs (37.3%) that had been distributed to the surveyed households could not be observed during the MIS. Taken together, the overall attrition of LLINs post-distribution corresponded to the 551 nets that migrated and the 4,325 missing, representing 4,876 out of 11,599 (42.0%) lost or displaced less than a year after distribution. Notably, this attrition rate is comparably higher than rates reported in other studies, particularly considering the short time gap post-distribution [36, 37]. Given the MIS used a representative sample, presumably a similar fraction of the 4,325 LLINs unaccounted for would have migrated to other households within the island or to households in the continental region of EG. If the latter, this would have most likely translated into an improving effect given malaria control in mainland EG is limited and transmission risk is significantly higher [38–40]. If nets from Bioko are reaching households in the mainland through familial networks and population movement between the island and the continent, this would represent an unintended but potentially beneficial cross-subsidization of malaria control in mainland. From the perspective of Bioko's elimination goals, however, this flow represents a resource leakage that complicates the achievement of sustained high coverage on the island. Furthermore, the number of nets that were discarded or destined for completely different uses remains unknown. Anecdotal observations have documented LLINs disposed of at dumpsites and water bodies, as well as repurposed for uses ranging from agriculture to recreation, consistent with reports from other settings [35]. The substantial LLIN loss documented here was also documented previously and was the main motivation for the shift in the LLIN distribution strategy [15].

MDCs remain commonplace LLIN distribution strategies. In 2024, around 133 million LLINs were distributed using MDCs [1]. Malaria control programs constantly strive for high coverage of this life saving intervention.

At the same time, given the ever challenging and increasingly limited financial landscape, programs must seek to optimize cost-effectiveness. The data used in this paper are unique in their spatial resolution and are also context-specific to Bioko Island. However, the findings of this study do point to a pervasive problem that may be only anecdotally documented elsewhere and invite further operational research across different endemic settings to evaluate the efficiency of LLIN distribution strategies.

Conclusion

LLIN migration after MDC can be substantial and often directed toward higher-risk households, suggesting informal redistribution may partially compensate for coverage gaps. However, high attrition and reverse migration highlight inefficiencies in door-to-door, MDCs. Demand-driven distribution systems offer a more efficient strategy in such settings.

Supplementary Information

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Supplementary material 1.

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Author contributions

TCS, GAG, and CAG conceived and designed the study. LAT contributed to the data curation and analysis. TCS, GAG, WPP, JNME, TBD, LMV, MRR, and IM were responsible for the management and supervision of field activities. DH, DSG and DLS contributed to the interpretation of results. TCS and CAG conducted the analyses, generated figures and tables, and wrote the first draft of the manuscript. All authors contributed to the final version of the manuscript.

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Availability of data and materials

The datasets and/or analysis used in this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Ethics approval to collect household census data during the 2014/2015 LLIN distribution was granted by the Equatorial Guinea Ministry of Health, Social Welfare, and Health Infrastructures. Informed consent was requested prior to collecting any data at time of distribution. Ethics approval for the 2015 MIS was provided by the Equatorial Guinea Ministry of Health, Social Welfare, and Health Infrastructures, and the ethics committee of the London School of Hygiene and Tropical Medicine (approval number 5556). Written informed consent was sought from each participating adult and on behalf of participating children.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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