

Efficacy and cost-effectiveness of environmental management for malaria control

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Summary

Roll Back Malaria aims at halving the current burden of the disease by the year 2010. The focus is on sub-Saharan Africa, and it is proposed to implement efficacious and cost-effective control strategies. However, the evidence-base of such information is scarce, and a notable missing element is discussion of the potential of environmental management. We reviewed the literature and identified multiple malaria control programmes that incorporated environmental management as the central feature. Prominent among them are programmes launched in 1929 and implemented for 2 decades at copper mining communities in Zambia. The full package of control measures consisted of vegetation clearance, modification of river boundaries, draining swamps, oil application to open water bodies and house screening. Part of the population also benefited from quinine administration and was sleeping under mosquito nets. Monthly malaria incidence rates and vector densities were used for surveillance and adaptive tuning of the environmental management strategies to achieve a high level of performance. Within 3-5 years, malaria-related mortality, morbidity and incidence rates were reduced by 70-95%. Over the entire 20 years of implementation, the programme had averted an estimated 4,173 deaths and 161,205 malaria attacks. The estimated costs per death and malaria attack averted were US\$ 858 and US\$ 22.20, respectively. Over the initial 3-5 year start-up period, analogous to the short-duration of cost-effectiveness analyses of current studies, we estimated that the costs per disability adjusted life year (DALY) averted were US\$ 524-591. However, the strategy has a track record of becoming cost-effective in the longer term, as maintenance costs were much lower; US\$ 22-92 per DALY averted. In view of fewer adverse ecological effects, increased sustainability and better uses of local resources and knowledge, environmental management – integrated with pharmacological, insecticidal and bednet interventions – could substantially increase the chances of rolling back malaria.

Introduction

Thirty years after the abandonment of the first 'global' campaign to eradicate malaria, the disease is again high on the international health agenda. Roll Back Malaria (RBM) is the new initiative and was first announced in May 1998 (WHO 1998). Its ambitious goal is halving the current malaria burden by the year 2010 and again five years later (Nabarro & Tayler 1998). There are four central features, which distinguish RBM from the former attempts to eradicate malaria. First, emphasis is placed on malaria control instead of eradication. Second, the main focus is on sub-Saharan Africa whereas before, interventions were mainly targeted to the Americas, Asia and endemic areas of Europe (Baird 2000). Third, it is a global partnership between development agencies, banks, the private sector, non-governmental organisations, foundations and a network of researchers. Fourth, it follows a horizontal approach and promotes the strengthening of local capacities and health systems, so that malaria can be dealt with locally (Nabarro & Mendis 2000). Since RBM has been launched, the initiative has obtained wide publicity and a pledged financial support of US\$ 1 billion per year in the form of grants and loans (Dove 2000). In view of a figure of this order of magnitude and the commitment by the various partners, RBM should not be allowed to fail (The Lancet 2000).

With the emphasis currently shifting from campaigning to implementation, there is a pressing need for information about the efficacy and cost-effectiveness of different intervention strategies, which might guide policy makers about how available resources can be used to obtain the maximum possible social benefit (Hutubessy *et al.* 2001). However, the existing evidence-based knowledge is sparse and has been derived from a very limited number of studies. This has been emphasised in a recent analysis of the cost-effectiveness of several malaria control measures in sub-Saharan Africa (Goodman & Mills 1999; Goodman *et al.* 1999). The researchers identified 14 individual studies, which aimed at prevention and treatment of malaria, and assessed cost-effectiveness by using a modelling

approach. The interventions included insecticide-treated bednets, indoor house spraying, chemoprophylaxis in childhood or pregnancy, intermittent treatment for pregnant women, improved malaria treatment and a hypothetical vaccine. Importantly, under the assumption of a low-income country with high levels of malaria transmission, all the interventions assessed appear to be cost-effective, at least in the short run. At present, no comparable cost-effectiveness analysis has been undertaken for environmental management, although this might be a potentially important component of a package of interventions to control malaria and sustain it in the long-term (Goodman *et al.* 1999; Lerer 1999). It has been stated that the lack of data has precluded such analyses.

We reviewed the literature about effective malaria control programmes in sub-Saharan Africa and identified a comprehensive study, which had been implemented at copper mines of the former Northern Rhodesia (now Zambia) between 1929 and 1949 (Watson 1953). The programme applied a multiplicity of interventions, most of which were centred on environmental management (vegetation clearance, modification of river boundaries, draining swamps, oiling and house screening). For some of the employees, it also included quinine administration for prevention and cure of malaria, and provision of mosquito nets. Costs were recorded, including physical resources and unit prices, and systematically accounted to the same cost position throughout the programme. Mortality, morbidity, malaria incidence rates and vector densities were monitored. We re-analysed the data and estimated the number of deaths, malaria attacks and disability adjusted life years (DALYs) averted, which allowed subsequent comparison of efficacy and cost-effectiveness of environmental management with other, currently more widely used malaria control interventions.

