Economic inequality caused by feedbacks between poverty and the dynamics of a rare tropical disease: the case of Buruli ulcer in sub-Saharan Africa

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Neglected tropical diseases (NTDs) have received increasing attention in recent years by the global health community, as they cumulatively constitute substantial burdens of disease as well as barriers for economic development. A number of common tropical diseases such as malaria, hookworm or schistosomiasis have well-documented economic impacts. However, much less is known about the population-level impacts of diseases that are rare but associated with high disability burden, which represent a great number of tropical diseases. Using an individual-based model of Buruli ulcer (BU), we demonstrate that, through feedbacks between health and economic status, such NTDs can have a significant impact on the economic structure of human populations even at low incidence levels. While average wealth is only marginally affected by BU, the economic conditions of certain subpopulations are impacted sufficiently to create changes in measurable population-level inequality. A reduction of the disability burden caused by BU can thus maximize the economic growth of the poorest subpopulations and reduce significantly the economic inequalities introduced by the disease in endemic regions.

1. Introduction

Long-term economic growth and advances in medicine and technology have contributed to a significant reduction in the burden of human infectious diseases around the world [1]. However, more than 1 billion people, most of them in tropical and subtropical countries, continue to suffer a disproportionate burden of disease and poverty [2,3]. Although the global distribution of communicable diseases can be partly explained by a gradient in climatic and biological factors [4,5], there is a growing focus on potential reinforcing feedback mechanisms between ecology, disease and economics, for explaining the distribution of both poverty and disease [6]. Households and individuals need economic resources to reduce their exposure to infectious diseases and to access quality healthcare [7,8]. Additionally, infectious diseases have short- and long-term impacts on economic growth through reduction of labour productivity, education and investments in order to accumulate economic capital [9–11]. Increasing recognition of the feedbacks between poverty and disease has led to integrative studies on disease-driven poverty traps [12–14].
Feedback mechanisms between poverty and disease ecology are especially important for the study of neglected tropical diseases (NTDs): they are closely associated with particular geographical and environmental conditions in the tropics; they thrive under conditions of poverty, poor sanitation and malnutrition; and they constitute a major barrier for the economic development of the populations affected [15,16]. In sub-Saharan Africa alone, the four most prevalent NTDs are estimated to cause more than 700 million infections per year [3]. But despite their many similarities, NTDs are a very heterogeneous group of diseases with respect to their prevalence, aetiological agents and health consequences. For instance, the four least prevalent NTDs—leprosy, leishmaniasis, dracunculiasis and Buruli ulcer (BU)—are responsible for hardly more than 50,000 infections annually [3], but this group is composed of highly stigmatizing and devastating chronic infections that are responsible for a great burden of disability and important economic impacts on affected households [3]. Although the population-level disability and economic burdens of these diseases is expected to be insignificant, they can constitute important barriers for the economic development and health of specific groups, especially the poorest subpopulations.

An illustrative example is BU, a necrotizing skin disease that caused less than 3000 cases worldwide in 2013, but with more than 90% of the global burden concentrated in sub-Saharan Africa [17]. BU arises in populations living near large bodies of stagnant and slow-flowing waters, where ecological conditions are suitable for *Mycobacterium ulcerans*, the agent responsible for the disease [18–20]. Despite its low incidence, the focal distribution of the disease makes it particularly devastating in endemic regions, where it contributes to significant disability and causes impoverishment of affected households [21,22]. Most of the morbidity is due to important delays in seeking treatment at the health services, which enables disease progression and leads to the formation of large ulcers. Treatment of these severe stages requires, in addition to the standard eight-week antibiotic therapy [23], surgical procedures involving debridement, skin grafts and much longer hospital stays [24–26]. Contraction of joint movement and functional limitations for life are a common outcome of large ulcers [26,27], which is associated with loss of employment and school abandon [28]. Despite its devastating consequences, measuring the economic impact of such a rare disease in endemic populations is challenging.

