Integrated Assessment **2:** 173–181, 2001.

Vector-borne diseases, development & climate change

Richard S.J. Tol [a,b,d,*] and Hadi Dowlatabadi [c,d,e]

[a] *Centre for Marine and Climate Studies, Hamburg University, Hamburg, Germany*
[b] *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*
[c] *Sustainable Development Research Institute, University of British Colombia, Vancouver, BC, Canada*
[d] *Centre for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, PA, USA*
[e] *Resources for the Future, Washington, DC, USA*

Submitted 28 November 1999; revised 24 May 2000

Vector-borne diseases are feared to extend their range in a future where global warming has occurred. There is considerable concern about scourges such as malaria re-invading currently temperate regions and reaching into higher altitudes in Africa. In this paper we examine the various factors thought to determine potential infectivity of malaria, and its actual outbreak in the context of a dynamic integrated assessment model. We quantify: (i) the role of demographics in placing a larger population in harms way; (ii) the role of climate change in increasing the potential geographic range and severity of the risk of infection; and (iii) the role of economic and social development in limiting the occurrence of malaria. We then explore the climate and economic implications of various climate policies in their effectiveness to limit potential infectivity of malaria. In illustration of these issues we present the climate-related and economics-related impacts of unilateral CO_2 control by OECD on incidence of malaria in non-OECD nations. The model presented here, although highly stylized in its representation of socio-economic factors, provides strong evidence of the role of socio-economic factors in determination of malaria incidence. The case study offers insights into unintended adverse consequences of well-meaning climate policies.

Keywords: climate change, climate policy, economic growth, malaria, trade, vector borne diseases

1. Introduction

Inter-annual climate variations and closely correlated changes in disease outbreaks in certain locations [2] give rise to legitimate concerns that climate change may well increase the incidence of vector-borne diseases. This is a good reason to want to reduce greenhouse gas emissions. However, emission abatement would take away scarce resources [6], perhaps also from health care. This could also increase the incidence of vector-borne diseases. Schelling [19] and Dowlatabadi [4] discuss this trade-off in a qualitative manner. This paper seeks to explore these concerns by quantifying the crucial links between emission reduction and vector-borne diseases. Although some quantitative conclusions can be drawn, we mainly highlight our lack of understanding.

2. The model

For our analysis, we need two trajectories. The first describes how emission abatement affects climate change, and how climate change affects vector-borne diseases. The second trajectory describes how emission abatement affects socio-economic development, and how such development ameliorates the incidence of vector-borne diseases. Before delving into the details of our model we need to emphasise two facts: (i) various factors, from the ecology of disease vectors to access to public health services (at different levels of income and development), cannot be accurately generalised into global response functions and (ii) the information needed to develop such functions at the appropriate spatial scales with the appropriate dynamics is far from our current capability. Nevertheless, the current generation of models can be used to examine the relative magnitudes of impacts from climate change and from climate policy on disease outbreak.

The model used for this study (*FUND*; [21,24]) is specified with different geographic resolutions for socio-economic and physical aspects of these simulations. The socio-economic components are aggregated into nine major world-regions.[1] *FUND* simulations run from 1950 to 2200, in time steps of a year. The *IMAGE* database of population, income, energy-use and emissions (Batjes and Goldewijk, 1994) is the basis for the calibration of the model to the period 1950–1990. *FUND*'s base scenarios of demographic and economic change are derived from the EMF Standardised Scenario. In addition, a library of alternative scenarios is available, permitting examination of alternative scenarios specified by the IPCC (Leggett et al., 1992).

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[*] Corresponding author: Dr. Richard S.J. Tol, Michael Otto Professor of Sustainability and Global Change Hamburg, Vrije and Carnegie Mellon Universities, ZMK, Troplowitzstrasse 7, 22529 Hamburg, Germany. Tel.: +49 40 428387007; Fax: +49 40 428387009; E-mail: tol@dkrz.de; http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/tol.html.

[1] OECD-A: USA and Canada; OECD-E: Western Europe; OECD-P: Japan, Australia, and New Zealand; CEE&fSU: Central and Eastern Europe and the former Soviet Union; ME: Middle East; LA: Latin America; S&SEA: South and Southeast Asia; CPA: Centrally Planned Asia; and AFR: Africa.

The atmospheric physics and climate change simulations of *FUND* are simulated globally. Emissions of carbon dioxide are tied to economic activity and policy. Emissions of other key greenhouse gases are assumed to follow exogenous scenarios. The atmospheric concentration of carbon dioxide is calculated from emissions using a five-box model:

$$Box_{i,t} = \rho_i Box_{i,t} + 0.000471\alpha_i E_t \tag{1a}$$

with

$$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}, \tag{1b}$$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes ($\rho = \exp(-1/\text{lifetime})$, with life-times of: infinity, 363, 74, 17 and 2 years, respectively). This model was originally developed by Maier-Reimer and Hasselmann [14]. We use a later variant parameterized by Hammitt et al. (1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is – on average – removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine et al. [20]. The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing *RF*), with an equilibration time-constant of 50 years. In the base case, equilibrium global mean temperature rises by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right)T_{t-1} + \frac{1}{50}\frac{2.5}{6.3\ln(2)}RF_t. \tag{2}$$

The equilibration time-constant is calibrated to the best guess temperature for the IS92a scenario of Kattenberg et al. [7].

