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Average Household Size and the Eradication of Malaria

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Short Summary

Malaria has disappeared in some countries but not others, and an explanation for the eradication pattern has been elusive. We show that the probability of malaria eradication jumps sharply when average household size in a country drops below four persons. Part of the effect commonly attributed to income growth is likely due to declining household size. The effect of DDT usage is difficult to isolate but we only identify a weak role for it. Warmer temperatures are not associated with increased malaria prevalence. We propose that household size matters because malaria is transmitted indoors at night, so the fewer people are sleeping in the same room, the lower the probability of transmission of the parasite to a new victim. We test this hypothesis by contrasting malaria incidence with dengue fever, another mosquito-borne illness spread mainly by daytime outdoor contact.

Background

Malaria is a parasitic disease that is transmitted to humans by infected *Anopheles* mosquitoes. It infects red blood cells, causing anemia, nausea, fever and sometimes death. There are about 225 million cases annually leading to 800 000 fatalities, of which 90 percent are in Africa, and most of whom are children.

It is a common misconception that malaria is a tropical disease. Although that is where it remains prevalent, it used to occur throughout the world, in all climate zones, from the tropics to the coast of the Arctic Sea (up to 70° N latitude). Malaria was endemic in Europe and North America during the 20th century, but has largely disappeared and has been unable to re-establish itself there in spite of frequent annual importation of cases.

An interesting aspect of this history is that the disease disappeared in many countries that made no special efforts to eradicate it, while remaining prevalent in other countries that tried. Numerous explanations for the global pattern of eradication have been suggested, such as a change in the feeding pattern of the insects, draining of wetlands, or intensive use of the insecticide DDT (dichlorodiphenyltrichloroethane). Despite superficial plausibility, such explanations begin to fail upon close examination. With regard to DDT, for instance, while about 75% of the world used it, with an average application interval of over 15 years, malaria only disappeared in 43% of the world's countries.

This study looks at the connection between declining average household size and the disappearance of malaria. The ongoing prevalence of malaria in tropical countries suggests a connection with socioeconomic conditions, but explanations have been lacking as to specific mechanisms by which the disease is affected by poverty. Back in the 1930s, Sidney Price James observed that the number of malaria cases was always higher in cottages in which big families slept together in one room, which was especially the case among the poor. This received little attention subsequently and research efforts focused on other factors.

In a 2009 analysis of the malaria trend in Finland over the interval 1750–2006, Finnish biologists Lena and Larry Huldén noted that while many standard theories of malaria disappearance had little explanatory power, mean household size appeared to correlate very closely over a long interval with the decline in malaria cases, which led them to ask whether this pattern might hold true globally. Together with Canadian economist Ross McKitrick, they have now developed and analyzed a large international data base and found that James' early conjecture appears to have been correct.

Study details

Data on malaria, insect vectors, demographic factors, sociological factors, and environmental factors for 232 countries or corresponding administrative units were compiled. Data for the year 2000 or the closest year thereto were obtained. Of these 220 countries, malaria was never endemic in 32, remains prevalent in 106 and has been eradicated from 82. Mongolia is the only country with an indigenous vector species but no historical or recent malaria. Thus indigenous malaria vectors (*Anopheles* species) are known from 188 countries, which is the sample for the analysis.

Explanatory variables include Gross Domestic Product (GDP) per capita, average household size, female literacy, urbanization and slums, latitude, mean temperature, forest coverage, Muslim population, national DDT usage, population density and national mean temperature (over the 1980-2008 interval).

The authors used regression analysis to determine which factors affect the probability that malaria will have been eradicated from a country, and, among those countries where it is still present, what affects the disease incidence in the population.

The authors included the Muslim fraction in society as an explanatory variable because households in strict Muslim countries are characterized by gender-segregated sleeping arrangements which, in varying degree, divides a household into smaller effective units, depending on how strictly the practice is applied. Hence these countries may have relatively large households on average, but effective household sizes below four persons as regards sleeping arrangements.

Note: DDT Usage

The only countries that use DDT for malaria vector control are those that have malaria, so the presence of malaria strongly predicts the use of DDT. Naively putting a DDT usage measure into the model would give erroneous results falsely suggesting that DDT causes malaria**.**

The remedy for this problem is to obtain a statistical instrument that measures the effect of DDT usage on malaria frequency and eradication probability, independent of a country's decision to use it in response to the presence of malaria. It is not easy to develop such an instrument. The authors' approach made use of the move by the United States to ban the production and use of DDT in 1971, which marked the start of worldwide efforts to withdraw the product from usage due to environmental concerns. This aspect of the usage decision was outside the control of most countries, and their willingness to use DDT after 1971 therefore reveals something about the aggressiveness of their anti-malarial stance.