There are two common traditions for modelling the economic impacts of disease [13]. Population-level (e.g. ‘macro’) methods focus on aggregated indicators, such as disease prevalence, life-expectancy or per capita income. There are a number of macro-oriented studies that have found substantial population-level economic impacts of disease [6,10,29]. A disadvantage of such approaches is that aggregated indicators necessarily ignore heterogeneity within populations, and they cannot be substantially influenced by rare diseases. By contrast, ‘micro-oriented’ approaches have focused on individual-level characteristics and behaviours, and thus measure either costs of illness or effects of disease on labour productivity or income [11,30,31]. The emphasis here tends to be on diseases with large impacts on the population, allowing for the economic burden to be extrapolated from individual-level effects. Not surprisingly, the rarest diseases on the basis of their insignificant population-level impacts have drawn much less or no attention in the literature of economic burden of disease, which contributes to their neglect in the global health agenda [16]. This paper aims to fill the gap and contribute to the economic analysis of rare-but-devastating diseases through specific models that account for feedbacks between economics and disease from individuals to the populations that they comprise.

Here, we use an individual-based model of BU, which accounts for realistic variability and heterogeneity in individual epidemiological parameters, to analyse the impact of this rare disease on the economic structure of human populations. More specifically, tracking information about each individual allows us to address issues of economic and health inequalities and to focus on worst-off groups within the populations. To construct the model, we first identify the key feedbacks between wealth and Buruli ulcer, which rely mostly on disparities in vulnerability and access to treatment as functions of economic resources. Then, multiple possible scenarios are simulated to study the impact of BU for the whole population and different subpopulations under a gradient of environmental risk. Finally, we test the potential health and economic impact of interventions that mitigate the disability burden of the disease.

2. Material and methods

Our modelling framework is based on coupled systems of human disease and economic growth, and stems from a recent body of theory on feedbacks between poverty and disease [12–14]. We adopt an individual-based approach to better capture within-population heterogeneities of BU disease, notably issues such as incubation period, individual delay in seeking medical treatment or treatment duration. A full description of the parameters and their associated values along with the complete algorithm and rationale for the coupled individual-based model is provided in the electronic supplementary material, S1.

(a) Epidemiological model

Our disease model is derived from the susceptible-exposed-infected-recovered (SEIR) framework [32] widely used to characterize epidemiological dynamics, and it is adapted to better capture the specificities of BU in rural populations (figure 1). The model takes into consideration susceptible individuals (S) that can become exposed to BU (E) depending on the interplay between an environmental risk and socio-economic susceptibility (β). Exposed individuals develop symptoms and become infected (I) after a certain incubation period (γ). A proportion of infected does not seek treatment at the health services (I<sub>es</sub>) and the rest (I<sub>s</sub>) seek treatment (T) after a certain delay (ε), which is dependent on socio-economic resources. Finally, non-seekers and individuals under treatment either fully recover (R) or recover with permanent disabilities (D), with probabilities depending on disease progression in each compartment. Importantly, untreated individuals have a smaller probability of full recovery (R) than those treated. We assume that individuals gain permanent immunity to BU after infection and, therefore, neither recovered nor disabled individuals can get re-infected. For the sake of simplicity, we assume that death and birth rates are equal so that the population is stationary [32].

To account for socio-economic differences in exposure, vulnerability and access to treatment for BU, we model the individual transmission rate of BU β<sub>i</sub>, the probability of seeking treatment σ<sub>i</sub> and the time to seek treatment ρ<sub>E</sub>, as linear functions of individual-level physical capital k<sub>i</sub>, which is a general proxy for individual wealth (see the electronic supplementary material, S1). Importantly, the model is stochastic and individual-based, so there is considerable heterogeneity in parameter values and
outcomes, as with real-world rare events. Therefore, theoretical values for all the epidemiological parameters are assigned to each individual (\(t_i\), \(p_{TI}\), etc.) but the final value and the subsequent links depend on the real value of the parameter for each individual (\(t_{BU}\), \(p_{BU}\), etc.), which are subject to the stochastic process.

