Which trap is best? Alternatives to human landing catches for malaria vector surveillance: a meta-analysis

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RESEARCH

Which trap is best? Alternatives to human landing catches for malaria vector surveillance: a meta-analysis

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Abstract

Background: Human landing catches (HLC) are an entomological collection technique in which humans are used as attractants to capture medically relevant host-seeking mosquitoes. The use of this method has been a topic of extensive debate for decades mainly due to ethical concerns. Many alternatives to HLC have been proposed; however, no quantitative review comparing HLC to alternative trapping methods has been conducted. Here, we present a meta-analysis of published literature on HLC and alternative trapping methods for outdoor Anopheles spp. collections.

Methods: A total of 58 comparisons across 12 countries were identified. We conducted a meta-analysis comparing treatment effects of HLC against alternative traps. To explain heterogeneity, three moderators were chosen for analysis: trap type, location of study, and species captured.

Results: According to our model, tent-based traps captured significantly more Anopheles than HLC (95% CI: [-.9065, -.0544]). Alternative traps in Africa captured more mosquitoes than outdoor HLC ([-2.8750, -.0294]) and alternative traps overall captured significantly more Anopheles gambiae s.l. than HLC ([-4.4613, -.2473]). A meta-regression showed that up to 55.77% of the total heterogeneity found can be explained by a linear combination of the three moderators included in our model and the interaction between trap type and species . Subset analysis on An. gambiae s.l. showed that light traps specifically captured more of this species than HLC ([-18.3751, -1.0629]).

Conclusions: Alternative traps captured more An. gambiae than HLC, however, we found no differences for capture of An. funestus s.l. Publication bias was found with an overrepresentation in the literature of results indicating that alternative traps are superior to HLC. Trap comparisons in the literature most commonly use total Anopheles collected/night as a metric for comparison, which may not be the optimal. These results identify trends in the literature which can be used to identify Anopheles collection alternatives to HLC. However, significant heterogeneity suggests a broader challenge with the literature. Further standardization and specific question-driven trap evaluations that consider target vector species and the vector control landscape are needed toallow for robust meta-analyses with less heterogeneity and to develop data-driven decision-making tools for malaria vector surveillance and control.

Keywords: *Anopheles*; collection; HLC; meta-analysis; mosquito

Background

The accurate understanding and quantification of the drivers of pathogen transmission by a vector could be critical for the effective control of such a vector. For mosquitoes, vectorial capacity, vector competence, and human-associated factors shape pathogen transmission parameters ([1, 2]). According to the Ross-MacDonald model, these transmission parameters describe the relationship between entomological indicators (such as abundance, feeding behavior, longevity, competence, dispersal) and epidemiological outcomes ([3]). Thus, the first step in understanding the dynamics between mosquitoes and mosquito-borne diseases is the estimation of these parameters. Of these, describing the vectorial capacity via mosquito sampling/collection is the most pertinent. This is because vectorial capacity incorporates key baseline information on mosquito abundance, diversity, distribution, biting frequency and behavior, mosquito survival, and incubation period of the pathogen ([4, 1]). Taken together, the synthesis of such key information is crucial for planning optimal mosquito intervention strategies.

The suitability of a mosquito collection method is species-specific and should be coupled with sampling methods that take advantage of specific behaviors. While there are about 4000 species of mosquito described today ([5]), only a few genera, such as *Aedes* and *Anopheles*, are efficient transmitters of human pathogens. Notably, *Anopheles spp.* transmit the parasites responsible for human malaria. Malaria is the most serious arthropod-vector borne disease causing morbidity and mortality in humans. To date, perhaps the greatest success recorded in the fight against malaria has been through the use of mosquito control interventions such as insecticide-treated nets (ITNs) and indoor residual spraying (IRS) that target *Anopheles spp.* adult females ([6], [7], [8]). Thus, mosquito surveillance methods that provide information on *Anopheles* biting and resting time, behavior, peak activity, distribution, diversity, and abundance should be prioritized. In addition, the influence of ecology and weather conditions on currently employed Anopheles surveillance methods should be studied. ([9], [10]).

To date, several methods have been employed in the estimation of mosquito vectorial capacity ([11, 12, 13, 10, 14]). Human landing catches (HLC) have been suggested as the gold standard for malaria vector surveillance, being widely used and the most direct way to measure biting on humans, and they can also be used to quantify indoor/outdoor biting and biting by time of night. ([15, 16, 17]). HLC is a method of mosquito collection that uses humans and their natural production of carbon dioxide (CO2), heat, and odor as bait to capture host-seeking mosquitoes. HLC is an important collection method because it uses humans as an attractant to determine *Anopheles* abundance over a set period and the daily human biting rate, a metric that when combined with data on presence of infective *Plasmodium* sporozoites gives the entomological inoculation rate (EIR) which describes the proportion of bites which are infective. By using humans as baits, HLCs facilitate the collection of human-biting mosquitoes capable of transmitting malaria parasites (*Plasmodium spp.*).

The use of HLC has been a topic of controversy. HLC requires collectors to stay awake during overnight collections, and although collectors may be provided with prophylaxis to protect them from malaria infection ([18]), they may be exposed to other vector-borne pathogens such as the causative agents of lymphatic filariasis, chikungunya, leishmaniasis, etc. ([16]). HLC also require expertise from both collectors and supervisors and are physically demanding, requiring collectors to stay up all night [19]. The results obtained through HLC, and some other trapping tools, are also heavily influenced by the attractiveness of the human collector to the *Anopheles* species ([20, 21]). Furthermore, HLC typically provides data on only mosquitoes that feed on human legs ([16, 17]) possibly ignoring populations that obtain a blood meal from other parts of the human body.

