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Unraveling the 'community effects' of interventions against malaria endemicity: a systematic scoping review

Yura K Ko ,[1,2] Wataru Kagaya,[3] Chim W Chan,[4] Mariko Kanamori ,[5,6] Samuel M Mbugua,[7,8,9] Alex K Rotich,[7,8] Bernard N Kanoi,[7,8] Mtakai Ngara,[1] Jesse Gitaka,[7,8] Akira Kaneko[1,4]

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For numbered affiliations see end of article.

Correspondence to
Dr Yura K Ko;
yurako0603@gmail.com

ABSTRACT

Objectives There is an urgent need to maximise the effectiveness of existing malaria interventions and optimise the deployment of novel countermeasures. When assessing the effects of interventions against malaria, it is imperative to consider the interdependence of people and the resulting indirect effects. Without proper consideration of the effects, the interventions' impact on health outcomes and their cost-effectiveness may be miscalculated. We aimed to summarise how the indirect effects of malaria interventions were analysed and reported.

Design We conducted a scoping review.

Data sources We searched PubMed, Web of Science and EMBASE.

Eligibility criteria We included studies that were conducted to quantify the indirect effects of any interventions for all species of *Plasmodium* infection.

Data extraction and synthesis We used a standardised data collection form to obtain the following information from each record: title, name of authors, year of publication, region, country, study type, malaria parasite species, type of interventions, type of outcomes, separate estimated indirect effect for different conditions, pre-specified to measure indirect effect, secondary analysis of previous study, methods of indirect effects estimation, terms of indirect effects, and if positive or negative indirect effects observed.

Results We retrieved 32 articles and observed a recent increase in both the number of reports and the variety of terms used to denote the indirect effects. We further classified nine categories of methods to identify the indirect effects in the existing literature and proposed making comparisons conditional on distance to account for mosquito flight range or intervention density within that range. Furthermore, we proposed using the words community effects or spillover effects as standardised terms for indirect effects and highlighted the potential benefits of mathematical models in estimating indirect effects.

Conclusions Incorporating assessment of indirect effects in future trials and studies may provide insights to optimise the deployment of existing and new interventions, a critical pillar in the current fight against malaria globally.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ The community effects of malaria intervention, especially the effects of community usage of long-lasting insecticidal nets (LLINs) on non-net users, have long been known.
⇒ The main mechanism of the indirect effects is known to be the changes in the number of malaria-infected individuals (drug or vaccine administration) or mosquitoes (vector control),

WHAT THIS STUDY ADDS

⇒ This research showed that evidence of the indirect effects of malaria intervention is rapidly increasing, especially for interventions other than LLINs.
⇒ We classified the way to identify the indirect effects by the existing literature into nine categories and proposed making comparisons conditional on distance to account for mosquito flight range or intervention density within that range.
⇒ We found the terms used for the indirect effects vary by study and proposed using the words community effects or spillover effects as standardised terms.
⇒ We highlighted the potential benefits of mathematical models in estimating the indirect effects.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Incorporating assessment of indirect effects may provide insights to optimise the deployment of existing and new interventions, a critical pillar in the current fight against malaria globally.

INTRODUCTION

The global fight against malaria has become increasingly challenging in recent years. Despite concerted scale-up of intervention tools, such as the widespread distribution of long-lasting insecticidal nets (LLINs), rapid diagnostic tests and artemisinin-based combination therapies, the estimated global case incidence of malaria in the past few years has stagnated at around 58 cases per 1000 population at risk, while the global mortality rate has remained at approximately 14 per 100 000 population at risk.[1] Moreover, although malaria remains a leading cause of healthcare spending in endemic countries,[2] the amount invested in 2022 fell short of the estimated USD 7.8 billion required globally to achieve the Global Technical Strategy targets set by the WHO.[1] It is anticipated that high-income nations and other international funders will continue to prioritise their efforts to address emerging diseases such as COVID-19 through 2024.[3] In this context, there is an urgent need to re-evaluate existing malaria interventions for more effective deployment, along with the employment of novel countermeasures to reduce the malaria burden more efficiently and cost-effectively.

Malaria is a vector-borne disease transmitted by *Anopheles* mosquitoes. When measuring the effects of interventions against such diseases, it is crucial to consider the interdependence in people, often referred to as 'dependent happenings'.[4] For instance, in malaria-endemic settings, a decline in the number of malaria-infected individuals or mosquitoes will reduce parasite reservoirs and means of transmission in a community, leading to a lower possibility of infection among all community members. Consequently, malaria control measures implemented in a community are expected to yield direct benefits for individuals receiving the interventions and indirect benefits for both individuals receiving and not receiving the interventions. Indirect effects can be defined as the unintended positive or negative consequences of an intervention that influences disease transmission or health outcomes. Thus, without proper consideration of the indirect effects, malaria interventions' impacts on health outcomes and their cost-effectiveness may be overestimated or underestimated. Therefore, adopting a comprehensive and standardised approach to identify both direct and indirect effects is imperative to gain a detailed understanding of intervention impacts. Moreover, evidence of indirect effects will influence policymakers' decisions. If the direct effects are equivalent, an intervention that broadly benefits those who do not receive the intervention is preferable to one that benefits only a limited number of people who receive the intervention.

