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Original Article

Modelling the Effect of Indoor Residual Spraying on Malaria Transmission in Nassarawa State, North-central Nigeria

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Abstract

Background: Indoor Residual Spraying (IRS) is one of the two major strategies recommended by the World Health Organization for malaria vector control. Between 2012 and 2013, IRS was piloted in two Local Government Areas (LGAs) of Nassarawa State, North-central Nigeria. Uncertainties remain as to whether the intervention led to a decrease in the rate of malaria transmission or not.

Methodology: A simple SIRS model was used to generate a system of ordinary differential equations. The solutions of the model, obtained through Euler's method, were adapted to malaria surveillance data obtained from one of the interventions LGAs to estimate model parameters. The rate of malaria transmission, obtained from the intervention LGA, was compared with the one obtained from a carefully selected control LGA to ascertain the effect of IRS on malaria transmission, assuming other model parameters remained constant.

Results: The results showed a good fit of surveillance data to the numerical solutions of the model. The estimated rate of malaria transmission in the intervention LGA was lower than the rate estimated in the non-intervention LGA, even though the difference was marginal (0.95 versus 1.05). Over two years, IRS activities reduced the rate of malaria transmission in the intervention LGA by 10%. The modest decrease was attributed to the way IRS was implemented and the uncertainties associated with using routine surveillance data in Nigeria.

Conclusion: Future IRS interventions should consider the effect of spray frequency on disease transmission and adopt a robust data collection strategy that will support proper monitoring and evaluation.

Keywords: Indoor Residual Spraying; Mosquito; Malaria; Nigeria; Nassarawa.

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Quick Response Code:

Introduction

Malaria is a life-threatening infection caused by Plasmodium parasite and transmitted through the bite of an infected female Anopheles mosquito.[1] It is an age-long disease that is associated with high morbidity and mortality, especially among young children, pregnant women and non-immune travelers. Although several countries have successfully eliminated the disease, malaria is still endemic in 85 countries.[2] According to the World Health Organization (WHO), 249 million cases of malaria were recorded in 2022, an increase of 5 million cases from the number reported in the preceding year.[2] Currently, only 29 countries account for 95% of all malaria cases, indicating that some countries bear a disproportionate burden of the disease.[2]

Nigeria, the most populous country in sub-Saharan Africa, has the highest burden of malaria in the world, accounting for 27% of all malaria cases and 31% of all malaria deaths.[2] The prevalence of malaria among children aged 6-59 months in the country is about 22%, with considerable variations across the states.[3] The National Malaria Elimination Programme (NMEP), under the Federal Ministry of Health, coordinates malaria control activities in the country with support from sister agencies and development partners. The NMEP is currently implementing a mix of interventions across the country, including malaria case management, integrated community case management of malaria, intermittent preventive therapy in pregnancy (IPTp), intermittent preventive therapy in infants (IPTi), distribution of long-lasting insecticidal nets (LLINs) and seasonal malaria chemoprevention (SMC).[4]

Indoor residual spraying (IRS) is the application of a long-lasting insecticide to mosquito-resting surfaces with a view to killing them.[5] It is the second most common vector control strategy after long-lasting insecticidal nets. When implemented correctly, IRS is highly effective, causing a rapid reduction in adult mosquito vector density and decreasing their lifespan.[5] In the mid-90s, several malaria control programmes in Asia and America successfully used IRS to accelerate gains in malaria elimination.[6,7] However, the use of IRS has declined in recent years due to several factors that included high cost, community acceptability, insecticide resistance and the need for repeated applications to provide optimal protection.[5]

Nonetheless, IRS is still recommended in low- and moderate-transmission settings where it could be used to reduce seasonal malaria peaks, in high-transmission areas where it could be used to rapidly bring transmission down to a level that is sustainable through high coverage of LLINs, in areas of significant economic importance where it could be used to mitigate the impact of malaria on economic development, and in urban areas with high population densities.[5]

In Nigeria, several IRS interventions were conducted over the last two decades. [8–10] Most of those interventions were small-scale pilot programmes that were implemented at the state level. Major pilot activities took place in 2008 when the World Bank supported IRS activities in six states.[10] More campaigns were implemented in Lagos and Nassarawa States between 2011 and 2013.[11] A handful of states and development partners continue to make efforts to either pilot or sustain IRS activities in various places, including Lagos and Borno States.[8,12]