In Africa, as elsewhere, alternatives to HLC have been proposed and evaluated under various conditions for the collection of *Anopheles* species. For example, varying designs of light traps including the Centers for Disease Control (CDC) light trap ([22, 23]) odor baited-traps ([24, 25]) electrocution traps ([26], [13]), decoy traps ([27]), tent traps ([28], [29]), barrier screens ([30]), and a combination of these traps ([31]) have all been explored as alternatives. Several of these alternative collection methods have been conducted in direct comparison with HLC with differing results ([20, 32, 33, 34, 12, 35, 36]). For example, one study comparing methods showed CDC miniature light traps captured at least twice the number of *Anopheles* captured by HLC ([37]). Perhaps what is often overlooked, for the efficiency of a trap type, is the sensitivity and correlation between host-seeking/resting behavior and malaria-pathogen transmission. In this respect, a trap would be apposite if it collects representative populations (or species) of adult females (fed and unfed). Such trap data would provide essential information on *Anopheles* abundance, human biting rate (HBR), and entomological inoculation rate (EIR). In recent years several programs have stopped HLC or had discussions about halting the use of HLC for various reasons including risk of exposure to other vector-borne diseases ([16]). Therefore, a comparable and effective collection method is needed for malaria vector surveillance. Indoors, CDC light traps have been used as an alternative to indoor HLC where an individual sleeps under a bed net and acts as an attractant towards the light trap, with conversion factors being developed; however, to date, no outdoor mosquito collection alternatives to HLC have been standardized for use in malaria surveillance and no systematic review or meta-analysis combining these results has been conducted.
Consequently, the aim of this literature review and meta-analysis is to determine which alternative outdoor mosquito collection methods for malaria surveillance are most comparable to outdoor HLC and examine variation in the literature and the effects of geography, general trap type, trap bias, and target species on collection results. Specifically, this study aimed to address whether publication bias, geographical location of the comparison study, species composition, and trap type (light trap, tent trap, electrocuting box trap), and categorical classification (biological, physical, chemical) had significant effects on the alternative trapping methods outdoors and their comparability to HLC.

Materials and Methods

Literature Search, Inclusion Criteria, and Study Selection

Preferred Reporting Items of Systematic reviews and Meta-Analyses (PRISMA) recommendations were followed for the literature search, creating the inclusion cri-

teria, and data extraction ([38]). Databases were searched independently during May 2020. Searching was done by a group of four researchers (SO, YW, SJ, VP) using ("human landing catches") AND (("human landing catches alternatives") OR ("HLC") OR ("vector surveillance")) as keywords. Keywords were employed respectively and the search results were combined using advanced search tools. No language or date restrictions were set. The specific databases searched were left up to the discretion of the researcher with the only requirement being that each investigator searched three separate databases. A total of nine databases were accessed, and five were unique (BASE, PubMed, Web of Science, Google Scholar, and Science.gov). After the removal of duplicates, there were 944 items left. For the next step, the paper titles and abstracts were screened by splitting into two groups (Group 1: JE, SZ, YW; Group 2: SO, SJ, VP, BM). Group 1 screened the first 472 papers and group 2 screened the last 472 sorted alphabetically by author's last name. Each member of the group voted on the eligibility of each paper. For Group 2, tiebreakers were included as eligible. A paper was eligible for inclusion if it received a majority vote as per the inclusion criteria.
The inclusion criteria were:

- A paper must be an entomological malaria surveillance experiment
- Outdoor HLC must have been performed
- The study must have involved an alternative trapping method
- The study must have recorded mean Anopheles captured per trap over a defined period or a similar metric/way of calculation.
- At least one *Anopheles* mosquito must have been captured by both outdoor HLC and alternative method

Acceptance for publication was also taken as a criterion for inclusion. No grey literature or conference abstracts were included. Data from a total of 20 articles were extracted. Figure 1 shows the PRISMA flow diagram.

Data Extraction and Preparation

Two researchers extracted the data (JE, SO). Any discrepancies were resolved by the lead author after revisiting the articles. The following variables were extracted from selected articles:

- **Author:** author(s) of the included study
- **Year:** included study publication year
- **Country:** country the experiment was performed in
- **Coordinates:** exact coordinates of experiment site if given in the included study. If testing was done at multiple sites or coordinates were not given, approximations were used
- **Trap name:** name of trap being tested
- **Species name:** name of species captured and identified during the experiment
- **Species:** categorical variable of captured species into one of three groups. The species categories were:
  - '*Anopheles gambaie*' – species belonging to *An. gambiae* species complex
  - '*Anopheles funestus*' - species belonging to *An. funestus* group
  - '*Anopheles* spp' - all other species not belonging to *An. gambiae s.l.* or *An. funestus s.l.*

- **Length:** the number of days collections were conducted.

Three additional variables were created:

- **Category:** categorical variable for the category classification of alternative trapping methods as defined in [20]. The type categories were:
  - 'Biological'
  - 'Chemical'
  - 'Physical'
  - 'Physical/Chemical'
- **Type:** categorical variable for the classification of alternative trapping methods. The type categories were:
  - 'Tent'
  - 'Light'
  - 'Electrocuting'
  - 'Other - Mechanical'
  - 'Other - Passive'
- **Africa:** categorical variable equal to 1 if the experiment was conducted in Africa or equal to 0 if the experiment was conducted outside of Africa. Africa was the only region with enough studies to be used as a moderator in analysis with enough statistical power.