The concept of indirect effects of malaria intervention, especially LLINs, has long been well known.[5] Nevertheless, the description of indirect effects in the WHO guidelines for vector-borne mosquito control only briefly states that community-level effects of insecticide-treated nets (ITNs) have not always been observed.[6] In addition, the scientific literature on malaria interventions that explicitly differentiate and thoroughly analyse their indirect effects is currently limited.[7] A recent systematic review of the indirect effects of interventions on health in low-income and middle-income countries by Benjamin-Chung *et al*[8] included only two malaria-related studies. Moreover, the methodology of measuring the indirect effects greatly varies, and the terms indicating the indirect effects are not standardised (eg, community effects,[5] spillover effects,[9] mass effects,[10] herd effects,[11] area-wide effects,[12] spatial effects[13] and positive externalities).[14] To address these knowledge gaps, we conducted a scoping review to summarise how the indirect effects of malaria interventions were analysed and reported.

METHODS

Search strategy and selection criteria

Literature search

We searched PubMed, Web of Science and EMBASE by title and abstracts. In addition, for grey literature, we searched OAIster by keywords. Initial searches were conducted in June 2023. We set the search terms as follows: ('malaria' OR 'plasmodium') AND ('indirect effect*' OR 'indirect protection' OR 'herd effect*' OR 'herd protection' OR 'community effect*' OR 'communal effect*' OR 'community-level effect*' OR 'community protection' OR 'communal protection' OR 'community-level protection' OR 'peer effect*' OR 'peer influence effect*' OR 'mass effect*' OR 'assembly effect*' OR 'spillover effect*' OR 'contextual effect*' OR 'free-rider' OR 'free rider' OR 'free-riding' OR 'free riding' OR 'positive externality' OR 'positive externalities' OR 'dependent happenings'). We conducted a secondary search including the term 'disseminated effect' in September 2024. A detailed description of our search strategy is listed in online supplemental table 1.

Eligibility criteria

We included studies that were conducted to quantify the indirect effects of any interventions for all species of malaria infection. We excluded non-original papers such as opinions and editorials. We only targeted articles written in English. We defined indirect effects as the impact accrued by either the non-intervention or intervention group in addition to the direct effects of the intervention. It should be noted that simple comparisons between treatment and non-treatment at a group or individual level are regarded as overall effects and total effects, respectively (online supplemental figure 1).[15] Studies that reported only overall/total effects were excluded from our review. However, if the treatment coverage in the community was considerably low, the group comparisons between treatment and control were considered indirect effects and were included in our review.

Study selection

We imported the data for each relevant publication into reference software (Rayyan, https://www.rayyan.ai/). Prior to the initial screening, duplicate records were deleted automatically. In the first review step, two reviewers (YKK, SMM) screened all records by title and abstract according to the eligibility criteria. Any discrepancies in the process were resolved by discussion between both reviewers. Once a record was selected, its full text was reviewed by at least two of five reviewers (YKK, WK, CWC, MK and AKR). Specific data (see the section 'Data extraction and analysis') were recorded and summarised in a tabular form through this second review step.

Any disagreement was addressed through discussion. Additional reference and citation searches were also conducted. The reference lists of the articles identified during the search were scanned manually, and eligible articles were included in the full-text reading. In addition, we included an additional article that was published after the initial screening.[16]

Data extraction and analysis

We used a standardised data collection form to obtain the following information from each record: title, name of authors, year of publication, region, country, study type, malaria parasite species, type of interventions, type of outcomes, separate estimated indirect effect for different conditions (yes/no), pre-specified to measure indirect effect (yes/no), secondary analysis of previous study (yes/no), methods of indirect effect estimation, terms of indirect effects, and if positive or negative indirect effects observed (yes/no). Positive and negative effects indicate that the indirect effects of the intervention lower or raise the risk of malaria outcome, respectively. A detailed description of the extracted data is in online supplemental table 2. Standardised labels were made for each term for inconsistencies of words, as listed in online supplemental table 3.

Quality of study methodology for estimating indirect effect

We used the classification of risk of bias for indirect effect estimation proposed by Benjamin-Chung *et al*.[8] We only assessed the risk of bias for field epidemiological studies, excluding mathematical modelling studies and experimental hut trials. Each eligible study was classified as 'very low', 'low', 'medium' or 'high' in terms of the reliability of indirect effect estimation.

Reporting of the results

We followed the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for scoping reviews (PRISMA-ScR).[17] The PRISMA-ScR checklist of the present study can be found in online supplemental file 2.