Emission abatement is restricted to industrial sources of carbon dioxide. The costs of carbon dioxide emission reduction are calibrated to the survey results of Hourcade et al. [6], supplemented with results of Rose and Stevens [18] for developing countries.[2] Regional relative costs are aggregated to a global average, that is, the weighted average of the regional and global average is taken, with the inverse variances as weights. This reduces the influence of a single study. It particularly influences the developing regions, for which much less information on emission abatement costs is available. Costs are represented by a quadratic function. Table 1 presents the parameters. Roughly, a 1% cut in emissions costs 0.02% of GDP; a 10% cut costs 2%.[3]

Table 1
Parameters of the CO_2 emission reduction cost function[a].

OECD-A[b]	2.08	CEE&fSU	2.05	S&SEA	2.13
OECD-E	2.32	ME	2.10	CPA	2.00
OECD-P	2.22	LA	2.13	AFR	2.09

[a] The proportional loss of GDP C in year t of proportional emission reduction R in year t follows: $C_t = aR_t^2$. The CO_2 reduction costs to GDP are modelled as a dead-weight loss to the economy. Emission reduction is brought about by a permanent shift in energy- and carbon-intensity.

[b] The regions of *FUND* are OECD-America (OECD-A), OECD-Europe (OECD-E), OECD-Pacific (OECD-P), Central and Eastern Europe and the former Soviet Union (CEE&fSU), Middle East (ME), Latin America (LA), South and Southeast Asia (S&SEA), Centrally Planned China (CPA) and Africa (AFR).

Source: After Hourcade et al. [6] and Rose and Stevens [18].

Trade ties the economies of the world together. The table above only captures the direct impacts of abatement on an economy. In our simulation we also include the effects of greenhouse gas emission reduction in the OECD on other regions. Emission abatement changes patterns of international trade and investment through changes in demand for fossil fuels, changes in competitiveness and changes in economic growth rates. Using a static computable general equilibrium model, Babiker et al. [1] investigate the implications of the OECD meeting its obligations under the Kyoto Protocol, excluding international trade in emission permits.[4] Non-OECD countries do not reduce their emissions. Babiker et al. [1] find that the costs of such a policy for non-OECD countries would be high, because exports to the OECD would fall substantially, not only for oil but for all other commodities. Non-OECD countries would also benefit from larger exports of energy-intensive goods and higher investments in such industries, but, according to the Babiker study, this does not offset the export losses. Babiker et al. [1] also considered the implications of tariffs and other trade protection strategies the OECD may employ to limit imports of energy-intensive goods. Such imports could negate the impact of their unilateral action on emissions control.

We parameterise international trade effects of carbon dioxide abatement by OECD countries based on the results of Babiker et al. [1], for a number of countries and regions. In order to reflect the geography of FUND, we aggregated their results to match the nine regions identified earlier. The ratio between income losses in OECD countries and income losses in non-OECD countries according to the model of Babiker et al. [1] is applied to the OECD income losses of table 1. In their study, Babiker et al. consider four different trade protection scenarios, we averaged the results from these scenarios to arrive at the trade protection scenario results used in this study. Our central case is the average of our protection and our non-protection cases. The average economic impacts of unilateral OECD carbon dioxide abatement on non-OECD countries are given in table 2. The table entries also reflect the standard deviation of these trade impacts as estimated from the variation between countries within our regions and between the scenarios of Babiker et al. [1].

We note that the impacts of unilateral action by OECD countries on the GDP of other regions have been studied by

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[2] Note that estimates of the costs of greenhouse gas emission reduction have not changed much since the IPCC's Second Assessment Report [6]. See, for instance, Weyant [26].

[3] Note that, although the *relative* costs of emission reduction do not differ too much between regions, the *absolute* costs do.

[4] International trade in emission permits is like to reduce emission reduction costs substantially [6], but is unlikely to be implemented before 2010.

Table 2
Percent income loss in non-OECD regions for each percent income loss in the OECD as a result of greenhouse gas emission abatement. (Standard deviations are given in brackets.)

