May 2020

Factors Limiting Effective Coverage of Indoor Residual Spraying Campaigns in Luapula Province, Zambia

Madeline Mackowski
Syracuse University

Recommended Citation

Mackowski, Madeline, "Factors Limiting Effective Coverage of Indoor Residual Spraying Campaigns in Luapula Province, Zambia" (2020). *Theses - ALL*. 400.
https://surface.syr.edu/thesis/400

Abstract

Background.

Malaria transmission control in endemic areas is dependent on both individual and community level protective measures. Indoor residual spray (IRS) campaigns work to reduce transmission of malaria illness by covering the walls of houses in areas at risk with an insecticide that kills mosquitoes landing there. The World Health Organization recommends IRS campaigns successfully spray at least 80% of structures to maximize impact of the campaigns against malaria vectors.

Methods.

Programmatic data from the 2016 IRS campaign conducted in Luapula Province, Zambia was used to examine the spatial distribution of houses missed during spray campaigns. Additionally, Poisson regression methods examine various factors associated with increasing IRS coverage at the community levels. Spatial distribution was assessed through a difference in K-function analysis.

Results.

A difference in K-function analysis suggested clustering of missed houses at all spatial scales examined. Poisson regression analysis suggested that lower population density and fewer nighttime lights were negatively associated with spray teams' ability to locate houses targeted for IRS implementation. Global Moran's I analysis confirms high levels of spatial autocorrelation among missed houses.

Conclusions.

These analyses indicate that the remoteness of structure location is a significant predictor of clusters of targeted structures being missed by spray teams during IRS campaigns. The impact that these missed clusters could have on the intended reduction of transmission control of malaria could be devastating for endemic areas, rendering many areas unprotected by IRS. Similar to issues of herd immunity, large gaps in coverage end up leaving all of the resources that are put into effective IRS program design and operations less effective if the minimum threshold is not met. Lack of threshold coverage may leave whole communities open to much higher levels of malaria transmission, and increased incidence of preventable malaria.

FACTORS LIMITING EFFECTIVE COVERAGE OF INDOOR RESIDUAL SPRAY CAMPAIGNS IN LUAPULA PROVINCE, ZAMBIA

by

Madeline D. Mackowski

B.S., Michigan State University, 2018
B.S., Michigan State University, 2018

Thesis
Submitted in partial fulfillment of the requirements for the degree of
Master of Science in Public Health

Syracuse University
May 2020

Acknowledgements

I would like to say thank you to my family for their constant support in pursuing all the challenges I have taken on. Especially my husband, Jacob, who has supported me endlessly to make this project possible. Special thanks to Dr. David Larsen, my thesis advisor, whose knowledge, academic support, and professional guidance has been invaluable throughout this process.

Many thanks to Dr. Brittany Kmush and Dr. Bhavneet Walia, who have not only served on this committee, but provided a great deal of insight which has allowed me to expand on my research and professional development. Another thank you to Dr. Lisa Olson-Gugerty, for the countless experiences of mentorship and guidance as my teaching mentor.

Additionally, I would like to thank the Department of Public Health for the academic, funding, and moral support I have received since my first day on campus. Thank you to all of the faculty and staff of the Public Health program who have all guided and supported me throughout this journey.

Table of Contents

List of Tables

List of Figures

Identifying Factors Limiting Effective Coverage of Indoor Residual Spray Campaigns in Luapula, Zambia

Introduction:

Malaria is a global disease caused by several species of parasites within the *Plasmodium* genus, although the most common infections are caused by *Plasmodium falciparum* and *Plasmodium vivax* (Trampuz et al. 2003). The *Plasmodium* life cycle is dependent on the transmission of the parasite between humans and mosquitoes (Rehman et al. 2011). Sporozoites are transmitted through the bite of the malaria vector, the female *Anopheles* mosquito, into the bloodstream of a human host where the parasite collects in the human liver, and then later, red blood cells. Mature sporozoites then release 'daughter parasites' called merozoites into the liver and bloodstream, the daughter parasites then continue infecting red blood cells throughout the body in the bloodstream (WHO, 2019). Once infected, disease symptoms appear between 10 and 15 days later, and begin as fever, chills and headache, and if untreated, can cause death through progressive multisystem organ failure (Trampuz et al. 2003).

The impact of malaria is seen globally, and specifically in the Middle East and areas of Africa (WHO 2019). One country significantly affected by malaria illness is Zambia. The World Health Organization's World Malaria Report estimated that there were nearly 16,000,000 people at risk of malaria illness in Zambia (WHO 2019). Of those at risk, upwards of 4,000,000 were infected, and over 7,000 died in the year 2015 (WHO 2019). Proportionally, that means that 25% of the population at risk were directly affected by malaria illness in 2015.

The ‘Malaria Operational Plan’ constructed by USAID separates the level of control and severity of malaria illness into three distinct regions within Zambia (USAID 2015). The highest burden falls in ‘zone 3’ which is defined as “Areas where progress in malaria control has been achieved but not sustained and lapses in prevention coverage have led to resurgence of infection and illness, and parasite prevalence in young children exceeds 14% at the peak of the transmission season” (Eastern, Luapula, Muchinga, Northern, and North-Western Provinces) (USAID 2015). Within ‘zone 3’, Luapula Province shows a relatively high burden of disease with an estimated 600-800 cases per 1000 people compared to 400 or less in surrounding Zambian Provinces (USAID 2015).

Transmission Control Methods

Primary methods of transmission control for areas with endemic malaria include insecticide treated mosquito nets and indoor residual spray (IRS) programs. While having been used earlier, IRS programs became more widely utilized in the 1950’s for the World Malaria Eradication Programme (Mabaso et al. 2004). The IRS campaigns that were designed for the eradication programme utilized the chemical insecticide dichlorodiphenyltrichloroethane, known commonly as DDT, to kill mosquitoes when landing on walls of the structure. The application of this chemical insecticide treatment specifically targets the female vector mosquitoes that land and rest on treated walls following a blood meal (WHO 2006). This method has historically been successful in largely eliminating malaria from areas of Latin America, Asia, and Russia for extended periods of time, and is still used today in the Middle East and Africa (WHO 2019). IRS is conducted by removing all of the possessions from the building, and then spraying all of the walls and surfaces in the residential structure with a chemical insecticide, of which there are several licensed for IRS campaign use, still including DDT in many areas (WHO 2006). When used appropriately, indoor residual spraying can be used to facilitate community-level protection against malaria transmission.

Individual level protective methods such as the insecticide treated mosquito net have made marked improvements in reducing malaria incidence over the last 20 years (Mabaso et al. 2004). However, the protection of healthy individuals against malaria alone is not entirely sufficient, as the transmission cycle is not stopped entirely unless both infected and healthy individuals are protected against further vector contact. Due to the lifecycle of the Plasmodium parasite, it is possible for uninfected vector mosquitoes to pick up the malaria parasite from the bloodmeal of an infected individual when biting, and then later transmit that parasite to an otherwise healthy host. For this reason, transmission control is improved through the protection of infected hosts by preventing the increased circulation of the parasite in the vector population.

In order for IRS campaigns to be effective, a certain percentage of structures need to be sprayed within the community to achieve ‘threshold coverage’. Threshold coverage with indoor residual spraying is similar to the concept of herd immunity with vaccinations, in which a certain number of people must be immunized to protect an entire community, the same concept applies here, only with vector control. Although there are documented positive effects, IRS campaigns have historically been assessed independently and without controls, so there is no definitive documentation of the direct impacts of IRS treatment on malaria outcomes (Pluess et al. 2010).

