Pilot decision workshop to aid prioritization of resources for malaria control in Ghana

Meeting report,
12–13 September 2022

World Health Organization

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Contents

ABBREVIATIONS

BAU	business as usual
IRS	indoor residual spraying
ITNs	insecticide-treated nets
MINT	Malaria Intervention Tool
NSP	National Strategic Plan
NSP_mod	Modified National Strategic Plan
PBO	piperonyl butoxide
STAR	Socio-Technical Allocation of Resources framework

SUMMARY

New technologies for malaria control will shortly become available. However, in the absence of new funding sources, these technologies can be funded only if malaria programmes cut back on some of their current activities or on levels of current coverage for specific interventions. To aid this challenging decision-making process, a robust and acceptable prioritization framework is needed for malaria programmes. On 12–13 September 2022, a 2-day workshop organized by the World Health Organization was held in Accra, Ghana (one of 11 high-burden malaria countries), with members of the Ghana National Malaria Elimination Programme and local technical experts to pilot a new prioritization framework (see **Annex 1** for the list of participants and **Annex 2** for the meeting agenda). The framework was based on application of the Malaria Intervention Tool (MINT) and the Socio-Technical Allocation of Resources (STAR) framework. Before the workshop, several simulations were conducted of the likely impact of the vector control provisions in the Ghanaian National Strategic Plan (NSP) and Modified National Strategic Plan (NSP_mod) – for both of which only partial funding is available – relative to business-as-usual and "no new interventions" baselines. According to this preliminary analysis, although NSP_mod shows smaller reduction in disease burden compared to NSP, this comes with a very large saving in costs, due to substitution of indoor residual spraying with pyrethroid–pyrole insecticide-treated nets and piperonyl butoxide (PBO) nets. This finding was somewhat controversial for the workshop participants, but it was agreed that more information would be needed before any conclusions about optimal resource reallocation could be reached. To this end, it was agreed to conduct additional analysis, revising assumptions on both current and optimal coverage levels, to take into account likely availability of resources. The feedback gathered from the participants through an anonymous evaluation questionnaire about the prioritization framework itself was broadly positive. Nevertheless, the workshop highlighted several critical modelling assumptions about costing, the baseline and budget for the decision, the lack of good-quality entomological data at a district level, and the values of the Ghanaian stakeholders, which can help refine and improve the prioritization methodology and guide similar workshops in future.

1. BACKGROUND

The past couple of decades have seen a renewed global focus on malaria control, with new funding streams coming through initiatives such as the Global Fund to Fight AIDS, Tuberculosis and Malaria, and the United States President's Malaria Initiative. As a result of this renewed focus, a range of new technologies are coming onstream, ranging from new vector control tools to a malaria vaccine, which can add to countries' armamentarium in the struggle against malaria.

Unfortunately, the global economic picture in general and the prospects for development aid for health in particular are looking increasingly unfavourable. At the same time, increasing mosquito resistance to insecticides – most importantly pyrethroids – challenges the gains that have been made to date.

Protecting current progress and advancing beyond by using new technologies will therefore occur in a challenging financial environment. Unless some source of additional money unexpectedly appears, the only way to introduce these new technologies into malaria programmes will be to swap them for something else. To do so rationally will require a robust prioritization framework that is informed by the best available evidence about effectiveness and cost-effectiveness, can be adapted to the specific context of local settings, and is sufficiently transparent to inspire confidence in stakeholders.

2. PROJECT OBJECTIVES AND THE CONTENT OF THIS REPORT

The objectives of the current workshop were:

- to try two complementary approaches – the Malaria Intervention Tool (MINT) and the Socio-Technical Allocation of Resources (STAR) framework – viewed as jointly having the potential to support planning for the control and management of malaria, with the focus on vector control interventions (namely, pyrethroid-only, pyrethroid–piperonyl butoxide (PBO) or pyrethroid–pyrole insecticide-treated nets (ITNs), and indoor residual spraying (IRS)); and

- to provide insights for the Ghanaian National Malaria Elimination Programme (NMEP) that complement other sources of information, support choices about vector control delivery, and help justify the need for resources for the programme.

MINT[1] is a tool developed by Dr Ellie Sherrard-Smith and Professor Tom Churcher at Imperial College London. MINT is a user-friendly web-based interface that allows users to perform interactive "what if" analyses to understand the effectiveness and cost-effectiveness of different vector control choices for territories and populations with particular entomological and epidemiological parameters. Behind the interfaces is a database containing pre-run 3-year trajectories for multiple combinations of parameter settings, based on simulations from the dynamic mechanistic mathematical model of *Plasmodium falciparum* malaria developed by Imperial College (Sherard-Smith et al., 2022).

1 https://mint.dide.ic.ac.uk/

STAR[2] is a process developed by Dr Mara Airoldi, Professor Gwyn Bevan and Professor Alec Morton, who were at the London School of Economics, and Jenifer Smith, who was Chief Medical Officer and Director of Public Health for the Isle of Wight (Airoldi et al., 2014). The aim of the STAR approach is to translate and apply cost-effectiveness and health economics concepts as part of a priority-setting exercise by stakeholders. The process is socio-technical in that it recognizes that a sound priority-setting process draws on human knowledge and is informed by human values in a deliberative setting (the social part), but also draws on evidence and scientific understanding (the technical part). A web-based software tool to support STAR is available, but it was not used in the current pilot because it was developed for a different context, with important differences in how several input and output values are processed; instead, the STAR displays were replicated in Microsoft Excel.

