The economic impacts of malaria: past, present, and future

Nikolas Kuschnig[a,*] Lukas Vashold[a]

[a] Vienna University of Economics and Business (WU)

September 30, 2022

Malaria places a great burden on the health and prosperity of many and occupies a great number of scientists and policymakers. The dynamics of the disease are tightly interwoven with economics — incidence is both tied to economic circumstances and impacts them. Economic research plays an important role in understanding and supporting the fight against malaria. The economic literature, however, features a number of peculiarities that can hamper accessibility and has been slow to approach interdisciplinary issues. Here, we explain the economic perspective and summarise the literature on the economic impacts of malaria. Malaria has severe impacts on individual and aggregate economic outcomes, including mortality and morbidity, but also indirect burdens that materialise with a delay. The fight against malaria is not an economic policy per se, but may provide beneficial economic spillovers and can be vital in establishing an environment that allows for prosperity. Economic insights can make a difference in the design and implementation of effective and efficient eradication and control strategies. This is critical in the light of increasing disease (re-)exposure due to climate change and the emergence of resistant vectors and pathogens.

Keywords: malaria, development, economic growth, education, health

*Correspondence to nikolas.kuschnig@wu.ac.at, Welthandelsplatz 1, 1020 Vienna, Austria. Both authors contributed equally. We thank Klaus Prettner and Jesús Crespo Cuaresma for their insightful comments.

1 Introduction

Vector-based diseases place a great burden upon affected populations. Among them, malaria is the most prevalent, with about 241 million cases and 627,000 deaths in 2020 (Global Malaria Programme, 2021). Today, the disease is endemic to tropical and sub-tropical regions, home to some of the poorest countries on earth. Whether and how these facts are related continues to occupy many scientists. Disease and economics interweave tightly in many dimensions that prove hard to disentangle. Research questions are complex and of a fundamentally interdisciplinary nature, making reliable analysis challenging. Insights into the economic impacts of malaria can only be obtained with a broad understanding of the disease and its interrelations. Similarly, economic circumstances play an important role in the spread, control, and eradication of malaria; evidenced by considerable interest from the wider literature.

The importance of economics for malaria is reflected in a large body of research. However, the relation is not as clear as it may seem and insights are not as accessible as one would like. The strong link between malaria, development, and poverty noted in macroeconomic studies (e.g. Gallup and Sachs, 2000) caught considerable attention. The same is true for the widespread backlash (e.g. Acemoglu and Johnson, 2007), pointing out a lack of causality. More nuanced economic studies do not command as much attention, but offer, e.g., robust evidence of malaria impacting human capital accumulation, labour productivity and a range of other important socioeconomic factors (see Kuecken et al., 2021, for a recent example). Meanwhile, more generalist approaches could benefit from an economic perspective (see Duflo, 2017, for an argument why this may be the case), but collaborations are rare, which is partly due to a lack of incentives. Knowledge of the economic impacts of malaria and a comprehensive understanding of the disease are vital for interdisciplinary research, but also for selecting efficient adaptation and mitigation measures (Sicuri et al., 2022).

Malaria has a wide range of economic impacts, ranging from immediate ones, due to mortality and morbidity, to indirect ones. Among many other impacts, the disease lowers cognitive skills (Venkataramani, 2012), educational attainment (Lucas, 2010), labour market participation (Hong, 2013), and affects fertility choices (Lucas, 2013), civil unrest (Cervellati et al., 2022a), as well as foreign direct investment (Cervellati et al., 2022b). Studies have found pronounced links between malaria and economic circumstances at large (Gallup and Sachs, 2000), although the strength of these links, and whether a causal relationship exists, remains debated (Acemoglu and Johnson, 2007; Cervellati and Sunde, 2011). Insights into the effects of control and eradication campaigns, like the one by Kuecken et al. (2021) for the recent 'Roll Back Malaria' campaign in sub-Saharan

Africa, can help with the efficient and effective use of sparse resources for the design, implementation, and funding of malaria control and eradication strategies.

However, insights are only useful when they are accessible, and both the languages of economics and malaria itself can be particular. With this in mind, we provide some background for the disease, and introduce essential features of the economic literature — most prominently its focus on identifying causal effects from non-experimental data. We review the literature on the economic impacts of malaria, both in micro- and macroeconomic terms. Topics include impacts at the individual-level, such as health and educational outcomes, at aggregate levels, such as economic development, and the economics of malaria eradication and control. The goal of this paper is to summarize and reconcile the economic literature, paving the way for future interdisciplinary research efforts. The fight against malaria will pose many known and unknown challenges — including climate change — and well-informed strategies are needed, as are knowledge spillovers across disciplines.

The remainder of this paper is structured as follows. Section 2 briefly provides some background on human malaria that may be skipped by readers that are well-informed on the disease. Section 3 engages with the economic impacts of malaria. The final Section 4 provides an outlook and concludes.

2 Malaria

Human malaria is caused by six *Plasmodium* parasite species — most notably *P. falciparum* and *P. vivax* — that are transmitted primarily via the bite of female *Anopheles* mosquitoes. Incidence is tied to the spread and activity of these vectors and depends on environments that are suitable in terms of climate, altitude, vegetation, and control measures (Ashley et al., 2018). This enabled the elimination of malaria from many temperate regions in the past (see Feachem et al., 2010, and c.f. Figure 1), and highlights the importance of human settlement and migration patterns (Carrasco-Escobar et al., 2022; Kounnavong et al., 2017). In recent years, however, gains against malaria have been stalling (Global Malaria Programme, 2021), which may be exacerbated by land use change and climate change in the future (Caminade et al., 2014; Patz and Olson, 2006).[1]

The disease is routinely separated into uncomplicated cases, with relatively mild symptoms like headache and fever, and severe malaria, which may cause anemia, respiratory

[1]The environmental suitability for malaria and, relatedly, the population at risk are likely to increase in the face of climate change (McMichael et al., 2006; Rocklöv and Dubrow, 2020). Due to climate change, malaria may decline in relative importance compared to arboviruses with *Aedes* mosquitoes as vectors (Mordecai et al., 2020).

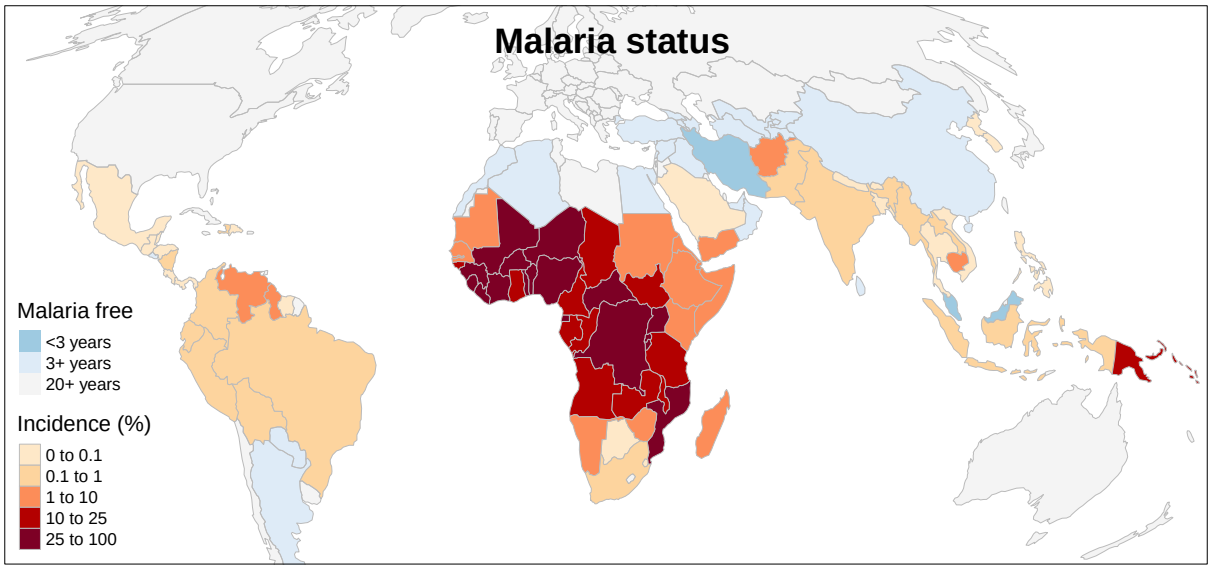

Figure 1: Global malaria status as indicated by the incidence in percent of the population at risk in 2018 or the time since the last indigenous case was recorded. Sources: World Health Organization, Global Health Observatory Data Repository/World Health Statistics and Global Malaria Programme (2021).

distress, renal failure, and neurological symptoms (Ashley et al., 2018). The severity of the disease relates to the species of the pathogen, with *P. falciparum* causing most acute cases and almost all deaths globally (Global Malaria Programme, 2021). The most severe neurological complication of an infection with *P. falciparum* is cerebral malaria, which invariably leads to death when untreated (Idro et al., 2010). Even when treated, its case-fatality rate is usually 10–20% (Ashley et al., 2018). Children, pregnant women, and patients with co-morbidities are most affected by cerebral malaria in endemic areas. Repeated exposure in adults leads to infection-immunity that protects against the effects of the disease to a degree, but not against infection. In addition, there are a number of inherited and acquired factors that affect chance of infection and severity (see Ashley et al., 2018), which are most prevalent on the African continent. Infection rates that dictate mortality and morbidity also depend heavily on vectors and their capacity to transmit malaria; some members of the African *A. Gambiae* complex are particularly efficient at human transmission.