Between 2012 and 2013, two IRS interventions were carried out in two Local Government Areas of Nassarawa State, North-central Nigeria.[13] These interventions were considered a success, having achieved lower densities of adult mosquitos in the two LGAs.[14] However, it is not clear if those interventions also led to a reduction in the rate of malaria transmission in the intervention areas or not. While it stands to reason that decreased mosquito density resulting from IRS should bring about a decrease in malaria transmission, this is not always the case as other factors, including local breeding sites, mosquito biting habits and spray coverage may all influence malaria transmission.

Assessing the effect of IRS on malaria transmission by evaluating malaria incidence data is more important from the programme's point of view because incidence data is a better indicator of impact compared to vector density. The aim of this study was to assess the effect of IRS intervention on the rate of malaria transmission in one of the two intervention LGAs of Nassarawa State, North-central Nigeria. Specifically, the study aims to adopt a modelling approach to estimate and compare the rate of malaria transmission between a sprayed and non-sprayed (control) LGA during the intervention period.

Methodology

Study Design

This study was a retrospective quasi-experimental study that modelled the effect of IRS intervention on malaria transmission in Nassarawa-Eggon LGA of Nassarawa State, North-central Nigeria. For comparison, Obi LGA of the same state was selected as a control setting. The intervention group comprised all residents of Nassarawa-Eggon LGA of Nassarawa State between June 2012 and May 2014, while the control group comprised all residents of Obi LGA during the same period. Although the two LGAs were not contiguous, the estimated population sizes of the intervention and control LGA, as of 2012, were comparable.[15]

Intervention Area

Between 2012 and 2013, The United States President's Malaria Initiative (PMI) supported the implementation of two rounds of IRS in Nassarawa State, North-central Nigeria. The IRS activities were implemented in two LGAs of the state, Nassarawa-Eggon and Doma. Nassarawa-Eggon, with an estimated land mass of 1,237 square kilometres, lies in the Sudan savannah belt, characterized by high rainfall and stable malaria transmission. Malaria cases are seen all year round with peaks recorded at the beginning and towards the end of the rainy season (March to October).[11,13] The LGA has both rural and semi-urban settings, but the predominant occupation in the LGA was farming. Administratively, the LGA was divided into 14 political wards, comprising 309 towns and villages. Prior to the IRS intervention in 2012, the total population of the LGA was 213,507 and the enumerated number of households was 29,572 (7.2 persons per household). [13,16]

IRS Intervention

Between 2012 and 2013, two rounds of IRS activities were implemented in Nassarawa-Eggon. The first was started on the 4th of April 2012 and lasted for 32 days. It covered 30,735 of the 31,132 structures identified by the spray operators (98.7% coverage).[13] During this round, the insecticide used was the pyrethroid alpha-cypermethrin, which has a duration of effectiveness of 4-6 months, depending on the type of formulation.[5] The second round took place a year after, commencing on the 11th of April, 2013, and lasting for 33 days. This time around, 31,451 of the 32,412 structures identified by the spray operators were covered (97.0% coverage).[14] During the second round, alpha-cypermethrin was substituted with deltamethrin (another pyrethroid), based on assessments by the National Malaria Control Programme (NMCP) and the PMI. The duration of effectiveness of deltamethrin is 3-6 months, depending on the type of formulation.[5] Between 2012 and 2013, when those activities were implemented in Nassarawa-Eggon, no such activities took place in Obi LGA.

Data Collection

The details of the IRS implementation were obtained from two end-of-spray reports, whereas monthly cases of malaria were obtained through desk reviews of the archived malaria surveillance data from the intervention and control LGAs. [13,14] Two trained research assistants performed manual data extraction in

Nassarawa-Eggon and Obi LGAs over a period of one week. The data was said to come from all reporting public health facilities in the LGAs between 2012 and 2014. The two officers used identical pro forma which captured the monthly number of malaria cases among all people between June 2012 and May 2014 (i.e. 24 months).