(b) Economic growth model

The economic dynamics are based on the simplest standard models of economic growth [13,14,33]. Individual income \(y_i\) is based on a simple Cobb–Douglas production function and is determined by the level of technology \(A\) and a combination of physical capital \(k\) and human capital \(h\), which exhibits diminishing returns to investment (0 < \(a_1 + a_2 < 1\)):

\[
y_i(t) = A y_i(t)^{a_1} k_i(t)^{a_2}.
\]  

(2.1)

In the economics literature, human capital typically refers to education and training, but it can also refer to health status as we define it here. In rural areas of sub-Saharan Africa where BU is endemic, individual income is mainly generated through physical labour and thus physical health as human capital, \(h\), is especially important. Equation (2.2) represents \(h\) as a function of health status given by an initial human capital for healthy individuals, \(h_0\), that is reduced in BU patients by \(w_i\):

\[
h_i(t) = h_0(1 - w_i).
\]  

(2.2)

As BU is initially painless and individuals can carry out normal lives until the disease is advanced, we assume for simplicity that infected individuals do not experience a reduction in human capital. For individuals under medical treatment, \(w_i = w_T\) and it is associated with hospitalization or daily visits to the healthcare centre that are responsible for the great indirect costs of the disease [21,22,34]. We attribute disabled individuals a reduced human capital, \(w_i = w_D\), to account for their reduced ability to work and the impact of functional limitations on school abandon and job loss [27,28], which is reinforced by the strong social stigma and mystical beliefs associated with the disease [35,36]. Finally, physical capital, \(k\), represents individual’s wealth, and its accumulation over time results from the investment of a proportion of current income at rate \(r_D\) while it depreciates at rate \(d_k\):

\[
k_{i,t+1} = r_D(y_i(t) - x) + (1 - d_k)k_{i,t}.
\]  

(2.3)

Direct non-medical costs associated with treatment (\(x\)) such as transportation to the health centre and feeding costs are deducted from income for individuals undergoing treatment [21,22,34]. Importantly, when the individuals in the model are renewed (one individual dies and is replaced by a new born), the offspring ‘inherits’ the physical capital of the individual they replace (their ‘parent’).

(c) Strategies for prevention of disability

We evaluate the potential impact that disease control strategies aimed at preventing disability in BU cases could have on health and economic outcomes of the population in the long term. We consider a scenario where improved management of BU cases (tertiary prevention) leads to a reduction of 50% in the individual probability of functional limitations, \(z_i\), once the patient is being treated at the health services [37]. This is mostly achievable through high-quality treatment complemented with intensive rehabilitation and physiotherapy [37,38]. We also estimate additional improvements where efforts are aimed at reducing the time to seek treatment (\(t_{BU,Max} = 30\) days) to limit disease progression (secondary prevention) prior to consultation at the health services. This reduction can be achieved in many different ways, such as awareness and education campaigns, active search of BU cases or decentralization of treatment [24,25].

(d) Choice of parameter values

A thorough literature review of the ecology, epidemiology and socio-economics of BU was performed prior to model development in order to identify all relevant parameters in the coupled system and to select appropriate parameter values (table 1). A fully detailed explanation of the choice of each parameter value along with the sources can be found in the electronic supplementary material, SI. In summary, demographic parameters such as population size and demographic rate were drawn to represent the demographic situation in many BU endemic regions in Central and West Africa. Epidemiological parameters such as incubation period or time to heal with treatment were selected from cross-sectional and longitudinal studies of BU cases in endemic regions. The economic system relies on classic models of economic growth, and we draw the values of many of the economic parameters from this literature [33]. We also used studies on BU socio-economic costs to estimate parameters such as treatment costs and human capital reduction.

(e) Model analysis

We run the simulations until equilibrium is reached and characterize important economic and epidemiological outcomes in the population, using the mean value of the last 10 years to obtain robust estimates. We explore model behaviour with a gradient of \(t_{BU,Max}\) to analyse all situations that could fit with different epidemiological conditions observed, from low endemic regions to high endemic regions.
areas located in high-risk clusters, where incidence levels reported for specific populations can be significantly higher. To evaluate the economic impact of strategies for prevention of disability mentioned earlier, variations in economic outcomes were estimated by comparing scenarios with and without interventions, under similar values of $b_{\text{Max}}$. We address the potential uncertainty surrounding the parameter values in our model by accounting for simultaneous variations in multiple epidemiological and economic parameters using the Latin-Hypercube sampling approach [39]. For this, we run 1000 simulations for each $b_{\text{Max}}$ with random and simultaneous variations of up to $\pm 25\%$ in parameter values. Finally, we quantify the impact of variations in parameter values on model outcomes through multivariate linear models under a gradient of environmental risks (see the electronic supplementary material, S2). All simulations are done in C++ and the model analysis is done in MATLAB, v. 2014b and R statistical software, v. 3.1.2.