In advance of the workshop, project participants received several briefing materials, including a summary of the main assumptions used for scenario simulations and background readings, so that they could familiarize themselves with the MINT and STAR tools. In addition, extensive communication took place between the analytical team from the World Health Organization (WHO) and the NMEP focal point, with the aim of clarifying key scenario assumptions and obtaining relevant data.

The workshop comprised a capacity-building introduction to MINT on Monday morning (12 September 2022), a project-specific MINT session on Monday afternoon and a STAR session on Tuesday morning (13 September). The aim was to help the NMEP evaluate relative value for money of three approaches defined by the NMEP: business as usual (BAU), the National Strategic Plan (NSP) and the Modified National Strategic Plan (NSP_mod), including consideration of equity and feasibility of alternative scenarios. A short hands-on session was also run, where workshop participants simulated impacts of some scenarios with MINT themselves to project epidemiological and economic impact.

The following three scenarios were agreed with the NMEP based on existing national planning and realistic future changes.

1. BAU maintains the intervention mix historically used within an area.
2. NSP extends BAU by bringing new pyrethroid–PBO ITNs into some regions (at a level deemed feasible, given potential supply constraints) and IRS into some regions.
3. NSP_mod looks at scenarios where some IRS is replaced with pyrethroid–PBO ITNs and novel pyrethroid–pyrole ITNs are introduced in specific sites.

3. MINT

The MINT session was led by Professor Tom Churcher from Imperial College London. MINT was used to simulate the impact of three scenarios – BAU, NSP and NSP_mod – on two outcomes: mean malaria cases averted per population in the 3 years since intervention, and total costs of scenario implementation. These outputs were then used within the STAR framework as a priority-setting exercise. Different coverage levels were considered: either maintaining the recently observed existing coverage or

2 https://startool.co.uk/

scaling up to national targets in that particular region (assumed to be 80% ITN use or 90% of sleeping structures sprayed for IRS). For more information about the modelled scenarios, see Annex 3.

No analysis of potential modifications to the vector control intervention mix within the current funding envelope was undertaken during the workshop. This was mainly the result of the data and time constraints of the projects – it was only possible to analyse three main scenarios provided by the country in advance of the meeting. However, the analysis was conducted at both aspirational target coverage levels and more realistic (current) coverage levels, based on actual use of ITNs and IRS in 2019. Moreover, the STAR prioritization framework is designed to be used iteratively, with additional scenarios often emerging as a result of a deliberative process, rather than being fully predefined in advance of the meeting. This is what occurred during the workshop, as discussed below.

The data to feed the MINT analysis were mainly provided by the NMEP, including on the district-level population, the seasonality of transmission, malaria prevalence in children under 5 years of age, region-level ITN use in the last survey (2019), districts where IRS was conducted before the current NSP, and district-level mass distribution campaign target levels for ITNs and IRS campaigns according to the three scenarios. In addition, assumptions were made (see **Annex 3**), based on the available sources of information, for the following MINT inputs: preference for mosquitoes blood-feeding outdoors; preference for mosquitoes biting people rather than alternative hosts; the level of pyrethroid resistance (as defined by mosquito mortality induced in a discriminating dose bioassay); any evidence of PBO synergy of pyrethroids; and several procurement inputs. The latter included the number of people per ITN required to achieve target coverage levels, the price of different types of ITNs, the cost per person of delivery of a mosquito net mass distribution campaign, and the IRS annual cost per person. Other vector control interventions (e.g. larval source management) and non-vector control interventions (e.g. use of seasonal malaria chemotherapy) were omitted; this is equivalent to the assumption that these interventions will remain constant over the 3-year period considered. All further modelling assumptions are outlined in Sherrard-Smith et al. (2022).

As there are about 260 districts in Ghana, to make the analysis with MINT feasible, it was necessary to group districts into a manageable number of cluster families that were broadly homogeneous with respect to the main parameters used by MINT. These parameters are:

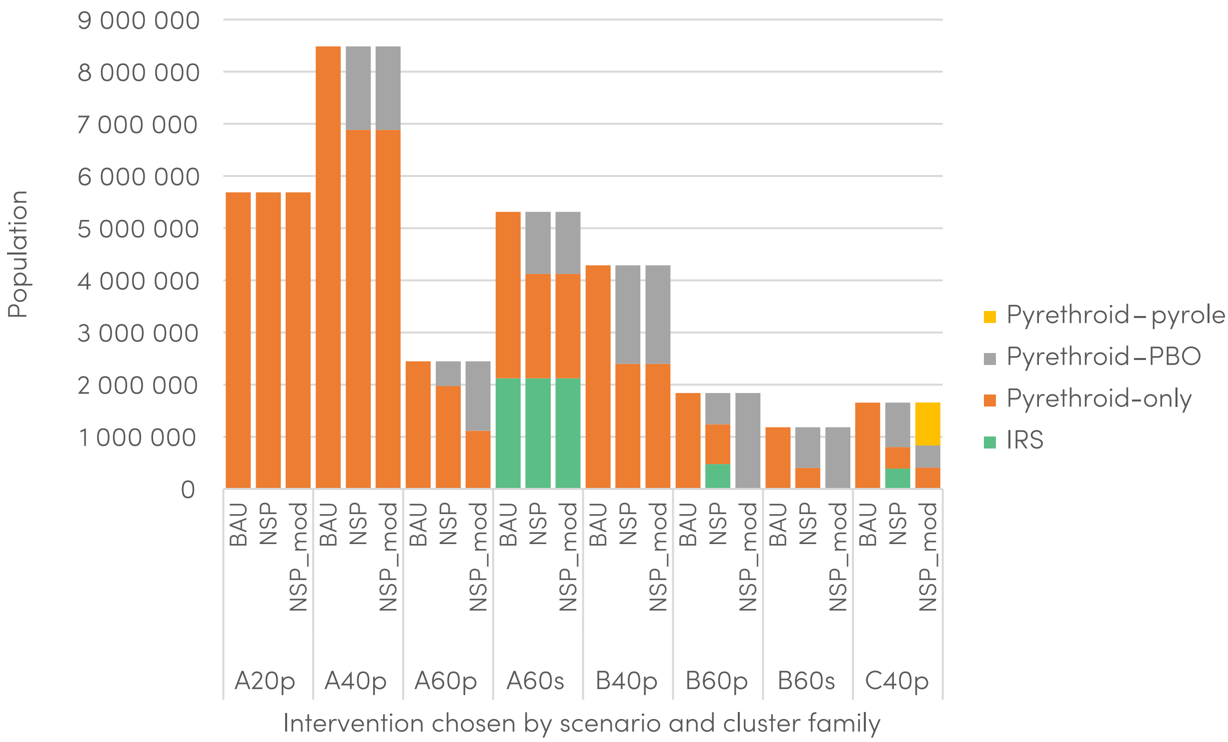
- current malaria prevalence;
- mosquito net population use in last survey (as a percentage); and
- seasonality of malaria transmission.

After this process, a total of eight cluster families were defined, accounting for 93% of Ghana's population.

In addition, as there is variation in terms of future intervention scenarios within some cluster families, additional splits resulted in 20 clusters that were amenable to analysis using MINT.

Three scenarios were analysed using MINT: BAU, NSP and NSP_mod. The distribution of vector control technologies across the cluster families for these three scenarios is shown in **Fig. 1**. Cluster families are coded Xyyk, where X is for malaria prevalence bands (A, B or C, with A having the lowest prevalence in children under 5 years of age (≤25%) and C the highest (36–45%)); yy is net population usage band (20, 40 or 60%); and k is either p for perennial or s for seasonal pattern of malaria transmission. **Fig. 1** shows how populations of all cluster families are allocated to the different technologies under consideration. For example, in cluster family A60p, under NSP_mod, just over half the population is given pyrethroid–PBO nets, and the remainder is given pyrethroid-only nets. As can be seen in the graph, the greater the baseline malaria prevalence in children under 5, the greater the number of technologies to be used for modelled scenarios.

Fig. 1. Distribution of vector control technologies across cluster families



4. STAR

Professor Alec Morton from the University of Strathclyde led the STAR session. He began it with two principles that seemed relevant in the light of the previous day's discussions and the interactions leading up to the workshop.

Although models can often be experienced as depriving decision-makers of agency and fail to secure influence for that reason, in fact, "models don't make decisions, people make decisions". In line with this, Tom Churcher's introduction to modelling communicated that modelling is about joint exploration and learning.

"In the real world, budgets matter". Although the NMEP provided the analytical team with extensive data about scenarios and associated coverage levels, little information was available about future budget levels, except NSP costing and historical information about malaria spending before 2021, both of which can be unrealistic in terms of projecting the real budgetary situation in the near future. According to the

