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Health Costs and Benefits of DDT Use in Malaria Control and Prevention

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Abstract

The Millennium Development Goal of achieving near-zero malaria deaths by 2015 has led to a re-examination of wider use of DDT (dichloro-diphenyl-trichloro-ethane) in indoor residual spraying as a prevention tool in many countries. However, the use of DDT raises concerns of potential harm to the environment and human health, mainly because of the persistent and bio-accumulative nature of DDT and its potential to magnify through the food chain. This paper quantifies the adverse effects of DDT on human health based on treatment costs and indirect costs caused by illnesses and death in countries that use or are expected to re-introduce DDT in their disease vector control programs. At the global level where the total population exposed to DDT is estimated around 1.25 billion, the findings indicate that while the use of DDT can lead to a significant reduction in the estimated $69 billion in 2010 U.S. dollars economic loss caused by malaria, it can also add more than $28 billion a year in costs from the resulting adverse health effects. At the country level, the results suggest that Sub-Saharan African countries with high malaria incidence rates are likely to see relatively larger net benefits from the use of DDT in malaria control. The net health benefits of reintroducing DDT in malaria control programs could be better understood by weighing the costs and benefits of DDT use based on a country's circumstances.

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1. Introduction

Malaria, which is a life threatening mosquito-borne infectious disease, poses a risk to approximately 3.3 billion people or approximately half of the world's population. Most malaria cases occur in Sub-Saharan Africa. Asia, Latin America, and to a lesser extent the Middle East and parts of Europe are also affected. In 2010, malaria was present in 106 countries and territories; there were 216 million estimated cases of malaria and nearly 0.7 million deaths – mostly among children living in Africa (WHO, 2011a).[2] In addition to its health toll, malaria places a heavy economic burden on many endemic countries. It has been estimated that malaria can decrease Gross Domestic Product (GDP) by as much as 1.3% in countries with high disease rates (QCIL, 2011).

Malaria can be prevented with a combination of available tools. The primary tools used for prevention are long-lasting insecticidal nets and Indoor Residual Spraying (IRS), which is the procedure in which insecticides are sprayed on the indoor walls of homes. In 2010, 73 countries, including 36 in the African Region, recommended IRS for malaria control and 13 countries reported using DDT for IRS (WHO, 2011a). Other vector control measures, for example, larvicidal and environmental management are also used when appropriate based on scientific evidence (WHO, 2011a).[3]

In 1998, *The Roll Back Malaria Partnership (RBM)*, a global framework for the coordinated action against malaria was launched as a partnership between the World Health Organization (WHO), United Nations Children's Fund (UNICEF), United Nations Development Program (UNDP) and the World Bank to provide a coordinated global response to the disease. RBM's vision is of a *world free from the burden of malaria*: to achieve the malaria-specific Millennium

[2] In Africa, a child dies every 45 seconds of malaria; the disease accounts for 20% of all childhood deaths.

[3] Malaria is curable. A combination of medicines and diagnostics are used for malaria case management. Malaria can be confirmed by parasitological diagnosis with either microscopy or a rapid diagnostic test. Artemisinin-based combination therapies are the recommended treatment against *P. falciparum* malaria. Chloroquine and primaquine are the treatment of choice against chloroquine-sensitive *P. vivax* malaria.

Development Goal by 2015, so that malaria is no longer a major cause of mortality and no longer a barrier to social and economic development and growth anywhere in the world.[4]

With less than five years from the internationally agreed deadline for achieving near-zero malaria deaths, the next few years will call for a massive international effort for a rapid and sustained scale up of malaria control measures. In 2006, the World Health Organization issued a statement recommending wider use of **DDT** (dichloro-diphenyl-trichloro-ethane) through IRS to reduce the prevalence of malaria on basis of high insecticidal activity, low acute mammalian toxicity, wide spectrum use, low price, and long duration of activity (WHO 2011b).[5] However, WHO's endorsement and consequent increase in the use of DDT has been criticized heavily on grounds of potential ecological harm and chronic adverse health effects due to the persistent and bio-accumulative nature of DDT (Cone 2009).

It is undeniable that a rapid control of malaria is vital to free malaria-prone countries from the scourge of this debilitating disease. A number of studies have quantified the economic benefits that these regions can derive by controlling malaria and has therefore been propagating a more widespread use of DDT in IRS. However, little analysis has been done to quantify the unintentional impacts (externalities) caused by DDT. This paper is an attempt to fill that gap by

[4] In particular, the targets of the Global Malaria Action Plan sponsored by The RBM are to:

- *Achieve* **universal coverage** for all populations at risk with locally appropriate interventions for prevention and case management by 2010 and sustain universal coverage until local field research suggests that coverage can gradually be targeted to high risk areas and seasons only, without risk of a generalized resurgence;
- *Reduce* global malaria **cases** from 2000 levels by 50% in 2010 and by 75% in 2015 (In 2000, there were between 350 and 500 million cases of malaria);
- *Reduce* global malaria **deaths** from 2000 levels by 50% in 2010 and to near zero preventable deaths in 2015 (In 2000, there were at-least one million deaths from malaria worldwide);
- *Eliminate* malaria in 8-10 countries by 2015 and afterwards in all countries in the pre-elimination phase today; and
- In the long term, *eradicate* malaria world-wide by reducing the global incidence to zero through progressive elimination in countries.

See Roll Back Malaria, 2012. GMAP- the Global Malaria Action Plan for details.

[5] Other chemicals have also been used for IRS but DDT has been found to be generally superior to all other alternatives on a number of counts.

quantifying externalities of DDT on human health based on area and population exposed to DDT, and the risks posed by the use of DDT. In order to gain a better understanding of the costs and benefits of DDT use to combat malaria, a separate countrywide analysis of all countries with high incidence of malaria has been carried out. The analysis includes not only countries where DDT is currently being used, but also countries where the introduction of DDT may help in lowering the incidence of malaria. The externalities are quantified in economic terms, wherever feasible, with estimates of direct treatment costs and indirect costs imposed by morbidity and mortality as captured by Disability Adjusted Life Years (DALY) to arrive at an overall estimate of the impacts. It is expected that the estimates presented in this paper would strengthen the understanding of net health benefits of reintroducing DDT in malaria control programs throughout the globe. The remainder of the paper is organized as follows: Section 2 summarizes the health effects of DDT and the risks posed by DDT-as cited in the literature. Section 3 provides estimates of population exposure to DDT. Direct and indirect estimates of health externalities of DDT are presented in Section 4. Direct and indirect costs of malaria are presented in Section 5, while Section 6 concludes the paper.