Figure 1 (below) shows the fraction of countries in our sample with malaria, the fraction using DDT, and the ratio of the two, by year, from 1951 to 2005. In 1951, 81% of the countries in our sample experienced malaria and 63% used DDT, a usage ratio of 0.78. This declined relatively steadily until the 1990s. As of 1971, 55% experienced malaria and 33% were using DDT, yielding a usage ratio of 0.60. In the 1990s the usage ratio began falling more rapidly, such that by 2005, 48% still experience malaria but only 4% use DDT, a ratio of 0.08.

Conditional on a country already having experienced malaria, an aggressive malaria control stance would be indicated by a willingness to use DDT right up to the year in which malaria was eradicated, despite the international pressure not to do so. The authors therefore defined a variable indicating if the year in which a country ceased using DDT was the same as the year malaria disappeared, or one or two years after that. This describes 18% of the sample, and was interpreted as an indication of aggressive DDT usage.

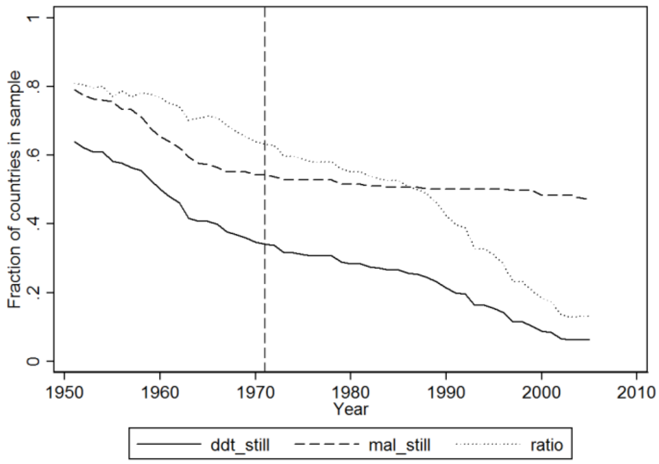


Figure 1. By year: fraction of countries in our sample in which malaria is still present (*mal_still,* dashed line), DDT is still used (*ddt_still*, solid line) and the ratio of the two (dotted line). Vertical dash line: 1971, year US banned DDT.

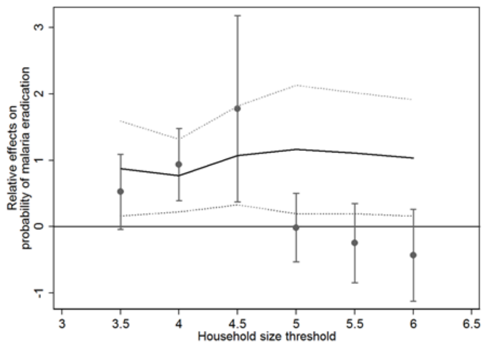
Results

What increases the probability of malaria eradication?

The table below presents some key results regarding factors affecting the probability of success in malaria eradication.

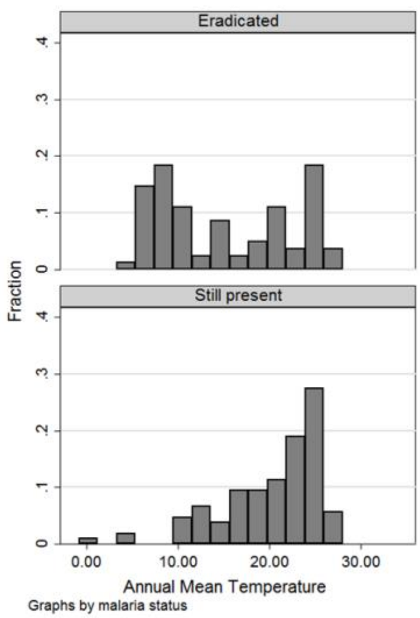
Explanatory variable	Effect on the probability of malaria eradication	
Higher income	positive	significant
Avg household size under 4 persons	positive	significant
Higher population density	positive	significant
Higher population growth rate	negative	weakly significant
% living in urban area	positive	significant
% Muslim	positive	significant
Mean national temperature	positive	significant
DDT used aggressively	positive	insignificant
Sample size	188	
Fraction of variance explained by model	78.3%	

Household Size Effect



The household size effect shows up strongly when measured as a binary indicator of whether a country's average household size is below a certain number of persons or not. The largest effects arise when the threshold is set to 4.0 or 4.5 persons: in these cases the threshold effect is larger than that associated with a one-standard deviation increase in real income.

In the Figure, filled circles show the effect when household size drops below the indicated threshold, with $\pm 2\sigma$ uncertainty ranges shown. The solid line shows the effect associated with a one standard deviation increase in average income, and the dotted lines show the corresponding $\pm 2\sigma$ ranges shown.