Materials and Methods

Study identification

We searched electronic on-line abstracting databases (Biological Abstracts[®], BIOSIS, Philadelphia, Pennsylvania, USA; and MEDLINE[®], US National Library of Medicine, Bethesda, Maryland, USA) for successful malaria control programmes carried out in sub-Saharan Africa that incorporated environmental management as the central feature. We used the following keywords: environmental management, malaria control, Africa, cost(s) and cost-effectiveness analysis. As a result we obtained a large number of references, which were scrutinized for detailed cost data of environmental management interventions and specific malaria related outcomes. None of the publications matched our requirements. We then hand searched the bibliographies of the most relevant manuscripts and also discussed the topic with malariologists. These two approaches guided us to the old literature of the pioneering work carried out in the first decades of the last century, before the advent and widespread use of dichlorodiphenyltrichloroethane (DDT).

Roan Antelope copper mine

We identified a large-scale, multifaceted malaria control programme that incorporated environmental management as the central feature. The records included a detailed account of costs, specifying for each environmental management intervention its physical resources and unit prices. The programme was initiated towards the end of 1929 at the Roan Antelope copper mine of Zambia, located in the Ndola Rural district, near the town of Luanshya. The area was known to be hyperendemic for malaria, as seen from the earliest medical records at the beginning of the programme implementation (Watson 1953). Subsequently, control interventions were extended to several copper mining sites nearby and control strategies were carried out for two decades (Watson 1953). At the time of

implementation, Zambia was known as Northern Rhodesia and was governed by the British colonial authority.

Zambia's first national malaria survey, carried out between 1969 and 1972, confirmed that malaria was highly endemic in the Ndola Rural district; 26.4% of the participants taken from a random population sample had malaria parasites in their blood. *Plasmodium falciparum* was the predominant species accounting for 86.8%, while *P. malariae* was found in 13.2% of malaria positive subjects (Wenlock 1978). Recent empirical approaches, assessing the distribution limits of *P. falciparum* transmission in sub-Saharan Africa, confirmed that the Ndola Rural district is characterised by stable endemic malaria conditions (Snow *et al.* 1999).

Entomological surveys

At the beginning of the anti-malarial work at the Roan Antelope copper mine, detailed entomological surveys were carried out in the designated control area. Mosquito larvae and adults were collected and identified. Adult mosquitoes were examined for the presence of blood, so that potential malaria vectors could be distinguished from other species of no medical importance. Subsequently, detailed ecological investigations of the larval habitat preferences of the malaria vectors were conducted. This formed the knowledge base for tailoring environmental management strategies, designed to remove or modify these larval habitats. Finally, a system of vector surveillance and monitoring was established, with weekly catches of adult mosquitoes in a number of selected locations within and outside the designated control area.

Environmental management

Multiple interventions, focusing on environmental management and targeting the larval stages of *Anopheles gambiae* and *A. funestus*, were put in place from November 1929

onwards. In the beginning, 300 men were recruited for implementing environmental management strategies, which consisted of (i) vegetation clearance along the Luanshya River and its tributaries; (ii) modification of river boundaries and removal of man-made obstructions; and (iii) draining flooded areas and swamps. After the first year of interventions, the water level of the main river had decreased substantially and the velocity was sufficiently high, so that larval development was interrupted. Subsequently, these interventions were maintained and accompanied by the regular application of oil to open water bodies. Finally, houses were screened and this measure was designed to interrupt adult malaria vectors entering the houses. Surveillance and monitoring of weekly adult mosquito catches and monthly malaria incidence rates served as tools for ongoing programme evaluation. After successful testing of the residual effect of DDT outside the designated control area, DDT became widely applied as an additional intervention strategy from late January 1946 onwards and served mainly as an adulticide.

Mortality, morbidity and malaria incidence

During the first 12 months of copper exploitation at the Roan Antelope mine, detailed records were kept with an appraisal of the causes of death among Europeans. The total number of Europeans who died of malaria between 1932 and 1938 are also available. Annual mortality rates due to diseases, recorded separately for Europeans and Africans, were monitored for the entire 20 years of programme implementation. The spleen rates of children younger than 15 years living on the mine compound were assessed at the beginning of the programme and again 5 years later. These rates were also compared with spleen rates measured among children living outside the control area. Monthly malaria incidence rates among the mine employees were recorded throughout the 20-year implementation period.