2. *Health Effects and Risks Posed by DDT*

DDT, a white tasteless and almost odorless crystalline solid, is an organochlorine contact insecticide that kills by acting as a nerve poison. DDT is categorized by the WHO as Class II "moderately hazardous". “Acute effects in humans who are exposed to low to moderate levels may include nausea, diarrhea, increased liver enzyme activity, irritation of the eyes, nose and/or throat. At higher doses, tremors and convulsions are also possible” (Pesticide Action Network-UK, 2011).

Health externalities from DDT exposure that are reported in various studies include: a poisoning hazard to children following acute ingestion, temporary damage to nervous system, possible carcinogenic effects (can cause liver, pancreas, testicular cancer, breast cancer, leukemia and lymphoma), development effects, adverse effects on the hormonal system and reproductive

effects in both male and female. In 2009, van den Berg's review of the literature (van den Berg 2009, page 1658)[6] stated:

> "Studies on [human] health effects of DDT have focused mostly on subjects in North America and Europe, who have generally been exposed to levels lower than those reported from areas with IRS. No global assessment has been made on the evidence of health risks of DDT in relation to IRS because the data are scarce. As an indication, however, initial work suggests that non-occupational exposure through IRS is associated with impaired semen quality in men (Aneck-Hahn et al. 2007; De Jager et al. 2006). Health effects of DDT and DDE that are most commonly suggested by studies in North America and Europe are early pregnancy loss, fertility loss, leukemia, pancreatic cancer, Neurodevelopmental deficits, diabetes, and breast cancer (Beard 2006; Chen and Rogan 2003; Cox et al. 2007; Eriksson and Talts 2000; Garabrant et al. 1992; Ribas-Fito et al. 2006; Snedeker 2001; Venners et al. 2005)... [As far as breast cancer is concerned,] even though the majority of results showed no causative association with DDT exposure (Brody et al. 2007), the latest evidence indicates an increased risk in women who were exposed at a young age (Cohn et al. 2007)."

In 2011, WHO published a comprehensive review of the human health aspects of DDT in IRS (WHO 2011c). Overall, these studies reveal a major concern, particularly in relation to the chronic health effects of DDT.[7]

Health externalities of DDT are a serious concern, because DDT is one of the Persistent Organic Pollutants (POPs) that bio-accumulate and externalities magnify through the food chain with the greater accumulation at the top of the food chain. DDT enters the environment when it is used. Dichlorodiphenyldichloroethylene (DDE) and Dichlorodiphenyldichloroethane **(**DDD) enter the environment as breakdown products of DDT. Although DDT, DDE, and DDD in the air are rapidly broken down by sunlight (half of the residues in the air breaks down within 2 days),

[6] Citation of van den Berg (2009) as the source for this text was inadvertently omitted in an earlier version of the working paper.

[7] Experimental studies on animals have demonstrated neurotoxic, carcinogenic, immunotoxic, and reproductive effects attributable to DDT and DDE (Turusov et al. 1973).

the chemicals are durable in soil (ATSDR, 2002). DDT in soil is breaks down slowly to DDE and DDD by microorganisms. Depending on the type of soil and climate, half of DDT in soil will break down in 2-15 years (ATSDR 2002).[8] Generally, a small amount of DDT goes through the soil into groundwater. DDT does not dissolve easily in water. However, DDT, and especially DDE, bio-accumulate, which means that it builds up in plants and in fatty tissues of fish, birds, and other mammals (ATSDR 2002). This magnification of DDT and its breakdown products through the food chain may increase the incidence of cancer, diabetes, and hormone disruptions that could result in potential reproductive failures in the population exposed to prolonged DDT use. DDT Exposure pathways include (i) eating contaminated foods, such as dairy products, root and leafy vegetables, fish and fatty meat; (ii) drinking breast milk from mothers who have been exposed to DDT; (iii) exposure of fetus through the placenta blood; (iv) breathing or swallowing soil particles near waste sites or landfills that contain DDT; and (v) breathing contaminated air or drinking contaminated water in or near houses- sprayed with DDT (ATSDR, 2002).

In terms of relevant exposure scenarios for the general population to DDT in countries using IRS, a few studies point to a concern about the levels of exposure for any of the end-points that were assessed. In North America, rather relatively high levels of exposure have been recorded in biological samples collected near the time of peak use during the 1960s (Eskenazi et al. 2006). The review by van den Berg (2009, page 1658) also draws attention to the fact that "High levels of human exposure to DDT among those living in sprayed houses, most of whom are living under conditions of poverty and often with high levels of immune impairment, have also been found in recent studies in South Africa and Mexico (Aneck-Hahn et al. 2007; Bouwman et al. 1991; De Jager et al. 2006; Yanez et al. 2002)."

Since DDT use is now legally allowed only for use in vector control; the main exposure will be among IRS spray operators[9] and also in houses where it is being used in IRS. In addition, some exposure among the general population can occur if the DDT is not stored and handled safely

[8] The process of degradation is dramatically slowed down in cooler climates.

[9] Occupational exposure

and also from illegal diversion of DDT.[10] Table 1 presents summary exposure assessments from the World Health Organisation (WHO 2011c, page 215, Table 43), measured as the total of DDT and DDE concentrations in the blood serum. The numbers indicate significant differences in the exposures of IRS spray operators, IRS exposed population and general population Accordingly, our study distinguishes three population groups in terms of exposure to DDT: IRS spray operators, population directly exposed to the IRS and the remaining non-IRS exposed population.

[Insert Table 1]

Table 2 presents the estimates of elevated risks of some of the diseases due to the DDT exposure by exposed population groups. These estimates are drawn from the Risk Ratio (RR) of the disease with and without DDT exposure listed in the literature. The RR of an IRS spray operator is based on the results of the highest exposure levels that is found among the existing studies, and presented in column 2. Assuming that the risk of a disease is directly proportional[11] to the DDT exposure levels, it is estimated that people in the IRS households will face 25% of the RR faced by the IRS spray operators and the people in the non-IRS households will face 10% of the RR faced by the IRS spray operators. Based on the exposure levels of the spray operators in Table 2, the risk among the IRS households and the non-IRS households in the area are then computed using differential exposure of the respective groups. The results are presented in columns 3 and 4.

[Insert Table 2]

[10] Even when DDT is not being currently used, exposure can still occur in the general population from the residue left over from its earlier use as DDT is a very long lasting chemical with a long half life. Exposure can also occur from illegal use of DDT in agriculture often referred to as "leakage from vector control operations into agricultural use".

[11] The relationship between the toxin levels and the risk of disease is generally non-linear over the total range of toxin accumulation. But for the shorter ranges of toxins, a linear relationship may be a reasonable approximation. Furthermore, it is difficult to model any non-linear relationships as it can take many functional forms and can differ with each toxin. So, the assumption of a linear relationship may be the only feasible option in this case.