Recent studies have shown that at least 80% or higher coverage is needed for indoor residual spray campaigns to be effective on the community level (Rehman et al. 2011). In keeping with the most current research, the World Health Recommends that IRS campaigns target at least an 80% threshold (WHO 2019). However, if threshold coverage is not achieved, there will be gaps in community protection, and the protective efficacy of indoor residual spray treatment is significantly reduced and generally ineffective in controlling transmission of malaria. Gaps in coverage of prevention program operations means malaria infections are still endemic in many countries.

Burden of Malarial Disease in Zambia

The prevalence of malaria illness has fallen significantly since the early 2000's. This can largely be attributed to the introduction of insecticide treated mosquito nets (ITN), which covers the sleeping area of the individual at risk, and prevents the malaria vector from biting (Bhatt et al. 2015). Zambia is one of 19 countries that still struggles to prevent and control malaria illness (USAID 2015). While Zambia receives international aid and philanthropic funding for malaria control programs, there are still significant gaps in coverage of protective measures, resulting in malaria illness remaining prevalent all across Zambia, and particularly in Luapula province (WHO 2019).

Limitations of Indoor Residual Spraying

Although indoor residual spray campaigns have already been shown to be effective when implemented at high coverage levels, the implementation of programs have run into difficulties in achieving full coverage due to several factors. One such factor is the lack of a public address system in Zambia (USAID 2015). Zambia, as well as many other malaria endemic countries, do not have formally documented or designed communities with unique identifiers or addresses that would allow for definitive mapping, targeting, and execution of indoor residual spray campaigns. Not only does this complicate IRS campaigns, but also many other community based public health programs. Other factors that could be negatively impacting the effective coverage of spray campaigns could be the remoteness of communities, density of natural vegetation, other naturally occurring barriers, and lack of identifiable roads that would make it difficult for non-native members of the community to locate and identify targeted structures. To compensate for the lack of documentation and visibility of household locations, satellite enumeration has been used to identify and target houses for spraying (Kamanga et al. 2015).

Satellite Enumeration

Satellite enumeration is a technique used for developing more accurate targeting maps and plans for indoor residual spray campaigns (Kamanga et al. 2015). Enumeration uses satellite imaging and geographic information systems (GIS) to pinpoint and document the locations of all the residential structures in a targeted area (Kamanga et al. 2015). This list and map of structures created through satellite enumeration can then be applied to other programs for targeting. The purpose of selecting certain structures within certain areas of the community as ‘targeted’ is to identify the best locations to focus IRS treatment to achieve the most cost and space effective treatment to achieve threshold coverage. This targeting strategy is also intended to ensure equal levels of coverage throughout the community and avoid clusters or pockets of high transmission (Akros, 2018).

These processes provide a comprehensive map for spray campaign workers to find and spray enough houses to achieve community coverage within the preassigned targeted areas without having to do ground level surveillance beforehand. This allows not only for more efficient operations, but more accurate operations as well (Akros, 2018). Although these maps are provided for spray teams to target houses and they have improved accuracy from previous methods, large numbers of houses are still missed in the process. This loss of targeted structures compromises the efficacy of the campaign and protection of the community.

The satellite enumeration data utilized for this study were obtained through the comprehensive database of the ‘mSpray’ program for indoor residual spray campaign data, which has been managed and stored by Akros through the mSpray program (Akros, 2018). Akros has designed a three stage process for theoretically efficient and effective indoor residual spray campaigns. The first stage of the process is satellite enumeration of the community to identify all potential structures. Then, structures within specific areas are targeted for spray treatment to provide the most efficient operational strategy for achieving threshold coverage of spray treatment. Lastly, the spray team operations are given the information and assigned specific zones to cover, and the spray campaign takes place (Akros, 2018). With these elements, structures are targeted on the basis of satellite identification and target technology as opposed to ground level targeting based on traditional land surveys.

Hypothesis

The reason large numbers of houses are missed is currently unknown. Our hypotheses are that missed houses in a spray campaign cluster together in space, and that remoteness is a primary factor in missing houses during spray campaigns. If our hypotheses are correct, and the structures being missed are clustered, then there are significant pockets of communities going consistently unprotected. This could be leading to unusually high transmission of malarial disease of residents in those lost pockets of structures comparative to the surrounding area. Additionally, this potential missing of clusters of targeted structures could impact the effectiveness of the entire IRS campaign through inability to meet the minimum threshold coverage, impacting not only that area, but the entire community.

Methods:

Study Design

This was a retrospective cross-sectional study which examined the geographic- and program-specific factors related to the ground identification of targeted structures by spray teams during an indoor residual spray campaign for the prevention of malaria transmission from the IRS campaign done in August of 2015, in Luapula Province, Zambia. The study design is based on a series of secondary analyses of the data to identify spatial and statistical patterns. These analyses can aid in the prediction of structure identification by spray teams to minimize loss and improve coverage of targeted structures in future spray campaigns.

Data

These data are the result of the efforts of the public health organizations, Akros, USAID, and the Zambian Ministry of Health. The organization Akros utilizes satellite enumeration techniques to locate and document the locations of individual residential structures as potential spray targets, then builds comprehensive databases designed to increase efficiency and accuracy of indoor residual spray campaigns and other public health programs. Although Akros identifies and designates all target structures and spray areas necessary for effective spray campaigns, the Zambian Ministry of Health uses and utilizes this data to designate target areas for spray treatment where spray teams are to locate all structures for the highest impact on malaria transmission.

In addition to enumeration and spray campaign data, remotely sensed data from Google Earth Engine was also used to access environmental data for statistical analysis of potential predictive factors affecting loss of targeted structures. Datasets were identified and obtained through the Google Earth Engine raster repository, and include measures of vegetation density, land cover type, nighttime light emissions, population density, distance to the nearest city, and global friction surface (table 1). This data will be used to determine if there were geographic, environmental, or topographical barriers that could have been barring spray teams from locating targeted structures (table 2).

Data on vegetation density and land cover type were obtained through Google Earth Engine and was created by NASA for the Terra Moderate Resolution Imaging Spectroradiometer Vegetation Indices database (MODIS, 2010). These data are both composed of two datasets, the first being a normalized difference vegetation index, the second being an enhanced vegetation index. Together the two datasets provide an accurate measure of vegetation density from a 16 day period in 2010 (MODIS, 2010). The difference between these two datasets is that the vegetation index provides vegetation density, while land cover data provides categorical data on the type of vegetation and land use for that area. This data provides a numeric value representing vegetation density with a pixel size of 250m (MODIS, 2010).

Nighttime light data was also obtained through Google Earth Engine, sourced from the National Center for Environmental Information through the National Oceanic and Atmospheric Administration (NOAA, 2010). Nighttime lights data was collected through a normalized difference of two satellites over each calendar year. The data used for this study utilized the normalized values for 2010, which is the year with the most recently published data to the year of the spray campaign, 2015. Resolution of nighttime lights data is 30 arc seconds, or approximately 1 kilometer (NOAA, 2010).

Similarly to the vegetation data, population density data from Google Earth Engine was also sourced from NASA. This dataset was created by the Socioeconomic Data and Applications Center, which utilized various countries' census data and population registrar data in coordination with relative spatial distribution to create an adjusted population density map (SEDAC, 2015).

This data was for the year 2015, and has a recorded resolution of 30 arc seconds (SEDAC, 2015).

Distance to nearest city and global friction surface data from Google Earth Engine were created through research done at the University of Oxford, and are utilized as part of the Malaria Atlas Project (Nelson et. al., 2018). These datasets were created to quantify traversability by incorporating factors such as roadmaps, vegetation, topography, railways, and bodies of water into measures of perceived travel time. Friction surface values incorporate these factors to measure the adjusted time to travel 1 meter. Likewise, the accessibility layer assesses and quantifies the distance and estimated time it takes to travel from a point in space to the nearest major city, measured by minutes per total distance (Nelson et. al., 2018). Both of these datasets have a resolution of 30 arc seconds (Nelson et. al., 2018).