Death, malaria attacks, and DALYs averted

The total number of deaths averted due to the implementation of the malaria control programme was estimated by the reduction of the malaria-related mortality rate and the total person life years at risk over the entire intervention period. The total malaria attacks averted were estimated by the reduction of the annual malaria incidence rate multiplied by the total person life years at risk.

DALYs averted were estimated following the methodology developed for the Global Burden of Disease study (Murray & Lopez 1996). We assumed equal malaria mortality and morbidity rates for Africans and Europeans in both genders. We stratified the Roan Antelope mine population into three age groups; (i) 0-4 years, (ii) 5-15 years, and (iii) over 15 years. Population estimates and corresponding age-specific percentages were calculated according to figures provided by Snow *et al.* (1999) for Africans living under stable malaria transmission. The annual population estimates of the mine were extrapolated from the available population data at the beginning of the control programme, and in 1939/40 and 1949/50 (Watson 1953). DALYs were calculated using a life expectancy at birth of 50 years from a West African model life table (United Nations 1982). A discount rate of 3% was used as suggested for standard calculation of DALYs without weighting for age, as its quantitative effect has been demonstrated to be of minor importance (Murray & Lopez 1996). The annual malaria mortality rates before and after programme implementation were calculated by dividing the total number of deaths due to malaria by the corresponding population at risk. The number of clinical attacks and deaths for each age group in a given year were estimated by using age-specific morbidity and mortality rates provided by Snow *et al.* (1999). Since no data were available on neurological sequelae and anaemia, we only used the number of clinical malaria attacks before and after programme intervention to calculate years of healthy life lost due to disability. From the original treatment records, disability duration of 9 days was derived

for a single malaria attack (Rodger 1944, Watson 1953). DALYs averted were then estimated as the difference between those that would have been obtained without programme intervention and those with intervention.

Programme efficacy and cost data

Programme efficacy was evaluated by comparing data obtained at baseline surveys, i.e. before the implementation of control measures, with those obtained during the maintenance phase of the environmental management interventions. We used site-specific historical controls of malaria-related mortality, children's spleen rate, malaria incidence and vector densities and estimated the reduction rates of these indicators over the course of programme implementation.

Detailed cost data for the control programme were obtained from the published programme budget. It included the high capital investment (recruitment of 300 men for vegetation clearance, modification of river boundaries and drainage of swamps) and the annual maintenance costs of these interventions, together with regular oiling of open water bodies. For each intervention, the physical resources and unit prices were specified. All costs were recorded in British pounds and the records suggest that costs were systematically accounted to the same cost position throughout programme implementation (Watson 1953). We converted these total annual costs in US\$ according to British historical statistics, which use an average of daily quotations (Mitchell 1988). Costs were then converted into 1995 US\$, using the purchasing power of the dollar, derived from the US consumer price index (US Census Bureau 1966; 1999).

Cost-effectiveness analysis

The costs per death and malaria attack averted were estimated by using the cumulative costs of the environmental management interventions implemented over the entire 20 years,

and the estimated number of deaths and malaria attacks averted due to control measures. We estimated the costs per DALY averted during the initial 3-5 year start-up period. Our calculations of the costs per DALY averted included the high initial capital costs. Costs per DALY averted were also calculated for 3-year intervals during the maintenance phase of the programme. These time periods are analogous to the short duration of current studies that are the basis of cost-effectiveness analyses (Goodman & Mills 1999).

Results

Roan Antelope copper mine

When copper mining commenced at the Roan Antelope mine in mid 1927, malaria was highly endemic and probably the leading cause of death. It was difficult to attract labour, particularly for night shifts, and workers expressed great fear of dying if they were to stay permanently. The first official labour register recorded a total work force of 1,100 men, but within a few months, only 700 remained at the mines. The others had abandoned the site. According to the traditional beliefs in the local communities, the nearby Luanshya River was the major source of illness. In order to avoid the risk of becoming sick, people had moved away from the vicinity of the river many years before copper mining started (Watson 1953). However, shortly after environmental management strategies for malaria control were put in place, the local people's beliefs about the danger of the river disappeared. New labour forces were attracted with ease, and the company grew rapidly. The designated control area had a size of approximately 32 km² and is depicted in Figure 1.