Although the risk of unintended health problems may vary by age and a number of other contributory factors, the RR has been used as an average measure of the increased risk for the exposed population in this study.

3. Estimates of Population Exposed to DDT

A number of countries currently use DDT for malaria control.[12] In addition, the re-introduction of DDT for lowering the spread of malaria is under consideration in some other countries, especially in Sub-Saharan Africa. By and large the population of the geographic location where DDT is currently being used or where it may be re-introduced faces the risk of exposure to DDT and is the focus of this analysis[13]. In order to determine the population exposed to DDT from its continued use or potential future use, detailed geographic data of DDT use at a sub-country level are required. However, while production and usage data on DDT is generally available at country level, sub-country level DDT usage data are scarce. In its absence, this study focused on a proxy, the malaria endemicity across countries to capture the current and potential exposure of population to DDT within each country given that the use of DDT is restricted to malaria eradication.[14]

The malaria endemicity in this study is based on the Global malaria atlas compiled by the Malaria Atlas Project (MAP) of the Oxford University. The data are based on 24,492 parasite rate surveys (*Plasmodiumfalciparum.* 24,178; *Plasmodium vivax.* 8,866) from an aggregated sample of 4,373,066 slides prepared from blood samples taken in 85 countries. The MAP study employs a new cartographic technique for deriving global clinical burden estimates of

[12] The following 13 countries reported using DDT for malaria control and prevention: Eritrea, Ethiopia, Gambia, India, Madagascar, Malawi, Morocco, Mozambique, Namibia, South Africa, Swaziland, Zambia, and Zimbabwe (WHO 2001a).

[13] LAC countries are excluded from the analysis, because all LAC countries phased out DDT use.

[14] As per WHO guidelines, use of DDT is only restricted to vector control. All other uses of DDT have been banned worldwide under the Stockholm Convention on Persistent Organic Pollutants. So, it is reasonable to assume that any future use of DDT will primarily be restricted to malaria endemic areas.

Plasmodium falciparum malaria for 2007. These estimates are then compared with those derived under existing surveillance-based approaches to arrive at the final data used in the malaria mapping (Hay et al., 2009).
(http://www.map.ox.ac.uk/media/maps/pdf/mean/World_mean.pdf, accessed 2011)

Malaria maps generally separate the malaria endemicity into three broad categories by *Plasmodium falciparum* parasite rate (PfPR), a commonly reported index of malaria transmission intensity: PfPR < 5% as *low* endemicity, PfPR 5%-40% as *medium/intermediate* endemicity, and PfPR > 40% as *high* endemicity. In the *low* endemicity category, there may not be much use of DDT as other measures of vector control can be generally adequate to eliminate malaria. In the *medium/intermediate* endemicity range one can expect to see the use of Insecticide Treated Nets (ITN)/Long-lasting insecticide treated nets (LLIN) along with targeted IRS to interrupt malaria transmission. In the *high* endemicity range, however, DDT is likely to have widespread use in IRS.

In this study, global mapping techniques were used to estimate population exposed to DDT. This involves combining spatial information of endemicity areas and administrative areas and then summarizing the estimates of population by the combined areas.[15] First, the malaria endemicity maps were overlaid on global population maps from Landscan 2005[16] (Dobson, 2000) and country-level population exposure in the three endemicity areas were then computed. Figure 1 presents country level estimates of the population exposure to DDT that is expressed by Malaria endemicity categories in 71 countries known for malaria prevalence. Table 3 summarizes the vulnerable population estimates for each category of malaria intensity by presenting the top-10 malaria cases based on total exposed population.

[Insert Figure 1]

[15] Due to the spatial reference of the data and the number of observations in the combined data, the use of Geographic Information Systems functions from ESRI ArcGIS (v 9.3.1) were used and automated in the python (v 2.5) language.

[16] This product was made utilizing the LandScan (2005)™ High Resolution global Population Data Set copyrighted by UT-Battelle, LLC, operator of Oak Ridge National Laboratory under Contract No. DE-AC05-00OR22725 with the United States Department of Energy.

[Insert Table 3]

Second, the number of people to be found in the IRS households and the non-IRS households in the three malaria endemic categories was estimated according to the following assumption:

Households in *Low* Endemicity Category:	10% IRS	90% non-IRS
Households in *Medium* Endemicity Category:	50% IRS	50% non-IRS
Households in *High* Endemicity Category:	80% IRS	20% non-IRS

Finally, in order to determine the number of IRS spray operators in a given area, data from IRS training manuals that indicate that 50,000 structures need 175 spray operators were used (USAID, 2009). The number of spray operators in each country was then calculated based on the number of IRS households.

The country-level estimates of the IRS households, the non-IRS households and the spray operators were later combined with the respective RR in each of the three population groups to estimate the increased incidence of the unintended diseases (health externalities) due to the DDT exposure.

4. Health Externalities of DDT

The direct and indirect economic losses arising from the increased risk of unintended diseases from the exposure to DDT in the affected population were then separately computed. The direct economic loss results from the treatment costs needed to treat the diseases, while the indirect economic costs arise as a consequence of increased morbidity and mortality.

The cost estimates due to DDT exposure were done in this paper under two alternative extreme scenarios: *DDT use widespread* and *DDT use restricted*. In the *DDT use widespread* scenario, it was assumed that all three malaria endemicity areas: *low*, *medium* and *high* will be subject to IRS with DDT of varying magnitudes; and therefore all the 71 countries with malaria endemicity

will experience some use of DDT. In the *DDT use restricted* scenario, it was assumed that DDT in IRS will be restricted to only the *high* endemicity areas, which involves 34 countries, and other methods not involving DDT will be employed in the other two lower endemicity areas, which involves 37 countries. So, the DDT use restricted scenario will have a significantly lower exposure to DDT among the population.

Direct Costs

The direct costs of health externalities will involve the total medical and other out-of-pocket expenditures required during the course of the disease for acute and chronic health endpoints of DDT. These costs can therefore be approximated using the expected increase in the incidence of diseases from exposure to DDT and the cost of treating these extra illnesses over the life time of the patient. At the outset, it should be noted that this estimate will not capture other costs of illness such as transportation to medical appointments, dietary restrictions, and expenditures for friends or family acting as caretakers. The computations of the *direct* costs for patients who face the incidence of various diseases due to the exposure to DDT require specific computation methods depending on the nature of the disease. The cost of the illnesses that can be cured by a one-time treatment is determined by the cost of each treatment multiplied by the extra incidence of a disease caused by the DDT exposure. For the other (chronic) ailments with no permanent cure, which require continuous medical treatment for the rest of the patient's life, the cost of the medical treatment will be the cost incurred by patients over their life time. However, data for the medical costs are generally available only on an annual basis for all current patients in each disease category. To approximate a lifetime cost, we assumed a steady state of disease prevalence where the new incidence is counterbalanced by the loss due to the death of the patients. In such a steady state scenario, the lifetime costs for all new patients every year can be approximated by the cost for all existing patients in a year. Then, the lifetime cost per patient is that total cost divided by the number of new patients in a year[17]. This cost per patient over the lifetime is then multiplied by the extra incidence of disease caused by DDT exposure to arrive at the total cost.