RESULTS

Study selection

Figure 1 illustrates a PRISMA flow diagram depicting the identification, screening, eligibility and exclusion process of the studies. A total of 664 articles were identified through database searches (n=570) and other sources (n=94). 368 duplicate articles were removed. 38 articles met the eligibility criteria after review of titles and abstracts; 258 studies were excluded for one or more of the four following reasons: (1) different meanings of indirect effect, (2) not malaria-specific intervention, (3) not intervention study and (4) not reporting indirect effect. Different meanings of indirect effect refer to studies that examined the relationship between malaria and other diseases or estimated indirect effects through causal mediation analysis[18] rather than the indirect effects as defined in our study. Notably, among the studies excluded because of different meanings of indirect effect, 14 studies evaluated the indirect relationship between COVID-19 and malaria.[19–32] Six articles were added from a manual search of reference lists of the 38 eligible articles from the initial screening, and one article published after the initial screening was added. Of these 45 studies, 32 were included in this review after full-text reading. The reasons for exclusion in the full-text reading were (1) reporting total effect only (n=7), (2) opinion or review article (n=3), (3) estimating indirect effect in the context of mediation analysis (n=2) and (4) not reporting indirect effect (n=1).

Study characteristics

Details of the 32 reviewed studies are summarised in online supplemental table 4. Most studies were set in African countries (n=25; 78%) and examined the indirect effects of interventions on *Plasmodium falciparum* (n=19; 59%). Temporal trends in study types, intervention types, and terms used to describe indirect effects are illustrated in figure 2. Overall, until year 2000, very few studies purposefully reported indirect effects. Subsequently, there was a sharp increase in reporting from

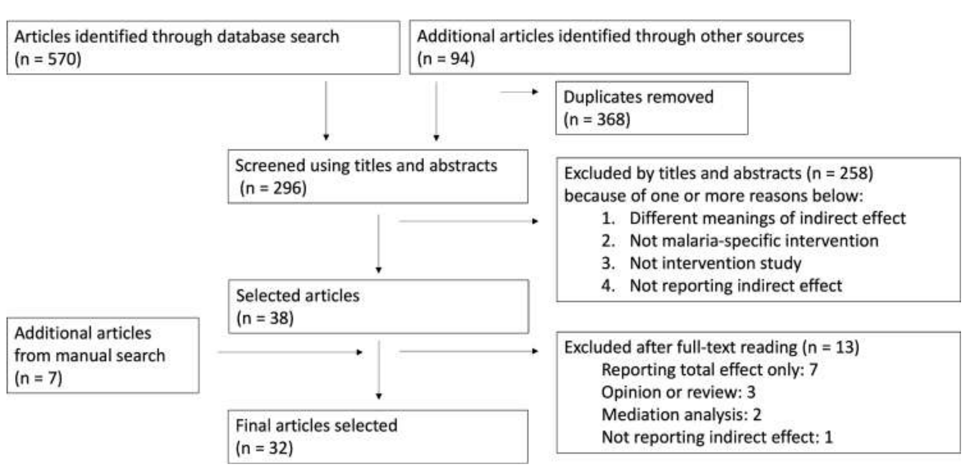

Figure 1 PRISMA flowchart of study selection. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analysis.