Region	Central case		No trade protection		Trade protection	
	Mean	(s.d.)	Mean	(s.d.)	Mean	(s.d.)
CEE&fSU	2.0	(0.5)	3.6	(1.0)	0.3	(−)
ME	10.0	(1.7)	12.2	(3.3)	8.4	(−)
LA	0.8	(0.7)	0.8	(0.5)	0.7	(1.3)
S&SEA	0.5	(0.7)	0.8	(0.7)	0.1	(1.2)
CPA	1.3	(1.6)	2.2	(3.2)	0.4	(−)
AFR	2.9	(0.5)	3.4	(1.0)	2.4	(−)

Source: After Babiker et al. [1].

a number of investigators. These other studies fall into three groups: (i) supporting the results of Babiker et al. (Kainuma et al., 1999), (ii) generating largely similar but smaller negative results (Bernstein et al., 1999; Tulpule et al., 1999), and (iii) generating small positive impacts for the GDP of non-OECD nations [13]. Table 2 shows that all non-OECD regions will lose from emission reduction in the OECD. For most regions, these loses will proportionally exceed the losses in the OECD itself. The regional differences are substantial. The Middle East, relying heavily on oil exports, is a big loser. Africa is the second biggest loser, because of the cut in its exports of oil (Nigeria, Libya) and because so much of its other exports are basic commodities. Latin America and South and Southeast Asia (also oil and commodity exporters) partially offset their losses by increased exports of energy-intensive goods and benefit from imports of oil at lower prices. A similar story holds for China. In these assessments the low standard deviation for GDP losses in Africa and the Middle East hint at a high likelihood of GDP losses from Annex-1 mitigation action. In the other regions chances of benefits from such initiatives are not negligible.[5]

Note that the impact of greenhouse gas emission reduction on international trade can only be reliably estimated in the short to medium run. Below, we apply the multipliers of table 2 only to the period 2000–2010.

Table 3
Additional deaths due to vector-borne diseases for a 1°C global warming. (Standard deviations are given in brackets.)

FUND region	Malaria		Schistosomiasis		Dengue fever	
	Mean	(s.d.)	Mean	(s.d.)	Mean	(s.d.)
OECD-A	0	(0)	0	(0)	0	(0)
OECD-E	0	(0)	0	(0)	0	(0)
OECD-P	0	(0)	0	(0)	0	(0)
CEE&fSU	0	(0)	0	(0)	0	(0)
ME	155	(112)	−64	(13)	0	(0)
LA	1,101	(797)	−114	(22)	0	(0)
S&SEA	8,218	(5949)	−116	(3)	6,745	(1,171)
CPA	0	(0)	−128	(25)	393	(68)
AFR	56,527	(40,919)	−503	(99)	343	(60)

Source: Tol [22].

For malaria, three model studies have been used to calibrate the meta-model used in this analysis. Martin and Lefebvre [12] indicate that in a $2\times CO_2$ world the land areas were malaria can be potentially transmitted increases by 7–28%, depending on the GCM used. Martens et al. [9–11] expect several million additional malaria cases by the year 2100. In turn, Morita et al. (1995) indicate a 10–30% increase in the number of people at risk from malaria for a doubled CO_2 world. For these three studies, the GCM-specific estimates of the increase in global malaria death toll have been scaled by the corresponding increase in the global mean temperature and then averaged. Martens et al. [9,11] standardise their results to an increase in the global mean temperature of 1.16°C. Martin and Lefebvre [12], and Morita et al. [15], however, present their results (for malaria only) for various increases in the global mean temperature (2.8–5.2°C). Both studies suggest that the relationship between global warming and malaria is linear. Next, the mean projections of the three studies were averaged. The yearly, regional death toll due to malaria was taken from Murray and Lopez [16], expressed as the fraction of total regional population. The regional death tolls are assumed to increase by the same relative amounts as the malaria potentials. In this way, current control of malaria is reflected, be it successfully as in Europe or less successfully as in Africa. Finally, we assume that the impact of climate change on changes in relative mortality due to malaria in each region changes uniformly throughout the world (cf. [22]).

We are well aware of the limitations of malaria potential as a risk indicator. In regions that are already saturated with malaria, an increase in the potential would not alter malaria incidence. In regions that are now almost free of malaria, a small increase in the potential could have dramatic implications. By equating a percent increase in malaria potential with a percent increase in malaria incidence, we assume that overestimates and underestimates average out. This assumption is a placeholder for further studies of the relationship between climate change and malaria.

For dengue and schistosomiasis, only Martens et al. [11] report model results. The same procedure was followed as above: the average of the estimated global change in death toll is assumed to hold for the relative, regional mortality taken from Murray and Lopez [16]. Again, a linear relationship is assumed between climate change and incidence of schistosomiasis and dengue fever (cf. [22]).

Table 3 summarizes the findings for a 1°C climate change, keeping population and income as it is today.

Vulnerability to vector-borne diseases strongly depends on access to basic health care and the ability to manage the natural environment. We recognize the complex social and institutional factors that determine public health services. Data and models to capture these are not available. In their place, we make the gross assumption of a linear relationship between access to public health services and regional per capita income. The data of the WHO [16] suggest a linear relationship between per capita income and mortality due to

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[5] The results for Central and Eastern Europe and the former Soviet Union are inexplicable to us. Russia could be expected to benefit through increased gas exports to, particularly, the European Union.