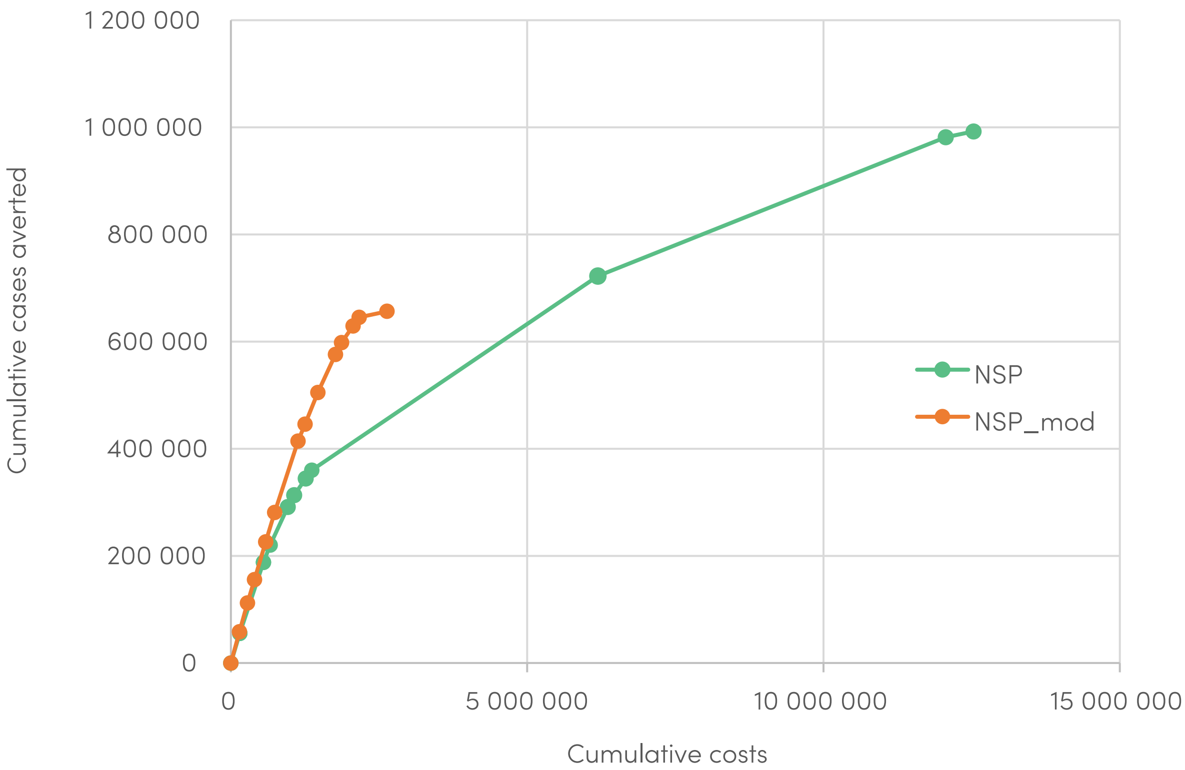
NSP document itself, the NSP faces a significant funding shortfall. Therefore it seems likely that this is both an important and a sensitive topic.

Alec Morton also discussed in his introduction the importance of appropriately identifying the baseline for prioritization. The working definition of a baseline that he used is that it is “what you are already committed to doing”. It is important that a baseline is realistic – that is, reflects actual funding and other constraints.

Alec Morton presented some results of the STAR analysis for multiple baselines in the form of a Pareto front. The Pareto front represents fundable interventions ordered by value for money (benefit–cost ratio) in a cumulative sense. It thus gives a clear picture of both the magnitude of spending and impact and how the return on investment varies at different funding levels.

Fig. 2 shows the Pareto fronts for NSP and NSP_mod relative to BAU at current coverage levels (the results for comparison at target coverage levels are qualitatively similar). From this display, it is clear that NSP achieves more benefit than NSP_mod but at massively greater cost. This is due to two very shallow segments in the Pareto curve, representing investments in districts targeted with IRS. In NSP_mod, the funding for additional IRS is redeployed to purchase pyrethorid–pyrole ITNs and additional pyrethroid–PBO ITNs, which in this case achieve similar results much more cheaply. Additional sensitivity analysis showed that the cost-effectiveness of pyrethroid–pyrole ITNs is highly sensitive to assumptions about the prices of these nets, and also showed how overall benefits decline as pyrethroid resistance increases. The results are also likely to be sensitive to assumptions about IRS pricing levels.

Fig. 2. Pareto fronts for NSP and NSP_mod, relative to BAU at current coverage levels



Despite the evidence suggesting greater value for money for NSP_mod compared with NSP, some members of the Ghana team still preferred to support additional investment in IRS, reflecting a view that the population should have access to what is perceived as a gold-standard technology. They also pointed out that the NSP strategy is still predicted to result in a greater number of total cases avoided than NSP_mod. The Ghana team accepted that identifying a realistic budget and baseline for analysis is important. There was also a strongly held view that planning should be undertaken both for realistic and aspirational budgets to enable agility in responding to new funding opportunities. In line with this, participants agreed that some further analysis would be performed, to consider an additional resource reallocation and take into account a more realistic budget constraint. A more detailed discussion is provided in section 6.

5. EQUITY

As well as the main STAR session, Alec Morton ran a dedicated session on equity, which is an important objective in malaria programme planning. According to the WHO Global Technical Strategy for Malaria, "equity in access to quality health services, especially for populations experiencing disadvantage, discrimination and exclusion, is essential". According to the Ghana NSP, "access to life-saving interventions, especially for the most vulnerable groups, is to be considered a human right".

Equity is a situationally dependent concept, and so it is important to unpack what it means in any particular context. A critical idea in health economics is the distinction between "horizontal" and "vertical" equity. Horizontal equity refers to the principle that people who are alike should be treated similarly, and vertical equity refers to the principle that people who are not alike should be treated differently. However, this raises the question of how to judge the "likeness" of people. Generally, this is done through membership of population subgroups (the United Kingdom Government calls these "strands") – for example:

- territorially defined subpopulations
- between regions
- between districts
- within districts
- urban versus rural subpopulations
- gender-based subgroups
- vulnerable populations
- language, religion and ethnicity subgroups.

Another important dimension of equity relates to the choice of the good (or bad) to be distributed. For example, equity may refer to equity of resourcing, equity of access to technology, or equalization of mortality or infection risk.

The concept of equity that seemed most salient to the workshop participants was equity of access and a focus on vulnerable populations. In correspondence before the workshop, the analytical team was told by the NMEP focal point that "when it comes to implementation of vector control activities like mass distribution and IRS, there is a deliberate plan and budget to target the most deprived and hard-to-reach areas. For example, although in urban areas we mostly target people living in slums, uncompleted buildings (mostly occupied by squatters) and people living in newly developing areas, in rural areas intensive efforts are made to reach everyone, including those living in areas difficult to access". This theme also came over strongly in the workshop, where participants discussed efforts to provide access to vector control to hard-to-reach or marginalized populations, such as prisoners, slum residents, riverine communities and those living in "witch camps" (refuges for women accused of witchcraft).