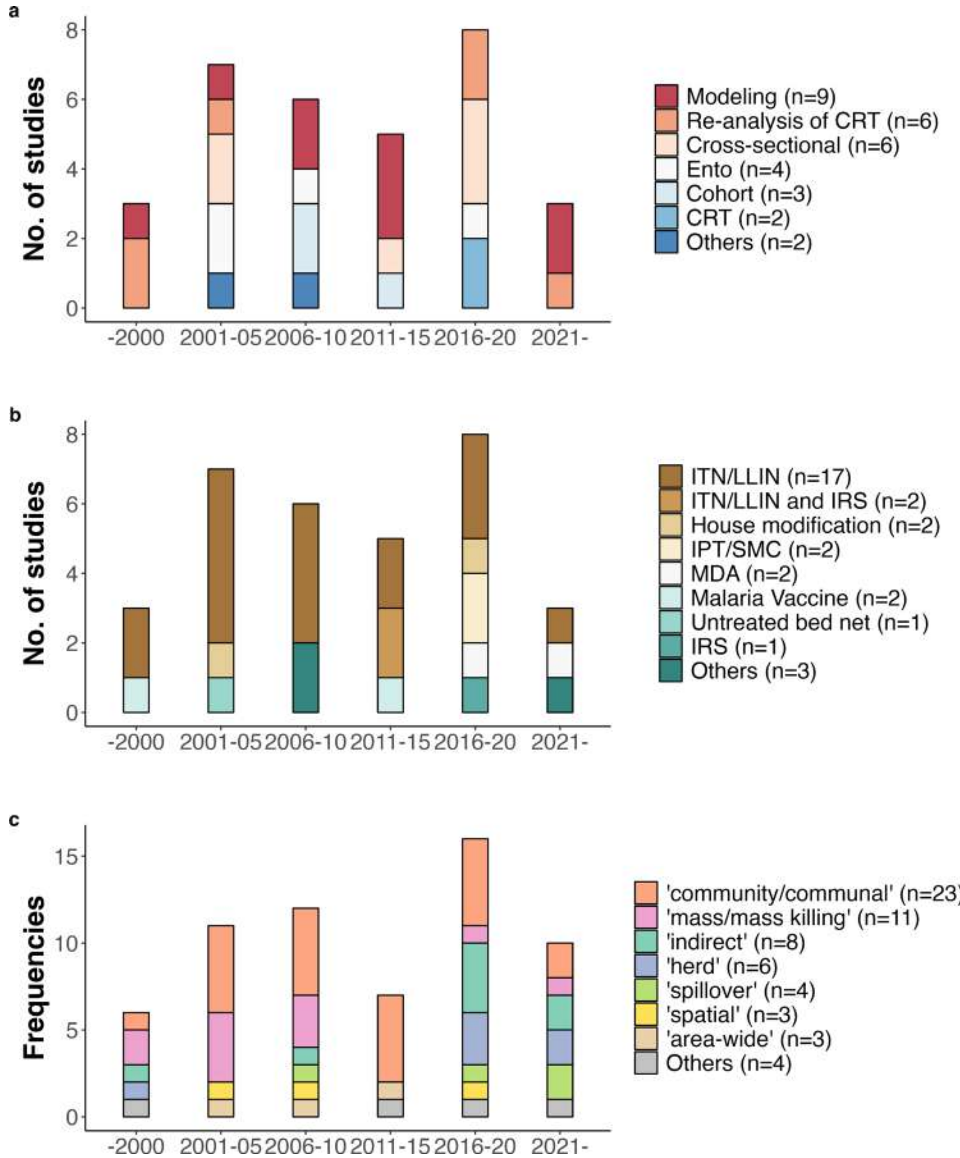

Figure 2 Time trend of study characteristics. (a) Study type. (b) Intervention type. (c) Term used to describe the concept of indirect effects. Note that for (c), the total number of terms in the graph does not correspond to the total number of studies (n=32), as multiple terms can be used in a single paper. CRT, cluster randomised trial; Ento, entomological survey; IPT, intermittent preventive treatment; IRS, indoor residual spray; ITN, insecticide-treated net; LLIN, long-lasting insecticide-treated net; MDA, mass drug administration. For the study type, 'Others' included analysis of passive case detection using surveillance data. For intervention type, 'Others' included access to free antimalarials, target subsidies of ITNs and reactive-focal chemoprevention with IRS. Regarding indirect effect terminology, 'Others' included assembly effects, population effects, group-level effects, positive externality and dependent happenings.

2001 to 2005, followed by a gradual decline. Since 2016, there has been an upward trend once again (figure 2a). The most common study type was mathematical modelling (n=9; 28%), followed by cross-sectional surveys (n=6; 19%) and re-analysis of cluster-randomised trials (n=6; 19%) (figure 2a). The most common interventions were ITNs or LLINs (n=17; 53%). Until 2015, the focus was primarily on ITN/LLIN-related interventions. However, since 2016, reports on various interventions such as house modification, intermittent preventive treatment (IPT), seasonal malaria chemoprevention (SMC) and mass drug administration (MDA) have emerged (figure 2b). The most common terms used for indirect effects were 'communal' or 'community' effect/benefit/protection (n=23; 72%), followed by 'mass' or 'mass killing' effect/benefit/protection (n=11; 34%). Until 2015, the use of communal/community effect and the mass effect dominated, but more recently, various terms have come into use, including herd effect, indirect effect, spatial effect and spillover effect (figure 2c). Among 22 studies eligible for quality assessment of evidence, 7 (32%) had high-quality evidence, 7 (32%) had moderate, 5 (23%) had low and 3 (14%) had very low-quality evidence. Of studies with high-quality evidence, 6 (86%) used cluster-randomised designs.