This analysis specifically looked at houses within targeted spray areas during this spray campaign as a means of evaluating full community protection against malaria infection through the documented achievement of threshold coverage. The outcomes of interest for this study were the houses that were within the targeted spray areas, but were not visited, and the overall efficacy of targeted spray areas. These targeted spray areas and the structures within were the units studied as the subject of interest in this project. The efficacy of each targeted spray area was also studied as a means of evaluating difference in planned outcome versus operational outcome.

Statistical Methods

Statistical analysis used both spatial analysis and regression methods to assess factors associated with IRS campaign efficacy. These analyses assess the spatial and statistical relationships between classes of structures identified in the mSpray data. For the most accurate analysis of potential factors driving loss of targeted structures, some structures and target areas were omitted from analysis as outliers.

Within the data, there were designated spray areas assigned as either ‘targeted’ or ‘not targeted. Within these spray areas there were a number of enumerated structures which were also designated as ‘targeted’ or ‘not targeted’ based on the spray area category. Only spray areas designated as ‘targeted’ and structures within those spray areas were included in this analysis. At the household level, there are three classes of residential structures within the original data. The first is ‘enumerated, visited, sprayed’ indicating that the structure was targeted, found, and sprayed. The second class is ‘enumerated, visited, not sprayed’, meaning the structure was targeted, visited, but not sprayed for some reason. The third class of structure is ‘enumerated, targeted, not visited’ meaning that the house was identified by satellite enumeration and targeted for spraying, but the house was not located by the spray team. This study focused on the third class of ‘enumerated, not visited’ structures. The first two classes of structures were combined into one dataset as ‘all visited structures’ as the comparison data against structures that were within targeted spray areas and not found.

Beyond the classifications of ‘missed’ or ‘visited’, the efficacy of all spray areas were calculated, and all houses within spray areas that had no coverage at all, regardless of targeting, were eliminated from analysis. This analysis focused only on structures missed that were within targeted spray areas, and had achieved at least partial coverage of enumerated structures within that area. Based on this exclusion criteria, analysis focused on factors associated with missed houses within targeted spray areas that have achieved some documented coverage of IRS treatment or at least locating targeted structures. Further comparative analysis between missed and visited structures also gives perspective on the significance of the environmental factors assessed.

Spatial point patterns will be analyzed using a difference in K-function, and Global Moran’s I analysis. The difference in K-function analysis is a spatial analysis tool that focuses on the degree of clustering existing among the two assigned structure classes of ‘visited’ and 'missed'. Results of the difference in K-function analysis shows the degree of clustering within different scales of view from immediate surroundings up to 6 miles (Balakrishnan et al. 2014). In addition to providing cluster pattern analysis, the difference in K-function can be interpreted to identify if missed structures are clustered together in space or more evenly dispersed. This information also provides initial insight into whether environmental phenomena may be affecting the loss of targeted structures prior to full regression analysis of environmental factors.

Following the analysis of spatial distribution and clustering, Poisson regression analysis was used to analyze the data. Poisson regression analysis predicts the statistical probability of how a categorical outcome will, or will not occur dependent on a series of external factors. For these regression models, the outcome of interest is whether or not a targeted structure was visited by a spray team on the spray area level. Environmental variables were analyzed as potential predictive factors of structures being located by spray teams.

$$\text{Odds Ratio} = (\, p \,/\, (1 - p))$$

$$\text{Logit} = \ln [\, p \,/\, (1 - p) \,]$$

$$L(\beta) = \Sigma(y_i x_i \beta - e^{xi\beta} - \ln y_i!)$$

Poisson regression analysis is done by combining the mSpray data with the raster data of the hypothesized external factors extracted from the Google Earth Engine databases using the statistical programs R, and Rstudio (RStudio Team, 2019). This overlay allows for Poisson regression analysis that will reveal if similarities and disparities in topography, community lighting, remoteness, population density, travel distance to major cities, and vegetation are significant factors affecting the outcome of interest, which is whether or not an enumerated structure was located by spray team operations. The output value of interest in any regression model is the beta value. The output of a regression model produces a beta for each covariate in the model which will be either positive or negative, indicating a positive or negative influence on the intercept. For this study, the beta is interpreted such that if there is a positive influence on the intercept, then that factor has a positive impact on the likelihood of structures being identified within those spray areas. Contrastingly, if the beta is negative, then it is interpreted as having a detrimental effect on the likelihood of structures being identified in those spray areas. These Poisson regression models assess factors potentially associated with program efficacy on the target area level. Other variables included in analysis are whether or not a structure was visited or missed as an individual predictor, i. This variable will be used in regression analysis to assess potential associations that will explain the loss of targeted structures during this IRS campaign.

Tests of spatial autocorrelation are statistical tools by which the relationship of points in space are assessed and statistically significant patterns of dispersion that are not detectable to the naked eye can be identified. Spatial autocorrelation is rooted in the concept of Tobler's first law of geography, stating that the closer objects that are to each other in space, the more similar those objects will be (Waller & Gotway, 2004). Global moran's I analysis is a spatial statistical method that identifies the degree of spatial autocorrelation existing among the residuals of regression models. If high levels of spatial autocorrelation are found to exist among the residuals of the model, then there is a need for a distance-weighted autocovariate to be created. The purpose of this autocovariate is to give an objective interpretation of the degree of association that covariates have on the model intercept. In this analysis, global moran's I analysis was done on all regression models to determine the degree of spatial autocorrelation occurring among both missed and visited structures, and the significance of the potential associations between the selected hypothesized environmental factors have on the efficacy of targeted spray areas.

Results:

Descriptive Statistics

The 2015 IRS campaign in Luapula Province, Zambia began with 219,813 residential structures enumerated and 769 identified spray areas. Of the total spray areas assigned and houses enumerated, 197,057 houses within 629 target spray areas were designated as targeted for treatment with indoor residual spray for this campaign. Of the 629 targeted spray areas, 82 were excluded from analysis due to no spray coverage at all, leaving 547 spray areas in the study data (figure 1). When assessing the efficacy of this campaign on the spray area level, it was observed that 410 (75%) of targeted spray areas achieved the recommended 80% threshold coverage, while 137 (25%) of spray areas did not (figure 2).