[17] Thus, if we have a steady state of 100 patients with 5 new patients contracting the disease every year and 5 patients dying, then on average, each new patient lives for 20 years and the lifetime cost for these 5 patients is the same as the annual cost of 100 steady state patients in a year.

In light of the difficulty of gathering treatment cost data for each country separately, the cost of treatment for a disease in each separate country was estimated using an indirect method based on such costs for the USA. The cost of treating a disease over the lifetime of the disease was first computed for the USA using data on all the health expenditures for treating cancer for 2009 (AMERICAN CANCER SOCIETY, 2009). These numbers were then made country specific by assuming that such costs were proportional to the per capita income in each country using Purchasing Power Parity (PPP) per capita GDP for each country. This is a conservative estimate since not all medical costs go down proportionately with the decrease in per capita income.[18]

As a first step, the *direct* costs of the health externalities of DDT were estimated by computing the extra incidence of *each* disease from DDT exposure in a country given the respective RR in each of the three population groups: IRS spray operators, IRS exposed households and non-IRS exposed households. The additional incidence of a disease in a country was then multiplied by the cost of treating the disease per patient over the lifetime of the patient in that disease category in each country. The costs from all the diseases were then aggregated to estimate the total *direct* cost of health externalities arising from the DDT exposure in a given country.

As an illustrative example, the increased *direct* costs from DDT exposure across all countries in Sub-Saharan Africa are shown in Figure 2.

[**Insert Figure 2]**

Under the *widespread DDT use* scenario, estimates indicate an increased *direct* cost of more than $3.03 billion, while a *restricted DDT use* scenario will result in a cost increase of nearly $0.60 billion. However, it should be noted that this is an underestimate as it does not include the effect of DDT in all disease categories because of the non-availability of data for some of the diseases and the costs should be used as a lower bound.

[18] The present estimation therefore provides a lower bound for such costs and the actual costs are likely to be higher.

Indirect Costs

The *indirect* costs of health externalities of DDT, on the other hand, depend on the valuation of the burden of the disease; and can be assessed using a number of epidemiological parameters such as incidence, prevalence, disease specific mortality, and disability caused by the disease. In this analysis, the burden of disease was estimated based on disability adjusted life years (DALY) approach.[19] DALY is a widely used approach to estimate the consequences of a disease over the lifetime of the patient and combines the effects of both increased morbidity (years of life lived with disease) and mortality (years of life lost due to premature mortality from the disease) into one composite index in terms of years of useful life lost. The DALYs for various disease categories by gender and age categories are published periodically by the WHO in different regions of the world as a measure of global burden of the disease.

The identification of the population facing exposure to DDT and the estimation of increased incidence of disease resulting from such exposure for the indirect cost estimation were done in the same way as discussed in the section on direct cost estimations. Since the DALY measures for various disease categories are available by age categories and gender, the increased incidence of the disease was also developed using the population ratios in each age and gender category. The extra DALY due to the increased incidence of a specific disease resulting from DDT was then determined using the DALY rates in each of the age and gender groups. This process of computation was repeated for each disease category separately as the DALY rates vary across each disease. The increased DALYs from each disease category for a country were then added to calculate the total probable DALY loss due to the exposure to DDT in that country. The DALY estimates for each disease category, which are reported in the WHO global

[19] In the literature, a number of alternative approaches have been used to assess burden of disease ranging from the Cost of incidence (COI), Human capital approach, Willingness to pay (WTP), Value of Statistical Life (VSL), Quality-adjusted life year (QALY) and DALY.

burden of disease 2006, are available by a number of distinct regions of the world (WHO, 2006). This computation was therefore conducted for each country using the DALY for the region in which the country is located.

The increase in DALY that will result from the increased disease incidence from the exposure to DDT in each country provided a physical measure of the DDT health externality. These physical measures in terms of years lost were then converted into monetary values using the per capita PPP GDP in each country. Like the estimation of direct cost, indirect costs were also separately estimated for the two scenarios, *DDT use widespread* and *DDT use restricted*. Once again, the increased *indirect* costs from DDT exposure across countries of Sub-Saharan Africa are shown in Figure 3 as an illustrative example.

[Insert Figure 3]

Estimates indicate that the *widespread DDT use* scenario is likely to result in an increased cost of more than $24.92 billion, while a *restricted DDT use* scenario will result in a cost increase of nearly $4.58 billion. Once again, this is an underestimate as it does not include the effect of DDT in all disease categories because of the non-availability of data for some diseases and the costs should be used as a lower bound.

5. *Direct and Indirect Costs of Malaria*

The analysis of the externality caused by the use of DDT is based on the assumption that there will be continued use of DDT in countries that are using it at present and countries facing high incidence of malaria will re-introduce DDT for malaria control. Hence, the analysis will be incomplete unless a comparison is made between the externality caused by the use of DDT and the cost savings that can be attained by lowering the incidence of malaria with the use of DDT. In order to determine such cost savings, the overall costs imposed on society by malaria in the vulnerable countries were estimated by examining both the *direct cost*s of treating the disease as well as the *indirect* cost caused by the increase in morbidity and mortality among malaria patients.

In the estimation of *direct* costs, annual incidence of malaria in each country and the cost for treating each incidence were considered. The annual incidence of malaria is published by the WHO for each country. Available data indicate that on average $5 is spent as a treatment cost for each incidence of malaria (MicrobiologyBytes, 2009). The incidence of malaria was multiplied by the treatment cost to estimate the total cost of treatment of malaria in each country. The results show that if malaria can be eradicated fully in the identified countries using DDT, it will result in a cost savings of $1.08 billion needed as the cost of malaria treatment. Since more than half of the malaria incidence occurs in the high malaria endemicity areas, the elimination of malaria from such areas with the use of DDT will reduce treatment costs by nearly $0.55 billion.

The estimate of *indirect* costs or welfare loss from malaria induced morbidity and mortality is once again based on the DALY lost from malaria. Following the process discussed earlier in the DALY estimations from the use of DDT, the monetary value of the DALY lost from malaria in each country was evaluated by multiplying the lost DALY with each country's per capita PPP GDP. Estimates based on the results show that the complete eradication of malaria with the use of DDT can lead to a reduction of indirect costs of $67.94 billion from lower morbidity and mortality in the affected countries. The elimination of malaria through the use of DDT in high malaria endemicity areas can result in reduction in indirect cost of more than $34 billion.