Initially, housing conditions were improved and houses were screened. Water supply and sanitation facilities were also improved and a hospital with basic diagnostic services was established. In addition to the environmental management strategies that protected everyone, additional control measures for Europeans and some of the African

employees consisted of: (i) quinine administration for prophylaxis and treatment of malaria, and (ii) sleeping under mosquito nets.

Baseline surveys

The total population initially living on the mining compound was estimated at 6,067, more than 80% of whom were Africans. Re-analysis of the first health statistics among 1,067 Europeans in the years 1929/30 confirmed that malaria was hyperendemic; 11 deaths were directly or indirectly related to malaria, therefore accounting for 44% of the total deaths. At this time, the overall annual mortality rate due to diseases was 23.4 per thousand. During the first year of record keeping, the malaria incidence rate among company employees was high and reached 514 per thousand (Table 1). The monthly incidence rates revealed that malaria transmission occurred throughout the year with a distinct peak towards the end of the rainy season in March/April. The baseline spleen rate measured in 232 children younger than 15 years and living on the mining site, was 36% (Table 1).

Entomological baseline surveys revealed that *A. funestus* and *A. gambiae* were the predominant malaria vectors. While *A. funestus* accounted for approximately 80% of adult catches, *A. gambiae* was the most abundant species encountered in larval catches. Detailed ecological studies on the larvae's habitat preferences showed that *A. gambiae* was found in open and unshaded natural or man-made pools close to the Luanshya River and its tributaries, as well as in open water tanks and in native wells loosely overgrown with grass. Reduction and elimination of such habitats was relatively straightforward. In contrast, *A. funestus* larvae preferred the shaded banks of the Luanshya River and its tributaries, and were also found in flooded areas and swamps, which were normally formed and sustained for an extensive period after the rainy season. Management of this aspect of the ecosystem was more challenging.

Reduction in mortality, morbidity and malaria incidence

Mortality rates due to diseases over the entire period of programme implementation, stratified by Europeans and Africans, are shown in Figure 2. There was a tremendous decrease in overall mortality rates, which occurred shortly after environmental management strategies were put in place. The mortality rate among the European community, which was 23.4 per thousand from April 1929 to March 1930, dropped to 13.2 in the year 1930 and was reduced by more than 50% in the subsequent year. Very similar reductions were also observed for the African population. Between 1935 and 1948 the annual mortality rates due to diseases remained relatively stable at a low level of 3-6 per thousand (Table 1). Although individual accounts of the exact causes of each death are not available for the entire 20 years of programme implementation, it is most likely that the overall reduction of mortality is mainly due to the reduction of malaria. This is well illustrated by the fact that the initial malaria-related mortality rate of 10.3 per thousand Europeans, was reduced to 0.5 between 1932 and 1938, as only 5 Europeans died of malaria, with approximately 10,000 years of European lives at risk during this period (Watson 1953) (Table 1).

The reduction in children's spleen rate was equally impressive. The initial spleen rate of 36% before programme implementation dropped to 6%, as measured among 203 children less than 15 years of age, 5 years after the malaria control programme was initiated. A cross-sectional survey in the mid 1930s among European children attending the Government school of Luanshya confirmed that malaria control measures were efficacious. There were only 3 out of 207 children presenting evidence of malaria. At the same time the spleen rate measured among 51 children living outside the control area was 45%.

The baseline annual malaria incidence rate among mine employees of 514 per thousand was halved after the first year of intervention (263 per thousand in 1930) and again 1 year later (151 per thousand in 1931). It remained stable at the lower level for the next two years, following a seasonal pattern with a distinct peak occurring towards the end

of the rainy season in March/April (Figure 3). There were a total of 1,619 malaria cases among Europeans between the end of 1937 and the end of 1942 (Rodger 1994). In this period, the European population was estimated at 2,300-2,500. Thus, there were between 11,500 and 12,500 person years at risk of malaria attacks, accounting for an annual malaria incidence rate of 130-141 (mean 135). Another sharp decline in the annual malaria incidence rate occurred shortly after the control area was expanded and DDT was systematically applied in the mid 1940s (Table 1).

Death, malaria attacks, and DALYs averted

Based on the annual population estimates, there were a total of 425,342 person life years at risk of malaria during the entire 20 years of programme implementation. The control programme reduced the annual malaria-related mortality rate from 10.3 to 0.5 per thousand and the incidence rate dropped from 514 to 135 per thousand. Therefore, the control programme averted an estimated 4,173 deaths and 161,205 malaria attacks (Table 2).