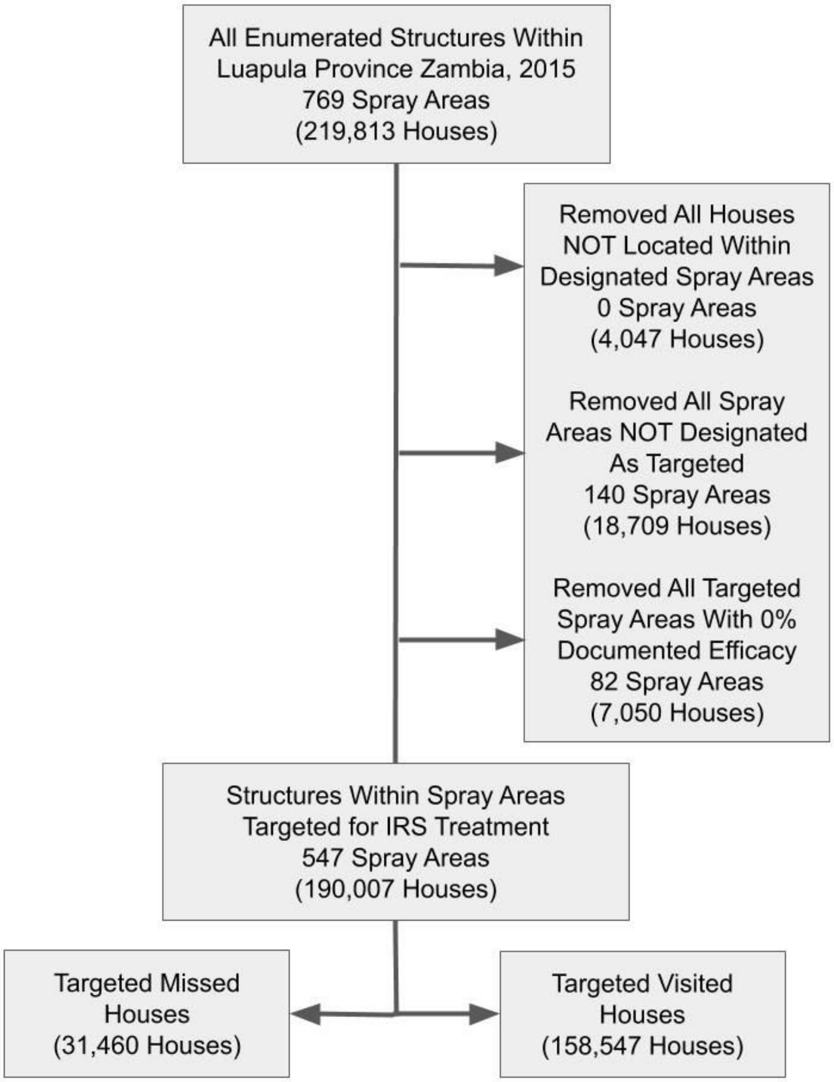

Figure 1. Inclusion and exclusion criteria utilized to narrow the sample population.

During the spray campaign, data was collected by spray team operations on houses targeted and located. On the individual structure level, IRS campaign operations achieved 79% coverage of all structures within studied target spray areas. However, the efficacy of all targeted spray areas was only 73.5% coverage, and the total efficacy of non-targeted spray areas was 2.3%. This added coverage had a positive impact on the campaign by increasing overall efficacy, and moving towards campaign-wide achievement of threshold coverage, further analysis showed that while 410 spray areas achieved effective coverage, this campaign needed to have 438 spray areas treated effectively in order to achieve threshold coverage (table 3). Although the spraying of non-targeted structures improves overall campaign efficacy, it is representative of some discrepancy in program design and operations, as only structures within targeted spray areas were supposed to receive IRS treatment.

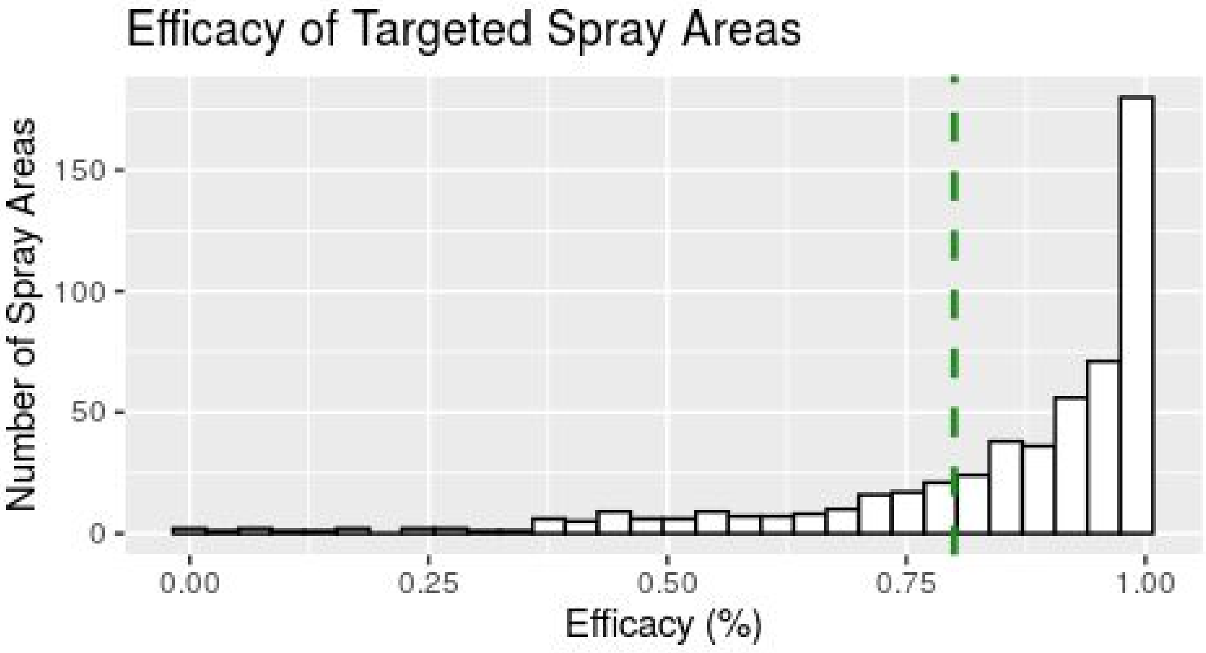

Figure 2. Distribution of Efficacy among targeted spray areas reached by spray teams during the IRS campaign in Luapula Province, Zambia 2015. Threshold coverage as reported by current research is 80% coverage, represented here by a dashed line as an x-intercept.

Difference in K-Function

Spatial analysis through difference in K-function showed that clustering is present among both visited and missed houses within targeted spray areas during the 2015 Luapula IRS campaign. Analysis showed extremely high levels of clustering of missed structures increasing through 4,000 meters, which then slightly decreased to more moderate clustering through 10,000 meters (Figure 3).

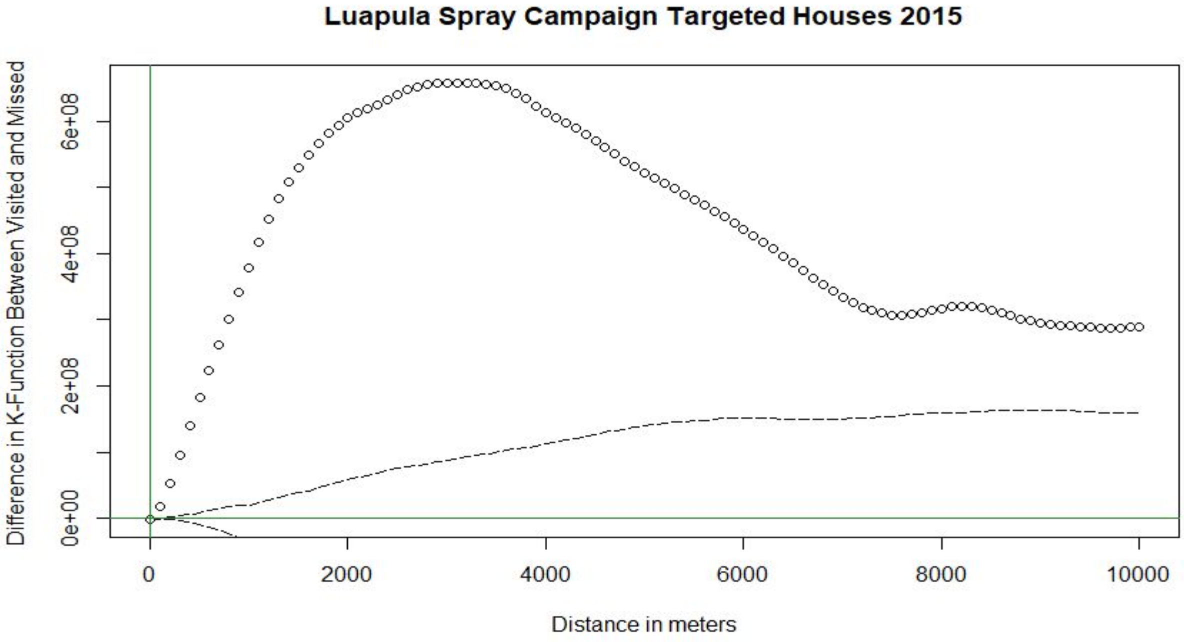

Figure 3. Difference in K-Function between houses visited and houses missed within targeted spray areas during the 2015 IRS campaign in Luapula Province, Zambia. Envelope was constructed through 99 simulations in R using the package 'splancs'.