Data Analysis

The data obtained was prepared in Microsoft Excel and double-checked for omission and erroneous entries. Thereafter, data analysis was performed in two stages. A preliminary statistical test was performed using an independent sample t-test to assess if there was a statistically significant difference in the total number of malaria cases between the two LGAs. For this purpose, a p-value less than 0.05 was considered statistically significant.

In the second stage, a simple SIRS model of malaria transmission in humans (with no vector component) was used to generate a system of ordinary differential equations. The base model was obtained from a previous study.[17] The equations were then solved numerically using Euler's method. Microsoft Excel solver function was then used to separately fit the numerical solutions of the model to the surveillance data from both control and intervention LGAs. The fitted parameters obtained from the control LGA, with the exception of the rate of transmission, were then applied to the intervention LGA, allowing the solver function to re-calculate the rate of transmission in the intervention LGA. The two rates of malaria transmission were then compared for any difference which may be attributed to the IRS intervention.

Model Assumptions

In this study, several assumptions were made which included the following:

The two LGAs, Nassarawa-Eggon and Obi LGAs were identical in terms of population size, geography and topography; The two LGAs had similar patterns with respect to vector composition, vector density and vector biting habit; Apart from the IRS intervention implemented in Nassarawa-Eggon, no other malaria control activities were taking place in both the intervention and control LGAs.; The surveillance data was complete and accurate, reflecting the exact number of malaria incident cases that took place in the two LGAs during the study period; The demographic characteristics, social beliefs and health-seeking behaviours of people in the two LGAs were identical; Mortality due to malaria was considerably low compared to the sizes of the intervention and control populations and The rate of recruitment of new susceptible persons is equal to the rate of exit of persons from the population in both the intervention and control LGAs.
Table 1 outlines the parameters defined in the model and the assumptions made with respect to their values in the intervention and control LGAs.

Model Equations

The study adopted a simple susceptible-infected-recovered-susceptible (SIRS) model with three state compartments; the susceptible humans (S_h), the infected humans (I_h) and the recovered humans (R_h).[17] A fourth compartment, the model compartment (M_h) was created to model the incidence data from the health facilities, which normally does not account for the exit from the infected compartment (recovered and dead individuals). The transfer of people across these compartments at any given point in time is represented by the compartmental model diagram and the system of ordinary differential equations given below:

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Table 1. Parameters used in the model and their definitions

Parameter	Definition
α	The rate at which infected persons successfully clear the malaria parasite and go back to the susceptible pool without developing immunity
β	The rate at which susceptible persons become infected with malaria following interaction with the infected vector (considering the effect of seasonality)
δ	The rate at which infected persons recover from malaria infection and slowly develop temporary immunity to malaria infection
γ	The rate at which recovered persons lose immunity from malaria over time and become susceptible again.
A	Amplitude (maximum displacement) of the seasonality-forced malaria transmission rate
ω	Angular frequency
ϕ	Phase angle
T	Time (measured in months)

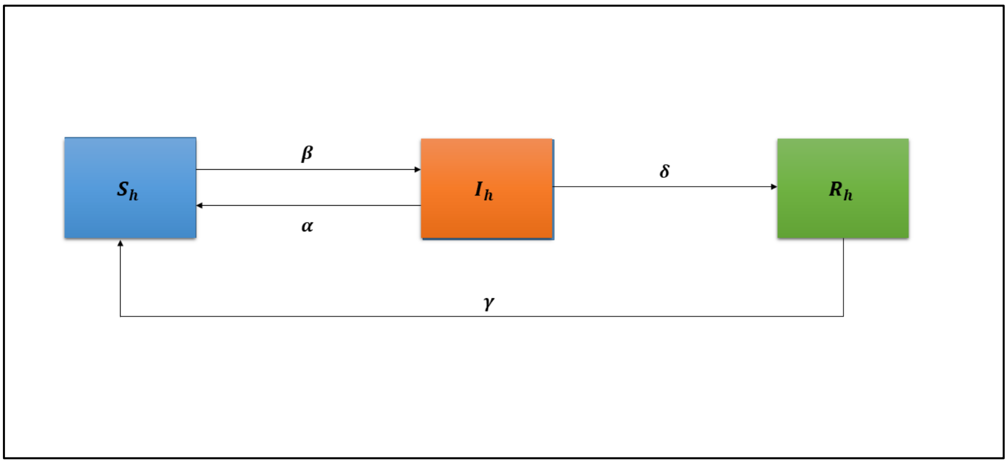

Figure 1: The SIRS model of malaria showing the compartments (states) and the parameters