6. *Discussion and Conclusion*

The estimates presented in this paper indicate that the use of DDT can provide large benefits from the effective control of mosquito vectors in malaria endemic countries.

[Insert Table 4]

Current estimates of the economic losses from malaria show that such losses exceed $69 billion in 2010 U.S. dollar annually. A major part of the loss is incurred primarily in three regions of the world, Sub-Saharan Africa (78%), South Asia (13%), and East Asia Pacific (8%). The analysis here reveals that in some Sub-Saharan countries, the losses caused by Malaria may even exceed 10% of the GDP. The use of DDT can be an effective means of lowering this loss in these affected

regions of the world. However, it should be noted that the use of DDT comes with significant unintended costs (externalities) to human health and the environment. The analysis reported in this paper indicates that the monetary value of health externalities of DDT alone can exceed $28 billion with widespread use of DDT in all malaria endemicity areas[20]. Hence some of the potential gains from lowering malaria incidence may be offset by the unintended costs of DDT use.

These estimates call for a country by country analysis that weighs the costs and benefits of DDT use. Such a comparison suggests that most countries in Sub-Saharan Africa facing high incidence of malaria may witness net benefits in malaria control from the use of DDT.

The analysis also shows that if the use of DDT is restricted to areas with the highest malaria endemicity (PfPR > 40%) then the health externalities caused by DDT are relatively small ($5 billion), while still helping in a major reduction in malaria incidence. The gains from the control of malaria in such a scenario can then greatly exceed the externalities caused by DDT in most countries. So, there may be a stronger case for using DDT in malaria vector control in areas with the highest malaria endemicity (PfPR > 40%).

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Table 1: Exposures of different populations, measured as total DDT or DDE concentrations

Tissue	**Occupational exposure (IRS spray operators)**		**Residents in IRS-treated homes**		**General population**	
	Total DDT	*DDE*	*Total DDT*	*DDE*	*Total DDT*	*DDE*
Blood serum (lipid adjusted)	Mean: 77.8 (8.7–241.1) µg/g lipid	Mean: 41.8 (7.1–131.8) µg/g lipid	Mean: 9.8 (1.09–21.8) µg/g lipid	Mean: 19.7 (0.8–77.9) µg/g lipid	Mean: 5.0 (0.38–26.1) µg/g lipid	Mean: 1.0 (0.2–3.18) µg/g lipid
	Median: 58.6 µg/g lipid	Median: 25.6 µg/g lipid	Median: 5.18 µg/g lipid	Median: 9.7 µg/g lipid	Median: 0.93 µg/g lipid	Median: 0.77 µg/g lipid
Umbilical cord blood	—	—	Mean: 29.9 µg/l	Mean: 60.3 µg/l	Mean: 15.0 µg/l	Mean: 3.1 µg/l
	—	—	Mean: 4.6 µg/g lipid	Mean: 9.3 µg/g lipid	Mean: 0.44 µg/g lipid	Mean: 0.36 µg/g lipid

Source: WHO 2011c. DDT in Indoor Residual Spraying: Human Health Aspects[21]

[21] Citation of WHO 2011c as the source for this table was inadvertently omitted in an earlier version of the working paper.

Table 2: The increased incidence (RR) of disease from exposure to DDT*

	IRS Spray Operators	**IRS Exposed Population**	**Non IRS Exposed Population**
Stomach Cancer	2.0	1.25	1.1
Liver Cancer	3.8	1.7	1.3
Pancreatic Cancer	4.8	1.9	1.4
Lung Cancer	1.8	1.2	1.08
Breast Cancer	3.04	1.6	1.25
Prostate Cancer	2.1	1.25	1.1
Lymphatic Cancer	1.8	1.2	1.08
Diabetes	2.74	1.45	1.18
Asthma	3.4	1.6	1.2
Abortion	1.6	1.15	1.06
Low Birth weight	3.1	1.5	1.2

Column 2 of this table was constructed using available information from the following sources (from top to bottom): Cocco et al. 2005; McGlynn et al. 2006; Garabrant et al. 1992; Austin et al. 1989; Pavuk et al. 2003; Settimi et al. 2003; Woods et al. 1987; Everett et al. 2007; Sunyer et al. 2005; Longnecker et al. 2005; Longnecker et al. 2001. Column 3 and Column 4 present authors' calculations.

*The Odds Ratio (OR) found in some studies has been approximated as the RR without a loss of accuracy since the incidence rates are very low.

Table 3: Top ten total vulnerable population estimates (in thousands) for three categories of endemicity (PfPR <5%, PfPR 5- 40%, and PfPR > 40%) with the percentage of the total national population

Rank	PfPR: <5%	PfPR: 5- 40%	PfPR: >40%
1	India (34150) (3%)	India (348899) (32%)	Nigeria (101569) (79%)
2	Indonesia (24230) (10%)	Indonesia (44870) (19%)	Democratic Republic of the Congo (37828) (62%)
3	Pakistan (23547) (15%)	Myanmar (35857) (77%)	Ghana (17369) (80%)
4	China (16252) (1%)	Ethiopia (34146) (47%)	Côte d'Ivoire (17218) (100%)
5	Kenya (10669) (31%)	Sudan (29714) (74%)	Burkina Faso (13405) (99%)
6	Ethiopia (10540) (14%)	Nigeria (26974) (21%)	Cameroon (10506) (62%)
7	Vietnam (9951) (12%)	Tanzania (21074) (57%)	Tanzania (10137) (28%)
8	Philippines (8828) (10%)	Democratic Republic of the Congo (18964) (31%)	Uganda (9639) (35%)
9	Thailand (5222) (8%)	Uganda (16367) (60%)	Mozambique (9495) (49%)
10	Yemen (4683) (23%)	Philippines (14984) (17%)	Mali (8635) (76%)

Table 4: Comparison of aggregate health cost (US $ million)

	Health Externalities of DDT		Malaria
	DDT Use *widespread*	DDT Use *Restricted*	
Direct Cost	3,032	598	1,091
Indirect Cost	24,920	4,578	69,061
Total Cost	**27,953**	**5,176**	**70,152**