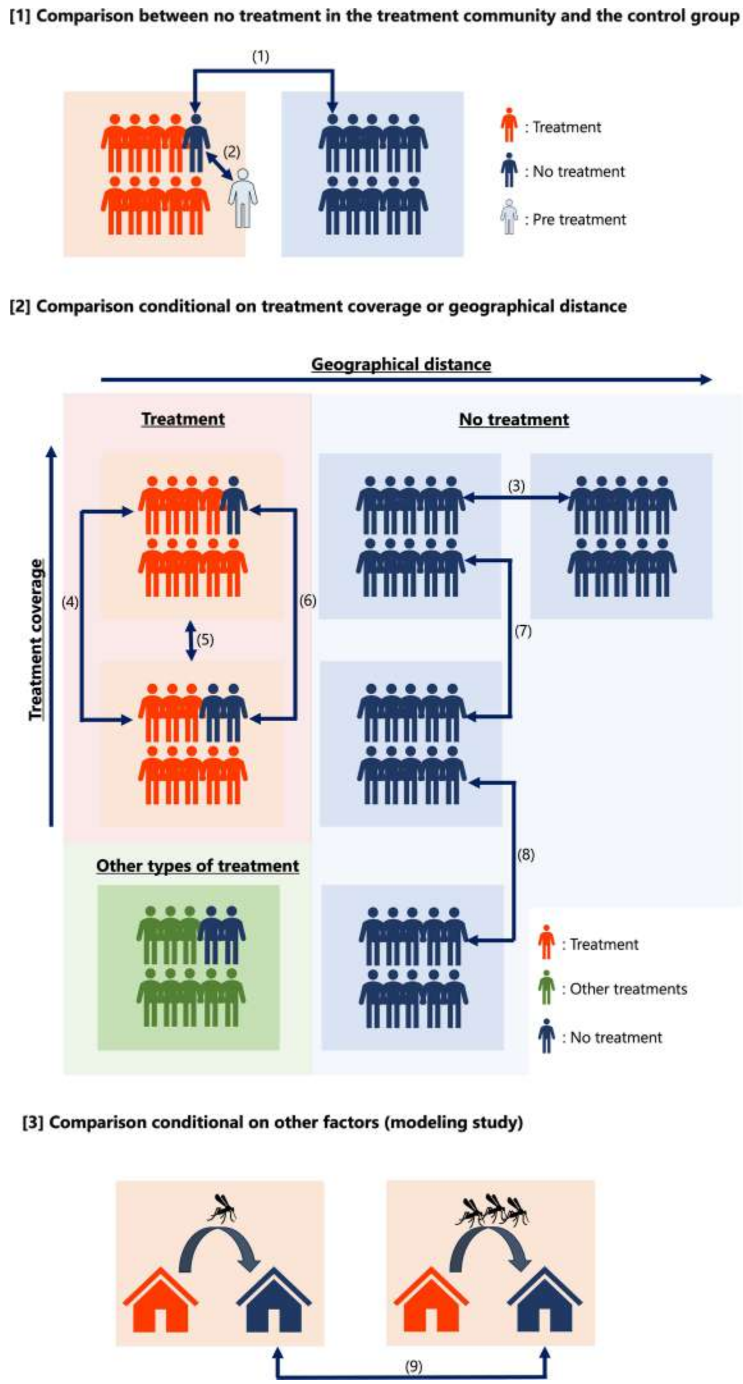

Figure 3 Categories of indirect effect analysis methods. [1] comparison between non-treatment recipients in the treatment community and the control group, (1) comparison not conditional on treatment density nor geographical distance, (2) pre-post comparisons among non-recipients, [2] Comparison conditional on treatment coverage or geographical distance, (3) comparisons among non-recipients according to distance to the treatment cluster, (4) comparisons within the treatment area according to the coverage among those who received the treatment, (5) comparisons within the treatment area according to the coverage, including both those who received treatment and those who did not, (6) comparisons within the treatment area according to the coverage among non-recipients, (7) comparisons among non-recipients according to the coverage of the nearest treatment clusters, (8) comparisons among non-recipients according to the types of treatment of the nearest treatment clusters, [3] (9) comparisons conditional on other factors such as the repellent and killing effects of ITNs, pre-erythrocytic or blood-stage vaccine efficacy, endemicity of study area and the connectedness between different areas. Type [3] only applies to mathematical modelling studies. If one of these did not apply, it was recorded as 'Others'.

Overview of methods for indirect effect analysis

Among all included studies, each intervention's indirect effect was evaluated in relation to reductions in malaria transmission. Figure 3 shows the categories of methods for indirect effect estimation identified through this review. In addition, a detailed description of the methods by intervention type is listed in online supplemental table 5.

Field studies (epidemiological and entomological studies)

Among field studies, including epidemiological and entomological studies, 59% pre-specified analysis of indirect effects (n=13). Comparisons of non-treatment populations in intervention communities with non-intervention communities or pre-post analyses of these populations ((1) and (2), respectively, in figure 3) were employed by eight studies.[10 33–39] On the other hand, comparison among no-intervention individuals/groups according to distance to the treatment household or the treatment coverage within a certain distance range was employed by 17 studies ((3)–(8) in figure 3).[5 10–13 35 38 40–48]