Publication dates of included studies ranged from 1995 to 2019. A total of thirty-one *Anopheles* species were represented in the meta-analysis. Four articles had experiments from South America, two from Asia, thirteen from Africa, and one from Oceania. This heterogeneity in experimental location was the reason behind creating a moderator for Africa, as opposed to a specific country or region. Across all included papers, there were a total of twelve unique countries (Figure 2).
If necessary, data were extracted from graphics using R version 3.6.3 [39] and the *metaDigitise* [40] package version 1.0.1. For articles that included multiple comparisons to HLC, the individual comparisons were added. Treatment effect sizes and standard errors were calculated using *esc* [41] package version 0.5.1 and were recorded during data extraction.

Statistical Analysis

Meta-analytic techniques were conducted using *metafor* [42] package version 2.4-0, *meta* [43] package version 4.11-0, and R. Some functions of the *dmetar* [44] package version 0.0.9 were also used in analysis which required installation from Github. The standardized mean difference "Hedges' g") of mosquitoes captured in the two methods was used as the effect size. Effect sizes were calculated with the control being the outdoor HLC; negative effect sizes indicated that outdoor HLC captured fewer mosquitoes than the alternative method. Mosquitoes captured were chosen as the outcome variable due to capture numbers being universally available across HLC and all alternative trapping methods. A random effects framework was used for the modeling to account for heterogeneity. τ^2, the variance of the distribution for the true effect size under such a framework was estimated using a restricted maximum likelihood (REML) approach. All random-effects models used the Hartung-Knapp adjustment for the variance of the pooled effects estimator. Moderator analysis was also performed under the random-effects framework.

Outlier detection was done using the *find.outliers()* function in the *dmetar* package. The approach to classifying a study as an outlier was a brute force approach wherein an included study for which the upper bound of the 95% confidence interval was lower than the lower bound of the pooled effect confidence interval was considered an outlier, or similarly for when the lower bound of the 95% confidence interval was higher than the upper bound of the pooled effect confidence interval. The method described above is not comprehensive for finding outliers; it is possible that outliers existed that were not considered.

Multi-model inference was done using the *multimodel.inference()* function in R, wherein all possible combinations of the Type, Africa, and Species variables with their respective interactions were fitted in a meta-regression. Model selection was based on having the lowest corrected Akaike Information Criterion (AIC). Resampling methods were used to validate the robustness of the meta-regression. The standard in meta-analysis is to use permutation testing [45]. Using *metafor*'s built in *permutest()* function, one thousand iterations were run.

Results

Random-Effect Meta Analysis

Analysis performed on fifty-eight comparisons of alternative traps to HLC showed that there was no statistically significant difference in the number of *Anopheles* collected between alternative traps and HLC. I^2 as a measure of heterogeneity was 98.3%. Coupled with the 95% confidence interval for τ^2 and the broad prediction interval, it is reasonable to assume there was high heterogeneity. The failure to reject the null hypothesis could be because the two groups were equal, or because of a lack of ability to detect the difference due to heterogeneity. Using moderator analysis and meta-regression, we attempted to explain the statistical heterogeneity present and quantify it. The results for the random effects meta-analysis are presented in Table 1. High heterogeneity can be potentially caused by a single study with an anomalous effect size. Of the original 58 comparisons, only 36 were synthesized after outlier removal. Alternative traps captured significantly more Anopheles mosquitoes than HLC when outliers were removed, however, there was still an indication of high heterogeneity (Table 2).

Explaining Heterogeneity

Moderator Analysis

Only one study that we synthesized had a trap that could be classified as an 'electrocuting' trap type. Resultantly, this study was excluded from the various moderator analyses. Our results showed that traps typed as 'Tents' captured significantly more *Anopheles* compared to HLC ($95\%\ \text{CI} : [-0.9065, -0.0544]$). Significant results were found in the full comparisons of studies performed on the Africa subgroup ($[-2.8750, -0.0294]$) and the *An. gambiae* subgroup ($[-4.6475, -0.2330]$) in their respective moderator analysis as well. Results for each moderator analysis are found in Tables 3-5. The assumption that there was not a common estimate of τ^2 across subgroups was made for analysis. For robustness, the results were computed under a change of assumption so that there was a common estimate of τ^2 across subgroups. No changes to statistical significance were detected for any group between the two assumptions.

Meta-Regression

Meta-regression was performed to see if the statistical heterogeneity could be explained using a linear combination of moderators instead of individual associations. The top regression model included Type, Species, Africa, and the interaction of Type and Species. Figure 2 shows the modeled average predictor importance plot. The fitted meta-regression model reported $R^2 = 55.77\%$ which, in the context of meta-regression, implies that the combination of these four variables explains 55.77% of the heterogeneity present. For the F-test of moderator coefficients, the effects of the predictors were robust as we obtained a significant p-value ($p^* = 0.0030$). While some individual t-tests on predictor coefficients showed statistical significance, many of the results do not have the necessary number of studies with power to detect statistical significance, even under permutation testing.

Analysis of Subsets

Of the total 58 comparisons synthesized, 23 of the comparisons were from captures involving *An. gambiae s.l.* and 11 were *An. funestus s.l.*, with the rest being other *Anopheles* spp. Further analysis was done individually on each species as a subset. Traps that involved light caught significantly more mosquitoes than their HLC counterparts for *An. gambiae s.l.* ($95\%\ \text{CI} : [-18.3751, -1.0629]$). There were no other statistically significant results; however, it should be noted that *An. funestus s.l.* did not have a single category that achieved sufficient statistical power. Tables 6, 7 in the Supplementary Information detail the full results for each species subset.