During the initial 3-5 year start-up period, the implementation of the control programme averted an estimated 2,439-3,172 DALYs. Since the population grew steadily over the course of programme implementation, and malaria-related mortality and incidence rates remained stable, the number of DALYs averted increased in proportion to the total population estimates. For example, the number of DALYs averted during the 3 year period of 1934-36 was 3,618, and increased to 10,976 for the period of 1947-49 (Table 2).

Cost of environmental management

Table 3 shows the capital investment and the annual maintenance costs of the environmental management interventions for the entire 20 year implementation period in British pounds and corresponding 1995 US\$. The cumulative costs were almost US\$ 3.6 millions. There was a high initial capital investment of more than US\$ 1 million, or US\$

167 per person living at the Roan Antelope copper mine. Before widespread use of DDT in 1946, the annual maintenance costs ranged between US\$ 103,666 and 190,279, or US\$ 5.2-23.4 per person.

The estimated costs per death averted over the entire programme implementation were US\$ 858. Averting a malaria attack was estimated at a cost of US\$ 22.20 (Table 2). During the first 3-5 years of programme implementation, the costs per DALY averted were relatively high, ranging from US\$ 524 to 591, largely due to the high initial capital investment. Costs per DALY averted decreased substantially over the course of programme implementation. They were US\$ 92 for the 3-year maintenance period of 1934-36 and dropped to US\$ 22 for the last 3-year increment of 1947-49.

Discussion

Our detailed re-analysis of a complex malaria control programme, built around environmental management and launched more than 70 years ago and sustained for two decades at the Roan Antelope mine of the copper belt in Zambia, revealed that the programme was highly successful. One year after interventions were put in place, the overall mortality and malaria incidence rates were reduced by approximately 50%. Malaria-related mortality and morbidity, as well as monthly malaria incidence rates continued to drop substantially, and they were reduced by 70-95% within 3-5 years after the onset of interventions. Reductions of this order of magnitude are striking, particularly for a malaria control programme being implemented in a highly endemic area of sub-Saharan Africa, where the most efficient malaria vectors occur (Rodger 1994; Watson 1953; Wenlock 1978). Calculation of reductions in malaria-related mortality, morbidity and incidence was obtained by comparing baseline rates before interventions with those observed over the course of programme implementation – an assessment based on historical controls.

The use of historical controls in this setting is justified on several grounds. First, the entire mining community is the unit of analysis, and the details of the environmental

management components were tuned to the local ecology. Second, although data that are comparable, and largely concurrent, to that assembled for the Roan Antelope mine are available for three other mining communities in the Zambian copper belt (Watson 1953), the ecological variation across communities is sufficiently great that the notion of comparison, or even control communities makes no sense. This stands in stark contrast to the randomised controlled trials, assessing the efficacy of a single intervention (e.g. insecticide treated bednets or novel antimalarial drugs or combination therapy), where the notion of concurrent comparison groups can be justified (Choi *et al.* 1995; Goodman & Mills 1999; Goodman *et al.* 1999). In effect, by using a community in its pre-intervention condition as a control, we are comparing the consequences of an intervention with what would be the natural history of transmission in the unperturbed state of the same ecosystem. Analogous evaluation strategies for complex programmes arise in a myriad of contexts – e.g. rehabilitation programmes for chronic heroin addicts or alcoholics (Dole *et al.* 1982; Singer 1986).

Emphasis of the malaria control programme evaluated here was on environmental management, and an array of interventions was applied simultaneously. They were targeted at source reduction of larval habitats of the predominant malaria vectors. During the last 5 years of the programme, DDT also came into play. Compared with other, currently more widely used malaria control measures, the programme was unique in many ways. First, it was carried out for an extensive period of time; namely, 20 years. Second, monthly malaria incidence rates and weekly adult malaria vector densities were used as ongoing system of surveillance and monitoring. Although sharp declines in malaria-related outcome measures were observed shortly after the programme was initiated, it was only after 3-5 years that the package exhibited a high level of performance. Outcome indicators remained stable thereafter, at much lower levels than in the pre-programme years. Third, the programme was well organized and rigorously implemented by the mining authorities, using a flexible

approach, and a system of mobilization, motivation and supervision of the local communities carrying out the control measures. Fourth, malaria control *per se* was not an altruistic goal in the context of health promotion for a community. It was simply a necessity to attract and sustain labour for the exploitation of a natural resource. It was a sound investment that led to prosperity. Fifth, there was sustained in-migration, since the total population grew at an annual rate of approximately 10%, which is unusual for sub-Saharan Africa and elsewhere, and can only be explained by an efficient malaria control programme that had been put in place. It is likely that the Roan Antelope mine would have suffered a ruinous outcome if it failed to control malaria, analogous to what the Dutch East India Company experienced in the 18th century (van der Brug 1997).