Figure 1 : Country-level Population Exposure to Malaria

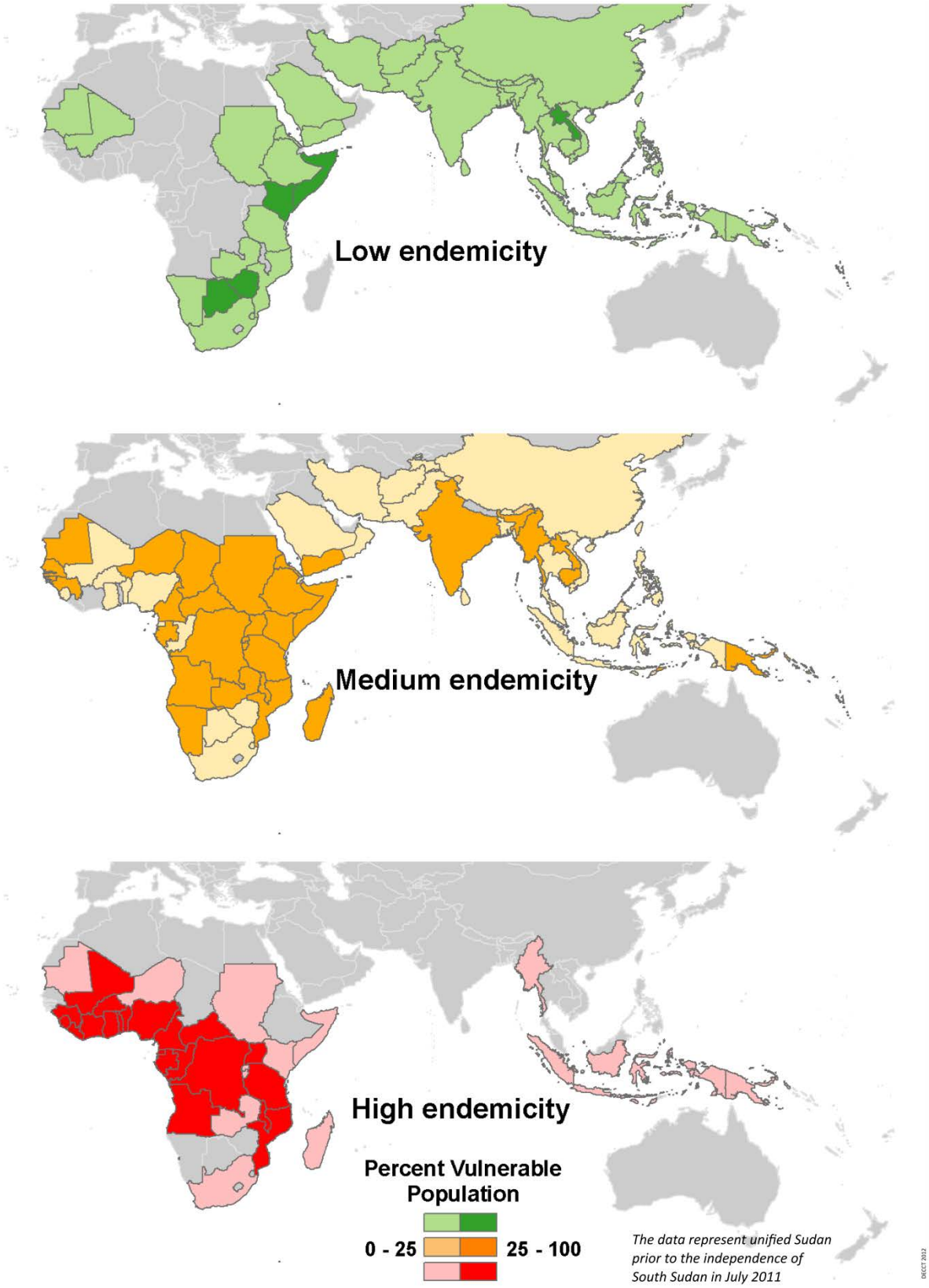

Figure 2 : Sub-Saharan Africa: Direct (treatment) costs of health externalities from widespread and restricted DDT use

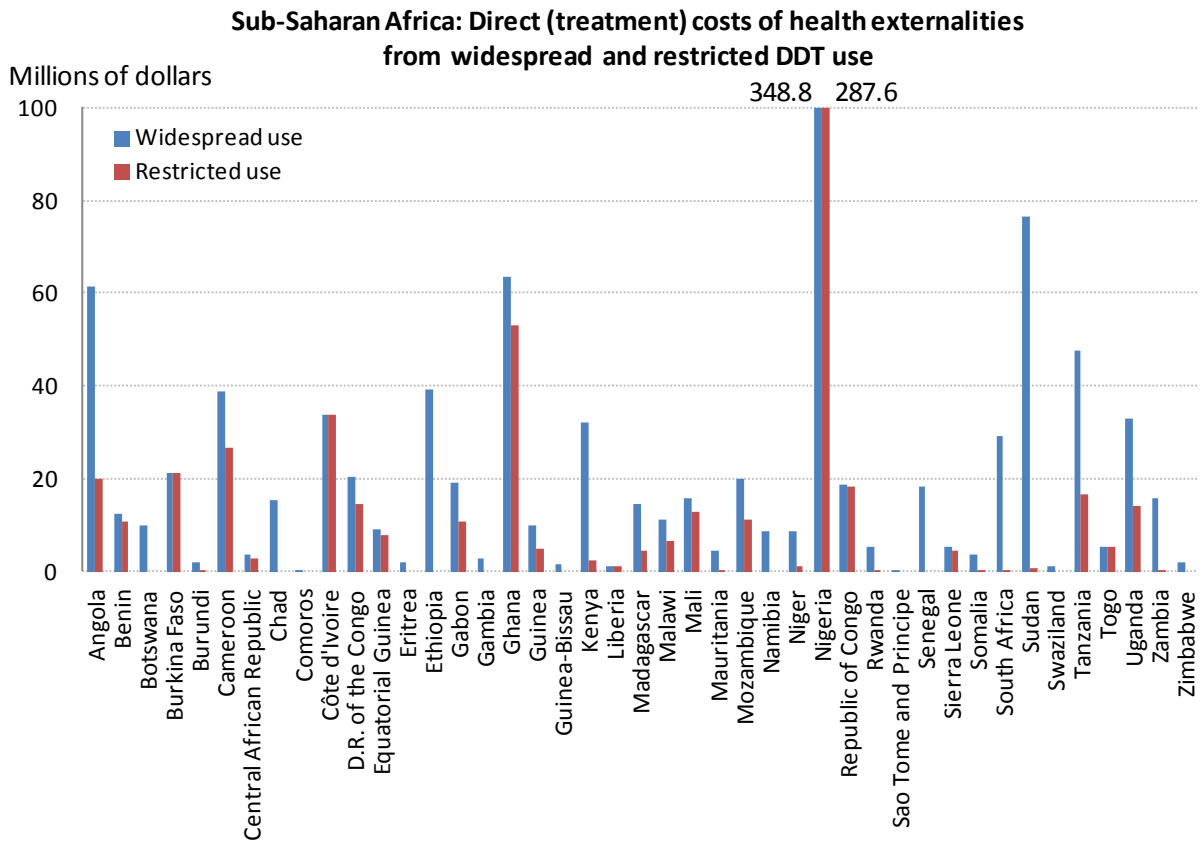

Figure 3 : Sub-Saharan Africa: Indirect costs (DALY) of health externalities from widespread and restricted DDT use