There were two patterns of comparisons conditioned on the distance to the nearest intervention. First, the comparisons among non-recipients based on differences in distance to the nearest intervention were reported in five studies[5 40 42 44 48] ((3) in figure 3), all of which evaluated the impacts of ITN. There were two analytical approaches. One was to compare between groups stratified by the distance category set at 100–400 m intervals, with the most distant group as the reference. In all studies, households without ITNs within 300–400 m of households with ITNs had the lowest risk of malaria-related outcomes (eg, malaria parasitaemia, mosquito density, anaemia and all-cause mortality). Another approach to measuring indirect effects by conditioning on distance was trend analysis, in which regression was performed with distance as an explanatory variable. Around year 2000, researchers simply incorporated distance into the model as a continuous variable,[40 42] but recently, Jarvis *et al* have used a quadratic term to account for the non-linearity called 'distance decay' in spatial analysis.[48] The study reported that for every additional 100 m that a control household was from an intervention household, the all-cause mortality for children aged 6–59 months increased by 1.7%.[48] Another approach conditional on distance was comparisons among non-recipients according to the types of treatment of the nearest treatment clusters ((8) in figure 3). Benjamin-Chung *et al* estimated the indirect effects of reactive-focal combination of chemoprevention and indoor residual spray among non-recipients who resided up to 3 km from the index cases.[16]

Regarding interventions conditional on treatment coverage, two patterns were observed: comparing among intervention populations ((4) and (5) in figure 3) and among non-intervention populations ((6) and (7) in figure 3). The definition of the areal unit for calculating intervention coverage varied from study to study, with a single cut-off determined by a 100-m to 3-km radius of the subject's household,[5 11 13 47] multiple distances used in an exploratory manner[10 43 45] and using primary sampling units.[12 46] There were also two approaches to analysing indirect effects: one in which groups were stratified by intervention coverage and the other in which regression analysis was performed by incorporating intervention coverage as an explanatory variable. In the analysis that stratified groups by intervention coverage, the coverage categories varied. For instance, Hawley *et al* defined ITN coverage categories as 1%–24%, 25%–49% and 50%–75%,[5] while Parker *et al* stratified MDA coverage as <70.6%, 70.6%–80% and >80%, based on tertiles of observed adherence.[11] A summary of intervention coverage and stratified categories for studies comparing outcomes conditional on treatment coverage is provided in online supplemental table 6.

Several approaches other than the above-mentioned methodology were used to evaluate the indirect effects (categorised as 'Others' in online supplemental table 4). Jarvis *et al* (2019) showed that the treatment effects changed after reallocating the treatment and control cluster assignments based on the distance to the nearest treatment cluster.[48] Oduor *et al* (2009) suggested positive indirect effects by confirming that the direct treatment effects were enhanced when spillovers to the neighbouring sublocations were accounted for.[9] In addition, Staedke *et al* (2018) evaluated the effect of IPT in school children by comparing the reduction in malaria prevalence in all age groups between the intervention and control clusters.[37] The risk reduction was regarded as a community-level effect because the treatment coverage was considerably low (only school children among all age groups). The detail of these methods was shown in online supplemental figure 2.

Only three studies examined indirect effect heterogeneity.[12 16 47] Escamilla *et al* (2017) reported that an increase in community bed net coverage was significantly associated with a decrease in malaria prevalence among children under 5 years and 5–19-year-olds, but no association was observed among adults older than 20 years.[47] In another study by Larsen *et al* (2014), subgroup analyses were performed, stratified by rural vs urban areas and low vs high malaria transmission; however, no significant effect heterogeneity was observed.[12] In four studies, positive indirect effects were not observed, or negative indirect effects were observed with increased treatment coverage.[43 45–47] All four studies were observational studies. Among the field studies, 59% pre-specified analysis of indirect effects (n=13).

Mathematical modeling studies

Among nine studies employing mathematical models,[14 49–56] two-thirds (n=6) aimed to estimate the indirect effects of ITNs/LLINs, comparing outcomes before and after the intervention in the non-intervention group or altering parameters of intervention coverage through simulation. No mathematical modelling studies conducted a comparison based on distance conditioning, likely due to the infrequent use of spatial data in malaria transmission models. One notable characteristic of mathematical models is their ability to vary efficacy by changing more detailed parameters of interventions, such as the repellent and killing effects of ITNs,[14] vaccine target for pre-erythrocytic or blood-stage *P. falciparum*,[54] endemicity of study area[55] and the connectedness between different areas[50 55] ((9) in figure 3).

We also found another mathematical modelling approach for estimating indirect effects. Unwin *et al* (2023) disentangled the direct and indirect effects of ITNs by comparing fixed entomological inoculation rates (EIR) over time in a counterfactual scenario with the reduction in EIR caused by a decrease in infected individuals and mosquitoes.[56]

DISCUSSION

To our knowledge, this is the first systematic scoping review on the indirect effects of malaria intervention. We reviewed studies whose titles or abstracts included terms indicative of indirect effects (except some articles from manual searches) and revealed that the number of such studies has increased in recent years, especially for interventions other than ITNs/LLINs. In addition, although not included in this review, an opinion piece[7] and a methodology study[57] have recently been published relating to the indirect effects of malaria intervention. In light of the increasing interest in the indirect effects of malaria interventions, a scoping review summarising previous studies is pertinent and salient.