Regression Analysis

Poisson regression analysis was used to assess factors potentially impacting the identification of houses at the spray area level. This analysis showed that in all models, all covariates except for land cover distribution are significant predictors of structures being missed (table 4). Furthermore, of the covariates assessed, the factors of light emissions and accessibility to cities are shown to be positively impacting the identification of targeted houses by spray teams. Other environmental factors considered, including accessibility, vegetation and friction surface were found to negatively impact the number of structures identified by spray teams (table 4). This indicates that targeted structures within less densely populated areas, with fewer nighttime light emissions and increased vegetation coverage are more likely to be lost and not treated by spray teams.

Global Moran's I

The global moran's I analysis tested the residuals of all models for spatial autocorrelation. High levels of spatial autocorrelation would violate the independence assumption and suggest that there is an underlying environmental factor influencing patterns of spatial distribution (Waller & Gotway, 2004). Moran's I tests of the residuals of the missed data regressions showed extremely high levels of spatial autocorrelation in all models (table 5). To account for the high levels of spatial autocorrelation, a distance-weighted autocovariate was created and incorporated into all missed structure models to objectively assess the impact of covariates of interest on the outcome without the interference of spatial autocorrelation.

Discussion:

These results show that structures missed by spray teams during indoor residual spray campaigns in Luapula Province, Zambia are not randomly distributed across space, but cluster in space. Further, these houses are more remote as measured by lower population density, more dense vegetation, and lower frequencies of nighttime light emissions. This negatively impacts campaign efficacy not only due to loss of targeted structures, but also due to loss of transmission control in the more rural communities which already have increased risk of malaria compared to more urban areas (Tatem et al. 2008). The difference in K-function analysis allows for visualization of cluster patterns of missed targeted structures, which also gives a new perspective on the perceived efficacy of IRS campaigns. Our difference in K-function, shown in figure 1, revealed high levels of clustering of missed structures from less than 100 meters increasing through 4,000 meters, and slightly decreasing to moderate levels of clustering through 10,000 meters, indicating smaller, more dense clusters accompanied by some larger clusters of structures in space. The most important information provided by spatial analysis of the missed structures is that there are extremely high levels of clustering among this group of structures, which carry implications of low to non-existent protection in pockets of these low efficacy areas of this IRS campaign. This was interpreted such that there were some external environmental factors driving the loss of enumerated targeted houses during spray campaigns.

A conceptual framework of potential factors affecting indoor residual spray campaign operations and outcomes was used for the selection of environmental factors for possible correlation to clusters of missed houses (figure 4). Factors selected for spray area level Poisson regression analysis were population density, nighttime lights as a representation of remoteness, vegetation density, global friction surface, land cover type, and accessibility represented by distance to the nearest major city. These factors were chosen because they were deemed to be the most representative of remoteness and of accessibility to residential structures in the absence of road maps and public address documentation. Remoteness and accessibility are the outcomes of interest because in Zambia, low degrees of urbanicity are known to be correlated with significantly increased risk of vector and parasite prevalence as well as malaria illness (USAID, 2015). Global Moran's I analysis of the residuals for original regressions showed high degrees of spatial autocorrelation across all missed models, but much less so in visited models. This indicated that there are strong spatial relationships existing between environmental factors and structures that were missed by spray team operations. The original missed data models were adjusted to account for this through the creation of a distance-weighted autocovariate. This autocovariate was incorporated into all missed structure regression models for the purpose of adjusting for the high levels of spatial autocorrelation expressed in the moran's I.

The adjusted regression models of missed structures showed that all covariates are still significant predictors of structures being located or lost by spray teams (table 4). Friction surface and accessibility are the most impactful predictors and are positively associated with the likelihood of a targeted structure being missed by spray teams. Vegetation was also positively associated, but was about equally as impactful as the vegetation covariate was in the visited structures model. Both distance to nearest city and friction surface covariates were also significant positive predictors in the visited structures model as well. These results support the initial hypothesis that structures further away from more densely populated areas are more likely to be missed by spray teams. All other covariates, including light, land cover, and population density are negatively associated with the likelihood of targeted structures being missed in both missed structure and visited structure models, however, the covariates for population density and nighttime lights are more impactful in the missed structure model. This indicates that lower population density and increased remoteness of structure are factors which are limiting the likelihood of structure identification. Given the difference in impact between missed and visited models, these can be considered contributing factors to the loss of targeted structures during this spray campaign. When categorized, negative predictors can be seen as a function of the remoteness of these missed structures, while positive predictors are a function of accessibility to structures.

Limitations

The data used for this study is representative only of the 2015 mSpray campaign in Luapula Province, Zambia. This study excluded spray data of structures located outside of assigned spray areas. Additionally, not all houses located and visited were treated with indoor residual spray for various reasons, meaning efficacy could be much lower than initially calculated. Locating houses within target areas is essential, but whether or not the house was treated is a major factor in meeting the necessary 80% threshold for effective transmission control of malaria.

Due to this data being only for Luapula Province in 2015, there could have been improvements made to enumeration, program design, and operational strategies to account for missing structures that have been implemented since the completion of this campaign that are unknown to the public. These analyses could also be representative of only this specific region and environment, as environments differ widely across not only Zambia, but all malaria endemic countries across Africa and the Middle East.

Although environments may differ, and this is a cross sectional examination of indoor residual spraying campaigns, it is not unreasonable to extrapolate that many IRS campaigns face similar challenges and gaps in coverage regardless of environment or time when looking at campaigns of the last five years and in process for the future. Also taking into account that while these analyses are specific to a single campaign, the methods used here may be applied to other campaigns in other regions for campaign specific analysis of spray area coverage and efficacy.

Conclusion:

Although there are limitations, this study is one of the first to examine the efficacy of spray team operations during IRS campaigns that have utilized mSpray satellite enumeration technology in their program design. The incorporation of satellite enumeration into IRS campaigns has already led to vast improvements in program design and coverage for better operational management and malaria transmission control. If gaps between satellite enumeration and program operations could be resolved, campaign efficacy could be further improved, reducing community level malaria transmission. Knowing that for this campaign, structures located in less urban areas and less populous areas are more likely to be missed by spray teams, preventative measures may be designed and implemented for more effective operations during IRS campaigns in the future.