Publication Bias

An unfortunate weakness of any meta-analysis is the lack of ability to include all available data. This is commonly referred to as the"file-drawer" problem i.e., many results that are not statistically significant are more likely to not become published ([40], [42], [43]). The funnel plot of the data wherein each comparison's standard error is plotted against the effect size is represented in Figure 4. One would typically expect the data to follow the prescribed funnel shape if publication bias was not present. However, the figure shows a large grouping at the top of the funnel – a deviation from the typical funnel shape. Further testing for publication bias was done using the Egger's test of asymmetry (see Table 8 for results). The graphical representation of the data with the p-value for the t-test of the intercept was not significant ($p^* = 0.058$) is a good indicator that publication bias is present in the analysis. Both the Egger's test, funnel plot, and the trim-and-fill analysis (Table 9) suggest the same conclusion.

Discussion

The need for suitable alternatives to HLC is desirable. In addition to ethical considerations, there are also biases (known but mostly uncharacterized) that may influence HLC's data. Therefore, the use of HLC must be either critically examined and understood or alternatives to HLC that ablates these biases should be sought. For example, collector bias may impact the number and quality of collections from HLC as individuals may have differing degrees of mosquito attraction, although this may be addressed to some extent with appropriate study design. Additionally, HLC collectors who are recruited and trained are mostly men between the ages of 20-50, while the populations most vulnerable to malaria are women and children. Vector control interventions are often selected for implementation based on data from HLC collections; however, the possibility of differential attraction between men and women and children may not be adequately considered. Alternative methods that can be used to address this bias may provide a broader understanding of vector bionomics. This meta-analysis aimed to compare alternative trapping methods to human landing catches.

To date, despite claims that HLC may put collectors at risk for infection with vector-borne pathogens, there is only one study that examined the safety risks of HLC for collectors, and this study focused exclusively on the risk of malaria [18]. In this work, the authors showed that when HLC collectors were provided with malaria prophylaxis, malaria incidence was lower than in non HLC collectors. However, no published study has reported the risk of mosquito collectors being exposed to other arthropod vectors or vector-borne pathogens. Without these data, it is not possible to conclusively state whether HLC collectors are at increased health risk or not.

Since the majority of studies comparing HLC and alternative traps were conducted in Africa, moderator analysis was conducted comparing studies in Africa with those conducted elsewhere in the world. This moderator analysis showed that in studies conducted outside of Africa, alternative traps did not capture more *Anopheles* than HLC. However, in Africa, the combination of all alternative traps collected more *Anopheles* than HLC. These results may be influenced by the fact that the majority of studies comparing alternative trapping methods to HLC were conducted in Africa (38/58). It is possible that additional studies showing HLC collecting more mosquitoes than alternative traps in Africa may have been conducted, but not published. The objective of these studies is often to investigate and identify alternative traps that can be used to replace HLC for mosquito collections, which may lead to publication bias and lack of reporting when HLC performs better. Alternatively, there may be differences in *Anopheles* species diversity or host-seeking behaviors in Africa that influence the geographical differences noted here.

When examining species as a moderator, the results indicated that in general, alternative traps collected more *An. gambiae s.l.* than HLC. However, heterogeneity was highest in this analysis. This finding was surprising because *An. gambiae s.l.* is often thought to be anthropophagic (human-host seeking) and HLCs are used to preferentially capture human host-seeking mosquitoes. Light traps, both baited and unbaited, captured significantly more *An. gambiae s.l.* than HLC when the analysis was performed on just the subset of *An. gambiae s.l.* One potential explanation for this result could be that the common alternative trap is the CDC light trap, which often uses humans as attractants. Even if this is the case, if the target species for collection is *An. gambiae s.l.* there is some evidence that alternative trapping methods may capture significantly more mosquitoes than HLC.

When examining trap type as a moderator, tent traps in particular collected an overall higher number of *Anopheles* than HLC. There is also evidence that CDC light traps are significantly more likely to capture more *An. gambiae s.l.* than HLC, but no other trap groups are. More studies on traps that specifically capture *An. funestus s.l.* are necessary to statistically determine which trap has the best potential to capture the species. It is possible that people are not reporting *An. funestus s.l.* in collections or that there is publication bias; however, there is no evidence to support this at this time.

Meta-regression methods show that a linear combination of these variables can explain over 55% of the statistical heterogeneity present. The remaining heterogeneity is clinical heterogeneity which indicates that future work addressing the questions of trap comparisons to HLC should use standardized and modified methods. When examining the source of heterogeneity in these studies, the best model suggests that trap type, species, geography (Africa or not), and interaction between group and species account for the most heterogeneity. Standardization of methods for future meta-analytic work should account for these variables. Future studies should address heterogeneity variables and publication bias by focusing on questions that address trap group and species outcome. Results should be published regardless of whether findings indicate alternative traps perform better than HLC.

Recommendations

When determining whether HLC should be replaced with alternative trapping tools, National Malaria Control Programs (NMCPs) should consider key data needs and select collection tools based on these priorities. A recent publication ([46]) was developed to help guide decision-makers on how to select appropriate mosquito collection tools for malaria program needs. To determine equivalency between HLC and alternative traps, two one-sided test analyses should be conducted. If equivalency is determined, no conversion factor would be needed. A major limitation in this approach is that the trap comparisons are based on the total number of *Anopheles* collected/night, and accurately estimating human biting risk remains a challenge. Alternative methods may collect more *Anopheles* than HLC, but this does not mean that they more accurately estimate biting risk. Therefore, if alternative approaches are used to replace HLC, correction factors may be necessary to estimate biting risk for the calculation of EIR. However, a precise conversion factor for metrics such as EIR may not be necessary. While EIR is a very valuable entomological indicator, these values are dynamic and absolute EIR numbers may not be necessary when a relative EIR could suffice to inform vector control decisions. Future work testing for equivalency will provide additional information. Additionally, to further understand the malaria vector landscape, a metric could be developed to show how HLC and alternative traps perform in the context of vector control interventions.