### 3. Results

#### (a) Population-level impact of Buruli ulcer

By simultaneously accounting for feedbacks between poverty and disease at the individual level, we show in figure 2 how the disease and economic dynamics interact within the population. An increase in the background environmental risk, represented by $b_{\text{Max}}$, results in a higher number of BU cases, with a limit at an incidence of approximately 24 cases $1000\text{py}^{-1}$ (figure 2a), which represents the influx of individual renewal by demography. This increase in incidence has an impact on the proportion of disabled in the population. Because individuals experience disabilities for life, the number of disabled in the population is considerably higher than the annual incidence of newly infected individuals (figure 2b). Figure 2c illustrates the

<table>
<thead>
<tr>
<th>symbol</th>
<th>variable</th>
<th>value or range</th>
<th>links</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>total population</td>
<td>50 000</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>demographic rate</td>
<td>24.5 per 1000py</td>
<td></td>
</tr>
<tr>
<td>$\beta_{\text{Max}}$</td>
<td>environmental risk</td>
<td>$10^{-5} \text{ to } 10^{-1}$</td>
<td>dependent on $K$ (see the electronic supplementary material, figure S1)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>individual transmission rate</td>
<td>$(0.2 \text{ – } 1) \beta_{\text{Max}}$</td>
<td>dependent on $K$ (see the electronic supplementary material, figure S1)</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>incubation period (days)</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>probability of seeking treatment</td>
<td>0.8 – 1</td>
<td>dependent on $K$ (see the electronic supplementary material, figure S1)</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>time to seek treatment (days)</td>
<td>7 – 365</td>
<td>dependent on $K$ (see the electronic supplementary material, figure S1)</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>time to heal with treatment (days)</td>
<td>60 – 365</td>
<td>dependent on $\tau_1$ (see the electronic supplementary material, figure S1)</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>probability of disability with treatment</td>
<td>0.05 – 0.5</td>
<td>dependent on $\tau_1$ (see the electronic supplementary material, figure S1)</td>
</tr>
<tr>
<td>$\tau_1$</td>
<td>time to heal without treatment (days)</td>
<td>60 – 365</td>
<td></td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>probability of disability without treatment</td>
<td>0.5 – 1</td>
<td>dependent on $\tau_1$ (see the electronic supplementary material, figure S1)</td>
</tr>
</tbody>
</table>

| economics |
|----------|------------------|------------------|---|
| $k_0$ | average initial physical capital or wealth ($) | 1750 | |
| $\alpha_1$ | returns to investment for $h$ | 0.5 | |
| $\alpha_2$ | returns to investment for $k$ | 0.33 | |
| $h_0$ | initial human capital | 1 | |
| $\lambda$ | treatment cost ($) | 1 | |
| $W_T$ | human capital reduction (under treatment) | 0.8 | |
| $W_D$ | human capital reduction (disabled) | 0.5 | |
| $\rho$ | level of technology | 0.21 | |
| $\rho_1$ | physical capital savings rate | 0.3 | |
| $\delta_2$ | physical capital depreciation rate | 0.1 | |

The 'T' subscript denotes a theoretical value. The real value ('R' subscript) for each individual depends on a stochastic process and is therefore subject to variability.

The different parameter values and links are explained in detail in the electronic supplementary material, S1. Simultaneous variations of up to $\pm 25\%$ around these parameter values are considered through Latin-Hypercube sampling.
The obvious interconnection between poverty and disease is gaining attention in recent years by international organizations and funding agencies, as they are both a major cause of morbidity and a barrier for economic development of the poor [15,16]. Neglected tropical diseases (NTDs) have received increasing attention in recent years by international organizations and funding agencies, as they are both a major cause of morbidity and a barrier for economic development of the poor [15,16].