Malaria is treated using one of a number of antimalarial medications (see Ashley et al., 2018). The most prominent antimalarials are derived from (a) chloroquine, the most widespread compound until recently, and (b) artemisinin, which revolutionized treatment starting in the 1990s. Resistance against established antimalarials is common, and artemisinin-resistant lines of *P. falciparum* are emerging in Southeast Asia (Ménard et al., 2016). Combination therapy, where antimalarials are combined with partner drugs, offers

the best treatment outcomes (Alven and Aderibigbe, 2019) and is effective at avoiding the emergence of resistance. However, combination therapy is more costly and — even more importantly — demanding in terms of expertise, logistics, and adherence.

The World Heath Organisation (WHO) recognises three main strategies for the control and potential elimination of malaria. First is vector control, with insecticide-treated bednets and indoor residual spraying with insecticides as the main interventions. These interventions have been highly effective and efficient where they are applicable,[2] but are under threat by emerging insecticide-resistance and changing bionomic traits among mosquitoes (Global Malaria Programme, 2021). Climate change and local land use changes are also likely to have impacts on vector types and abundance (see e.g. Gottdenker et al., 2014; Rocklöv and Dubrow, 2020). Second is chemoprophylaxis for susceptible populations, such as children, pregnant women, or travellers. This strategy may reduce morbidity, prevent infection, and decrease the rate of transmission (Global Malaria Programme, 2021). Third, new malaria vaccines can play an important role in reducing malaria incidence and severity in children (Datoo et al., 2022), although many open questions remain (see e.g. Olotu et al., 2016; Doshi, 2020). These strategies can differ considerably in effectiveness, efficiency, and requirements for implementation. As laid out later, economics and thus economic research plays a crucial for these considerations.

3 The economics of malaria

Millions of malaria cases globally impose an exceptionally high burden of disease on affected populations. This burden is concentrated in some of the world's poorest countries (see Global Malaria Programme, 2021, and c.f. Figure 1). Control and treatment of the disease and, as a result, the burden it imposes are heavily reliant on socioeconomic circumstances, leading to the notion of malaria being a "disease of poverty" (see e.g. Worrall et al., 2005). Effective vector control, efficient prophylaxis, vaccination programmes, and successful therapy require ample financial resources, structure, and know-how. Beyond the impacts of economic structures on malaria, there are also considerable vice versa impacts — i.e. economic impacts of malaria. The existence of these impacts is relatively uncontroversial, but their scale and the mechanisms behind them remain the subject of a large and diverse body of literature.

The economic impacts of malaria manifest in several ways. For one, there is an enormous direct burden in terms of premature mortality and morbidity. A way to quantify

[2] The efficacy and efficiency of such measures depends (inter alia) on the feeding behavior of predominant vectors. Species in Africa tend to feed and rest indoors (Sherrard-Smith et al., 2019); in Latin America and South-East Asia, bites occur more frequently in the outdoors (e.g. Saavedra et al., 2019).

this burden are disability-adjusted life years,[3] which can be economised, e.g., using yearly average per capita income. Bloom et al. (2022) use this approach and attribute direct costs in the hundreds of billions to malaria. They place the direct cost of malaria as the third largest among all infectious diseases, topped only by HIV/AIDS and tuberculosis. This approach may still underestimate the impacts of morbidity — infections with malaria may "result in recurrent debilitating bouts of illness, which prevents individuals from supplying their labour productively" (Cole and Neumayer, 2006, p.919). In another study, Cervellati et al. (2022a) put the number of workdays that are directly lost to malaria in affected agrarian households at 20–60 per year. Such estimates of the direct economic cost of malaria cover one important dimension, but are by no means comprehensive. The total economic impacts of malaria may be considerably larger.

Indirect and long-term economic impacts of disease are likely to be decisive elements, but are considerably harder to trace and quantify. One problem is the long time period until impacts on economic outcomes materialize and fully manifest, which may mask causal links. For example, Barreca (2010) finds increased poverty rates after high in-utero and postnatal exposure to malaria, while Hong (2013) documents increased occurrence of chronic diseases in old age — both using US data. Another prominent argument concerns even longer-term development impacts of malaria (see Sachs and Malaney, 2002; Malaney et al., 2004). Evolutionary pressure gave rise to genetic dispositions, such as the sickle cell trait or the lack of the Duffy antigen receptor, that offer some protection against malaria, but can themselves be harmful or even fatal.[4] This would suggest that the long-term development impacts of the disease are roughly comparable to the drawbacks from these dispositions. A more immediate type of long-term impact concerns economic growth and poverty, which may reflect aggregate direct and indirect impacts on smaller, individual scales.

The crux of much economic research on malaria is related to this multiplicity of connections and possible pathways — the causal identification of impacts. Generally, estimated effects are correlations that may occur for many reasons, but they are not causal relations. For example, in a well-known study, Gallup and Sachs (2000) report strong correlations of economic growth and poverty with malaria. Their findings cannot be interpreted causally,

[3]The measure takes into account both mortality (via years of life lost) and morbidity (via years lived with disability) effects. Life expectancy is another popular measure of overall health, but does not adequately reflect the burden implied by morbidity.

[4]Variants of the haemoglobin beta gene offer protection against severe malaria. They give rise to the sickle cell trait in heterozygous form, but cause deadly sickle cell disease when both parents are affected. The Duffy antigen acts as a receptor for *P. vivax*, offering Duffy-negative individuals some protection (Ashley et al., 2018). Infections with *P. vivax* are extremely rare in sub-Saharan Africa, where the population is almost entirely Duffy-negative.

i.e. they suggest a connection, but not a cause and effect relationship, due to a series of limitations. To unveil a causal effect, we would ideally compare hypothetical outcomes with and without the cause (see e.g. Imbens, 2020).[5] Since we can only ever observe one outcome, we need to infer causal differences using an *identification strategy* (see e.g. Athey and Imbens, 2017). A classic example for such a strategy is a randomised experiment that enables control over known and unknown confounding factors that could influence results. Good experimental data can get us closer to true causal effects, but often we have to rely on observational data instead (e.g. due to budgetary, ethical, or operative constraints). In order to identify any causal effect using observational data, additional care and the right setting are required. In very simple settings, we can argue for some causality when the right variables are controlled for. However, this is not possible when any important factors are unobservable, effects occur simultaneously, the selection process of observations is relevant, or in the presence of many other complications. In such cases, specialised methods and elaborate identification strategies, such as instrumental variables or quasi-experimental research designs, can help distil causal effects.

For these reasons, the economic literature lays much emphasis on strong identification strategies. As a result, findings are generally very reliable and estimated effects reflect what they ought to — causal relations. However, further challenges for insightful and practical research remain, and there are certain trade-offs for identification. Strong identification strategies often need tightly focused research questions or specific settings. If studies are specific, e.g. in terms of region or time, even reliable findings can be limited in their applicability — i.e. how well they generalise — and thus in their practical utility.

This issue is exacerbated by the heterogeneity of malaria and its interaction with other factors. Pathogens vary in regional spread and severity (Ashley et al., 2018); vectors are arguably even more heterogeneous. Impacts are moderated by socioeconomic circumstances, health status, and available interventions, all of which are highly variable over time, space, and individuals. As a result, studies like Bleakley (2010)'s analysis of childhood exposure to malaria during eradication campaigns in the early to mid 1900s Americas, must primarily be understood within their specific contexts — generally applicable insights are rare.