It is interesting to compare the efficacy and cost-effectiveness of the integrated control programme reviewed here with other malaria interventions that are currently used. The reductions in malaria-related outcome measures were considerably higher than those observed in other malaria control programmes, probably due to the nature of the integrated control approach, implementing a multiplicity of interventions simultaneously. In this connection, it is crucial that the performance of each intervention in the package of interventions contributes to the overall success of the programme. To achieve this overarching goal, the design and the evaluation methods of the control programme need sufficient flexibility to retarget and redesign existing interventions to ultimately obtain the desired outcome. Interestingly, a promising experimental design stems from industrial management in the 1960s, known as ‘evolutionary operation’ (EVOP) for process improvement (Box & Draper 1969). The basic idea is to start with a given operation mode, based on the best available knowledge. It is then followed by an evolutionary development scheme, applying a carefully planned set of variations to the components of the process in consecutive cycles. The malaria control programme reviewed here is an excellent example of this approach, and it is surprising, how creative the design was at the time of

implementation. Malaria incidence rates and adult mosquito densities were monitored from the onset of implementation and facilitated the adaptive tuning of the interventions, so that the package displayed a high level of performance. Although the concept of EVOP has been successfully applied in many fields – e.g. selections among strains of crop plants or screening of chemical compounds for therapeutic uses (Finney 1982) – its application to tropical disease control has been neglected so far.

Our estimated costs of US\$ 858 per death averted was between the cost-range of US\$ 219 and 2,958 estimated for insecticide treated bednets in The Gambia, Ghana, Kenya and South Africa (Goodman & Mills 1999; Goodman et al. 2001). Our estimated cost of US\$ 22.20 per malaria attack averted was only slightly higher than the one estimated for insecticide treated nets in The Gambia, which was US\$ 15.75 (Graves 1998). The initial costs per DALY averted were relatively high, but were followed by an increasing cost-effectiveness in the maintenance phase, confirming previous studies that applied environmental management strategies (Bos & Mills 1987). Importantly, no long-term comparison of cost-effectiveness analyses can be made with the currently proposed malaria control interventions, as their long-term sustainability has yet to be demonstrated.

Interestingly, the discovery and widespread application of DDT and other powerful insecticides starting in the mid 1940s, was followed by a conceptual change in malaria control, as it was believed that the disease could be eradicated by the use of insecticides alone (Harrison 1978). Consequently, environmental management was almost forgotten worldwide until the 1980s (Ault 1994). This is very unfortunate, since environmental management has a long-term track record of successful malaria control in a diversity of ecological, epidemiological and socio-economic settings. Before Watson started his work at copper mines of Zambia, he was successfully engaged in malaria control on peninsular Malaysia, initially in urban and semi-urban areas along the coast, and then in rural rubber and tea plantations (Watson 1921; Field & Reid 1956). In the 1910/20s, malaria was also

controlled successfully in the Indonesian archipelago (Swellengrebel 1950; Takken *et al.* 1990) and two decades later, vegetation clearance proved effective to control malaria in Borneo (Mc Arthur 1947; 1954). However, understanding the epidemiology of malaria in the tropical forests of Borneo is mandatory, as large-scale deforestation is certainly not an appropriate approach for disease control (Bradley 1994). Finally, several water management strategies have been successfully applied in south-east Asia to avoid or reduce breeding of malaria vectors in riceland habitats, including intermittent irrigation, periodic flushing of ricefields and shifting planting schedules outside the optimal mosquito breeding periods (Worth 1937; Russell *et al.* 1942; Lacey & Lacey 1990). However, water management, particularly the drainage of malaria vector-producing swamps, is conflicting with the interest of preserving the world's wetlands and needs to be taken into account by control programmes (Grillet 2000).

Renewed interest in environmental management has been observed over the last 10-15 years, partly as a result of emergence and rapid spread of vector resistance to insecticides and more rigorous toxicologic testing (Lacey & Lacey 1990; Ault 1994). A recent study in Sri Lanka demonstrated that the costs of periodic river flushing to eliminate mosquito breeding habitats compared favourably with impregnated bednets (Konradsen *et al.* 1999). Concluding, environmental management has already demonstrated long-term sustainability, has no or fewer adverse ecological effects than currently used malaria control strategies, and can potentially make better use of local resources and knowledge, hence, contributing to local self-reliance (Bos & Mills 1987; Singer 1989). Urban and periurban environments, which are rapidly growing in all malarious countries, are of particular interest, as the implementation of sound environmental strategies – integrated with concurrent malaria control tools – could form an intervention package to substantially reduce the current burden of the disease (Trape 1987; Knudsen & Slooff 1992).