(c) Impact of strategies for prevention of disability
We show in figure 4 how public health strategies that improve management of clinical cases with the aim of reducing disabilities can improve economic equity in populations suffering from BU. Although the impact of these strategies on the average wealth of the population is negligible, their impact is significantly higher in the worse-off groups. In our simulations, improved management increases the wealth of the poorest subgroups by about 10% on average (solid lines), compared with a situation where there is no such strategy. Furthermore, the differential impact they have on best- and worst-off groups contributes to the depolarization of wealth and disabilities in the population, which results in a great reduction of wealth inequalities of approximately 20% on average, and up to 50% in the best scenarios (dashed lines). Additional improvements can be achieved in both the wealth of worse-off groups and wealth inequalities when combining these strategies with those aiming at reducing the time to seek treatment and hence disease progression in BU patients (see the electronic supplementary material, S4).
diseases and economics, showing that populations with high prevalence of diseases and low economic resources can theoretically be trapped in a ‘vicious cycle’ of long-term poverty and high disease burdens [12–14]. While such models may apply to diseases like malaria, hookworm or schistosomiasis, they do not provide insights on the impact of diseases with low prevalence but great disability burden. Our results for BU show how even low incidence levels of

**Figure 3.** Impact of Buruli ulcer on economic inequalities. (a) Impact of Buruli ulcer incidence on the mean wealth of different population subgroups. (b) Distribution of wealth at equilibrium in populations under different environmental risks. (c) Link between incidence and wealth inequality at equilibrium for a gradient in environmental risk. The colour changes with the environmental risk, from dark blue at the lowest risk towards dark red at the highest risk. Each dot represents one simulation with parameter values selected through Latin Hypercube sampling, and the larger circles represent the mean value of all 1000 simulations for each $\beta_{\text{Max}}$.

**Figure 4.** Economic impact of strategies aiming at prevention of disabilities. (a–c) Impact on the wealth of different subgroups of the population. The solid lines represent the average wealth increase in subgroups and the dashed lines show minimum and maximum increases at different incidence levels. In all cases, the wealth in the population at equilibrium for each simulation in the model with intervention is compared with the wealth at equilibrium for a simulation with the same parameter values in the model without intervention. (d) Reduction of wealth inequality for a gradient in environmental risk. The colour changes with the environmental risk, from dark blue at the lowest risk towards dark red at the highest risk. Each dot represents the decrease in Theil Index for one pair of simulations with parameter values selected through Latin Hypercube sampling, and the larger circles represent the mean decrease in all 1000 simulations for each $\beta_{\text{Max}}$. 
disease can have a significant impact on the population through feedbacks that drive inequalities. A high environmental risk can lead to long-term clusters of disease and poverty in subgroups of the population and this effect is stronger when coupled to poor economic conditions.

Despite research progress in areas like ecology, epidemiology and social sciences, many aspects surrounding BU epidemiology and socio-economic feedbacks are still poorly understood and can be highly context specific. For this reason, the aim of this study was to present a general modelling framework for understanding the feedbacks between the environment, BU and poverty that can be tailored to local populations or adapted to other rare tropical diseases. We rely on conservative assumptions for many of the parameters (electronic supplementary material, S1c), especially for those with important impacts on model outcomes in the sensitivity analysis (electronic supplementary material, S2). We take parameter uncertainty into account in the presentation of model results by including multiple simulations with random variations of up to ±25% in our parameter estimates, in order to show the range of potential economic outcomes. This necessarily implies that economic estimates in this study are subject to considerable uncertainty, especially at higher incidence levels. An important assumption of this study is that individuals get permanent immunity after recovery from BU infection. In the absence of immunity, the potential outcomes of the disease could be even more devastating (electronic supplementary material, S3).