Temperature

If one looks at annual mean temperature in isolation, it could easily yield the mistaken view that higher temperature results in a higher likelihood of malaria occurring in a country. For instance, a simple comparison of histograms showing the fraction of countries by temperature, dividing the sample into places where malaria has been eradicated (top panel) versus where it is still present (bottom panel), could lead to the inference that the higher the mean annual temperature, the greater the number of countries with malaria.

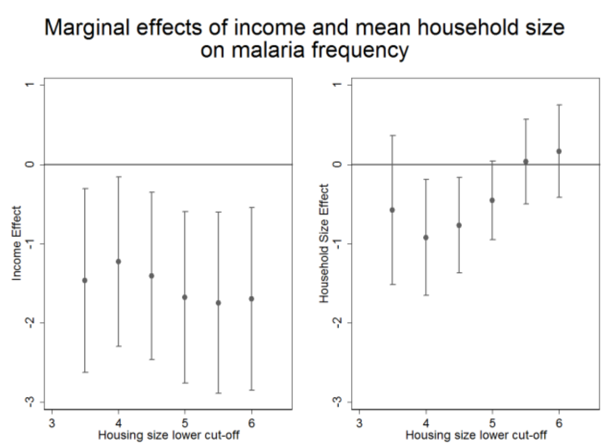
But this is incorrect because it fails to control for the influences of income, household size and other socioeconomic characteristics. The multivariate analysis shows that when these factors are controlled, higher temperatures are actually associated with a small but significant increase in the probability of malaria eradication.

What factors decrease malaria incidence?

The table below presents some key results regarding factors affecting the number of cases per 100,000 each year in countries where malaria is still present.

Explanatory Variable	**Effect on rates of malaria infection**	
Higher income	negative	significant
Avg household size under 4 persons	negative	significant
Higher population density	negative	insignificant
Higher population growth rate	negative	insignificant
% living in urban area	negative	insignificant
% Muslim	negative	significant
Mean national temperature	negative	insignificant
DDT used aggressively	negative	insignificant
Sample Size	188	
Fraction of variance explained by model	0.306	

The regression results show that when household size drops below a four-person threshold, about one-third of the effect that would otherwise be attributed to income disappears and instead is attributable to small household size.



Regarding temperature, the analysis of disease incidence again shows that higher temperatures, if anything, are associated with lower disease incidence, but the effect is statistically insignificant.

An Explanatory Mechanism

The mosquitoes responsible for malaria pick up the parasite from humans. At the local level, practically all *Anopheles* species feed at night. The female mosquito gets the infection from a human blood meal. After egg laying it returns to the same approximate location for another blood meal. The parasite multiplies sexually in the mosquito. The process takes ~10–16 days and is completed when the infective form of the parasite reaches the salivary glands of the mosquito, which allows it to be transferred to another human through the bite.. Early experiments with *Plasmodium vivax* showed that an infective mosquito will bite 30–40 times (James 1926). For a new person to be infected, a mosquito carrying the mature parasite back to its feeding location must find a victim who is not already infected. Therefore the more people who are sleeping together in the same room, the higher the probability of spreading the infection to a new person. Reinfection is thus a stochastic process, and below a certain threshold number of persons sleeping together, *Plasmodium* infection success rates drop below the replacement rate and it begins to disappear from the human population, even without other control measures. This study indicates that the threshold is likely crossed when average household size drops below somewhere between 4.0 and 4.5 persons.

The hypothesis was tested by re-doing the analysis using data on the incidence of dengue fever, which, like malaria, is mosquito-borne and has wide geographic distribution, but is spread by different species that are active during the day in shaded places and only occasionally at night. Thus its transmission mechanism is not expected to be sensitive to household size, but to factors affecting outdoor exposure. In the dengue re-analysis, the household size effect disappeared, as did the Muslim effect, and the income effect became much smaller and less significant. The measure of aggressive DDT usage became marginally significant (p=0.073).

Conclusions

These findings suggest that as average household sizes continue to decline around the world, malaria will also gradually disappear. The authors did not differentiate between adult and children household members. There is evidence that the threshold is not affected by the fraction of children, since the effect has been observed in populations of soldiers where children are not present. The result raise the possibility that in regions with large households (or large populations sharing sleeping quarters, such as lumber camps or military barracks), the eradication of malaria will require segmenting sleeping quarters into smaller units, such as with mosquito nets. The average number of bed nets per person in 35 African countries is 0.21. In Vanuatu (average household size 5.6) a high provision of individual bed nets has, in combination with effective drug distribution and surveillance, been credited with the disappearance of malaria since 1996. Use of individual bed nets emulates a house with several bedrooms, making it more difficult for an infective vector to transmit the parasite to new household members.

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