$$\frac{dS_h}{dt} = -\beta S_h + \alpha I_h + \gamma R_h$$

$$\frac{dI_h}{dt} = \beta S_h - \alpha I_h - \delta I_h$$

$$\frac{dR_h}{dt} = \delta I_h - \gamma R_h$$

$$\frac{dM}{dt} = \beta S_h$$

$$\beta = A\sin(\omega t + \varphi)$$

Ethical Considerations

This study reviewed the archived malaria surveillance data from over a decade ago. The data contained no identifying information with respect to the persons or facilities involved. Thus, informed consents were not obtained from the patients.

Results

A total of 48 data points were obtained from the intervention and control LGAs, representing monthly cases of malaria recorded in the two LGAs between June 2012 and May 2014. The data corresponds to the time when the IRS was implemented in Nassarawa-Eggon LGA of Nassarawa State, North-central Nigeria.

Statistical test

The mean (SD) number of malaria cases per month recorded in the intervention LGA was 1,290 (757) cases, compared to 1,133 (608) cases recorded in the control LGA. Although the mean number of malaria cases in the intervention LGA was higher than the corresponding number in the control LGA, the difference (157 cases, 95% CI: -241 to 556) was not statistically significant ($T_{46} = 0.794$, $p = 0.431$).

Model solutions

Overall, the results of the model-fitting showed a good fit between the numerical solutions and the malaria surveillance data in both the intervention and control LGAs. In the control LGA, the R^2 value obtained was 98.8%, whereas in the intervention LGA, the R^2 value obtained was 95.6%. Figure 2 shows the level of fit between the numerical solutions of the model and the surveillance data in the control LGA, while Figure 3 shows the same fit in the intervention LGA. The two models were fitted with identical parameters, except for the rate of transmission, which the model was allowed to re-calculate for the intervention LGA.

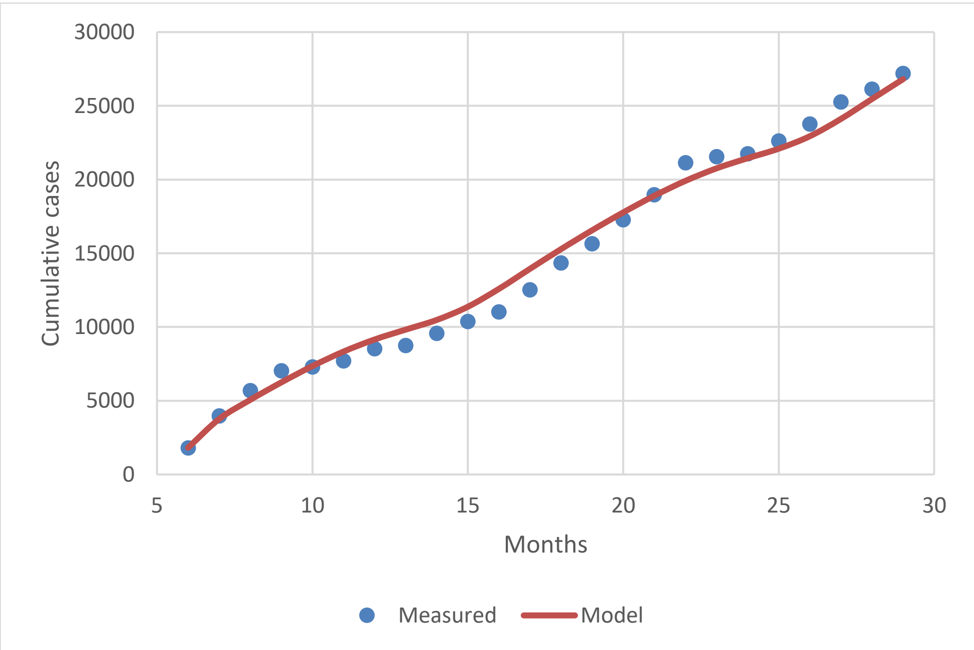

Figure 2. Curve-fitting of model solutions to the surveillance data in the control LGA