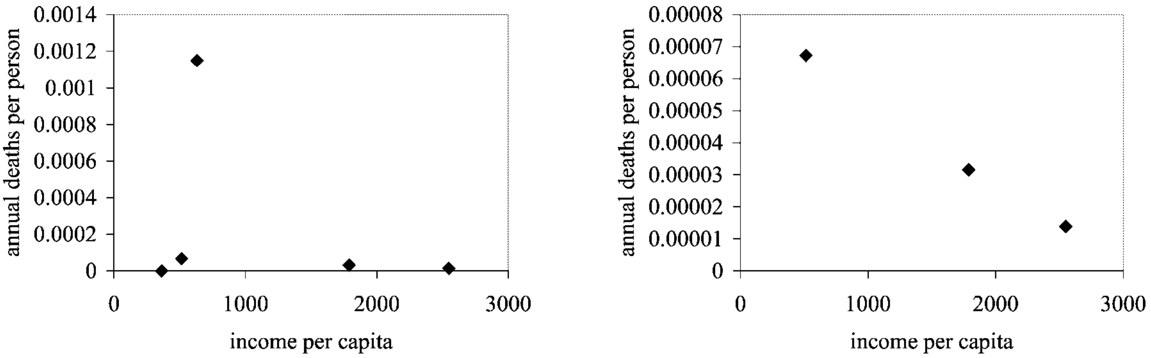

Figure 1. The relationship between per capita income and malaria incidence in *FUND*'s five developing regions (left panel); the right panel depicts the same omitting Africa and China.

Table 4
Percentage change in cumulative climate change induced vector borne mortality in <column> due to a 1% emission reduction in 2000–2009 in <row>.

Emissions reducing region	Consequent change in regional cumulative mortality due to climate change, ignoring effects of unilateral mitigation on inter-regional trade and economics				
	ME	LA	S&SEA	CPA	AFR
OECD-A	−0.01	−0.01	−0.12	−0.13	−0.18
OECD-E	−0.01	−0.01	−0.09	−0.10	−0.14
OECD-P	0.00	0.00	−0.03	−0.04	−0.05
CEE&fSU	−0.01	−0.01	−0.11	−0.13	−0.18
ME	**0.33**	0.00	−0.02	−0.02	−0.03
LA	0.00	**0.22**	−0.03	−0.03	−0.04
S&SEA	0.00	−0.01	**0.13**	−0.06	−0.09
CPA	−0.01	−0.01	−0.07	**0.05**	−0.12
AFR	0.00	0.00	−0.02	−0.02	**0.15**

malaria, schistosomiasis, and dengue fever for the Middle East, Latin America, and South and Southeast Asia. China (too low mortality) and Africa (too high) mortality are outliers. See figure 1 for malaria. A regression of vector-borne mortality and per capita income suggests that populations with an income above \$3100 per capita, with a standard deviation of \$260/capita, are not vulnerable to vector-borne diseases. Because of the outliers, the standard deviation is increased to \$1000/capita (cf. [23]). The recent malaria outbreak in the southern fringes of the former Soviet Union are a good illustration of the income effect.

Although the qualitative relationship between wealth and health within a country is undisputed (e.g., [5,25]) our empirical base for performing a cross-national extrapolation is, of course, very weak. We therefore rely on a sensitivity analysis to test the robustness of our findings (see below).

The model for vector-borne diseases thus becomes:

$$m_{r,t,d} = \alpha_{r,d} T_t^{\beta} \left(\frac{y_c - y_{t,r}}{y_c - y_{1990,r}} \right)^{\gamma} \quad \text{if } y_{t,r} \leqslant y_c. \qquad (3)$$

In this model, y (per capita income), plays a critical role in limiting mortality, m. Here, $m_{t,r,d} = 0$ if $y_{t,r} > y_c$; m denotes mortality at time t for region r and disease d. α is a parameter linking temperature change to, the benchmark impact of climate change on vector-borne diseases; cf. table 4; y denotes per capita income; T denotes the change in the global mean temperature relative to 1990; y_c is a parameter, denoting the per capita income at which vector-borne mortality becomes zero; $y_c = \$3100/\text{capita}$ (with a 1 s.d. range of \$2100–4100/capita); β and γ are parameters, denoting the non-linearity of mortality in temperature and income, respectively; $\alpha = 1$ (0.5–1.5); $\gamma = 1$ (0.5–1.5) (cf. [21]).

3. Results

In presenting our findings we step through the various factors of global change considered by *FUND*. Integrated assessments permit us to examine the impact of climate change, demographic change, economic change, and climate policy separately.

First, we present the impact of climate change alone. Figure 2 displays the additional number of deaths due to malaria, schistosomiasis, and dengue fever. Keeping the number of people and their income as today. Our simulations suggest an expected increase in vector-borne disease mortality of about 250,000 per year. There is a high degree of uncertainty in this estimate as depicted by the range of future mortality.