Heterogeneities can also be problematic in terms of conclusions drawn — even within a narrow context. Most studies investigate average effects, and do not delve deeper into how they arise. However, averages may mask vital insights, e.g. when different strata of society

[5] An example for a potential causal effect and outcome is the days of schooling received with and without a malaria infection. These could, e.g., be confounded by social status — less affluent children might be more likely to experience an infection and, unrelated to their health status, have fewer opportunities to attend school.

are afflicted differently, that would allow for much more effective, targeted interventions. This issue is also pronounced at an aggregate level — while malaria may hamper economic development in Nigeria, it could have no effect in Vietnam. The analysis of heterogeneous effects has seen a lot of progress in recent years, and many new specialised methods are available (e.g. Athey and Imbens, 2016; Hahn et al., 2020). However, any statistical method is limited by data — and more flexible ones even more so. The availability and quality of data is particularly disadvantageous in poorer regions, which are also hit the hardest by malaria (c.f. Figure 2).

Hence, accurate and detailed insights into the economic impacts of malaria are of great importance, but difficult to obtain. The intensive interplay of malaria and economics as well as the countless connections to other relevant factors can confound estimates, and thus, insights. Clever research design can prevail against these issues, but further challenges must be overcome. Ideally, insights translate into improved real-life circumstances (e.g. by informing policy to reduce education losses due to malaria). This requires results to be applicable to relevant situations, somewhat generalisable, and sufficiently in-depth.

With this background information in mind, we can now provide an overview of the economic impacts of malaria. In the following subsections, we review the current state of the economic literature on malaria, both on a microeconomic level and a macroeconomic level, and the economics of its eradication.

The microeconomic impacts of malaria

Microeconomic studies of malaria focus on its impacts at an individual level, and are typically confined to certain countries and narrow causal pathways. This allows them to obtain strong causal evidence, but their generalisability can often be lacking. Results may not have direct implications for current efforts at controlling or eliminating malaria. However, they illuminate certain mechanisms behind impacts, guide theory and provide a foundation for further studies. Notably, there are few results for contemporaneously most affected regions (e.g. sub-Saharan Africa) from these studies, in part due to data issues. An important exception is the study by Kuecken et al. (2021) that analyses the effects of the recent 'Roll Back Malaria' campaign on a broad set of demographic and economic indicators for 27 Sub-Saharan countries.

A common identification strategy of microeconomic studies is a quasi-experimental research design. One popular example is induced by the emergence of historical malaria eradication programmes. Differences in pre-eradication exposure, inter alia due to ecological conditions favouring spread of vectors and parasites, are used to assign quasi-randomised control and treatment groups from observational data. Eradication programmes can have considerable impacts on malaria exposure that are arguably unrelated to other impor-

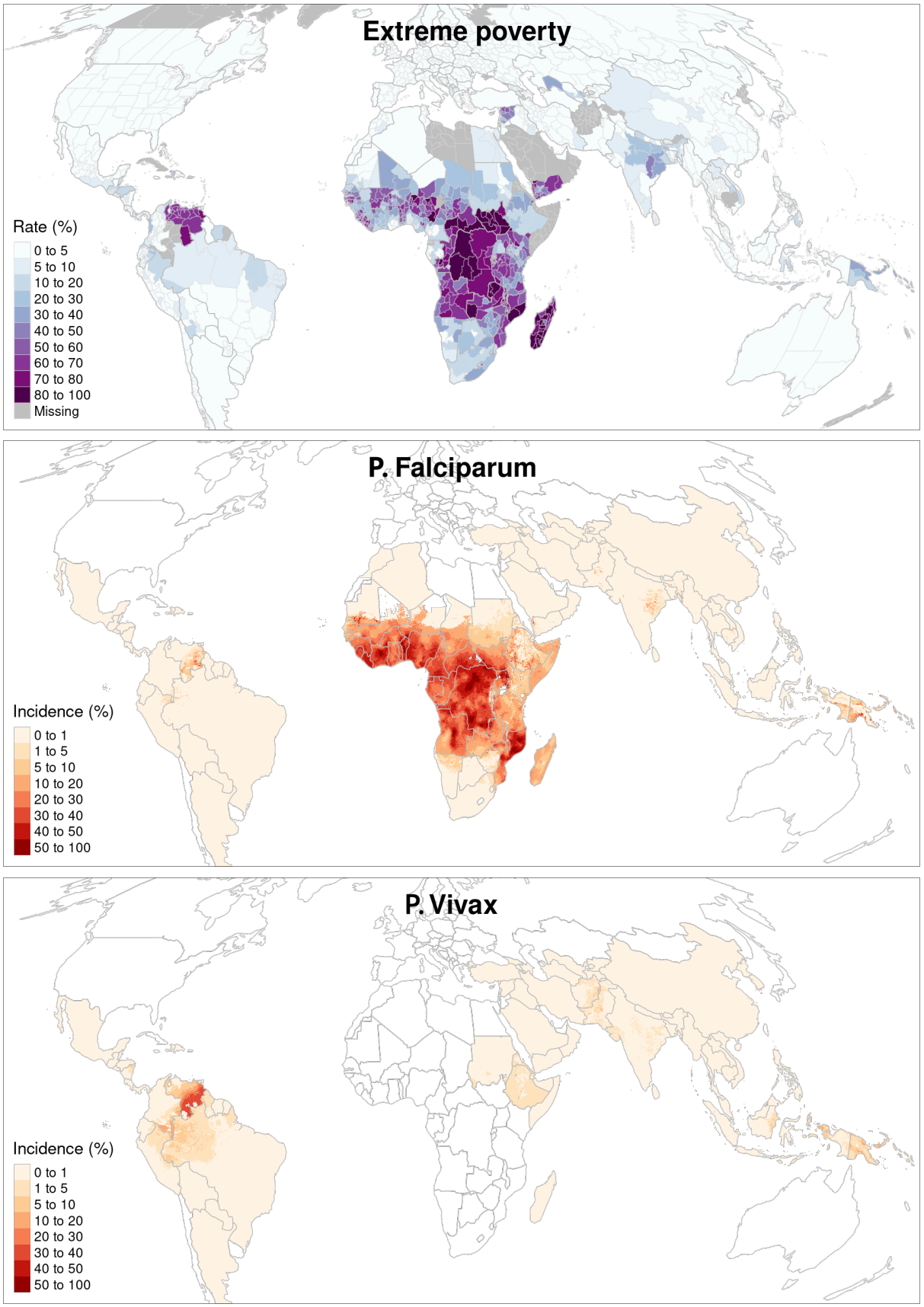

Figure 2: Subnational measures of recent extreme poverty rates, i.e. population living with less than $1.9 per day (top), incidence rates from 2019 of *P. falciparum* (mid), and *P. vivax* (bottom). Sources: World Bank (2022) and Universidad Católica Andrés Bello (2022) for poverty rates, and Battle et al. (2019) and Weiss et al. (2019) for *Plasmodium* incidence rates.

tant factors. These programmes are usually driven by independent advances in the understanding of malaria transmission and prevention methods that stem from outside the region where they apply.[6] There are only few experimental studies, due to their cost and ethical concerns. A recent exception is Dillon et al. (2021), who estimate that an infection reduces workers' weekly earnings by around 10%, primarily driven by reduced labour supply. In their randomised control trial, sugarcane plantations workers in Nigeria were offered malaria testing and treatment, with the week of the offer being randomised. Dillon et al. (2021) also find that news of a negative test increases daily productivity due to selection to more challenging and hence more rewarding tasks. Despite some limitations, microeconomic studies and their strong identification strategies have produced several important findings.

A recurrent finding is that early-life exposure to malaria is likely to impact future economic outcomes through various channels beyond contemporaneous morbidity and mortality. One prevalent channel is the ability to accumulate human capital in the form of education. Malaria affects children's educational capacity directly by leading to poorer nutritional status, impairing brain development, lowering cognitive performance (Kihara et al., 2006), and increasing school absenteeism (Thuilliez et al., 2010). Antimalarial campaigns in turn have positive effects on schooling performance in the form of increases in test scores (inter alia in Mexico, see Venkataramani, 2012), providing further evidence for the adverse effects of malaria on cognition. Various studies in the microeconomic literature have found positive effects of malaria eradication on educational outcomes and human capital accumulation in terms of years spent in school — for example in the US (Barreca, 2010), Paraguay and Sri Lanka (Lucas, 2010), India (Cutler et al., 2010), and 27 sub-Saharan countries (Kuecken et al., 2021).