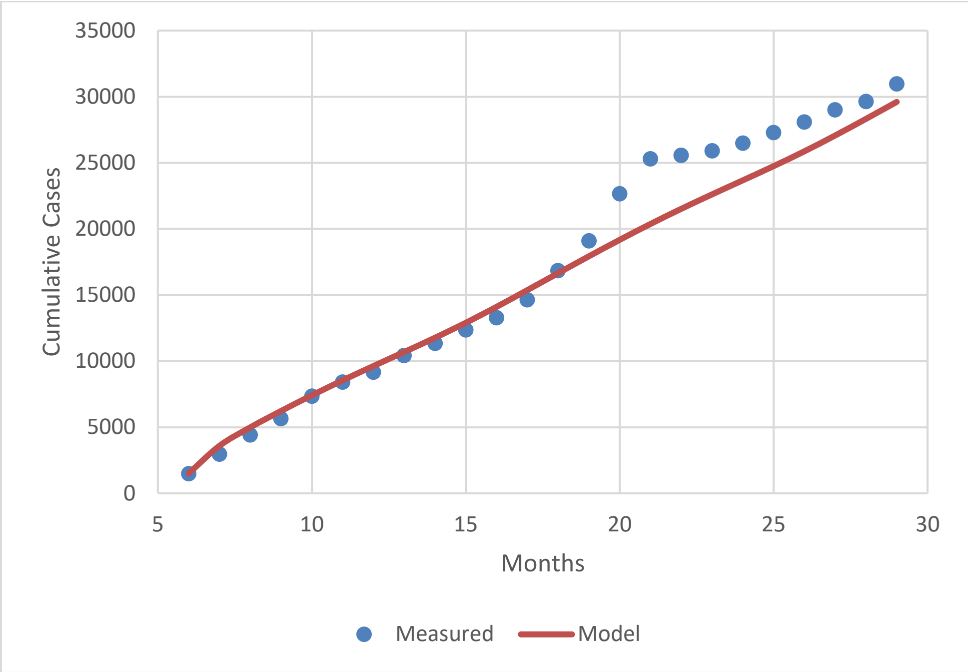

Figure 3. Curve-fitting of model solutions to the surveillance data in the intervention LGA

As shown in Table 2, several of the model parameters estimated in the control LGA were forced on the model in the intervention LGA. Those parameters included the rate of recovery (with and without immunity), and the waning immunity rate. Although the model was allowed to estimate the seasonality parameters in the two settings, the returned set of parameters was nearly identical, except for the amplitude, which was lower in the intervention setting, indicating a lesser influence of seasonality on malaria infection in Nassarawa-Eggon LGA compared to Obi LGA.

Table 2. Parameter values estimated in the control and intervention LGAs

Parameter	**Control**	**Intervention**
Rate of recovery without immunity (α)	0.3275	0.3275
Rate of malaria transmission (β)	1.0514	0.9486
Rate of recovery from infection (δ)	0.5051	0.5051
Immunity waning rate (γ)	0.4714	0.4714
Amplitude (A)	0.6656	0.1957
Angular frequency (ω)	0.5635	0.5635
Phase angle (φ)	3.4437	3.4437

Likewise, the rate of malaria transmission estimated in the intervention LGA (0.9486) was lower than the rate estimated in the control LGA (1.0514), even though the difference was marginal (0.1028). This implies that during the 24-month period, the two rounds of IRS interventions in Nassarawa-Eggon LGA led to a 10% reduction in the rate of malaria transmission compared to the control LGA, assuming all other disease parameters remained constant.