Population growth increases the number of people at risk from vector-borne disease (even if their range is unchanged). Rolling in the impact of population growth and geographic extension of potential outbreaks of vector-borne disease, the expected mortality is almost tripled to over 700,000 deaths per year. As noted earlier, economic growth if assumed to confer access to public health services can act to suppress outbreak of vector-borne disease and mortality even when the potential for their occurrence rises. Inclusion of the impact of economic growth on realised mortality due to vector-borne diseases keeps the annual death toll below 150,000 cases per year. If economic growth proceeds according to the scenarios explored here, there is a happy prospect that mortality from vector-borne diseases can be eradicated by about 2080, as all regions acquire a sufficient standard of living to afford effective health care and environmental management.[6] The timing of this obviously varies with the assumed cut-off per capita income, and differs per region. Figure 3

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[6] A successful and cheap vaccine may bring this date closer.

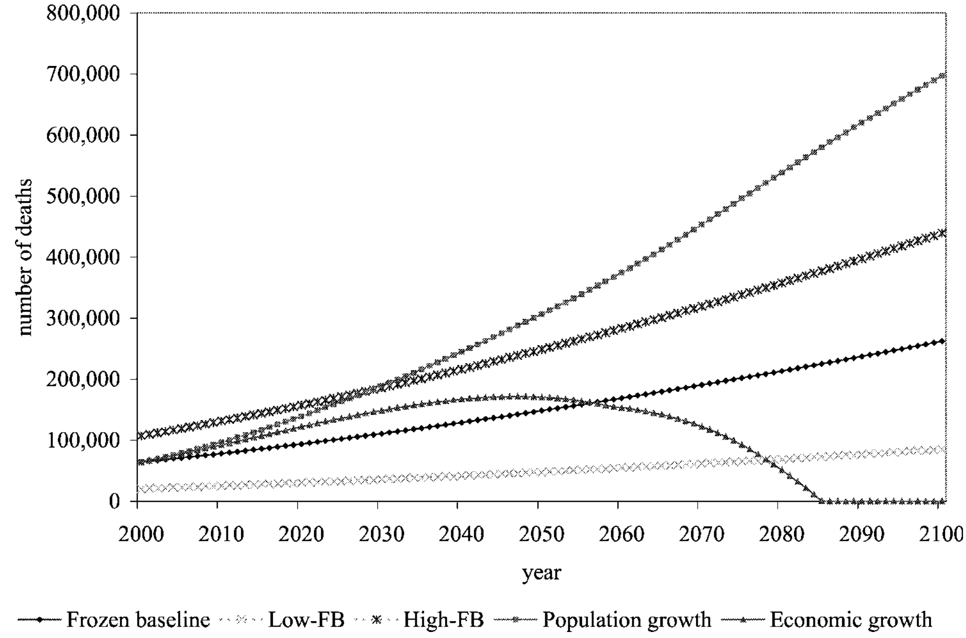

Figure 2. World wide climate change induced vector borne mortality for five different cases. In 'frozen baseline', climate changes but economy and population are as in 1990. 'Low-FB' and 'High-FB' are the same, but the sensitivity of vector-borne diseases to climatic change is set at its best guess minus or plus its standard deviation. In 'population growth', the scenario for demographic development is added. In 'economic growth', the scenarios of increasing per capita income is also added.

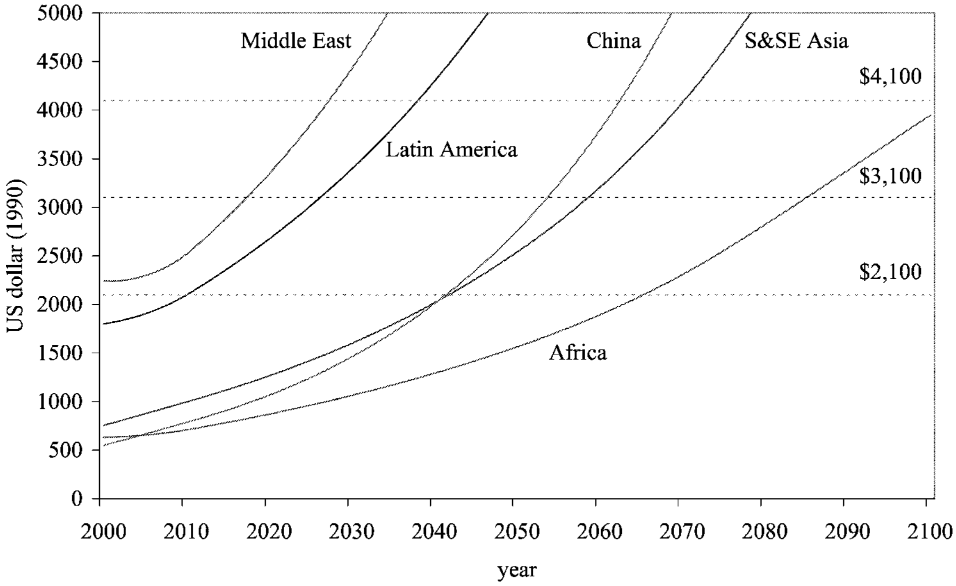

Figure 3. Per capita income in five regions and three alternative cut-off incomes for vector-borne disease mortality.

illustrates this. It displays the scenarios for the per capita income in the five regions currently prone to vector-borne diseases, and when these cross \$3100, the central estimate for the cut-off income, and \$2100 and \$4100, the low and high estimates of per capita income at which mortality from vector-borne diseases can be cut down to insignificant numbers.