We found that several terms have been used to convey indirect effects. Apart from the 'mass/mass killing' effect, which refers to the reduction of malaria transmission by decreasing the mosquito abundance or density through insecticides, other terms such as community effects, spillover effects, mass effects and herd effects have been used interchangeably to denote indirect effects. Historically, indirect effects of malaria control interventions have often been labelled as community effects, especially for ITNs/LLINs (online supplemental figure 3) and in the WHO vector control guideline.[6] In recent years, there has been more diversity in the terminology, particularly for interventions other than ITNs/LLINs. This diversity of terminology may create confusion and make it difficult for literature search on this topic. We propose using either community effects or spillover effects, a widely used term in general epidemiology,[8 58] when reporting indirect effects in malaria control, regardless of the type of intervention.

We found that studies varied in their methodology for estimating indirect effects, although most can be typified into nine categories (figure 3). Since malaria parasites are transmitted via mosquitoes, it is appropriate to make comparisons conditional on distance to account for mosquito flight range or intervention density within that range. Without data on treatment coverage or distance to intervention areas, only simple comparisons between non-recipients in the treatment community and the control group ((1) and (2) in figure 3) can be employed. However, it is important to acknowledge the limitations of these methods, particularly the potential for systematic bias between comparators and the inability to observe dose-response relationships. There were no consistent criteria for conditioning on treatment coverage or distance. For instance, both approaches were frequently used in studies assessing the indirect effects of ITNs/LLINs (online supplemental table 5). Rather than determining whether to condition on treatment coverage or distance based solely on the type of intervention, it is likely that the study design and the available data will dictate the method of comparison. For instance, if all intervention areas exhibit high coverage rates (≥80%), it is more appropriate to compare outcomes based on distance to the treatment areas rather than conditioning on treatment coverage. In fact, the studies we reviewed, which conditioned on coverage, had a wide range of treatment coverage (online supplemental table 6). Furthermore, when examining indirect effects in the context of multiple interventions (eg, factorial design), conditioning on distance may be more appropriate, as it is not feasible to compare different interventions in terms of coverage ((8) in figure 3).[16]

According to our results, non-recipients can be categorised into two groups based on how the data was collected. The first group consists of non-recipients who were within the control cluster/area and were originally sampled as direct effect comparators ((3), (7) and (8) in figure 3). The second group comprises those who were in the intervention cluster/area but did not receive the intervention because they were non-eligible ((6) in figure 3). The former are often intended to be sampled and, therefore, allow for easier pre-sample size calculations for indirect effect estimation. The latter, however, require prior knowledge of the proportion of non-eligibles, making sample size calculations more difficult and likely to result in underpowered studies. Moreover, even within the framework of a randomised trial, it might not be comparable among non-eligibles. Therefore, when comparing the non-treated within intervention clusters, double-randomised trials,[59] which minimise selection bias and unmeasured confounding, are considered the recommended approach.[8 58] However, we did not find any studies in our review that performed two-stage randomisation. One possible reason is that a double-randomised trial is not always feasible, especially in the evaluation of malaria interventions. Because of the additional allocation of controls within the intervention cluster, more samples or reduced intervention coverage are needed to obtain sufficient power for the estimation of the indirect effect. In addition, in malaria, there are interventions that target subpopulations in the community, such as IPT, SMC, and vaccination targeting children or pregnant women. In these interventions, untargeted individuals in the treatment group and their counterparts in the control group (ie, individuals who would be ineligible if they were assigned to the treatment group) may be comparable, effectively emulating a cluster-randomised trial design, which would not necessarily require a two-stage randomisation. If using a cluster-randomised design or analysing observational studies in which ineligible populations are not comparable to eligible populations, matching should be considered. It should be noted, however, that even with matching, unmeasured confounding may remain, and external validity may be reduced.[58 60]

Four studies either did not identify a positive indirect effect or reported a negative indirect effect.[43 45–47] There are several reasons for not observing positive indirect effects. First, indirect effects, in general, tend to be smaller than direct effects; studies designed to detect direct effects as primary objectives are often underpowered to detect indirect effects.[8] For instance, vector control measures reduce malaria transmission by reducing EIR in the community, but EIR and parasite prevalence are not linearly related,[61] and a substantial EIR reduction would be required to reduce malaria prevalence among non-recipients. In addition, it should be noted that subgroup analysis of indirect effects for effect heterogeneity would have even lower power. Second, there is the potential confounder of residents' behaviour associated with both intervention compliance and the outcome. Residents' compliance with interventions may depend on their perception of the risk of malaria transmission in the community and mosquito density.[62] For example, increasing community net usage is often associated with increasing mosquitos and malaria risk.[63] So, comparisons between non-recipients, especially when conditioned on coverage, may underestimate indirect effects. In addition, characteristics of non-recipients such as socioeconomic status, healthcare access and malaria preventive behaviour may be different according to community treatment coverage, especially in an observational study setting.[64] Third, migration of infected individuals and mosquitoes between targeted and untargeted areas may have reduced the impact of the intervention in targeted areas.[39] No field studies conducted to date have taken into account these human and mosquito mobility to estimate indirect effects. Nevertheless, the impact of mosquito and human migration on transmission could be partially captured through the distance-conditioned analysis.