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Discussion

This study modelled the dynamics of malaria in Nassarawa-Eggon LGA of Nassarawa State using routine surveillance data to evaluate the effect of two rounds of IRS implemented in 2012 and 2013. Regarding the statistical approach, the study found no significant difference in the monthly incidence of malaria between the intervention and the control LGAs. In 2018, a similar study that compared the prevalence of malaria in two communities of Jigawa State found that the prevalence of malaria among children under the age of five years in the IRS intervention community (30.3%) was even higher than the prevalence in the control community (23.1%).[10] Several reasons may explain these findings, for example, the considerable time lag between IRS implementation and data collection for evaluation may undermine the true effect of IRS on malaria incidence. It was noted that in the referenced study, the IRS in the Auyo community was implemented in 2016, whereas data for evaluation was collected in 2018 – at least two years after the IRS was implemented. According to the WHO, most of the pyrethroid insecticides used for IRS last for between 3-6 months.[5]

Another factor that could account for the observed non-difference is the adequacy or inadequacy of routine malaria surveillance data as a proxy for true malaria incidence. The malaria surveillance data is typically obtained from public primary and secondary health facilities, where only a proportion of cases are present for treatment. In reality and due to high endemicity, a large number of malaria cases may pass undetected, especially among older children and adults with partial immunity. In addition, due to the prevailing socio-economic circumstances and cultural beliefs, many patients with malaria often resort to self-treatment or visit other service providers, including private facilities, patent medicine vendors and traditional healers. Such cases of malaria will not be captured in the facility-based surveillance data.

Furthermore, the lack of baseline comparability between the intervention and control areas requires careful assessment. For instance, when piloting IRS interventions, control programmes typically choose highly burdened areas for implementation.[10] This means that even when the IRS works, it is often difficult to appreciate it because the comparator area will most likely be a lesser-burdened area to begin with. An alternative to this is to use a control before-and-after design, where the intervention area serves as its own control. Such considerations were deemed impractical in this study because no malaria data could be obtained for the two years preceding the IRS implementation.

Nevertheless, several researchers have noted that even when IRS implementation and surveillance data were undertaken concurrently, technical challenges may still compromise the effectiveness of the IRS.[6] Such technical challenges often involve a lack of adequate spray expertise, poor adherence to spray guidelines, sub-optimal quality of the insecticide, limited coverage and vector resistance to insecticide.[5]

Accordingly, carefully designed studies aimed at evaluating the effectiveness of the IRS in diverse settings have reported clear and substantial effectiveness of the IRS against malaria transmission. The effectiveness of IRS may be demonstrated both when IRS is used alone or in combination with other vector control strategies, even though IRS tends to have a greater impact on malaria transmission when combined with LLIN.[18] In 2016, for instance, a study carried out in Lagos, south-western Nigeria, found that the prevalence of parasitaemia among children under the age of five years was significantly lower in an IRS-implementing community compared to a non-implementing community (1.3 versus 5.8%, $p< 0.001$).[19] The researchers attributed the difference to IRS implementation in the intervention area.

Similarly, a recent systematic review and meta-analysis that investigated the impact of IRS on malaria transmission concluded that IRS as a vector control strategy is associated with a significant decrease in malaria transmission (OR=0.35, 95% CI: 0.27–0.44). The factors that were significantly associated with higher effectiveness were the use of pyrethroid insecticides, high spray coverage (above 80%) and concurrent use of insecticide-treated nets (ITNs).[20]

Regarding the model output, this study found that IRS intervention in Nassarawa-Eggon, over a period of two years, led to a 10% reduction in the rate of malaria transmission. In Cote d'Ivoire, a similar study that examined facility-based surveillance data from 2018 to 2022 found that two rounds of IRS intervention in 2020 and 2021 averted 14,170 cases of malaria in the intervention area.[21] The figure represented a 24.7% reduction in the incidence of malaria during the intervention period. This is considerably higher effectiveness compared to what was observed in this study. It was noted, however, that the IRS programme in Cote d'Ivoire used clothianidin, a newer insecticide that when used correctly, could provide protection for up to 8 months.[7,22] In addition, the researchers did not use the data from the country's Health Management Information System (HMIS) due to inadequacies identified in the system, opting to review medical records stored in the reporting facilities and directly assessing the number of malaria cases during the intervention period.[21]

This study demonstrated the relevance of mathematical modelling in understanding and evaluating the effectiveness of public health interventions. Even when statistical techniques fail to detect any effect, mathematical modelling can reveal salient features about disease dynamics which could potentially lead to better and evidence-informed decision-making. In this study, the model suggested a modest decrease in the rate of malaria transmission associated with IRS interventions in Nassarawa-Eggon LGA, even as the statistical approach failed to detect such a difference. This study observed that while IRS remains an effective vector control strategy, carefully designed studies are needed to demonstrate its impact and special attention must be paid to how it is implemented, the insecticide used, the time and frequency of spray, the degree of coverage and importantly, the quality of data reporting for monitoring and evaluation.