The scarcity of data on the relationship between poverty and key epidemiological parameters, such as disease risk or health seeking behaviours in tropical regions, makes it challenging to realistically model socio-economic feedbacks for NTDs. As a conservative choice, we consider linear functional relationships between epidemiological parameters and socio-economic status. However, the gap between wealthier and poorer populations may be even greater. For instance, the probability of seeking treatment can be very low in poor populations until a certain economic threshold is attained, or it may exhibit diminishing returns after that and be invariably high for wealthier subgroups. The use of less conservative, nonlinear functional forms (logarithmic, exponential or sigmoidal) may therefore be more appropriate in some cases, which would result in more inherent nonlinearities in the system with stronger feedbacks. This would potentially increase not only the gap between wealthier and poorer populations as a result of the disease, but also the economic benefits of interventions. Future studies could greatly benefit from a better understanding of the socio-economic determinants of NTDs, through systematic field data collection.

Owing to their tendency to cause significant life-long disability, the population-level effect of BU and other rare tropical diseases is high even at their characteristic low incidences. As opposed to malaria or hookworm, which have a small but cumulative effect on a great proportion of the population, BU is devastating for the very few who are affected. Our results demonstrate that at these low incidence levels, the inequalities created in the population as a result of highly debilitating diseases can be significant. A sustained long-term annual incidence of 5 to 20 cases 1000py−1 can leave a significant proportion of the population with permanent disabilities. In the context of low-resource settings, where no subsidies exist for disabled individuals and most economic activities rely heavily on physical labour, such a disability burden results in a major economic burden. As a result, Buruli ulcer can create a polarization in the distribution of wealth in the population, dragging part of it into a spiral of poverty and disease while the aggregate economy is generally not affected. Although BU incidence in affected regions within endemic countries rarely exceeds 1 case 1000py−1 [18,40–42], the highly focal distribution of the disease results in clusters within endemic regions, with some populations having up to 5–20 cases 1000py−1 [18,20,41,43,44]. Therefore, while the economic outcomes shown in this study might not be appropriate for reported BU incidence levels at national or regional scales, they can reflect the situation of many high-risk populations within endemic regions (figure 5), and can also correspond to incidence levels observed for other rare tropical diseases [3].

In our analysis, the background environmental risk was the main determinant of the long-term clusters of poverty and disease in our model. Pathogens responsible for NTDs like BU are highly embedded in their local environment and their risk is highly sensitive to environmental changes. Exploitation of natural resources or improvement in infrastructure is necessary for economic growth in tropical countries, but this often comes at
the expense of rapid environmental change that can increase the prevalence of local infectious diseases [46]. For instance, changes in agricultural practices, deforestation and the construction of roads and dams have contributed to the emergence of BU endemic areas [18–20]. Given the potential that some NTDs have to drag part of the population into poverty, the negative consequences of environmental degradation could fall disproportionately on few individuals, while most of the population enjoys the economic benefits. Investment in the public health system can help alleviate these indirect negative consequences in subgroups of the population and contribute to health equity.

This study illustrates how a reduction of the disability burden caused by BU, which could be extended to other devastating NTDs, is not only important on public health grounds but is also justified as a social justice intervention. Prevention of disability, one of the main goals of the World Health Organization strategy for BU [37], can maximize the economic growth of the least well-off and reduce significantly the economic inequity generated by the disease. A combination of early detection of cases with improved case management has the greatest potential to achieve this. The benefits of awareness, education campaigns and active search of BU cases have been previously reported [24,25], but research on BU treatment and management lags way behind most of the other NTDs [38]. Many of the financial and geographical barriers associated with late presentation of cases [35,47] could be overcome with a change to a decentralized all-oral antibiotic therapy, given in an outpatient basis [48]. In addition, implementation of simplified wound dressing and rehabilitation programmes, among others, could greatly improve case management [38]. Investing on research and action against highly debilitating diseases like BU should be on the agenda of international organizations and funding agencies.

In conclusion, we provide a general framework to study feedbacks between environmental risks, BU and economics and show that even rare diseases can be a source of health and economic inequalities in endemic populations. Although highly prevalent diseases such as malaria or hookworm have provided important cases for studying economic feedbacks because the links are evident at the population level, a number of neglected diseases may have a profound impact on the economic structure of human populations even at low prevalence levels. Understanding the feedbacks between the environment, NTDs and poverty at both individual and population levels is thus key to finding new ways of fighting these dreadful threats.


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