For this study, the number of *Anopheles* spp. collected per trap per night was used since this was the standard metric represented in the literature when comparing traps to HLC. Although this is the standard, it is not necessarily the best approach. Not all *Anopheles* spp. are malaria vectors, and without a question driven approach to identify which traps are best for certain species, it is not possible to determine which trap will be best in certain situations. A question driven and resource directed approach to trapping mosquitoes for malaria surveillance is necessary. An entomological surveillance planning tool (ESPT) helps guide decision-makers in deciding which trap is best for specific questions related to malaria vector control [46]. This tool may also be used to determine which trapping methods can or should be compared in future studies. It is important to note that one major advantage of HLC is that they provide the ability to understand the specific location and biting times of human-seeking mosquitoes. To date, alternative traps can not reliably replicate this. If the question driven approach is asking when and where mosquitoes bite, there may not be a fully suitable alternative to HLC. There also needs to be a way to minimize heterogeneity. Moving forward, studies should be designed considering target species and trap types. For example, there may be one group or trap type that collects more total numbers of *An. gambiae s.l.*, such as the light trap [Table 6], which does not perform as well for *An. funestus s.l.*

When deciding on a collection tool, multiple traps should be used to determine which traps are ideal for specific species. Future studies should report results whether they are capturing more or fewer mosquitoes than HLC along with a corresponding variance metric. Reporting these data will allow for a more robust meta-analysis. Standardized reporting is necessary for robust meta-analysis. Temporal analysis of when the mosquitoes were captured was purposely left out of this study because of the lack of standardization of reporting make it impossible to synthesize. Standardization techniques in this area could add another moderator to control for heterogeneity and account for the effects of seasonal biases.

Conclusions

The results of the meta-regression show that a large percentage of the heterogeneity present in the analysis comes from variations of traps, locations, and species collected. There is not a consensus among publications in the field over whether a specific trap can be used as a "magic bullet" alternative to HLC. However, the data here provide some evidence that tent traps capture more *Anopheles* spp., and collections using alternative light-based traps capture more *An. gambiae s.l.* than HLC. Even so, the high between-study heterogeneity and publication bias cannot be ignored. Instead, research on alternative traps should be conducted by performing question-driven studies to address which traps are best for which species. If programs want to examine *Anopheles* spp. diversity in an area, different trapping tools may be necessary than for programs that are just interested in a specific vector, such as *An. gambiae s.l.*, or have a specific bionomic question. We suggest that the goal should not be to determine which alternative trap can replace HLC, but rather instead to identify the optimal trapping tool for question-driven collections needed to inform decisions about appropriate malaria control interventions or for basic research. A baseline assessment of mosquito collection tools relative to HLC in specific locations could be conducted to determine the best tools in specific contexts in response to indicator-driven questions by using the ESPT tool and evaluating results at regular intervals to determine representativeness [46]. In addition, very few studies evaluating collection tools when compared to HLC describe the vector control context and landscape in which the study is being conducted. For example, conducting a study in a context where a vector control tool such as mass distribution of ITNs is used is likely to influence mosquito biting and resting behavior and the resulting entomological indicators compiled by mosquito collection tools. Under this framework, future meta-analyses could better characterize the landscape of malaria vector behavior by reducing between-study heterogeneity, allowing for recommendations for malaria vector control interventions that are tailored to local vector ecology.

Appendix

Discussion on Trap Category

Our initial results did not include moderator analysis results using the trap 'Category' variable. This is because classification for each trap is highly subjective; there was a grey area where traps would fall but under new categorization that would not be an issue. It is our recommendation that this area should be more formally designed within the academic community to allow for use in further analysis.

When examining trap category as a moderator there is still heterogeneity, and no trap type showed a significant difference in *Anopheles* spp. collected per night compared to HLC. When examining sub trap types, there were 25 studies that used biological traps and 22 of those were human-baited alternative traps. Although there is high heterogeneity, there is evidence that human-baited alternative traps capture significantly more *Anopheles* spp. per night than HLC ($g = -0.3940$). Multimodel inference added 'Category' and the interaction between 'Category' and 'Species' to the regression model, but the R^2 value decreased slightly. It is highly likely that there is a significant correlation between 'Type' and 'Category'; this is one possible explanation as to why the results from adding the new variables do not improve the heterogeneity explained. When analysis was performed on the *Anopheles gambiae* and *Anopheles funestus* subsets, neither subset offered statistically significant results. However, many categories in both the subsets lack the necessary studies synthesized for statistical power.

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Abbreviations
Human Landing Catches - HLCs Entomological Surveillance Planning Tool - ESPT

Availability of data and materials
The datasets compiled, used, and/or analysed during the current study are available from the corresponding author on request. R scripts used for analysis are available in the malaria_meta_analysis repository, https://github.com/JordanEckert/malaria_meta_analysis.

Competing interests
The authors declare that they have no competing interests.

Consent for publication
Not applicable

Authors' contributions
JE, SO, BM, and SZ conceived the study and participated in its design and coordination. JE, SO, YW, SJ, VP, and SZ reviewed the literature. JE conducted all statistical analysis and figures. JE, SO, NL, SZ wrote the manuscript. YW created maps. JE, SO, BM, YW, SJ, VP, NL and SZ participated in data interpretation and revisions. All authors read and approved the final manuscript.