High infant and child mortality rates due to malaria may affect the fertility choices of parents. The "child-survivor hypothesis" postulates that parents base their choices on the number of surviving children; e.g. as a guarantee of a suitable heir or as a kind of old-age insurance (Sachs and Malaney, 2002). The empirical evidence on direct fertility impacts is somewhat mixed. Lucas (2013) finds that malaria eradication increased fertility and led to a younger maternal age Sri Lanka, while Wilde et al. (2020) document a recent rise in total fertility in sub-Saharan Africa. Conversely, Kuecken et al. (2021) provide empirical support for reduced fertility in recent sub-Saharan Africa. Higher exposure to malaria campaigns (in terms of proportion of lifetime in their post-period) showed no

[6] For example, Bleakley (2010) argues that eradication programmes in the US South were not primarily driven by developments inherent to the area and its residents. Instead, the knowledge US Army doctors gained in Cuba and the Panama Canal zone spurred advancements and enabled the programmes. Several smaller projects in rural Southern towns were followed by large-scale efforts of the federal government at the start of World War I, primarily to reduce the number of troops unfit for service.

discernible impact on the probability of the first birth, but reduced the probability of a second birth by around two percentage points. The overall probability of a woman giving birth in a given year was reduced by 0.4 percentage points. These findings also lend some support to the "child-survivor hypothesis".

Fertility choices, in turn, play an important role in the investment in education of children. A higher number of dependants in the household implies that average education investments are reduced, leading to a quantity–quality trade-off in children's education (Sachs and Malaney, 2002). Hence, besides reducing the capacity of children to receive an education, exposure to malaria may also decrease the resources available for their education; in part also by diverting some of them on spending for the treatment of the disease. This impact on education can be particularly pronounced for females — high fertility rates imply that women spend much of their working years with child-related activities, constraining employment choices and their time in labour markets. This is exacerbated by frequent and severe infections of children, which increase care needs (Asenso-Okyere et al., 2011). As a result, the opportunity cost of female education is raised and educational investment is biased towards males. These impacts on gender disparities are still under-explored in the empirical literature, warranting further research. Generally speaking, however, empirical assessments of antimalarial campaigns almost unequivocally showed higher educational attainment and better educational outcomes, including improvements in literacy rates in adulthood.

By depressing human capital accumulation over the lifetime, childhood exposure to malaria has adverse effects on future labour productivity in adulthood and resulting economic outcomes. Spending on the treatment of the disease can also divert resources from other forms of consumption or investment. A number of empirical studies establish such effects at a microeconomic level. Reductions in early childhood exposure to malaria led to greater incomes and consumption in adulthood in the US, Brazil, Colombia, and Mexico (Bleakley, 2010); India (Cutler et al., 2010); Uganda (Barofsky et al., 2015); and Vietnam (Laxminarayan, 2004). In another study on the US, Barreca (2010) finds that high in-utero and postnatal exposure to malaria is linked to higher poverty rates later in life. The recent antimalarial campaign in 27 sub-Saharan countries increased the probability of being employed in adulthood, with a marginal increase in treatment intensity raising the probability by 6 percentage points (Kuecken et al., 2021). Hong (2013) finds that early exposure to malaria in US veterans (prior to the eradication of malaria) is associated with more frequent chronic diseases in old age (specifically rheumatism/musculoskeletal, rectum/haemorrhoids, and eye diseases) and less frequent labour force participation.

A different strand of the literature focuses on the impacts of economic conditions on malaria. Pan and Singhal (2019), for example, find that a large-scale agricultural exten-

sion programme in Uganda reduced the proportion of household members with malaria by 8.9 percentage points. Their results suggest that these reductions were primarily driven by income gains and a resulting increase in ownership and usage of bednets. This highlights the interdependencies between malaria exposure, access and affordability of protective equipment, and economic outcomes. From a researcher's point of view, entangled effects make obtaining robust and accurate insights challenging. This is particularly the case for analyses of aggregate impacts that account for spillovers, as is the focus of macroeconomic studies. Policy-wise however, interdependencies may be an opportunity, allowing for beneficial spillover effects.

The macroeconomic impacts of malaria

Macroeconomic research questions related to disease focus on the impacts on economic growth and development at large, as well as the related impacts on poverty. These studies deal with aggregated units of observations, be it countries or sub-national administrative units, and generally have a broader concept of potential impacts and how they may manifest. This holistic approach makes strong identification strategies elusive, since factors of interest often cannot be disentangled from others. Instead, macroeconomic studies rely more heavily on theory than microeconomic ones, with the latter offering an important impetus to guide this theory. Nonetheless, good insights into the macroeconomic effects of malaria (or disease in general) are essential in delivering a bigger picture and can play a deciding role for policymakers (see e.g. Sicuri et al., 2022).

One of the main challenges for the assessment of macroeconomic effects of malaria and other diseases lies in disentangling the potential pathways. One of the earliest studies on the economic effects of malaria, by Barlow (1967), acknowledges counteracting impacts along four axes: 1) increasing population growth, leading to lower per capita income, 2) rising quantity and quality of labour inputs for production, leading to higher per capita income, 3) lowered household saving and capital inputs for production (larger households tend to consume more), leading to lower per capita income, and 4) potential additional effects on output, including the exploitation of new, malaria-free territories. Studies without strong enough identification strategies and theoretical grounding run the risk of conflating impacts of interest (e.g. of malaria eradication on income) with counteracting (e.g. increasing population) and confounding factors (e.g. reverse causality from income being spent on malaria prevention).

Empirical macro-level studies often build on the theoretical notion of conditional convergence (see Barro, 1991), where economies converge to similar levels of prosperity, governed by structural features of specific countries — such as the prevalence of malaria. A prominent example is the work of Gallup and Sachs (2000), who find strong correla-

tions between economic growth rates and a malaria index. Specifically, they found that a ten percent reduction in malaria intensity (an index that combines information about the population at risk and the share of cases with *P. falciparum*) was associated with 0.3% higher growth. Contemporaneous work by McCarthy et al. (2000) reports somewhat smaller, but still significantly positive effects. These figures are likely excessive due to the confounding of effects mentioned above. One concrete example is the omission of other important structural features like the health status (e.g., the burden of HIV or the age structure), such that malaria-related variables may include their effects. These omitted features complicate the identification of causal effects of individual diseases on macroeconomic quantities.

More generally, the impacts of health improvements on macroeconomic outcomes are still debated in the economic literature. Acemoglu and Johnson (2007) set out to identify the causal effects of health improvements on demographic and macroeconomic variables, in part as a response to the complications faced by studies like Gallup and Sachs (2000). They posit that increases in life expectancy following what they call the "international epidemiological transition" — referring to the wide-spread expansion of health interventions, introduction of novel drugs and chemicals, and more effective public health measures in the 1940s — led to increases in population growth, but was not accompanied by significant increases of aggregate economic growth. Specifically, they find that reductions in mortality at the time — also induced by a reduction of malaria exposure — did not increase the average economic output growth per capita. One important caveat of this finding by Acemoglu and Johnson (2007) is that impacts are likely to vary across developmental stages of countries.

The notion of different types and drivers of growth at certain developmental stages — a feature of *unified growth theory* — has strong implications for the impacts of infectious diseases. Increased life expectancy, i.e. lower mortality, will make it more worthwhile for individuals to invest in education, raising the opportunity costs (in terms of lost income) of having children. The result are reduced fertility rates in the medium-term. At the same time, the higher human capital stock increases economic output, leading to a sustained increase in average incomes. This process in the interplay of reduced mortality rates and the lagged reaction of fertility rates is referred to as the "demographic transition" (Galor and Weil, 2000). The burden of infectious diseases may inhibit this demographic transition, inducing a form of poverty trap (Cervellati and Sunde, 2005). For countries that have undergone this transition, increased life expectancy raises income per capita, as shown empirically by Cervellati and Sunde (2011).[7] It is likely that rising average

[7] Cervellati and Sunde (2011) use the same data as Acemoglu and Johnson (2007) to show that the effects of increased life expectancy hinge crucially on whether countries have gone through the demographic

income per capita does not occur in the short term — the productivity and education gains from reduced malaria exposure take time to manifest (also see Lucas, 2013).