In the climate change impact community carbon dioxide mitigation policy is often advocated as a first line of response to concerns about the geographic expansion of potential outbreaks of vector-borne disease. Table 4 is used to display the impact of carbon dioxide mitigation policy on vector borne mortality. The simulation results are shown for nine regions each of which engage in reduction of total carbon-dioxide emissions by 1% per year for the period 2000–2009, ignoring international trade effects.[7] Table 4 shows the change in cumulative mortality for the five regions that suffer high levels of vector-borne disease mortality over the period 2000–2100 expressed as a percentage of the busi-

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[7] We restrict the analysis to emission reduction in the period 2000–2009 because the trade effects are calibrated to current international trade patterns.

ness as usual scenario. Emission abatement in one region *reduces* vector borne mortality in other regions by decreasing climate change. However, if the costs of emission reduction are high, implementation of the climate policy can *increase* malaria mortality in regions close to the income threshold at which malaria can be eradicated. Hence, the boldface meanings in table 4 depict regions where emission controls slow economic development to the point where the eradication threshold is not reached. Hence, incidence of malaria increases as a consequence of climate policy.

Figure 4 shows the change in cumulative climate change induced vector borne mortality as a function of emission reduction in the OECD, and as a function of the trade effects. If there is no trade effect, emission reduction in the OECD reduces mortality (cf. table 4). An annual 3% emission reduction for the period 2000–2009 – roughly what is required under the Kyoto Protocol – would cut cumulative mortality by about 4% (some 400,000 people). An annual 1% emission reduction would save some 2%, or 200,000 people. The cost of each life saved (from mortality due to vector-borne disease) by such an emission reduction policy would be roughly $250,000. It is not difficult to generate a great many other policies that can save lives at risk from vector-borne diseases at far lower cost. But of course, there are other benefits from reducing climate change as well.

As noted earlier, even if the OECD were to implement unilateral action to control climate, there can be impacts on the economy of non-OECD countries through trade. If we include such trade effects in our central case, only half as many lives are saved through unilateral climate policy implemented in the OECD. For an annual 1% emission reduction. Some 100,000 lives would be saved, at a cost of roughly $450,000 per life. At higher efforts to reduce carbon dioxide, say 3% annual emission reduction, mortality actually *increases* by about 4%. Figure 4 displays the effect if including trade effects from climate policy along the sensitivity of mortality to assumed severity of trade effects. The change in mortality is roughly linear in the trade effect.

Figure 5 displays a sensitivity analysis around the case of a 1% annual emission reduction in the OECD for the years 2000–2009. Important variables are varied between their high and low values one at a time; see equation (3), tables 3 and 4. In the central case, cumulative climate change induced vector borne mortality is reduced by some 1%. This *relative* number hardly changes if the sensitivity of vector borne diseases is altered by plus or minus its standard deviation. If mortality is more than linear in per capita income ($\gamma = 1.5$), emission reduction is less successful in reducing mortality, because the trade effect increases in importance relative to the climate effect. If mortality is more than linear in climate ($\beta = 1.5$), the reverse happens, and this effect is larger. For a higher income threshold (above which vector borne diseases are eliminated) than the central case of $3100 per capita, emission abatement is more effective in reducing mortality. Because baseline malaria is eradicated later, the slow climate effect increases in importance relative to the fast income effect. If climate change is less pronounced, or trade effects more pronounced, emission abatement is more effective in reducing mortality.