Figure 4. Conceptual Framework of Potential Factors Associated with Continued Malaria Endemicity in Luapula Province, Zambia 2015

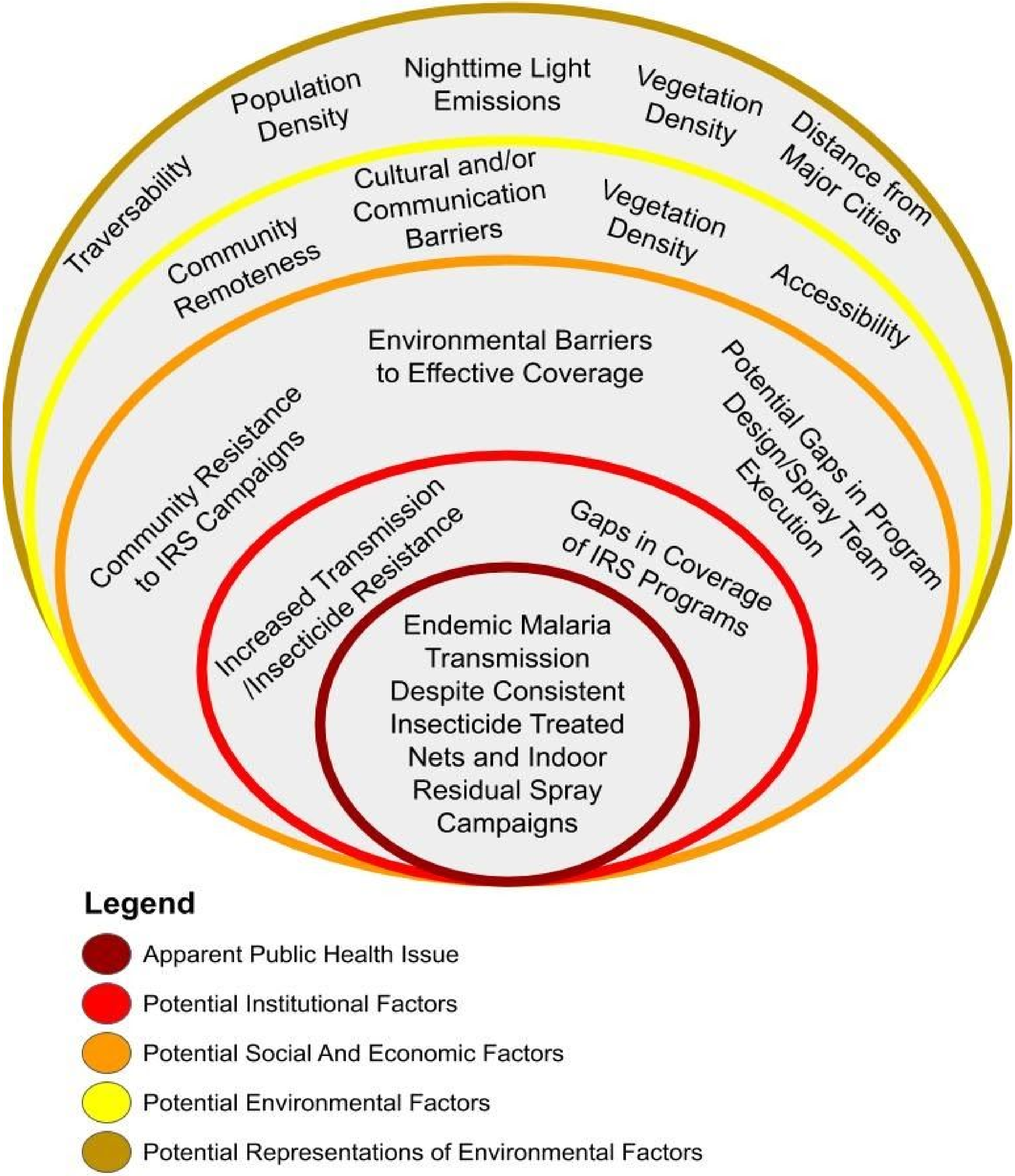

Table 1. Descriptive Statistics of Environmental Data for Luapula Province, Zambia

Environmental Data for Missed Structures

Variable	Missed Mean	Minimum	Maximum	sd
Friction	0.005022368	0.0005	0.069509	0.01011073
Population	40.12723	2.036	75.137	18.82954
Light	8.510362	4	42	6.689595
Landcover	72.32327	30	210	50.49798
Accessibility	47.88214	0	184	44.35917
Vegetation	5841.781	1679	7892	890.2426

Environmental Data for Visited Structures

Variable	Mean	Minimum	Maximum	sd
Friction	0.0055077	0.0005	0.081144	0.01144514
Population	37.69972	0.3956	75.1367	16.28339
Light	8.028717	4	42	6.658624
Landcover	71.90865	30	210	50.37754
Accessibility	56.89666	0	184	48.01032
Vegetation	5812.793	1679	7915	930.2975

Table 2. Unit of Measurement of Environmental Data for Luapula Province, Zambia

Environmental Factor	Unit of Measurement
Friction Surface	Environmentally Adjusted Time to Travel 1 meter
Population Density	Census Reported Number of Persons Per km
Light Emissions	Average Intensity of Nighttime Light Emissions as Measured by Satellite
Land Cover Distribution	Numerical Values Assigned to Land Covering Vegetation by Size and Density
Accessibility to Cities	Travel Time from Location to Nearest Major City in Minutes
Vegetation Density	Normalized Vegetation Density Indices Measured By Satellite

Table 3. Average Efficacy of Spray Areas in Luapula Province, 2015

Efficacy Status	N	Efficacy
Achieved Threshold	410	75.00%
Missed Threshold	137	25.00%
Total	547	100.00%
Target Threshold	438	80% - 85%

Table 4. Scaled/Distance Adjusted Regression Coefficients of Environmental Factors Associated with Loss of Targeted Structures

Predictor	B	p	Significant
Adjusted			
Intercept	-1.82E-01	<0.0001	*
Friction	-3.77E-03	1.54E-01	*
Population	-3.29E-02	<0.0001	*
Light	1.19E-03	6.96E-01	
Landcover	-4.42E-03	1.04E-01	
Accessibility	3.93E-02	<0.0001	*
Vegetation	-1.09E-02	<0.0001	*
Autocovariate	8.49E-12	8.32E-01	
Unadjusted Friction Surface			
Intercept	-1.81E-01	<0.0001	*
Friction	7.05E-03	4.41E-03	*
Autocovariate	9.67E-12	8.09E-01	
Unadjusted Population Density			
Intercept	-1.81E-01	<0.0001	*
Population	-2.40E-02	<0.0001	*
Autocovariate	9.01E-12	8.22E-01	
Unadjusted Light Emissions			
Intercept	-1.81E-01	<0.0001	*
Light	-1.22E-02	<0.0001	*
Autocovariate	9.97E-12	8.03E-01	
Unadjusted Landcover Distribution			
Intercept	-1.81E-01	<0.0001	*
Landcover	-1.36E-03	5.88E-01	

Autocovariate	9.82E-12	8.06E-01	
Unadjusted Distance to City			
Intercept	-1.82E-01	<0.0001	*
Accessibility	3.12E-02	<0.0001	*
Autocovariate	9.71E-12	8.08E-01	
Unadjusted Vegetation Density			
Intercept	-1.81E-01	<0.0001	*
Vegetation	-5.18E-03	3.86E-02	*
Autocovariate	9.77E-12	8.07E-01	

Table 5. Distance Weighted Global Moran's I Analysis of Environmental Factors Associated With Loss of Targeted Structures

Model	Moran's I	P-Value	Spatial Pattern
Model 1	5.11E-01	2.20E-16	Clustered
Friction Surface Unadjusted	5.11E-01	2.20E-16	Clustered
Population Density Unadjusted	0.50897	2.20E-16	Clustered
Light Emissions Unadjusted	0.51059	2.20E-16	Clustered
Landcover Distribution Unadjusted	5.11E-01	2.20E-16	Clustered
Accessibility to Cities Unadjusted	5.09E-01	2.20E-16	Clustered
Vegetation Density Unadjusted	5.10E-01	2.20E-16	Clustered

Resources

Alout, H., Djegbe, I., Chandre, F., Djogbenou, L. S., Dabire, R. K., Corbel, V., & Cohuet, A. (2014). Insecticide exposure impacts vector-parasite interactions in insecticide-resistant malaria vectors. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1786), 20140389–20140389.

Balakrishnan, N., Colton, T., Everitt, B., Piegorsch, W., Ruggeri, F., & Teugels, J. L. (Eds.). (2014). Ripley's K Function. In *Wiley StatsRef: Statistics Reference Online* (Vol. 81, p. 403). John Wiley & Sons, Ltd.