Still, the effects of malaria on economic development remain disputed. Depetris-Chauvin and Weil (2018) find a lack of effects in the very long run, using the prevalence of the sickle cell trait as an indicator of high historical exposure to malaria. They argue that, historically, the "disease was not very important, primarily because the vast majority of deaths that it caused were among the very young, in whom society had invested few resources" (p.1232 Depetris-Chauvin and Weil, 2018).[8] Other recent work on the macroeconomic impacts of malaria using cross-country comparisons confirms positive economic effects of malaria eradication (Berthélemy and Thuilliez, 2015; Datta and Reimer, 2013; Sarma et al., 2019), albeit of a considerably smaller magnitude than the results of Gallup and Sachs (2000) imply. Most of these studies employ a form of panel (also called longitudinal) regression setting, where the inclusion of unit-specific effects purges unobserved time-invariant differences (see e.g. Sarma et al., 2019). This alleviates some concerns compared to a purely cross-sectional approach, but confounders and contemporaneous relationships remain problematic.

Recent macroeconomic work generally pursues one of two directions. First, there is less focus on malaria-specific impacts, as opposed to general health impacts on larger scales. Identifying disease-specific impacts is considerably more challenging at this scale — especially considering the importance of comorbidities. This can be challenging, since the combination of various diseases into a single index as a measure of health is "likely to be a source of misspecification" (footnote 1 in Bleakley, 2010) and may thus have only limited informative value. Second, there are more targeted macroeconomic studies using within-country variations as identification strategies. Geo-referenced data, which is often derived from remote sensing sources, is used commonly to identify unconfounded variation of malaria exposure and outcome variables. These studies arguably bridge a gap to more micro-level ones, putting more emphasis on identification, while operating at a (focused) macro-level (see Bloom et al., 2019, for an in-depth discussion of the reconciliation of micro- and macroeconomic evidence).

Among the more targeted studies, Cervellati et al. (2017) use different indices of malaria incidence and exposure in combination with a satellite-derived proxy for economic activity in Africa. They document a negative association between them that is robust to a

transition. For countries that have not, higher life expectancy had either no or a negative effect on per capita income. In contrast, in countries that had already transitioned, increases in life expectancy were accompanied by substantive increases in average incomes.

[8] Notably, their model does not incorporate microeconomic evidence of impacts on human capital and labour productivity. They follow Ashraf et al. (2008) instead, who report small impacts from morbidity.

number of different specifications. Cervellati et al. (2022b) use geo-referenced data on Chinese investments and the social media posts of Chinese workers to investigate the potential effects of malaria exposure on foreign investments and worker settlement. They show that African regions with higher malaria exposure attract fewer Chinese investments. Highly exposed regions show lower levels of Chinese economic activity and a lower density of Chinese workers. In yet another study, Cervellati et al. (2022a) document an increase in civil violence for regions prone to epidemic outbreaks. This effect is particularly strong during short harvesting seasons of high-calorie subsistence crops. Higher prevalence of immunity (either by the sickle cell trait or acquired through previous infection) or antimalarial policies attenuate this effect.

Overall — even though there remains some disagreement on the specific effects of malaria and other infectious diseases on macroeconomic outcomes — there are clear impacts on the individual level that have at least some repercussions for the economy at large. In this sense, Bleakley (2009) stresses the importance of eradicating tropical diseases for economic development, but acknowledges that it is not a panacea that can fix everything.

The economics of eradication

The eradication or control of malaria is a forefront issue for many international organizations and governments, motivated by the tremendous human and economic burden of malaria. An important question is whether to pursue eradication or control. So far, successful eradication has mostly been limited to temperate regions (c.f. Figure 1).[9] Countries in the tropical zones, however, have been much less successful in either achieving sustained reductions of malaria cases, or eliminating the disease altogether. Beside possible regional factors, these countries are among the poorest ones in the world and suffer from economic constraints (c.f. Figure 2).

Cost and cost-benefits are obvious factors in the decision of whether to opt for controlling or eliminating the disease. Eradication efforts are generally more expensive in the short-run, and it should be no surprise that spending per case is higher in countries that strive for elimination (see Haakenstad et al., 2019, and c.f. Figure 3). Moreover, the marginal cost per reduced case increases as the burden of malaria decreases. The benefits of eliminating malaria still greatly outweigh the costs (Shretta et al., 2016), and simple

[9]The WHO considers a country to be malaria-free if zero indigenous cases have been reported for more than three consecutive years. The latest countries to achieve this and be certified as malaria-free were El Salvador and China in 2021 (Global Malaria Programme, 2021). The Islamic Republic of Iran and Malaysia reported zero indigenous cases for the third consecutive year, while Cabo Verde and Belize reported zero indigenous cases for the second year in a row (Global Malaria Programme, 2021).

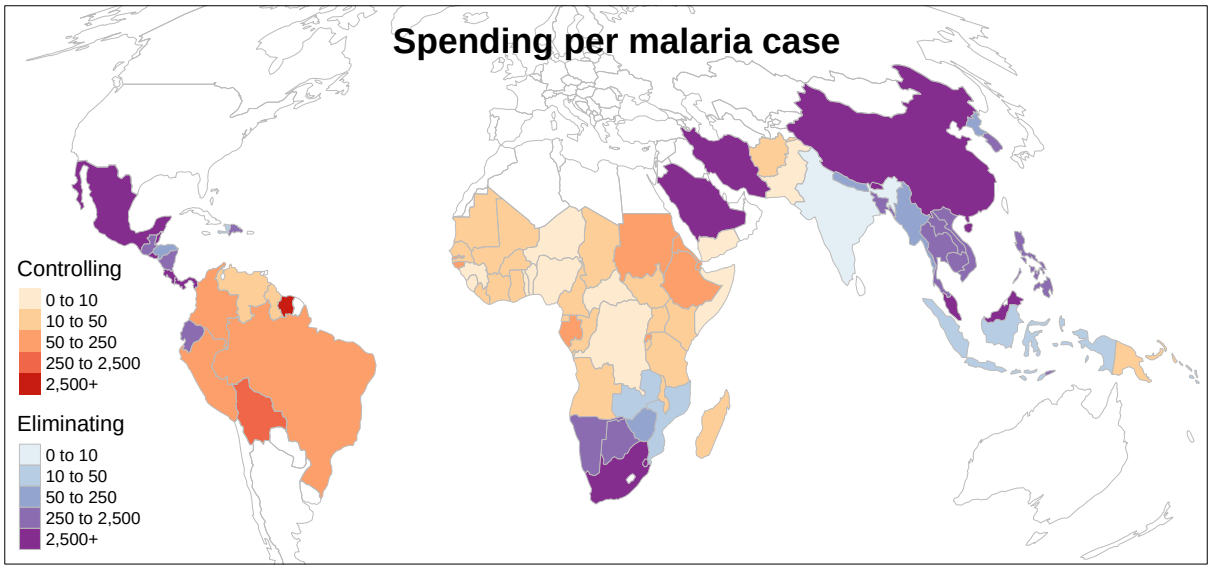

Figure 3: Total spending per malaria case in 2016, separated by strategy — countries looking to control malaria in orange (mostly in South America and sub-Saharan Africa) and ones that target eradication (mostly in Central America, Southern Africa, the Middle East, and East Asia). All values in 2018 US$. Source: Haakenstad et al. (2019).

cost-benefit analysis cannot reflect either the true cost or benefit of one approach. For one, eradication leads to a much lower risk for resurgence. The increase of malaria cases in the 1930–2000 period can largely be attributed to weakening control programmes. A decrease in cases saw reduced recurrent expenditure and aid, leading to resource constraints (Cohen et al., 2012). Furthermore, benefits of full eradication may also extend to other countries that benefit from fewer imported cases (Shretta et al., 2016).

The ecological integrity of biospheres also has to be considered in the fight against malaria. Land-use changes like deforestation may exacerbate malaria transmission, undermining control and elimination efforts (Berazneva and Byker, 2017; MacDonald and Mordecai, 2019; Santos and Almeida, 2018). Other types of land-use change, such as agricultural expansion, as well as urbanization and related land management, on the other hand underpin the success of many eradication programmes (Fornace et al., 2021). The effects of land-use change are vital, but cumbersome to pursue — they are often location-specific and global scale analyses may suffer from conceptual and methodological issues (see e.g. Kuschnig, 2021). Eradication programmes also have the potential to threaten natural ecosystems. Swamps are commonly drained during these programmes, which removes their ecosystem services (e.g. their roles as carbon sinks and biodiversity hotspots). While such interventions are recognized to reduce the risks of malaria

transmission substantially (Keiser et al., 2005), the environmental impacts of malaria eradication programmes arguably remain underexplored.