Because the prioritization exercise focused on allocation of vector control technologies to districts, this equity concept was not directly relevant, since there will be vulnerable populations within all districts. However, there is some indirect relevance, since such vulnerable populations will not be spread evenly across districts (e.g. some marginalized populations might be more prevalent in particular geographical settings).

Data limitations meant that it was not possible to fully account for such differences and additional costs, and only some limited comment on geographical equity could be made. **Fig. 1** suggests that the more advanced technologies (especially pyrethroid–pyrole and pyrethroid–PBO ITNs) are more targeted to high-burden areas; from that point of view, NSP_mod can be viewed as being more equity promoting. It also seems that the current coverage is higher in rural areas than in urban areas, but this may reflect human risk perception and behaviour rather than policy choice.

As in most settings, thinking about prioritization is heavily framed by equity concepts that are deeply embedded and not often explicitly discussed. Two important ideas were expressed during the workshop.

Withdrawal of IRS from areas that were initially targeted for receiving it under the original NSP would be hard to justify, even if IRS is replaced with other technologies; as can be seen in **Fig. 1**, no cluster that has IRS under BAU has that provision withdrawn under either NSP or NSP_mod.

All areas of the country, including the low-risk areas, should be provided with some form of vector control.

Both of these points result in significant resource commitments, which constrain other decisions.

6. EVALUATION QUESTIONNAIRE

The general tone of the workshop was positive, with active engagement and frank yet constructive discussion. All participants, other than the facilitators, completed an evaluation questionnaire (see **Fig. 3**) on the second day. There were 10 responses. The level of agreement was high, with standard deviation <0.75 on all questions.

Fig. 3. Questionnaire feedback from the workshop

The qualitative feedback highlighted the Ghanaian participants' appreciation of the effective organization and facilitation of the workshop. It showed a desire for more hands-on experience with the MINT and STAR tools, and further contextualization of the analysis to the Ghanaian setting.

7. MAIN CONCLUSIONS AND RECOMMENDATIONS

The initial premise of the workshop was that decisions on malaria control (and vector control specifically) are set to become considerably more challenging, as new and generally more costly technologies become available while the available budget is unlikely to increase. The workshop validated this premise, highlighting the difficult trade-offs faced by the NMEP as it struggles in its mission to provide the best possible level of protection to the Ghanaian population within the limited available resources.

Although the analysis does not immediately inform upcoming decisions faced by the Ghanaian NMEP, the workshop demonstrated the capabilities of the tools and clarified critical assumptions (e.g. that the baseline should be current rather than target coverage). An important part of the discussion was consideration of a realistic budget constraint. Until now, discussions have focused mainly on the relative value for money of different scenarios, largely because of time and data limitations. Before the workshop, information was only provided on NSP costing and on past (pre-2021) spending on malaria vector control in Ghana, with both of these sources of information being far from perfect. Although NSP costing is mostly aspirational, some workshop participants pointed out that basing budget forecasting on historical spending may be too pessimistic, as some unexpected sources of funding may become available. Therefore, it was agreed to conduct an additional analysis to look at how impact could be optimized and to validate the plan of the programme to target high-burden districts with pyrethroid–pyrole ITNs, not only within the current funding envelope, but also for scenarios with 10%, 20% and 30% additional resources. Discussions are ongoing to clarify the parameters for subsequent runs of MINT that could more directly inform upcoming national planning decisions.

Equity was highlighted as a very important dimension to consider. For example, an important discussion occurred around introducing pyrethroid–PBO and pyrethroid–pyrole ITNs in some districts, at the expense of cancelling previously agreed coverage with IRS, and the trade-offs involved in such a decision. It was pointed out that removing IRS may lead to loss of coverage, which may be hard to compensate for with ITNs locally, partly as a result of socioeconomically determined differences in ownership and use, even if it means an improvement at the national level due to release of funds for improved ITNs in other districts.

In general, the piloted approach appeared to be well received and to meet a perceived need to provide analytic support for prioritization debates in malaria control. In-country capacity-building will be important to ensure that any methods are locally owned. Some further technical development is necessary to better enable sensitivity analysis, and provide greater transparency and flexibility in programme costing.

8. LIMITATIONS AND SUGGESTIONS FOR IMPROVEMENT

Limitations can be separated into project-specific and tool-specific limitations. Some of the limitations belonging to the first group have been discussed above. One project-specific limitation is a lack of reliable district-level entomological data on local pyrethroid resistance. This meant that assumptions had to be made, which were only partly addressed with sensitivity checks. The difference in effectiveness and cost-effectiveness between different types of nets will be highly dependent on the validity of such assumptions; without this information, it is hard to optimize the use of nets. In addition, the prices for some interventions cannot be fully known in advance, which can also affect relative value for money of different scenarios.

With regard to tool-specific limitations, it should be pointed out that, although combining STAR with MINT can be very useful for exploring trade-offs using different intervention mixes within a current or likely budget envelope, a strong in-country capacity for planning is also needed. Nevertheless, both the MINT and STAR tools are designed to make this decision-making process more intuitive and straightforward.