Beier, J. C., Keating, J., Githure, J. I., Macdonald, M. B., Impoinvil, D. E., & Novak, R. J. (2008). Integrated vector management for malaria control. *Malaria Journal*, *7*(Suppl 1), S4.

Bhatt, S., Weiss, D. J., Cameron, E., Bisanzio, D., Mappin, B., Dalrymple, U., Battle, K. E., Moyes, C. L., Henry, A., Eckhoff, P. A., Wenger, E. A., Briët, O., Penny, M. A., Smith, T. A., Bennett, A., Yukich, J., Eisele, T. P., Griffin, J. T., Fergus, C. A., … Gething, P. W. (2015). The effect of malaria control on Plasmodium falciparum in Africa between 2000 and 2015. *Nature*, *526*(7572), 207–211.

Bridges, D. J., Pollard, D., Winters, A. M., Winters, B., Sikaala, C., Renn, S., & Larsen, D. A. (2018). Accuracy and impact of spatial aids based upon satellite enumeration to improve indoor residual spraying spatial coverage. *Malaria Journal*, *17*(1), 93.

CDC-Centers for Disease Control, & Prevention. (2009). *CDC - Malaria - About Malaria - Biology*. https://www.cdc.gov/malaria/about/biology/index.html

Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H49C6VHW

Checchi, F., Stewart, B. T., Palmer, J. J., & Grundy, C. (2013). Validity and feasibility of a satellite imagery-based method for rapid estimation of displaced populations. *International Journal of Health Geographics*, *12*(1), 4.

Chisha, Z., Larsen, D. A., Burns, M., Miller, J. M., Chirwa, J., Mbwili, C., Bridges, D. J., Kamuliwo, M., Hawela, M., Tan, K. R., Craig, A. S., & Winters, A. M. (2011). *Enhanced* *surveillance and data feedback loop associated with improved malaria data in Lusaka, Zambia*. https://doi.org/10.1186/s12936-015-0735-y

Didan, K. (2015). MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-04-01 from https://doi.org/10.5067/MODIS/MOD13Q1.006

D.J. Weiss, A. Nelson, H.S. Gibson, W. Temperley, S. Peedell, A. Lieber, M. Hancher, E. Poyart, S. Belchior, N. Fullman, B. Mappin, U. Dalrymple, J. Rozier, T.C.D. Lucas, R.E. Howes, L.S. Tusting, S.Y. Kang, E. Cameron, D. Bisanzio, K.E. Battle, S. Bhatt, and P.W. Gething. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature* (2018). doi:10.1038/nature25181

DMSP-OLS Nighttime Lights Time Series - Version 4 (2010). Image and Data processing by NOAA's National Geophysical Data Center. DMSP data collected by the US Air Force Weather Agency.

Dormann, C. F., Mc Pherson, J. M., Araujo, M. B., Bivand, R., Bolliger, J., Carl, G., Davies, R. G., Hirzel, A., Jetz, W., Daniel Kissling, W., Kuhn, I., Ohlemuller, R., Peres-Neto, P. R., Reineking, B., Schroder, B., Schurr, F. M., & Wilson, R. (2007). Methods to account for spatial autocorrelation in the analysis of species distributional data: a review. *Ecography*, *30*, 609–628.

Dye, C., & Hasibeder, G. (1986). Population dynamics of mosquito-borne disease: effects of flies which bite some people more frequently than others. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *80*(1), 69–77.

Edition, S. (n.d.). *For the control of vectors and pests of public health importance*. https://apps.who.int/iris/bitstream/handle/10665/69223/WHO_CDS_NTD_WHOPES_GCDPP_2006.1_eng.pdf?sequence=1&isAllowed=y

Eisele, T. P., Larsen, D., & Steketee, R. W. (2010). Protective efficacy of interventions for preventing malaria mortality in children in Plasmodium falciparum endemic areas i88 Keywords Systematic review, malaria prevention, child mortality, insecticide-treated mosquito nets, indoor-residual spraying, intermittent preventive therapy in pregnant women. *International Journal of Epidemiology*, *39*, 88–101.

Elliott, P., & Best, N. (2014). Geographic Patterns of Disease. In *Wiley StatsRef:*

Statistics Reference Online. John Wiley & Sons, Ltd.

Escamilla, V., Emch, M., Dandalo, L., Miller, W. C., Martinson, F., & Hoffman, I. (2014). Lessons from the field Sampling at community level by using satellite imagery and geographical analysis. *Bulletin of the World Health Organization*, *92*, 690–694.

Friedl, M., Sulla-Menashe, D. (2019). MCD12Q1 MODIS/Terra+Aqua Land Cover Type Yearly L3 Global 500m SIN Grid V006 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2020-04-01 from https://doi.org/10.5067/MODIS/MCD12Q1.006

Goodman, C. A., Coleman, P. G., & Mills, A. J. (1999). Cost-effectiveness of malaria control in sub-Saharan Africa. *The Lancet*, *354*(9176), 378–385.

IRS-position.indd. (n.d.). https://apps.who.int/iris/bitstream/handle/10665/69386/WHO_HTM_MAL_2006.1112_eng.pdf?sequence=1

Kamanga, A., Renn, S., Pollard, D., Bridges, D. J., Chirwa, B., Pinchoff, J., Larsen, D. A., & Winters, A. M. (2015). Open-source satellite enumeration to map households: planning and targeting indoor residual spraying for malaria. *Malaria Journal*, *14*, 345.

Kiware, S. S., Chitnis, N., Devine, G. J., Moore, S. J., Majambere, S., & Killeen, G. F. (2012). Biologically meaningful coverage indicators for eliminating malaria transmission. *Biology Letters*, *8*(5), 874–877.

Kleinschmidt, I., Bagayoko, M., Clarke, G. P., Craig, M., & Le Sueur, D. (2000). A spatial statistical approach to malaria mapping. *International Journal of Epidemiology*, *29*(2), 355–361.

Larsen, D. A., Borrill, L., Patel, R., & Fregosi, L. (2017). Reported community-level indoor residual spray coverage from two-stage cluster surveys in sub-Saharan Africa. *Malaria Journal*, *16*(1), 249.

Liu, Z., Soe, T. N., Zhao, Y., Than, A., Cho, C., Aung, P. L., Li, Y., Wang, L., Yang, H., Li, X., Li, D., Peng, Z., Wang, J., Li, Y., Yang, Z., Zhou, H., Wang, Q., Kyaw, M. P., Cao, Y., & Cui, L. (2019). Geographical heterogeneity in prevalence of subclinical malaria infections at sentinel endemic sites of Myanmar. *Parasites & Vectors*, *12*(1), 83.

Lu, B., Charlton, M., Harris, P., & Fotheringham, A. S. (2014). Geographically weighted regression with a non-Euclidean distance metric: a case study using hedonic house price data. *International Journal of Geographical Information Science: IJGIS*, *28*(4), 660–681.

Mabaso, M. L. H., Sharp, B., & Lengeler, C. (2004). Historical review of malarial control in southern African with emphasis on the use of indoor residual house-spraying. *Tropical Medicine & International Health: TM & IH*, *9*(8), 846–856.

Magaço, A., Botão, C., Nhassengo, P., Saide, M., Ubisse, A., Chicumbe, S., & Zulliger, R. (2019). Community knowledge and acceptance of indoor residual spraying for malaria prevention in Mozambique: a qualitative study. *Malaria Journal*, *18*, 27.

Malaria Operational Plan 2015.pdf. (n.d.).