Finally, one must ask what will replace the colonial infrastructure that facilitated the successful programmes mentioned above. We believe that a well-supported health service infrastructure expanded beyond curative medicine, including personnel with training and expertise in hydrology and entomology would be a response to meeting the tremendous challenge of halving the current burden of malaria within 10 years (Shiff 2000; Utzinger *et al.* 2001). In view of this conclusion, launching of a systemwide initiative on malaria and agriculture has to be applauded (SIMA; see web page: www.iwmi.org/sima.htm). Its collaborative organization should be encouraged, as it promotes an excellent platform for integrative approaches for sustainable malaria control.

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Table 1

Characteristics of the mine population, disease- and malaria-related mortality, children's spleen rate and malaria incidence rate before the implementation of malaria control measures (1929/30), 10 years later (1939/40) and at the end of the programme (1949/50).

	Year		
	1929/30	1939/40	1949/50
Population (%)			
Africans	5,000	20,610	36,481
Europeans	1,067	1,976	4,025
Overall mortality due to diseases (per thousand per annum)			
Africans	32.3	3.5 ^a	3.7
Europeans	23.4	3.9 ^a	4.6
Malaria-related mortality (per thousand per annum)			
Europeans	10.3	0.5 ^b	--
Spleen rate in children < 15 years (%)	36	6 ^c	
Malaria incidence (per thousand per annum)	514	135 ^d	16 ^e

^a Average for years 1938, 1939, 1940 and 1941.

^b Between 1932 and 1938, there were approximately 10,000 European life years at risk of malaria, with 5 deaths occurring due to malaria.

^c Assessed in April 1935, among 203 children born on Roan Antelope mine (spleen rate among children living in a nearby village: 45%).

^d Between November 1937 and October 1942 a total of 1,619 malaria attacks were recorded among Europeans, with an estimated population of 2,300-2,500 (Source: Rodger 1944).

^e Malaria incidence dropped substantially after the extension of the control area and regular DDT application from 1946 onwards

Table 2

Estimated deaths, malaria attacks and DALYs averted due to malaria control measures and corresponding costs

	Estimated cases averted	Cumulative costs (1995 US\$)	Cost/case averted (1995 US\$)
Deaths			
Entire period: 1930-1949	4,173	3,578,611	857.56
Malaria attacks			
Entire period: 1930-1949	161,205	3,578,611	22.20
DALYs			
3 year start-up: 1930-1933	2,439	1,442,767	591.49
5 year start-up: 1930-1935	3,172	1,663,424	524.36
Maintenance: 1934-1936	3,618	331,240	91.56
Maintenance: 1937-1939	5,366	417,121	77.73
Maintenance: 1940-1942	6,969	419,828	60.24
Maintenance: 1943-1946	9,034	724,873	80.24
Maintenance: 1947-1949	10,976	242,782	22.12

Table 3

Total monetary investment for environmental management in the Roan Antelope copper mine for the entire programme implementation between 1930 and 1949. Annual costs in British pounds (£) were converted into 1995 US\$. Cumulative costs and annual costs per person were also calculated based on population estimates.

Year	Total annual costs (in £)	Exchange rate (£ to US\$)	Purchasing power (1995 US\$ = 1.000)	Annual costs (1995 US\$)	Cumulative costs (1995 US\$)	Population estimates	Annual costs per person
1930	25000.00	4.862	8.335	1,013,119	1,013,119	6067	167.0
1931	3251.00	4.277	9.864	137,154	1,150,273	6919	19.8
1932	4749.00	3.504	11.103	184,759	1,335,032	7891	23.4
1933	2338.98	4.218	10.920	107,735	1,442,767	9000	12.0
1934	2142.81	5.041	9.597	103,666	1,546,433	10264	10.1
1935	2654.18	4.903	8.990	116,991	1,663,424	11706	10.0
1936	2498.10	4.971	8.905	110,583	1,774,007	13351	8.3
1937	2727.97	4.944	8.335	112,415	1,886,422	15226	7.4
1938	3405.85	4.890	9.148	152,356	2,038,778	17365	8.8
1939	3660.83	4.460	9.331	152,350	2,191,128	19804	7.7
1940	3937.43	4.030	9.148	145,159	2,336,287	22586	6.4
1941	4225.41	4.030	8.232	140,178	2,476,465	24100	5.8
1942	4582.23	4.030	7.283	134,491	2,610,956	25717	5.2
1943	6213.00	4.030	6.979	174,743	2,785,699	27441	6.4
1944	6829.00	4.030	6.914	190,279	2,975,978	29281	6.5
1945	6805.00	4.030	6.792	186,265	3,162,243	31244	6.0
1946	7249.00	4.030	5.942	173,586	3,335,829	33339	5.2
1947	4586.00	4.030	4.848	89,599	3,425,428	35575	2.5
1948	5235.85	3.680	4.478	86,282	3,511,710	37960	2.3
1949	5070.68	2.800	4.712	66,901	3,578,611	40506	1.7