Another important aspect is that the fight against malaria may become more tenuous in the future. Climate change is likely to increase vector and parasite suitability (Pascual et al., 2006; Patz and Olson, 2006), potentially making present control measures less effective. Similarly, the resistance of vectors and parasites to commonly used control methods is increasing, presenting another major ecological obstacle (Ferguson et al., 2010). Concerted efforts to effectively control or eradicate malaria hinge on the provision of sufficient funds. In 2016, US$4.3 billion was spent on malaria worldwide increasing by an annual rate of 8.5% from 2000 to 2016, with the bulk stemming from development assistance for health (Haakenstad et al., 2019). Despite these increases in spending, total resources spent on malaria control and eradication efforts in 2020 fell short of the US$6.8 billion funding target of the WHO (Global Malaria Programme, 2021). The full impact of the COVID-19 pandemic and the associated economic crisis on international and domestic funding for malaria remains to be unraveled. 2020 marked the first year with a rise in malaria deaths after almost two decades of falling numbers, increasing by roughly 12% compared to 2019. Around two thirds of this increase were attributed to service disruptions during the pandemic (Global Malaria Programme, 2021). Ongoing restrictions have and will likely impede eradication and control measures (Sicuri et al., 2022). However, the resumption and continuation of such efforts is of utmost importance. The impacts of climate change and environmental degradation on these funding targets is still uncertain and deserves further evaluation.

4 Conclusion

In this paper, we reviewed the literature on the economic impacts of malaria. We put the focal points and crucial issues of economic studies into context — most prominently causal identification — and discussed how they guide research. We documented clear evidence of adverse effects on individuals, including impacts on health, productivity, fertility choices, and education. These microeconomic effects generally varied with disease severity and prevalence, socioeconomic status, location, and time horizon. Evidence for macroeconomic effects was not as clear-cut, in part due to the number and variety of channels through which impacts can potentially unfold, complicating the identification of aggregate causal effects. However, most evidence points towards non-negligible macroeconomic impacts of malaria, particularly in sub-Saharan Africa.

It is clear that malaria hampers development and economic prosperity, but there remains much room for research in the realm of malaria and its interactions with the human

and natural environment. The link between economics and the disease — while established in numerous studies — still warrants further research, both on the micro- and macroeconomic levels, as does the reconciliation of empirical evidence across these levels. Particular blind spots that deserve a better understanding include the heterogeneity of effects, e.g. across socioeconomic status and location, and spillover effects. The economics of eradication strategies, and their wider impacts, remain under-explored. Climate change makes the adjustment of interventions to effectively control or eliminate malaria a pressing issue. Increased potential for resurgence means that malaria-free countries must be prepared to maintain this status. A better understanding of the interplay of natural environments and vector-borne diseases, as well as repercussions for health and economics, is urgently needed. More and improved new insights can help in the fight against malaria; economic research can play an important part in overcoming future challenges.

References

Daron Acemoglu and Simon Johnson. Disease and development: the effect of life expectancy on economic growth. *Journal of Political Economy*, 2007. doi:10.1086/529000.

Sibusiso Alven and Blessing Aderibigbe. Combination therapy strategies for the treatment of malaria. *Molecules*, 24(19):3601, 2019. ISSN 1420-3049. doi:10.3390/molecules24193601.

Kwadwo Asenso-Okyere, Catherine Chiang, Paul Howard Thangata, and Kwaw S. Andam. Interactions between health and farm-labor productivity. *International Food Policy Research Institute (IFPRI)*, 2011. doi:10.2499/9780896295421.

Elizabeth A. Ashley, Aung Pyae Phyo, and Charles J. Woodrow. Malaria. *Lancet*, 391(10130): 1608–1621, 2018. ISSN 0140-6736. doi:10.1016/S0140-6736(18)30324-6.

Quamrul H. Ashraf, Ashley Lester, and David N. Weil. When does improving health raise GDP? *NBER Macroeconomics Annual*, 23, 2008. doi:10.1086/593084.

Susan Athey and Guido Imbens. Recursive partitioning for heterogeneous causal effects. *Proceedings of the National Academy of Sciences*, 113(27):7353–7360, 2016. ISSN 0027-8424. doi:10.1073/pnas.1510489113.

Susan Athey and Guido W. Imbens. The state of applied econometrics: causality and policy evaluation. *Journal of Economic Perspectives*, 31(2):3–32, 2017. doi:10.1257/jep.31.2.3.

Robin Barlow. The economic effects of malaria eradication. *American Economic Review*, 57(2): 130–148, 1967. URL https://www.jstor.org/stable/1821615.

Jeremy Barofsky, Tobenna D. Anekwe, and Claire Chase. Malaria eradication and economic outcomes in sub-saharan Africa: evidence from Uganda. *Journal of Health Economics*, 44: 118–136, 2015. doi:10.1016/j.jhealeco.2015.08.002.

Alan I. Barreca. The long-term economic impact of in utero and postnatal exposure to malaria. *Journal of Human Resources*, 45(4):865–892, 2010. ISSN 0022-166X. doi:10.3368/jhr.45.4.865.

Robert J. Barro. Economic growth in a cross section of countries. *Quarterly Journal of Economics*, 106(2):407–443, 1991. ISSN 0033-5533. doi:10.2307/2937943.

Katherine E. Battle, Tim C. D. Lucas, Michele Nguyen, Rosalind E. Howes, Anita K. Nandi, Katherine A. Twohig, Daniel A. Pfeffer, Ewan Cameron, Puja C. Rao, Daniel Casey, Harry S. Gibson, Jennifer A. Rozier, Ursula Dalrymple, et al. Mapping the global endemicity and clinical burden of Plasmodium vivax, 2000–17: a spatial and temporal modelling study. *Lancet*, 394(10195):332–343, 2019. ISSN 0140-6736. doi:10.1016/S0140-6736(19)31096-7.

Julia Berazneva and Tanya S. Byker. Does forest loss increase human disease? Evidence from Nigeria. *American Economic Review*, 107(5):516–21, 2017. doi:10.1257/aer.p20171132.

Jean-Claude Berthélemy and Josselin Thuilliez. The economics of malaria in Africa. In *The Oxford Handbook of Africa and Economics*. 2015. doi:10.1093/oxfordhb/9780199687107.013.034.

Hoyt Bleakley. Economic effects of childhood exposure to tropical disease. *American Economic Review*, 99(2):218, 2009. doi:10.1257/aer.99.2.218.

Hoyt Bleakley. Malaria eradication in the Americas: a retrospective analysis of childhood exposure. *American Economic Journal: Applied Economics*, 2(2):1–45, 2010. ISSN 1945-7782. doi:10.1257/app.2.2.1.

David E. Bloom, David Canning, Rainer Kotschy, Klaus Prettner, and Johannes J. Schünemann. Health and economic growth: reconciling the micro and macro evidence. *NBER Working Paper*, 2019. doi:10.3386/w26003.

David E. Bloom, Michael Kuhn, and Klaus Prettner. Modern infectious diseases: macroeconomic impacts and policy responses. *Journal of Economic Literature*, 2022. ISSN 0022-0515. doi:10.1257/jel.20201642.

Cyril Caminade, Sari Kovats, Joacim Rocklov, Adrian M. Tompkins, Andrew P. Morse, Felipe J. Colón-González, Hans Stenlund, Pim Martens, and Simon J. Lloyd. Impact of climate change on global malaria distribution. *Proceedings of the National Academy of Sciences*, 111(9): 3286–3291, 2014. ISSN 0027-8424. doi:10.1073/pnas.1302089111.

Gabriel Carrasco-Escobar, Jose Matta-Chuquisapon, Edgar Manrique, Jorge Ruiz-Cabrejos, Jose Luis Barboza, Daniel Wong, German Henostroza, Alejandro Llanos-Cuentas, and Tarik Benmarhnia. Quantifying the effect of human population mobility on malaria risk in the

Peruvian Amazon. *Royal Society Open Science*, 9(7):211611, 7 2022. ISSN 2054-5703. doi:10.1098/rsos.211611.

Matteo Cervellati and Uwe Sunde. Human capital formation, life expectancy, and the process of development. *American Economic Review*, 95(5):1653–1672, 2005. ISSN 0002-8282. doi:10.1257/000282805775014380.

Matteo Cervellati and Uwe Sunde. Life expectancy and economic growth: the role of the demographic transition. *Journal of Economic Growth*, 16(2):99–133, 2011. ISSN 1573-7020. doi:10.1007/s10887-011-9065-2.