Mapping Travel Times with malariaAtlas and Friction Surfaces. (n.d.). https://medium.com/@abertozz/mapping-travel-times-with-malariaatlas-and-friction-surfaces-f4960f584f08

Miller, E., Dushoff, J., & Huppert, A. (2016). The risk of incomplete personal protection coverage in vector-borne disease. *Journal of the Royal Society, Interface / the Royal Society*, *13*(115), 20150666.

Moukam Kakmeni, F. M., Guimapi, R. Y. A., Ndjomatchoua, F. T., Pedro, S. A., Mutunga, J., & Tonnang, H. E. Z. (2018). Spatial panorama of malaria prevalence in Africa under climate change and interventions scenarios. *International Journal of Health Geographics*, *17*(1), 2.

mSpray | Akros. (n.d.). Akros. Retrieved January 23, 2020, from https://akros.com/mspray/

Mueller, D. H., Wiseman, V., Bakusa, D., Morgah, K., Daré, A., & Tchamdja, P. (2008). Cost-effectiveness analysis of insecticide-treated net distribution as part of the Togo Integrated Child Health Campaign. *Malaria Journal*, *7*(1), 73.

Mutuku, F. M., King, C. H., Mungai, P., Mbogo, C., Mwangangi, J., Muchiri, E. M., Walker, E. D., & Kitron, U. (2011). Impact of insecticide-treated bed nets on malaria transmission indices on the south coast of Kenya. *Malaria Journal*, *10*(1), 356.

Nájera, J. A., González-Silva, M., & Alonso, P. L. (2011). Some lessons for the future from the Global Malaria Eradication Programme (1955-1969). *PLoS Medicine*, *8*(1), e1000412.

N’Guessan, R., Boko, P., Odjo, A., Chabi, J., Akogbeto, M., & Rowland, M. (2010). Control of pyrethroid and DDT-resistant Anopheles gambiae by application of indoor residual spraying or mosquito nets treated with a long-lasting organophosphate insecticide, chlorpyrifos-methyl. *Malaria Journal*, *9*(1), 44.

Ouédraogo, M., Samadoulougou, S., Rouamba, T., Hien, H., Sawadogo, J. E. M., Tinto, H., Alegana, V. A., Speybroeck, N., & Kirakoya-Samadoulougou, F. (2018). Spatial distribution and determinants of asymptomatic malaria risk among children under 5 years in 24 districts in Burkina Faso. *Malaria Journal*, *17*, 460.

Parham, P. E., & Hughes, D. A. (2015). Climate influences on the cost-effectiveness of vector-based interventions against malaria in elimination scenarios. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *370*(1665), 20130557–20130557.

Pluess, B., Tanser, F. C., Lengeler, C., & Sharp, B. L. (2010). Indoor residual spraying for preventing malaria. *Cochrane Database of Systematic Reviews* . https://doi.org/10.1002/14651858.CD006657.pub2

President’s Malaria Initiative Strategy 2015-2020. (n.d.). https://www.usaid.gov/sites/default/files/documents/1864/PMI%20Strategy%202015-2020.pdf

Rehman, A. M., Coleman, M., Schwabe, C., Baltazar, G., Matias, A., Roncon Gomes, I., Yellott, L., Aragon, C., Nseng Nchama, G., Mzilahowa, T., Rowland, M., & Kleinschmidt, I. (2011). How Much Does Malaria Vector Control Quality Matter: The Epidemiological Impact of Holed Nets and Inadequate Indoor Residual Spraying. *PloS One*, *6*(4), e19205.

RStudio Team (2019). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/.

Smith, C. M., Le Comber, S. C., Fry, H., Bull, M., Leach, S., & Hayward, A. C. (2015). Spatial methods for infectious disease outbreak investigations: systematic literature review. *Eurosurveillance*, *20*(39), 30026.

Tewara, M. A., Mbah-Fongkimeh, P. N., Dayimu, A., Kang, F., & Xue, F. (2018). Small-area spatial statistical analysis of malaria clusters and hotspots in Cameroon;2000–2015.

BMC Infectious Diseases, *18*(1), 636.

Trampuz, A., Jereb, M., Muzlovic, I., & Prabhu, R. M. (2003). Clinical review: Severe malaria. *Critical Care / the Society of Critical Care Medicine*, *7*(4), 315–323.

Waller, L., & Gotway, C. (2004). Applied Spatial Statistics for Public Health Data. Hoboken, NJ:
John Wiley & Sons.
World Health Organization, United Nations. (2019). *World malaria report 2019*.

Yakob, L., Dunning, R., & Yan, G. (2011). Indoor residual spray and insecticide-treated bednets for malaria control: theoretical synergisms and antagonisms. *Journal of the Royal Society, Interface / the Royal Society*, *8*(59), 799–806.

Zhou, G., Githeko, A. K., Minakawa, N., & Yan, G. (2010). Community-wide benefits of targeted indoor residual spray for malaria control in the Western Kenya Highland. *Malaria Journal*, *9*(1), 67.

Madeline Mackowski M.S.

madelinedhilton13@gmail.com

Education:

2020 - Syracuse University, Syracuse, NY, M.S. Public Health.

2018 - Michigan State University, East Lansing, MI, B.S. Microbiology.

2018 - Michigan State University, East Lansing, MI, B.S. Genomics and Molecular Genetics; Minor: Dance Performance and Pedagogy.

Professional Positions:

2018 - Present, Graduate Teaching Assistant, Public Health, Syracuse University, Syracuse, NY.

Fall 2019, Listed Instructor, Falk College Department of Public Health Undergraduate Data Management Course, Syracuse University, Syracuse, NY.

Summer 2019, Graduate Intern, YWCA of Syracuse and Onondaga County, Syracuse, NY.
Focus: Program Design, Management, and Coordination.

2018-2019, Graduate Research Assistant, Public Health, Syracuse University, Syracuse, NY.

2018 - 2019, Graduate Athletics Tutor, Syracuse University, Syracuse, NY.
Focus: Biology, Microbiology, Chemistry, Biochemistry, Genetics.

Summer 2018, Research Intern, Kraig Biocraft Laboratories, Lansing, MI.
Research: Genetic Modification of Entomological Species for Improved Performance in Commercial Manufacturing.

2015 - 2018, Undergraduate Research Assistant, Biochemistry Department, Michigan State University, East Lansing, MI.
Research: Flint Water Crisis Impact on Bacteriophage Titers and Variants in Surrounding Communities.

2016 - 2018, Undergraduate Teaching Assistant, Biology Department, Michigan State University, East Lansing, MI.

Summers 2013 - 2017, Purchasing Assistant, Macomb Community College Budget Office, Sterling Heights, MI.

Publications/Awards:

Falk College Graduate Research Award, 2019.

JAMA Publication: “Association Between Repetitive Head Impacts and Mortality Among NFL Players.” ~ Second Author

Thesis: “Identifying Factors Limiting Effective Coverage of Indoor Residual Spray Campaigns in Luapula, Zambia”

Professional Skills:

Computer/Software:

- Microsoft Office (Excel, PowerPoint, Word, Outlook)
- Google Drive Systems (Slides, Sheets, Docs)
- Adobe
- RStudio
- Google Earth Engine
- QGIS
- ArcGIS

Laboratory Skills and Experience Including

- Pipetting
- PCR/qPCR
- Gel Electrophoresis
- SDS Page
- Western/Northern Blotting
- Buffer/Reagent Preparation
- Bacterial Cell Culture
- Viral Culture
- Water Sample Analysis
- Primer Design; Microinjection
- Distillation
- Liquid Chromatography
- Environmental Sample Collection/Treatment
- DNA Analysis
- Protein Analysis
- Microscope
- Biohazard Disposal Protocol
- PPE
- Gram Staining
- Sterilization/Autoclave Procedures