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Figures

prisma.jpg

Figure 1 PRISMA guidelines were used for study selection and inclusion for the meta-analysis

Malariamap.jpg

Figure 2 Study locations were distributed around the world, although most studies were conducted in the African continent. Heat map coloration indicates the number of studies in each location with darker colors indicating a higher number of studies.

importance.png

Figure 3 Using multimodal inference, importance for the model's fit shows that individual 'Group', 'Species', 'Africa' and the interaction of 'Group' and 'Species' variables meet the threshold and are classified as important variables to be included in the final model.

Funnelplot.png

Figure 4 A funnel plot of the standard errors versus effect size. Each study was created to examine publication; the studies should follow the outlined funnel shape if publication bias is not present. However, this figure shows that there is publication bias in this meta-analysis.

Tables

Table 1 Random-effect Meta-Analysis. Results reveal that there is no statistically significant difference between alternative trapping methods and HLC in terms of total *Anopheles* collected

n	Hedge's g	95% Confidence Interval	τ^2	I^2
58	-0.8544	$[-1.751, .0562]$	10.6943	98.3%

Table 2 Random-effect Meta-Analysis with Outlier Removed. Results show that alternative trapping methods collected significantly more *Anopheles* mosquitoes than HLC.

n	Hedge's g	95% Confidence Interval	τ^2	I^2
36	-0.5905	$[-0.7574, -0.4235]$	0.1618	78.6%

Table 3 Subgroup Analysis using 'Type'. Subgroup analysis shows that tent traps capture significantly more *Anopheles* mosquitoes than other trap types. Only one electrocuting trap study was included in this, so it was removed for analysis.

	n	Hedge's g	95% Confidence Interval	τ^2	I^2
Tent	17	-0.4805	$[-0.9065, -0.0544]$	0.5766	88.9%
Light	17	-2.4770	$[-5.7332, 0.7792]$	38.8561	98.8%
Other - Passive	14	-0.0650	$[-0.6150, 0.4851]$	0.8245	96.4%
Other - Mechanical	9	-0.2083	$[-1.2493, 0.8327]$	1.7961	98.3%

Table 4 Subgroup Analysis using 'Africa'. Subgroup analysis shows that alternative trapping methods performed in Africa capture significantly more *Anopheles* mosquitoes than HLC.

	n	Hedge's g	95% Confidence Interval	τ^2	I^2
Studies not in Africa	20	.1748	$[-0.3243, 0.6738]$	1.0598	96.5%
Studies performed in Africa	37	-1.4522	$[-2.8750, -0.0294]$	16.8795	98.3%

Table 5 Subgroup Analysis using 'Species'. Subgroup analysis shows that alternative trapping methods capture significantly more *Anopheles gambaie* than HLC

	n	Hedge's g	95% Confidence Interval	τ^2	I^2
Gambiae Complex	23	-2.3543	$[-4.4613, -0.2473]$	22.2930	97.7%
Funestus Group	11	0.5875	$[-1.1705, 2.3455]$	6.6345	99.0%
Anopheles spp.	24	-0.1930	$[-0.7835, 0.3975]$	1.8459	97.2%

Table 6 Subgroup Analysis using 'Type' for *Anopheles gambiae*. Subgroup analysis using the 'Type' moderator on the subset of *Anopheles gambiae* s.l. shows that traps that incorporate light capture significantly more mosquitoes than HLC. The 'Other' group was collapsed into a single group to increase statistical power for analysis.

	n	Hedge's g	95% Confidence Interval	τ^2	I^2
Tent	11	-0.5231	$[-1.0929, 0.0468]$	0.6146	90.6%
Light	5	-9.7190	$[-18.3751, -1.0629]$	47.9384	99.3%
Other	6	-0.2434	$[-1.2149, 0.7282]$	0.8077	94.5%

Table 7 Subgroup Analysis using 'Type' for *Anopheles funestus*. Subgroup analysis using the 'Type' moderator on the subset of *Anopheles funestus* s.l. shows that no trap type had signficant results when compared to HLC. The 'Other' group was collapsed into a single group to increase statistical power for analysis, however, the number of synthesized studies for each group was below the traditional threshold of $n \geq 5$ limit. More synthesized studies are required for definitive analysis.

	n	Hedge's g	95% Confidence Interval	τ^2	I^2
Tent	4	-0.3539	$[-2.0478, 1.3399]$	1.0098	89.5%
Light	4	2.8827	$[-1.6527, 7.4181]$	7.9393	97.6%
Other	3	-1.1428	$[-5.9189, 3.6333]$	3.6761	99.4%