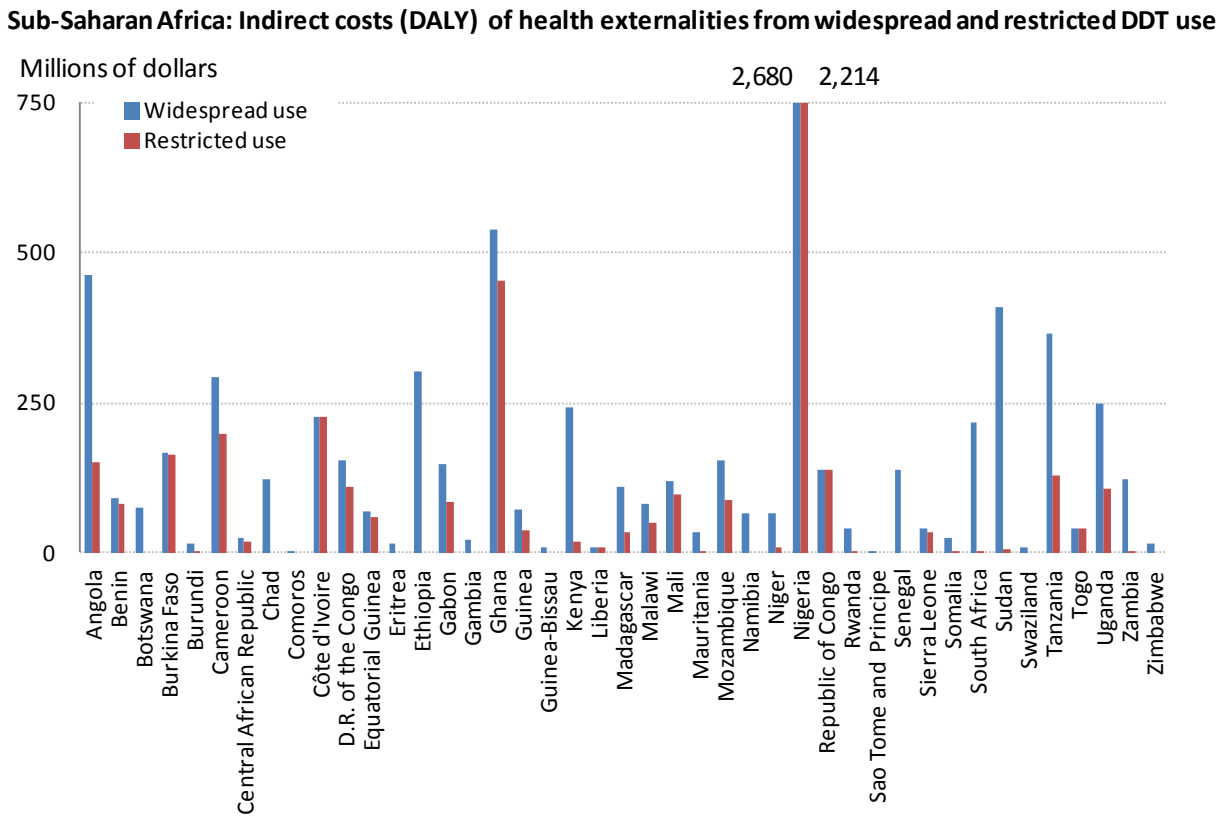

Figure 4 : Sub-Saharan Africa: Direct (treatment) costs for malaria

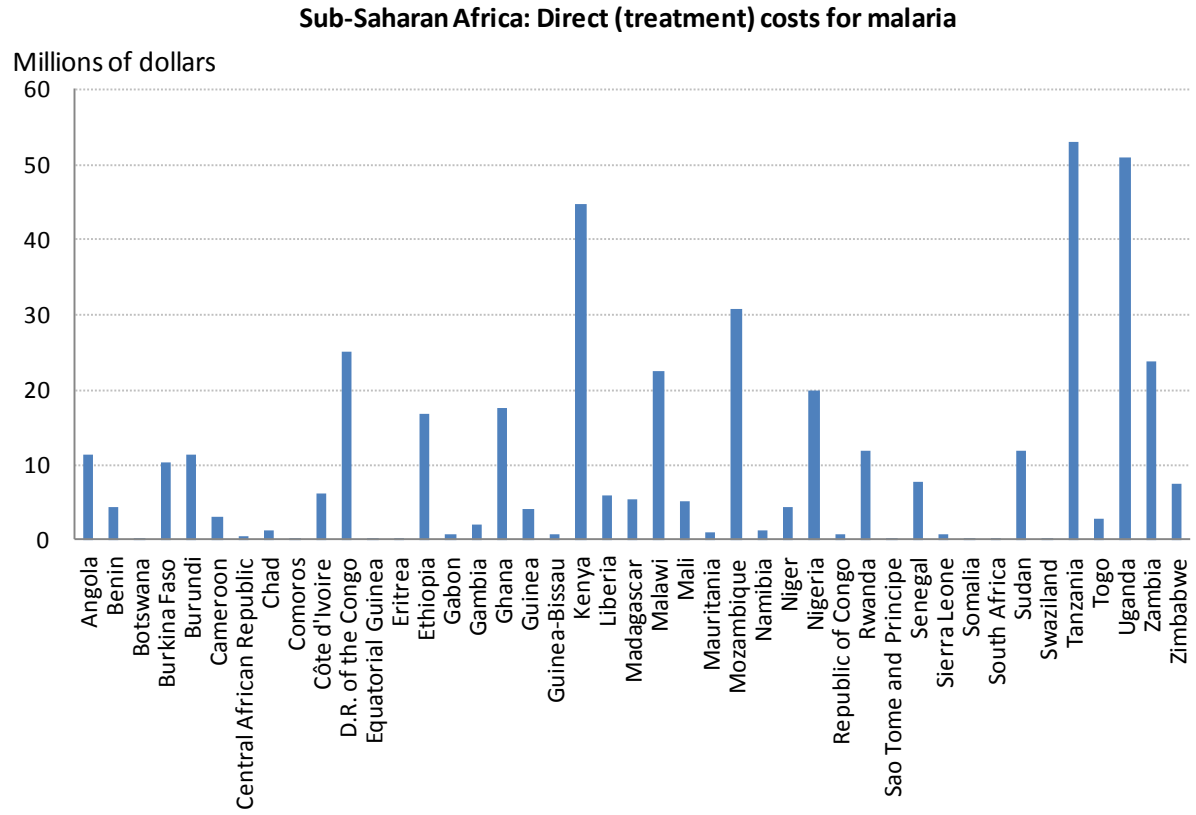

Figure 5 : Sub-Saharan Africa: Indirect costs (DALY) for malaria

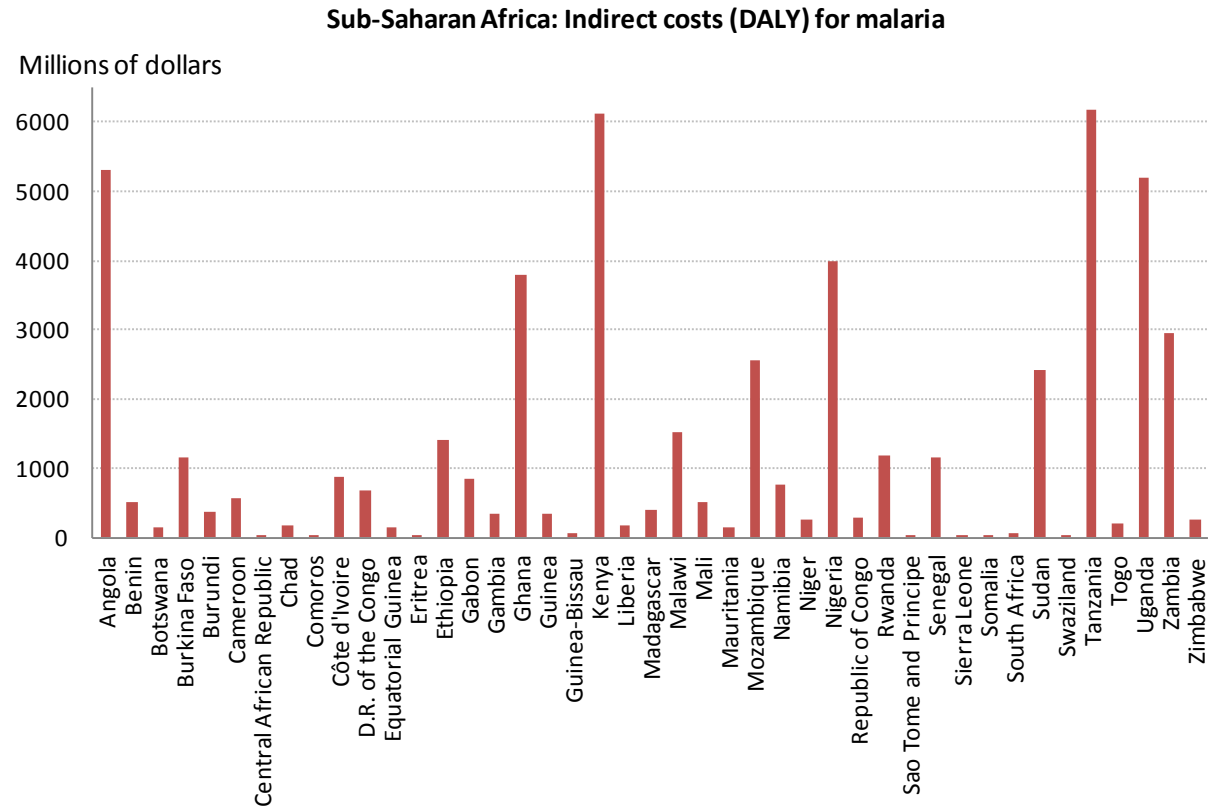
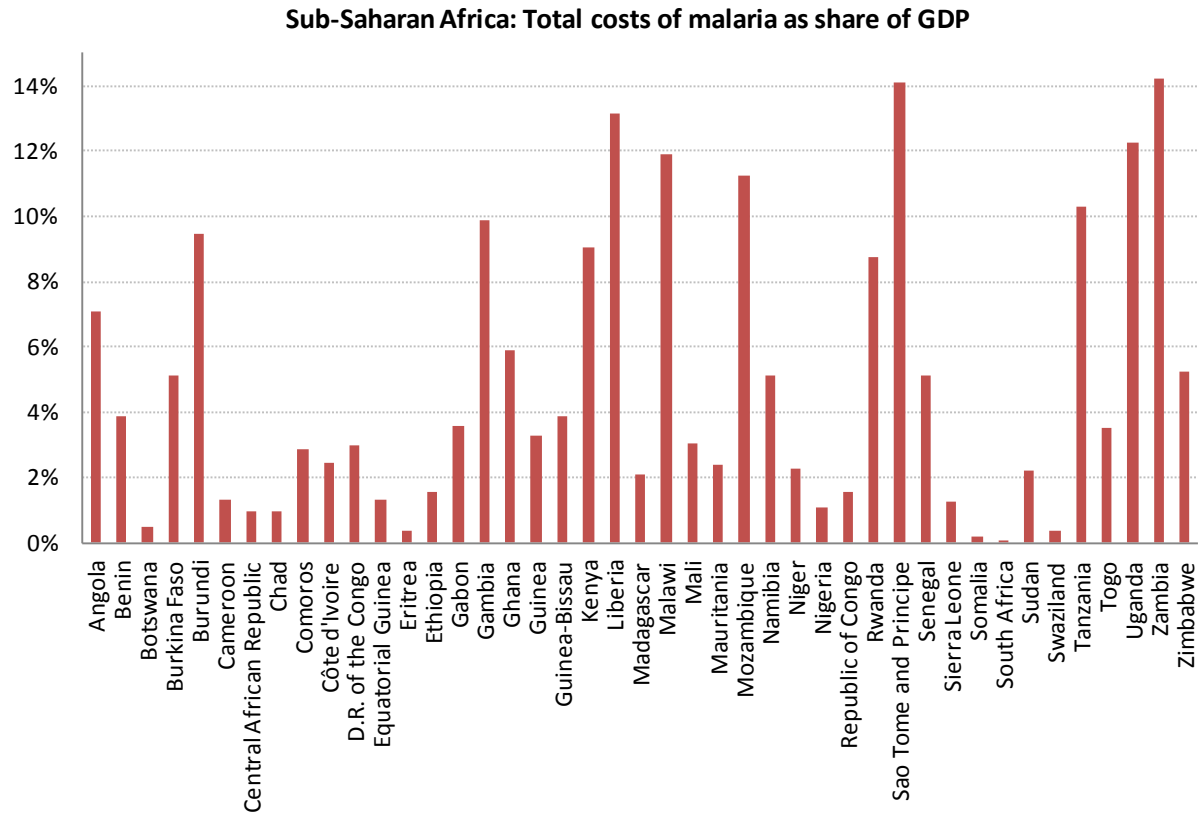
Figure 6 : Sub-Saharan Africa: Total costs of malaria as share of GDP