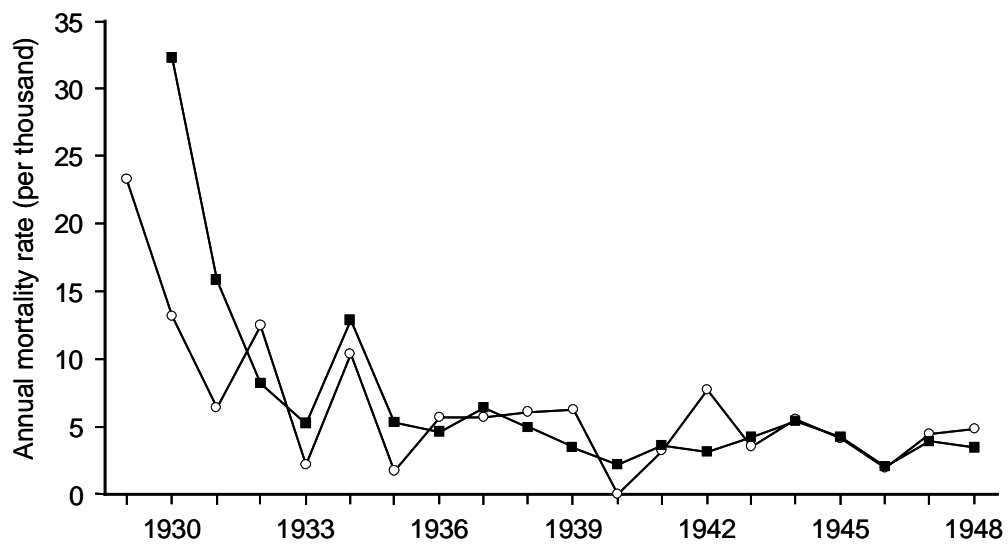


Figure 2

Annual mortality rates due to diseases among Europeans (○) and Africans (■) living and working at the Roan Antelope copper mine (Source: Watson 1953)

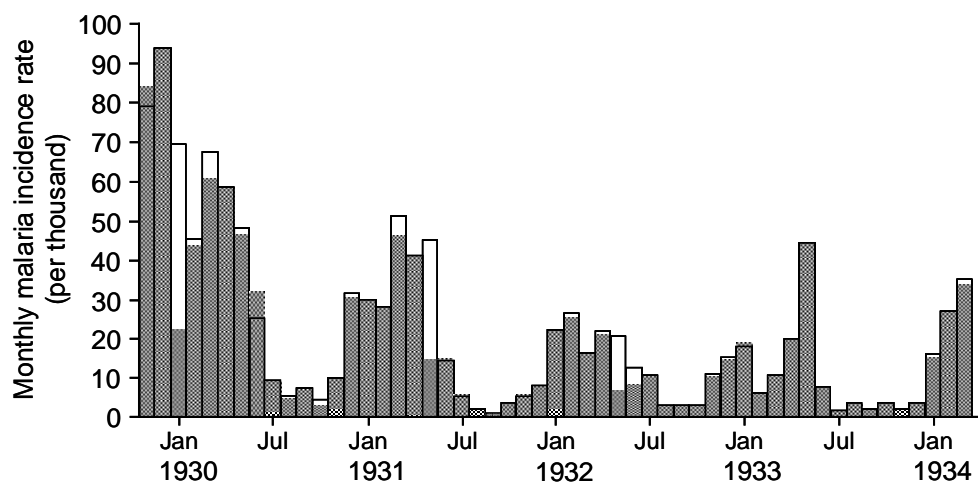


Figure 3

Monthly malaria incidence rates among copper mine employees between November 1929 and March 1934 (Source: Watson 1953).