Matteo Cervellati, Elena Esposito, and Uwe Sunde. Long term exposure to malaria and development: disaggregate evidence for contemporaneous Africa. *Journal of Demographic Economics*, 83(1):129–148, 2017. ISSN 2054-0892. doi:10.1017/dem.2016.27.

Matteo Cervellati, Elena Esposito, and Uwe Sunde. Epidemic shocks and civil violence: evidence from malaria outbreaks in Africa. *Review of Economics and Statistics*, pages 1–46, 2022a. doi:10.1162/rest_a_01050.

Matteo Cervellati, Elena Esposito, Uwe Sunde, and Song Yuan. Malaria and Chinese economic activities in Africa. *Journal of Development Economics*, 154:102739, 2022b. ISSN 0304-3878. doi:10.1016/j.jdeveco.2021.102739.

Justin M. Cohen, David L. Smith, Chris Cotter, Abigail Ward, Gavin Yamey, Oliver J. Sabot, and Bruno Moonen. Malaria resurgence: a systematic review and assessment of its causes. *Malaria Journal*, 11(1):1–17, Dec 2012. ISSN 1475-2875. doi:10.1186/1475-2875-11-122.

Matthew A. Cole and Eric Neumayer. The impact of poor health on total factor productivity. *Journal of Development Studies*, 42(6):918–938, 2006. ISSN 0022-0388. doi:10.1080/00220380600774681.

David Cutler, Winnie Fung, Michael Kremer, Monica Singhal, and Tom Vogl. Early-life malaria exposure and adult outcomes: evidence from malaria eradication in India. *American Economic Journal: Applied Economics*, 2(2):72–94, 2010. ISSN 1945-7782. doi:10.1257/app.2.2.72.

Mehreen S. Datoo, Hamtandi Magloire Natama, Athanase Somé, Duncan Bellamy, Ousmane Traoré, Toussaint Rouamba, Marc Christian Tahita, et al. Efficacy and immunogenicity of R21/Matrix-M vaccine against clinical malaria after 2 years' follow-up in children in Burkina Faso: a phase 1/2b randomised controlled trial. *Lancet Infectious Diseases*, 0(0), 9 2022. ISSN 1473-3099. doi:10.1016/S1473-3099(22)00442-X.

Saurabh C. Datta and Jeffrey J. Reimer. Malaria and economic development. *Review of Development Economics*, 17(1):1–15, 2013. ISSN 1363-6669. doi:10.1111/rode.12011.

Emilio Depetris-Chauvin and David N. Weil. Malaria and early African development: evidence from the sickle cell trait. *Economic Journal*, 128(610):1207–1234, 2018. ISSN 0013-0133. doi:10.1111/ecoj.12433.

Andrew Dillon, Jed Friedman, and Pieter Serneels. Health information, treatment, and worker productivity. *Journal of the European Economic Association*, 19(2):1077–1115, 2021. ISSN 1542-4766. doi:10.1093/jeea/jvaa024.

Peter Doshi. WHO's malaria vaccine study represents a 'serious breach of international ethical standards'. *BMJ*, 368:m734, 2 2020. ISSN 1756-1833. doi:10.1136/bmj.m734.

Esther Duflo. The economist as plumber. *American Economic Review*, 107(5):1–26, 2017. ISSN 0002-8282. doi:10.1257/aer.p20171153.

Richard G. A. Feachem, Allison A. Phillips, Geoffrey A. Targett, and Robert W. Snow. Call to action: priorities for malaria elimination. *Lancet*, 376(9752):1517–1521, 2010. ISSN 0140-6736. doi:10.1016/S0140-6736(10)61500-0.

Heather M. Ferguson, Anna Dornhaus, Arlyne Beeche, Christian Borgemeister, Michael Gottlieb, Mir S. Mulla, John E. Gimnig, Durland Fish, and Gerry F. Killeen. Ecology: a prerequisite for malaria elimination and eradication. *PLOS Medicine*, 7(8):e1000303, Aug 2010. ISSN 1549-1676. doi:10.1371/journal.pmed.1000303.

Kimberly M. Fornace, Adriana V. Diaz, Jo Lines, and Chris J. Drakeley. Achieving global malaria eradication in changing landscapes. *Malaria Journal*, 20(1):1–14, Dec 2021. ISSN 1475-2875. doi:10.1186/s12936-021-03599-0.

John Luke Gallup and Jeffrey D. Sachs. The economic burden of malaria. *American Journal of Tropical Medicine and Hygiene*, 64(2):85–96, 2000. doi:10.7916/D8XP7BSD.

Oded Galor and David N. Weil. Population, technology, and growth: from Malthusian stagnation to the demographic transition and beyond. *American Economic Review*, 90(4):806–828, 2000. ISSN 0002-8282. doi:10.1257/aer.90.4.806.

Global Malaria Programme. *World malaria report 2021*. World Health Organization, 2021. ISBN 978-92-4-004049-6. URL https://www.who.int/teams/global-malaria-programme/reports/world-malaria-report-2021.

Nicole L. Gottdenker, Daniel G. Streicker, Christina L. Faust, and C. R. Carroll. Anthropogenic land use change and infectious diseases: A review of the evidence. *EcoHealth*, 11(4):619–632, December 2014. ISSN 1612-9210. doi:10.1007/s10393-014-0941-z.

Annie Haakenstad, Anton Connor Harle, Golsum Tsakalos, Angela E. Micah, Tianchan Tao, Mina Anjomshoa, Jessica Cohen, Nancy Fullman, Simon I. Hay, Tomislav Mestrovic, Shafiu

Mohammed, Seyyed Meysam Mousavi, Molly R. Nixon, David Pigott, Khanh Tran, Christopher J. L. Murray, and Joseph L. Dieleman. Tracking spending on malaria by source in 106 countries, 2000–16: an economic modelling study. *Lancet Infectious Diseases*, 19(7):703–716, 2019. ISSN 1473-3099. doi:10.1016/S1473-3099(19)30165-3.

P. Richard Hahn, Jared S. Murray, and Carlos M. Carvalho. Bayesian regression tree models for causal inference: regularization, confounding, and heterogeneous effects. *Bayesian Analysis*, 15(3):965–1056, 2020. ISSN 1936-0975. doi:10.1214/19-BA1195.

Sok Chul Hong. Malaria: an early indicator of later disease and work level. *Journal of Health Economics*, 32(3):612–632, 2013. ISSN 0167-6296. doi:10.1016/j.jhealeco.2013.03.004.

Richard Idro, Kevin Marsh, Chandy C. John, and Charles R. J. Newton. Cerebral malaria: mechanisms of brain injury and strategies for improved neuro-cognitive outcome. *Pediatric research*, 68(4):267, Oct 2010. doi:10.1203/PDR.0b013e3181eee738.

Guido W. Imbens. Potential outcome and directed acyclic graph approaches to causality: relevance for empirical practice in economics. *Journal of Economic Literature*, 58(4):1129–79, 2020. doi:10.1257/jel.20191597.

Jennifer Keiser, Burton H. Singer, and Jürg Utzinger. Reducing the burden of malaria in different eco-epidemiological settings with environmental management: a systematic review. *Lancet Infectious Diseases*, 5(11):695–708, Nov 2005. ISSN 1473-3099. doi:10.1016/S1473-3099(05)70268-1.

Michael Kihara, Julie A. Carter, and Charles R.J.C. Newton. The effect of Plasmodium falciparum on cognition: a systematic review. *Tropical Medicine & International Health*, 11(4): 386–397, 2006. doi:10.1111/j.1365-3156.2006.01579.x.

Sengchanh Kounnavong, Deyer Gopinath, Bouasy Hongvanthong, Chanthalone Khamkong, and Odai Sichanthongthip. Malaria elimination in Lao PDR: the challenges associated with population mobility. *Infectious Diseases of Poverty*, 6(1):1–9, 12 2017. ISSN 2049-9957. doi:10.1186/s40249-017-0283-5.

Maria Kuecken, Josselin Thuilliez, and Marie-Anne Valfort. Disease and human capital accumulation: evidence from the roll back malaria partnership in Africa. *Economic Journal*, 131 (637):2171–2202, 2021. ISSN 0013-0133. doi:10.1093/ej/ueaa134.

Nikolas Kuschnig. Inadequate methods undermine a study of malaria, deforestation and trade. *Nature Communications*, 12(1), 2021. doi:10.1038/s41467-021-22514-4.