A number of other limitations for both frameworks were discussed during the workshop. For example, it was mentioned that it would be particularly important to expand MINT's capability to model other malaria interventions, including non-vector control interventions, as well as to expand the number of insecticide options that can be modelled with IRS. However, at least initially, a focus on vector control interventions may be useful, given the large share of budgets that they account for. This analysis needs to be embedded in the broader picture of allocating resources for malaria control, particularly given the competition for resources arising from new interventions in other areas, such as malaria vaccines. In general, this framework is well suited to modelling the effect of the whole NSP, especially as MINT is expected to increase its capabilities to model other interventions in the future.

Other suggestions for improvement were voiced by the workshop participants, including the need to validate MINT predictions in the future, the need to model routine distribution of ITNs in MINT, and the importance of specifying shipping costs of ITNs to countries as an additional cost. Another comment was the perceived limitation of both the MINT and STAR tools to produce a national overview of the outputs stratified subnationally. For STAR, it was pointed out that independence of interventions is not very realistic. Although this was not a concern in the current project, as only one intervention per district was modelled, it will be a greater issue in the future, when the impact of whole packages will need to be modelled. This may be addressed in the future as MINT evolves, since it may potentially be designed to model impact of intervention packages, which in turn will be more realistically considered within the STAR framework.

Some other, more specific concerns were also voiced. For example, it was pointed out that "low" and "high" terms for such MINT inputs as "preference for biting indoors" and "preference for biting people" may be somewhat confusing to users. As an alternative, a continuous variable may be used, but this can also be problematic because of a lack of data. Some further suggestions were made regarding clarifying that "confidence intervals" in the MINT output actually mean "best versus worst case" scenarios, rather than proper confidence intervals. It was also pointed out that rounding numbers on MINT outputs may not always be useful.

Finally, a few words are in order regarding the potential to use the existing STAR tool and guidance as part of a priority-setting exercise of the type discussed in this report. For the purpose of the pilot workshop, an ad hoc Excel-based tool was used, because the existing tool had been developed for a different context. Specifically, the existing STAR tool can work with up to 48 different interventions (up to eight priority areas with up to six interventions in each). On the other hand, in this project, the analytical team had to work with only one priority area and four interventions over three scenarios at two coverage levels, but over 20 geo-clusters. As well, the original STAR tool is designed to convert health states into scores from 1 to 100, which was not the case in this project, as all analysis was conducted based on number of cases averted. The general feedback received was that the ad hoc STAR tool presented during the workshop will require significant adaptation to ensure that it can be used independently by decision-makers in the context of malaria national strategic planning, including capabilities for additional customization to address the needs of a local context. Likewise, the existing STAR tool guidance will need to be updated to be more relevant to the context of NMEP decision-making.

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ANNEX 1. LIST OF PARTICIPANTS

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ANNEX 2. MEETING AGENDA

DAY 1 - 12 SEPTEMBER 2022		
09:00–10:30	Capacity-building session about Imperial Malaria Model and MINT tool	Tom Churcher
10:45–12:00	Capacity-building session (continued)	Tom Churcher
13:00–13:15	Introductory remarks	Kezia Malm; Jan Kolaczinski
13:15–13:20	Declaration of interest	Yevgeniy Goryakin
13.20–13.30	Background and objectives of the workshop	Yevgeniy Goryakin
13:30–14:45	Validating MINT inputs	Tom Churcher; Alec Morton
15:00–15:30	Hands-on exercise	Tom Churcher
15:30–16:30	Presenting MINT outputs; checking their face validity	Tom Churcher
16:30–17:00	Discussing the need for additional sensitivity analysis on key MINT parameters	Alec Morton

DAY 2 - 13 SEPTEMBER 2022		
9:00–10:00	Exploration, display and validation of STAR outputs	Alec Morton
10:15–11:00	Exploration, display and validation of STAR outputs (continued)	Alec Morton
11:00–12:00	Discussion of optimal vector control scenario choices, including consideration of equity and possible resource reallocation	Alec Morton
13:00–14:00	Discussion and conclusions	Kezia Malm; Jan Kolaczinski; Alec Morton; Tom Churcher
14:00–14:30	Workshop evaluation	Alec Morton

ANNEX 3. SUMMARY OF MODELLING ASSUMPTIONS

Main assumptions

- Only vector control interventions (long-lasting insecticidal nets (LLINs); PBO; Interceptor G2 (IG2); IRS; but not larval source management (LSM)1) were modelled. The intervention types included were those recommended by WHO guidelines for large-scale deployment.

- MINT assumes that only one type of net will be provided in a given district. For example, if LLINs are expected to be distributed in a given district, it is assumed that no other nets will be distributed in the same district.

- Some donors (e.g. PMI, the Global Fund) are major sources of the nets used in Ghana. Nevertheless, for the purpose of this analysis, it was assumed that the NMP will have ultimate control over all the distributed nets, all used with the goal of reaching target coverage. Doing otherwise would lead to the optimal strategy choice being heavily distorted by what is available from donors in a particular year.

- Remaining stocks from previous years were not taken into account, mainly because of a lack of district-level data. However, in principle, this can be done if the relevant data are available.