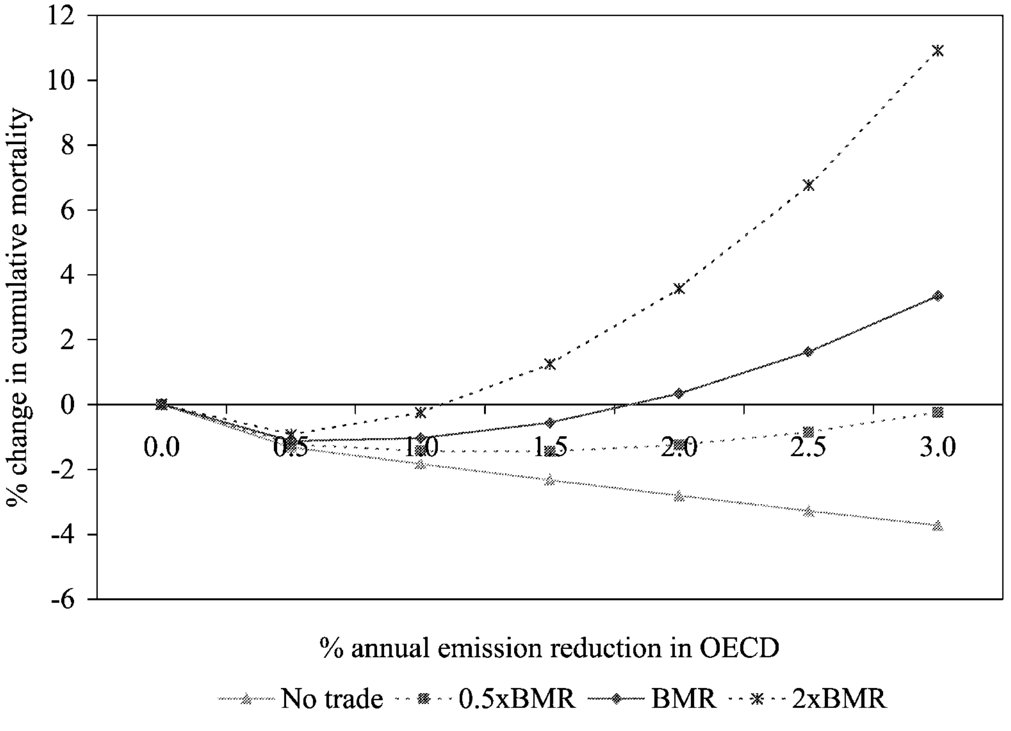

Figure 4. Changes in world wide climate change induced vector borne mortality due to carbon dioxide emission reduction in the OECD in the period 2000–2009. Four cases are displayed. 'No trade' is without the effects of OECD emission reduction on other economies. 'BMR' is with such effects, according to the paper of Babiker, Maskus and Rutherford [1]. '0.5×BMR' and '2×BMR' are sensitivity runs to test the mortality results to severity of trade effect at one half and double the base case estimates.

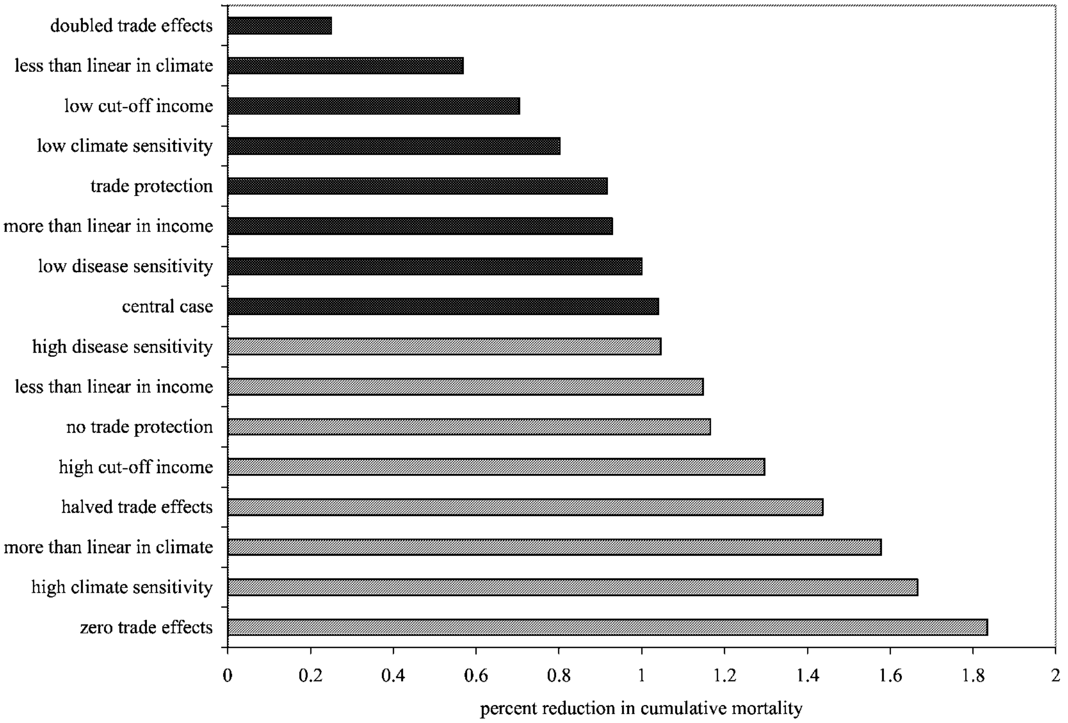

Figure 5. Sensitivity analysis of the change in world wide climate change induced vector borne mortality due to a 1% annual emission reduction in the OECD for the period 2000–2009. See text for a description of the alternative parameter choices.