Figures

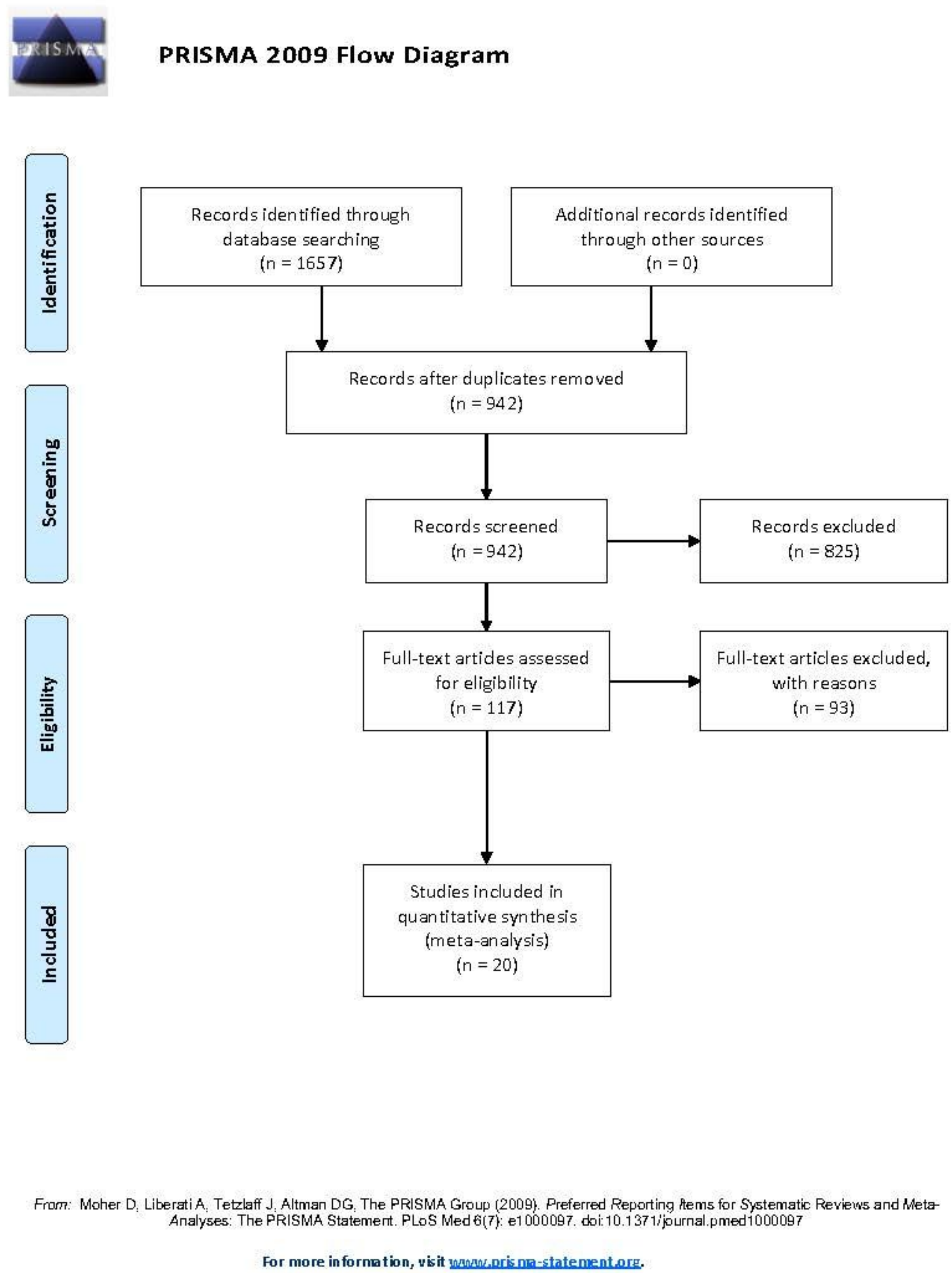
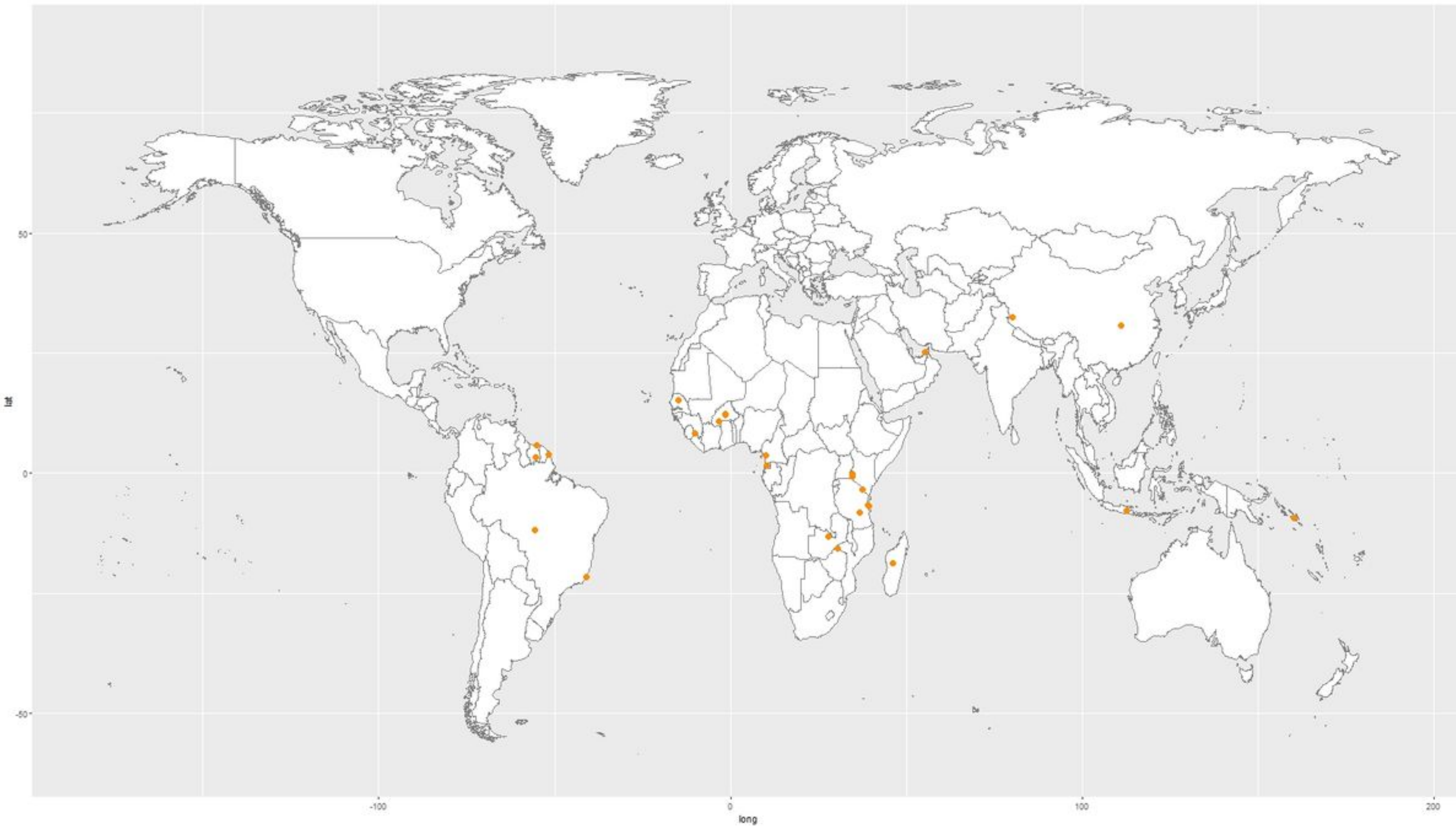