Ramanan Laxminarayan. Does reducing malaria improve household living standards? *Tropical Medicine & International Health*, 9(2):267–272, Feb 2004. ISSN 1360-2276. doi:10.1046/j.1365-3156.2003.01171.x.

Adrienne M. Lucas. Malaria eradication and educational attainment: evidence from Paraguay and Sri Lanka. *American Economic Journal: Applied Economics*, 2(2):46–71, 2010. ISSN 1945-7782. doi:10.1257/app.2.2.46.

Adrienne M. Lucas. The impact of malaria eradication on fertility. *Economic Development and Cultural Change*, 2013. doi:10.1086/669261.

Andrew J. MacDonald and Erin A. Mordecai. Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *Proceedings of the National Academy of Sciences*, 116(44):22212–22218, 2019. doi:10.1073/pnas.1905315116.

Pia Malaney, Andrew Spielman, and Jeffrey Sachs. The malaria gap. *American Journal of Tropical Medicine and Hygiene*, 71(2):141–146, 2004. doi:10.4269/ajtmh.2004.71.141.

Desmond McCarthy, Holger C Wolf, and Yi Wu. The growth costs of malaria. *NBER Working Papers*, (7541), 2000. doi:10.3386/w7541.

Anthony J. McMichael, Rosalie E. Woodruff, and Simon Hales. Climate change and human health: present and future risks. *Lancet*, 367(9513):859–869, March 2006. ISSN 0140-6736. doi:10.1016/S0140-6736(06)68079-3.

Didier Ménard, Nimol Khim, Johann Beghain, Ayola A. Adegnika, Mohammad Shafiul-Alam, Olukemi Amodu, Ghulam Rahim-Awab, et al. A worldwide map of Plasmodium falciparum K13-propeller polymorphisms. *New England Journal of Medicine*, 374(25):2453–2464, 2016. ISSN 1533-4406. doi:10.1056/NEJMoa1513137.

Erin A. Mordecai, Sadie J. Ryan, Jamie M. Caldwell, Melisa M. Shah, and A. Desiree LaBeaud. Climate change could shift disease burden from malaria to arboviruses in Africa. *Lancet Planetary Health*, 4(9):e416–e423, September 2020. ISSN 2542-5196. doi:10.1016/S2542-5196(20)30178-9.

Ally Olotu, Gregory Fegan, Juliana Wambua, George Nyangweso, Amanda Leach, Marc Lievens, David C. Kaslow, Patricia Njuguna, Kevin Marsh, and Philip Bejon. Seven-year efficacy of RTS,S/AS01 malaria vaccine among young African children. *New England Journal of Medicine*, 374(26):2519–2529, 6 2016. ISSN 1533-4406. doi:10.1056/NEJMoa1515257.

Yao Pan and Saurabh Singhal. Agricultural extension, intra-household allocation and malaria. *Journal of Development Economics*, 139:157–170, 2019. ISSN 0304-3878. doi:10.1016/j.jdeveco.2019.03.006.

M. Pascual, J. A. Ahumada, L. F. Chaves, X. Rodó, and M. Bouma. Malaria resurgence in the east African highlands: Temperature trends revisited. *Proceedings of the National Academy of Sciences*, 103(15):5829–5834, Apr 2006. ISSN 0027-8424. doi:10.1073/pnas.0508929103.

Jonathan A. Patz and Sarah H. Olson. Malaria risk and temperature: Influences from global climate change and local land use practices. *Proceedings of the National Academy of Sciences*, 103(15):5635–5636, Apr 2006. ISSN 0027-8424. doi:10.1073/pnas.0601493103.

Joacim Rocklöv and Robert Dubrow. Climate change: an enduring challenge for vector-borne disease prevention and control. *Nature Immunology*, 21:479–483, May 2020. ISSN 1529-2916. doi:10.1038/s41590-020-0648-y.

Marlon P. Saavedra, Jan E. Conn, Freddy Alava, Gabriel Carrasco-Escobar, Catharine Prussing, Sara A. Bickersmith, Jorge L. Sangama, Carlos Fernandez-Miñope, Mitchel Guzman, Carlos Tong, Carlos Valderrama, Joseph M. Vinetz, Dionicia Gamboa, and Marta Moreno. Higher risk of malaria transmission outdoors than indoors by Nyssorhynchus darlingi in riverine communities in the Peruvian Amazon. *Parasites & Vectors*, 12(1):1–15, 12 2019. ISSN 1756-3305. doi:10.1186/s13071-019-3619-0.

Jeffrey Sachs and Pia Malaney. The economic and social burden of malaria. *Nature*, 415(6872): 680–685, 2002. ISSN 1476-4687. doi:10.1038/415680a.

Augusto Seabra Santos and Alexandre N. Almeida. The impact of deforestation on malaria infections in the Brazilian Amazon. *Ecological Economics*, 154:247–256, 2018. ISSN 0921-8009. doi:10.1016/j.ecolecon.2018.08.005.

Nayantara Sarma, Edith Patouillard, Richard E. Cibulskis, and Jean-Louis Arcand. The economic burden of malaria: revisiting the evidence. *American Journal of Tropical Medicine and Hygiene*, 101(6):1405–1415, 2019. ISSN 0002-9637. doi:10.4269/ajtmh.19-0386.

Ellie Sherrard-Smith, Janetta E. Skarp, Andrew D. Beale, Christen Fornadel, Laura C. Norris, Sarah J. Moore, Selam Mihreteab, Jacques Derek Charlwood, Samir Bhatt, Peter Winskill, Jamie T. Griffin, and Thomas S. Churcher. Mosquito feeding behavior and how it influences residual malaria transmission across Africa. *Proceedings of the National Academy of Sciences*, 116(30):15086–15095, 7 2019. ISSN 0027-8424. doi:10.1073/pnas.1820646116.

Rima Shretta, Anton L.V. Avanceña, and Arian Hatefi. The economics of malaria control and elimination: a systematic review. *Malaria Journal*, 15(1):1–14, 2016. ISSN 1475-2875. doi:10.1186/s12936-016-1635-5.

Elisa Sicuri, Francesco Ramponi, Iris Lopes-Rafegas, and Francisco Saúte. A broader perspective on the economics of malaria prevention and the potential impact of SARS-CoV-2. *Nature Communications*, 13(2676):1–3, May 2022. ISSN 2041-1723. doi:10.1038/s41467-022-30273-z.

Josselin Thuilliez, Mahamadou S. Sissoko, Ousmane B. Toure, Paul Kamate, Jean-Claude Berthélemy, and Ogobara K. Doumbo. Malaria and primary education in Mali: A longitudinal study in the village of Donéguébougou. *Social Science & Medicine*, 71(2):324–334, Jul 2010. ISSN 0277-9536. doi:10.1016/j.socscimed.2010.02.027.

Universidad Católica Andrés Bello. Encuesta nacional de condiciones de vida, 2022. URL https://insoencovi.ucab.edu.ve/indicador-pobreza. accessed 2022-01.20.

Atheendar S. Venkataramani. Early life exposure to malaria and cognition in adulthood: evidence from Mexico. *Journal of Health Economics*, 31(5):767–780, 2012. doi:10.1016/j.jhealeco.2012.06.003.

Daniel J. Weiss, Tim C. D. Lucas, Michele Nguyen, Anita K. Nandi, Donal Bisanzio, Katherine E. Battle, Ewan Cameron, Katherine A. Twohig, Daniel A. Pfeffer, Jennifer A. Rozier, Harry S. Gibson, Puja C. Rao, Daniel Casey, Amelia Bertozzi-Villa, et al. Mapping the global prevalence, incidence, and mortality of Plasmodium falciparum, 2000–17: a spatial and temporal modelling study. *Lancet*, 394(10195):322–331, 2019. ISSN 0140-6736. doi:10.1016/S0140-6736(19)31097-9.

Joshua Wilde, Bénédicte Apouey, Joseph Coleman, and Gabriel Picone. The effect of antimalarial campaigns on child mortality and fertility in sub-Saharan Africa, 2020.

World Bank. Global subnational poverty atlas, 2022. URL https://datacatalog.worldbank.org/search/dataset/0042041. accessed 2022-01-20.

Eve Worrall, Suprotik Basu, and Kara Hanson. Is malaria a disease of poverty? a review of the literature. *Tropical Medicine & International Health*, 10(10):1047–1059, 2005. doi:10.1111/j.1365-3156.2005.01476.x.