4. Discussion

The results expressed in figures 4 and 5 suggest that the Kyoto Protocol may increase, rather than reduce climate change induced vector borne mortality, an outcome that is far from the intentions of the architects of the Kyoto Protocol. That is, the climate conditions would improve, but the socio-economic conditions would deteriorate. In the domain of vector-borne disease we contend that the overall impact of the latter may well dominate the former. We recognize the limitation of using income as a proxy variable for public health, but the scare public health resources in Africa and Asia are likely to be adversely affected by the performance of the local economy. A costly climate policy, whether of domestic origin or unilaterally undertaken by the OECD, is likely to harm the economies and hence public health in the South. This would reduce or reverse the health benefits of a slower climate change. The only remedy appears to be compensating actions to support Southern economies in general or invest in their public health directly.

The results presented in this paper are only a first cut at the problem. Many factors are omitted from this analysis. Major omissions include a more realistic relationship between socio-economic factors and public health as well as development and incidence of other diseases, such as cardiovascular diseases which are also affected by both climate and development. A true integrated assessment is far beyond our current capability. Nevertheless, our findings show the possibility of significant indirect interactions between climate policy and health outcomes. The strength and potential perversity of such interactions highlight the need for a concerted effort to better characterise and represent such issues in assessment of climate change impacts and climate policy design.

Another omission from our study is the impact of international trade in emission permits on regional economies. Should such a trading system come into being, involve developing countries and emission entitlements be allocated on something akin to a per capita basis, then substantial income transfers from the OECD to non-OECD regions can be expected. These are three big ifs. Furthermore, it is uncertain whether such transfers would do the most deserving much good. Cooper [3] points at corruption, with revenues of the sales of emission permits disappearing to Swiss bank accounts or worse. McKibbin and Wilcoxen (1998) point at the possibility of Dutch disease,[8] particularly in smaller countries with a narrow export base. Nevertheless, the sums involved in international trade of emission permits are substantial[9] and dwarf the budgets for health care in most potential emission permit seller countries. Such transfers of wealth, if applied appropriately to local development projects, could more than offset the negative impacts of reduced growth in the OECD.

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[8] An economy suffers from Dutch disease if government exports (usually, of natural resources) outcompete private exports through the exchange rate, thus eroding the industrial potential of that economy.

[9] For instance, if the emissions targets of the Kyoto Protocol are met with a full global trading scenario, the DICE98 model [17] generates permit sales from the less developed countries to the OECD of \$8 billion per year, the G-CUBED model [13] finds annual sales worth \$11.5 billion, and the SGM model [8] \$13 billion/year.

There are of course other ways to limit the effects of emission abatement in the OECD in developing countries. These include making OECD emission reduction as cheap as possible, increasing development aid, and freeing international markets to stimulate growth in developing countries. Compensating the developing countries for their incurred losses would increase the emission reduction costs to the OECD by some 80%.

A further caveat about these findings is that the people inhabiting regions in *FUND* are assumed to be homogenous, that is, we do not consider age distribution, income distribution, population density, elevation, land cover or land use differences within each region. All of these factors influence the prevalence of vector-borne diseases. Income distribution within each region is perhaps the most serious omission in this study, because it too would be effected by greenhouse gas emission abatement.

Another major omission of the current analysis is that it is restricted to *climate change induced* vector borne mortality. Non-climate-related vector borne mortality is ignored. However, this is likely to respond to health care spending as well. Including this effect would seriously tilt the balance in favour of not reducing greenhouse gas emissions.

Finally, our knowledge of malaria dictates the need to model the problem at a high enough resolution to capture vector breeding grounds, their micro-climate and human activity changing these and the intersection vectors and hosts. This is far from the capability of integrated assessment models developed to look at the problem of climate change on a global scale.

5. Conclusions

Climate change could increase vector borne mortality. Greenhouse gas emission reduction could ameliorate this increase by limiting climate change. However if such a policy is costly it would also reduce economic growth, consequently spending on health care would diminish and mortality from vector borne diseases would rise. In this paper, we attempt a first estimate of the trade-off between these two effects. We find that, for the emission reduction efforts currently on the political agenda, the adverse health effects of reduced economic growth may outweigh the beneficial health effects from lessened climate change. Policy makers are unlikely to knowingly embrace such perverse outcomes. Developing better assessments to quantify this trade-off is warranted.

Acknowledgements

Earlier versions of this paper were presented at the Center for Integrated Study of the Human Dimensions of Global Change Meeting, Carnegie Mellon University, Pittsburgh, May 23–25 and EMF Workshop on Climate Change Impacts and Integrated Assessment, July 26–August 3, Snowmass. Comments of the participants, particularly Roy Darwin and Tony McMichael are gratefully acknowledged. Liz Casman greatly helped improve contents and exposition. Two anonymous referees greatly helped improve the exposition. This research was made possible through support from the National Science Foundation (SBR-9521914) and Carnegie Mellon University, and has been generously supported by grants from the Electric Power Research Institute, the ExxonMobil Corporation, and the American Petroleum Institute. All views expressed herein are those of the authors and all remaining errors are a reflection of their fallibility.

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