Figure 1

PRISMA guidelines were used for study selection and inclusion for the meta-analysis



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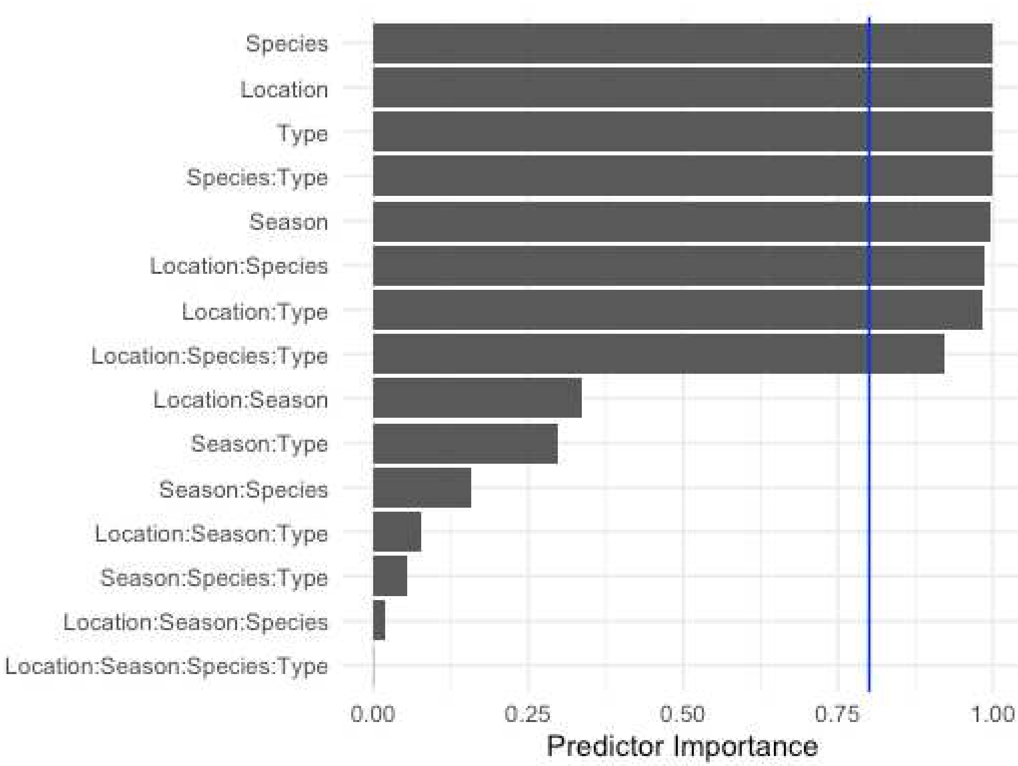

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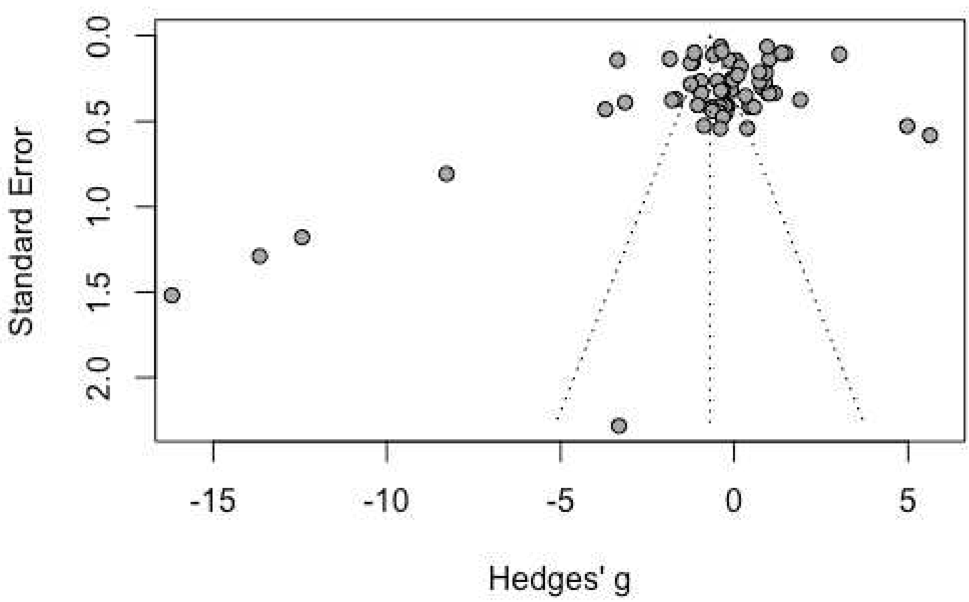

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A funnel plot of the standard errors versus effect size. Each study was created to examine publication; the studies should follow the outlined funnel shape if publication bias is not present. However, this figure shows that there is publication bias in this meta-analysis.