This study is not without limitations. The retrospective nature of the study and the considerable time lag between IRS implementation and the review means that the socio-economic, demographic and environmental contexts in which the IRS was implemented could not be adequately described or accounted for. Consequently, the study was unable to evaluate the role of other malaria control interventions that might have taken place concurrently during the IRS implementation in Nassarawa State.

The study is also limited by the quality of surveillance data reporting because the District Health Management System (DHIS) platform was at its inception when the intervention was implemented. The study noted that reporting then was sub-optimal and irregular. Reporting errors could introduce significant uncertainties in the model by increasing the errors (residuals) term. The considerable challenge in accessing data prior to 2012 also means that the study could not adopt a before-and-after design, an approach that would likely control for the effect of contextual factors in the intervention LGA.

Conclusion

This study examined the effect of IRS on malaria transmission in Nassarawa State, North-central Nigeria using a retrospective quasi-experimental approach. Even though the study found no significant difference in the number of malaria cases recorded in the intervention and control LGAs, a SIRS model estimated a lower transmission rate in the intervention LGA. Important limitations were noted, including the considerable time lag between intervention and the study, as well as uncertainties around the reported cases of malaria. It is recommended that future studies address these limitations by adopting comprehensive IRS implementation protocols and data-gathering activities for proper monitoring and evaluation.

The study therefore proffered the following policy recommendations: Future IRS interventions should consider the effect of spray frequency on the rate of malaria transmission, especially when using insecticides that have short half-lives. This is necessary as insecticides have various durations of effectiveness which may not cover the entire season of peak malaria transmission. In this regard, other factors should be considered such as the timing of the spraying exercise, the quality of the formulated insecticide and the level of expertise of the sprayers.

Future IRS interventions should incorporate strong monitoring and evaluation components that will provide quality data for the assessment of project implementation, outcome and impact. This is important as IRS is expected to affect both the malaria vector indices and the incidence of malaria. The data-gathering mechanism must be strengthened so that real-time quality data for evaluation can be obtained either from the DHIS platform or from the reporting facilities in the sprayed areas.

The National Malaria Elimination Programme (NMEP) should revisit the implementation of various IRS programmes in the country with a view to reviving them. The implementation of the IRS should target highly burdened areas, where substantial gains could be made by spraying relatively small areas. These areas could be high-density urban areas, areas with large seasonal peaks, areas where malaria has a significant economic impact and areas with sustained malaria transmission despite high LLIN coverage. This is very important, given that when correctly implemented, IRS is highly effective in the control of mosquitoes and other disease-spreading vectors.

The NMEP should carefully consider the feasibility and sustainability of IRS vis-a-vis the other malaria control strategies. Oftentimes, concerns relating to the high cost of implementation, demand for trained workforce, social acceptance and spread of insecticide resistance are raised. [23,24] These challenges, however, are by no means restricted to the IRS. There are practical suggestions to limit the cost of the IRS, such as community-led IRS programmes, where health extension workers supervise and manage spray activities in their local domains.[6] Other approaches include the use of targeted sprays, where only selected foci are spayed as well as the use of longer-lasting insecticides, usually in combination or rotational basis to maximize the effectiveness and minimize the spread of resistance. It is important to note that while newer insecticides such as clothianidin come at a higher cost compared to DDT and pyrethroids, they often come with superior advantages. Clothianidin has been shown to provide effective coverage for up to 10 months after a single spray, making it ideal for areas with long rainy seasons. It has also shown widespread activity against various species of mosquito with no demonstrable resistance to deter its application.[25]

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