- The target coverage for the nets was assumed to be achieved in the first year after the mass campaign, with the effect falling off steadily in the following 2 years. Unfortunately, MINT cannot (yet) model the effect of routine campaigns to maintain target coverage levels in the years following the mass campaign.

- Although NSPs usually last for 5 years, the MINT approach of modelling on a 3-year basis is fully consistent with this, as it can help inform any possible mid-term reviews. In addition, as the main aim of this exercise was to evaluate relative value for money of alternative strategies, rather than predict their total impact, it should be sufficient to use a 3-year horizon.

- Cost savings from preventing malaria were not considered.

Site inputs for MINT tool modelling

Population

- District-level values for 2021 were provided by the NMEP. Constant population by district over time was assumed.

Seasonality of transmission

- District-level information was provided by the NMEP.

Current malaria prevalence in children under 5

- District-level information for 2021 was provided by the NMEP. These estimates included the effect of previous interventions.

1 Currently, MINT cannot model the effect of LSM campaigns.

Mosquito inputs

Preference for biting indoors

- This value was "high" for all districts, based on Sherrard-Smith et al. (2019), Fig. 3.[2]

Preference for biting people

- This value was "high" for all districts, given the information in Table A-2 in the PMI Ghana Malaria Operational Plan FY 2022.

Pyrethroid resistance

- Nationwide existence of resistance in all districts was assumed.
- In addition, levels of pyrethroid resistance were assumed to vary by district/cluster. Because of a lack of data, cluster-specific average values for the levels of insecticide resistance could not be estimated. Therefore, the following assumptions were made, based on the understanding that the NMEP is guided by local knowledge about insecticide resistance levels when targeting local districts with PBO or IG2 nets.
    - In clusters where only LLIN nets or IRS are to be distributed in all three future scenarios, 40% and 60% levels of resistance, respectively, were assumed.
    - In clusters to be targeted with PBO nets (but not with IG2 nets) as per NSP or NSP_mod, 60% resistance levels were assumed.
    - In clusters to be targeted with IG2 nets as per NSP_mod, 80% resistance levels were assumed.

Evidence of PBO synergy

- This synergy was assumed to exist in all districts.

Past vector control inputs

Mosquito net use in last survey (%)

- Region-level information for 2019 on ITN use the night before the survey was provided by the NMEP.

Districts where IRS was conducted last year (before current amended NSP started)

- District-level information was provided by the NMEP.
- It was assumed that, in such districts, 60% IRS coverage was provided.

Future scenarios

Background

- District-level information on interventions to be provided as per the three main scenarios (BAU, NSP and NSP_mod) was provided by the NMEP, with two associated coverage/usage levels (current and target coverage).
    - Current coverage scenario: nets coverage/usage in the targeted districts was assumed to be equal to net coverage/usage as per the Malaria

2 https://www.pnas.org/doi/10.1073/pnas.1820646116

- Indicators Survey conducted in 2019; IRS coverage in targeted districts was assumed to be 60%.
  - Target coverage scenario: nets coverage/usage in the targeted districts was assumed to be 80%, and IRS coverage in targeted districts was assumed to 90%.
- Each district was assumed to be targeted with only one intervention (e.g. only LLINs, PBO, IG2 or IRS).
- Nets were assumed to be delivered in mass distribution campaigns every 3 years. IRS was assumed to be delivered annually.

BAU scenario

- District-level information on targeting with LLIN or IRS was provided by the NMEP. No PBO or IG2 nets are to be provided under the BAU scenario.

NSP

- District-level information on targeting with LLIN, PBO or IRS was provided by the NMEP. No IG2 nets are to be provided.

NSP_mod

- District-level information on targeting with LLIN, PBO, IG2 or IRS was provided by the NMEP.

Procurement inputs

Background

- Coverage and usage terms are interchangeable. Coverage/usage is defined as the percentage of people living in a given area directly protected with the nets (e.g. the percentage of people in the area who slept under the net the night before).
- To evaluate the cost of the mass net distribution campaign, it was assumed that enough nets will be procured to ensure the defined level of net usage.
- In general, countries will know best what level of net procurement is needed to ensure the expected target coverage/usage. In MINT, the default is 1.8 people per net[3] to ensure 80% population coverage level, but, under its NSP, Ghana expects that two people per net will be needed to ensure this coverage level.

Number of people per net to achieve target coverage/usage

- Based on the Ghana NSP, Bhatt (2015) and Fig. S7.1 in the supplementary part of the MINT paper, the following number of nets per person to ensure target coverage levels is assumed (this can be subject to sensitivity analysis):
  - 80% target usage/coverage: two people per net
  - 20–60% target usage/coverage: four people per net.

3 Extract from MINT paper: "In the main text of the manuscript we present results which assume 1.8 people per net, though this value can be changed in the online tool. This value corresponds to about 80% of the population being covered by a mosquito net according to the association published in Bhatt et al. 2015."

Procurement buffer percentage

- 7%

Price of intervention inputs

- The prices below for nets are based on the Global Fund reference price list.[4]

Pyrethroid-only nets (for commodity only)

- US$ 2.16. A median standard reference price for pyrethroid-only ITNs was assumed, which includes hooks, strings and bag, but does not include the cost of delivery.