Recently, there has been a substantial upsurge in the number of mathematical modelling studies on malaria.[65] In agent-based models, estimating the impact of an intervention in the non-intervention population is straightforward within any simulation; thus, we had expected a greater number of modelling studies that estimated indirect effects. However, only nine mathematical modelling studies were included in our review. It is possible that our screening, based on keywords in titles and abstracts, excluded many of these studies. This also supports the importance of our proposal on standardising the terms used to refer to an indirect effect. An advantage of mathematical modelling is the ability to examine changes in indirect effects not only by varying the coverage of the intervention but also by adjusting other parameters, such as deterrent and insecticidal effects in the case of ITNs/LLINs, simultaneously. It would be beneficial to take advantage of mathematical models and consider parameters for which data are not reliably quantified. For example, the main advantage of house modification is that once installed, it remains semipermanent. Therefore, its effect is less susceptible to variations in human behaviour,[66] such as repurposing and inconsistent uses of LLINs.[67] Incorporating such behaviours into the model and estimating the indirect effects on those who do not receive the intervention will have important implications for the widespread implementation of the intervention. On the other hand, it should be noted that many malaria transmission models did not explicitly account for the spatial distribution of humans and vectors,[49 51 53 54 56] which can sometimes offset the indirect effects of interventions. Therefore, the values estimated by mathematical models, especially regarding their magnitude, should be interpreted with caution.

One of the limitations of our study is that the search strategy may not have captured all relevant articles. We searched for keywords in the titles and abstracts, potentially missing studies that only reported the indirect effects of malaria interventions within the full text of the article. While efforts were made to manually include references cited for indirect effects, they were unlikely to be complete. Additionally, Benjamin-Chung *et al* noted evidence of publication bias reporting for indirect effects.[8] Second, we did not summarise the magnitude of indirect effects for each intervention in this review, as the primary aim of this scoping review was to identify how the indirect effects of malaria interventions were analysed and reported. Moreover, since these effects are likely to vary due to factors such as region, population and seasonality, and given that most of the included studies were on LLINs, we believe that comparing the effects of different interventions is challenging. A more comprehensive systematic review of the evidence on indirect effects, along with meta-analyses estimating the pooled effects of the indirect effects for each intervention, is warranted as more studies reporting these outcomes are published in the future. Third, we could not assess the quality of evidence in each mathematical modelling study due to the lack of expertise in this field. More collaboration with mathematical modellers specialising in malaria transmission is needed to develop standardised grading for evaluating the quality of such studies in estimating the indirect effects of malaria intervention. Nonetheless, this review aimed to pave the way for improved design and reporting of future research on the indirect effects of malaria interventions. By highlighting this critical area, we hope to contribute to a more appropriate evaluation of intervention effectiveness.

In conclusion, our review notes an increase in the number of studies that measured the indirect effects of malaria interventions in recent years. We outline nine comparative schemes by which indirect effects of malaria interventions can potentially be quantified, and propose standardised terms for describing indirect effects. We further support the use of mathematical models to inform the evaluation of indirect effects of malaria interventions. Incorporating assessment of indirect effects in future trials and studies may provide insights to optimise the deployment of existing and new interventions, a critical pillar in the current fight against malaria globally. In addition, evidence about the cost-effectiveness of interventions, taking into account the indirect effects, will lead to better-informed decisions by policymakers.

Author affiliations

[1]Department of Microbiology, Tumor and Cell Biology, Karolinska Institute, Stockholm, Sweden
[2]Department of Virology, Tohoku University, Sendai, Japan
[3]Department of Ecoepidemiology, Institute of Tropical Medicine (NEKKEN), Nagasaki University, Nagasaki, Japan
[4]Department of Virology and Parasitology, Osaka Metropolitan University, Osaka, Japan
[5]Department of Public Health Sciences, Stockholm University, Stockholm, Sweden
[6]Institute for the Future of Human Society, Kyoto University, Kyoto, Japan
[7]Center for Research in Infectious Diseases, Directorate of Research and Innovation, Mount Kenya University, Thika, Kenya
[8]Centre for Malaria Elimination, Mount Kenya University, Thika, Kenya
[9]School of pharmacy and health sciences, United States International University Africa, Nairobi, Kenya

X Yura K Ko @YuraKKo3

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ORCID iDs

Yura K Ko http://orcid.org/0000-0002-3493-0180
Mariko Kanamori http://orcid.org/0000-0001-8733-1336

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