Pyrethroid–PBO nets (for commodity only)

- US$ 3.09. A median standard reference price for pyrethroid–PBO ITNs was assumed, which includes hooks, strings and bag, but does not include the cost of delivery.

IG2 nets (for commodity only)

- US$ 3.44. As reliable prices for IG2 nets are not yet available, the most expensive pyrethroid–PBO net price listed was assumed.

Mosquito net mass distribution campaign delivery cost per person (US$)

- US$ 2.75 (provided baseline value in MINT) was assumed.

Annual cost of IRS per person (US$)

- US$ 5.70 (taken from a recent systematic review).[5]

Cluster assumptions

- Fundamentally, there are two clustering approaches underlying this analysis. First, as a result of prior subnational intervention tailoring work conducted in Ghana, district-level intervention scenarios were defined according to stratification analysis as described by the NMP. In each district, intervention options were selected by the NMP according to comprehensive review of local epidemiological and entomological data.
- Secondly, districts were clustered to enable analysis in MINT. This is because there are 260 districts in Ghana; if each district had a separate simulation, this would greatly complicate and lengthen the analysis.
- When defining clusters, districts were separated into areas with very similar epidemiological and entomological characteristics, as well as similar future scenario options compatible with MINT.
- The clusters were defined based on the following inputs required for MINT simulations:
    1. Seasonality of transmission
    2. Current malaria prevalence in children under 5 years of age
    3. Preference for biting indoors

4 https://www.theglobalfund.org/media/5861/psm_llinreferenceprices_table_en.pdf

5 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8324482/

4. Preference for biting people
5. Level of pyrethroid resistance
6. Evidence of PBO synergy
7. Mosquito net population use in last survey (%)
8. Whether IRS was conducted last year
9. Percentage protected with IRS
10. Procurement, distribution and prices
11. Future district-level intervention options

- Inputs 3, 4 and 6 do not differentiate between districts and so are not relevant for clustering purposes. Inputs 8 and 9 are perfectly correlated – that is, in all districts where IRS was conducted last year, the percentage protected is always 60%; otherwise it is 0%.
- Levels of pyrethroid resistance are also assumed to vary by cluster, so input 5 is also not relevant for clustering purposes. The same applies to input 10.
- Therefore, to define clusters, the focus was on inputs 1, 2, 7, 8 and 11.
- Note that this is different from stratification analysis performed for the purpose of subnational tailoring of interventions. In this case, the definition of clusters relies on differences in key epidemiological parameters as defined by MINT.
- For consistency with MINT, the most recent malaria prevalence in children under 5 years of age is mapped to coverage bands corresponding to the bands used in MINT (≤25%; 26–35%; 36–45%; 46–55%; >55%), and ITN use in last survey is similarly mapped to 20% (for values ≤30%), 40% (for values >30% and ≤50%) or 60% (for values >50%).
- A key question is how many clusters are optimal for the analysis. In this case, a choice was made to analyse the top 20 clusters (see Table A1), which will cover about 90% of the population, with a good geographical spread. The resulting 20 clusters are very similar in all respects, including interventions targeted in future modelled scenarios, thus making them amenable to the MINT analysis.

Table A1. Cluster definitions (top 20 clusters)

CLUSTER NAME	MALARIA PREVALENCE (%)	MOST RECENT NET USE (%)	SEASONALITY
A20p_llin_llin_llin	≤25	20	Perennial
A40p_llin_llin_llin	≤25	40	Perennial
A40p_llin_pbo_pbo	≤25	40	Perennial
A60p_llin_llin_llin	≤25	60	Perennial
A60p_llin_llin_pbo	≤25	60	Perennial
A60p_llin_pbo_pbo	≤25	60	Perennial
A60s_irs_irs_irs	≤25	60	Seasonal
A60s_llin_llin_llin	≤25	60	Seasonal
A60s_llin_pbo_pbo	≤25	60	Seasonal
B40p_llin_llin_llin	26–35	40	Perennial
B40p_llin_pbo_pbo	26–35	40	Perennial
B60p_llin_irs_pbo	26–35	60	Perennial
B60p_llin_llin_pbo	26–35	60	Perennial
B60p_llin_pbo_pbo	26–35	60	Perennial
B60s_llin_llin_pbo	26–35	60	Seasonal
B60s_llin_pbo_pbo	26–35	60	Seasonal
C40p_llin_pbo_ig2	36–45	40	Perennial
C40p_llin_llin_llin	36–45	40	Perennial
C40p_llin_irs_ig2	36–45	40	Perennial
C40p_llin_pbo_pbo	36–45	40	Perennial

- The names of the clusters were chosen to be informative. For example, the first capital letter represents local under-5 malaria prevalence according to the following rule: ≤25% (A); 26–35% (B); 36–45% (C). The two digits that follow the letter represent the local net usage band (20%, 40% or 60%) in the previous survey. The letters “s” or “p” that follow represent seasonal or perennial transmission patterns. Finally, the main interventions are indicated, provided according to the three scenarios (in this order): BAU, NSP and NSP_mod.

- For example, by looking at the A60s_llin_pbo_pbo cluster, one can immediately identify that the under-5 malaria prevalence is ≤25%; the most recent net use was around 60%; transmission had a seasonal pattern; and the modelled interventions are to be targeted as follows: LLINs (BAU), PBO (NSP) and PBO (NSP_mod).

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