

CHIMP: A SIMPLE POPULATION MODEL FOR USE IN INTEGRATED ASSESSMENT OF GLOBAL ENVIRONMENTAL CHANGE

Brian S. Fisher^a, Guy Jakeman^a, Hom M. Pant^a, Malte Schwoon^{b,c} and Richard S.J. Tol^{c,d,e}

^a Australian Bureau for Agricultural and Resource Economics, Canberra, Australia

^b International Max Planck Research School of Earth Systems Modelling, Hamburg, Germany

^c Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany

^d Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

^e Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

July 4, 2005

Working Paper FNU-68

Abstract

We present the Canberra-Hamburg Integrated Model for Population (CHIMP), a new global population model for long-term projections. Distinguishing features of this model, compared to other model for secular population projections, are that (a) mortality, fertility, and migration are partly driven by per capita income; (b) large parts of the model have been estimated rather than calibrated; and (c) the model is in the public domain. Scenario experiments show similarities but also differences with other models. Similarities include rapid aging of the population and an eventual reversal of global population growth. The main difference is that CHIMP projects substantially higher populations, particularly in Africa, primarily because our data indicate a slower fertility decline than assumed elsewhere. Model runs show a strong interaction between population growth and economic growth, and a weak feedback of climate change on population growth.

Key words

population model, long term projections, global change, integrated assessment

1. Introduction

Population growth is one of the main drivers of global change. Resource use is given by resource use per capita times the number of people, emissions by emissions per capita times the number of people. Projections of population are therefore a key component of scenarios that drive models of global change. Yet, there is little discussion on population projections. Most analysts¹ simply adopt the projections generated by a small group of demographers

¹ SGM/MiniCAM, IMAGE and AIM are exceptions to this rule. These modelling teams have their own, little publicised population model.

interested in the long run, that is, Lutz *et al.* (2004), UN (2003), US Census Bureau (2003), and World Bank (2002).

At the same time, demographic models are largely self-contained. However, there is little reason to assume that population is independent of other drivers of global change (e.g. economic growth) or of global change itself (e.g. climate-change-induced mortality). Also in other respects, the current generation of demographic models leave much to be desired. The first chapter of the review by the US National Research Council (Bongaerts and Bulatao, 2000, p. 30) makes for a chilling read. “Recent projections [are] made without a firm theoretical basis. The general assumption is that future [...] trends will follow trajectories similar to those in the past [...] derived informally from an understanding of past trends.” Sanderson (1998) calls the standard models “non-causal”, and shows how adding correlates of fertility and mortality increases the predictive abilities of demographic models.

In this paper, we present a population model that is simple enough to be adopted in most integrated assessment models of global change, and that generates sufficient statistics on population. Our model can reproduce some of the results of other projections, although we need to push parameter values beyond credibility to do so. The model responds to economic growth and to global change.

We use per capita income as the main driver of demographic change. Other researchers have advocated such things as education, labour participation and medical care. However, these matters are closely correlated to per capita income. Moreover, projections of per capita income are widely available, while projections of education and health care are not.

The paper is set-up as follows. Section 2 describes model and data. It also compares the four main processes of CHIMP (fertility, mortality, AIDS, migration) to other demographic models used in this field. Section 3 shows results and sensitivity analyses. Section 4 discusses fertility, the single most important process for long-term projections. Sections 3 and 4 also compare CHIMP results to those of other demographic models. Section 5 shows scenario analyses for global change. Section 6 concludes.

2. The model

This section describes version 1.0 of the Canberra-Hamburg Integrated Model of Population (CHIMP). CHIMP draws on the population module of ABARE’s Global Trade and Environment Model (GTEM; Pant, 2002) for fertility and mortality, but modifies the convergent properties of fertility, modifies mortality to include AIDS, and adds migration. We discuss functional form and parameters, distinguishing between the standard functions and best guess parameter values (which together form the “base case”) and alternative functions and values (which are used in sensitivity analyses).

2.1. Population cohorts

The core of the population model is the age/sex cohort structure. We distinguish 17 ($NA=16$) age-cohorts of 0-4, 5-9, ..., 75-79, and 80+. We distinguish two sexes, male and female. The time step of the model is equal to the age-cohort, namely 5 years. The size C of an age/sex cohort in region r of sex s and age a at time t follows from:

$$(1) \quad C_{r,s,a,t} = C_{r,s,a-1,t-1} (1 - M_{r,s,a-1,t-1}) \forall r, s, t, a = 1, 2, \dots, NA - 1$$

where M is the mortality rate, specified below. That is, in each period, people either die or promote to a higher age cohort. People do not change sex. The size of the youngest cohort ($a=0$) is specified below. The size of the oldest cohort follows from:

$$(2) \quad C_{r,s,NA,t} = C_{r,s,NA-1,t-1}(1 - M_{r,s,NA-1,t-1}) + C_{r,s,NA,t-1}(1 - M_{r,s,NA,t-1}) \forall r, s, t$$

That is, people above 80 years of age either die or remain in their age cohort. The total population P of region r at time t follows from:

$$(3) \quad P_{r,t} = \sum_{s=f,m} \sum_{a=0}^{NA} C_{r,s,a,t}$$

Statistics such as the share of people under 15 or above 65 and the dependency ratio are readily computed.

Data for age/sex cohorts and fertility and mortality rates for 1997 are taken from the International Data Base (IDB) of the U.S. Census Bureau, International Programs Center (version May 2000). Data for mortality rates are taken from United Nations, Demographic Yearbook (Historical Supplement, March 2000) except for Bangladesh and India (WHO South East Asia Regional Office) and China (Clinical Trial Service Unit & Epidemiological Studies Unit, Oxford University, UK). The IDB is the most comprehensive international database. However, many small countries are excluded from the database, while for other countries the most recent entries date back to the 1960s or even 1950s. The same is true for the Demographic Yearbook. Observations from before 1987 were excluded. Missing observations were replaced by regional averages.

2.2. Fertility

The size of the first cohort is given by:

$$(4) \quad C_{r,s,0,t} = G_{r,s} \sum_{a=4}^9 C_{r,f,a,t-1} F_{r,f,a,t-1} \forall r, t$$

where G is the share of boys or girls within the newborns, assumed to be constant over time, and F denotes fertility. That is, only women of age 15-49 have children. The fertility rate is age-dependent.

Fertility rates for the base year (1997) are as observed. Fertility rates for later periods are perturbed with the change in per capita income. Fertility follows

$$(5a) \quad F_{r,f,a,t} = F_{r,f,a,t-1} \left[1 + \sum_g W_{r,g,t-1} \eta_{g,a} \frac{y_{r,t} - y_{r,t-1}}{y_{r,t-1}} + \alpha_g I_{g=2} \left(\frac{F_{conv,a}}{F_{r,a,t-1}} - 1 \right) \right]$$

where y is per capita income, g denotes income group ($y < \$540/\text{person}/\text{year}$, $\$540/\text{p}/\text{yr} < y < \$7,000/\text{p}/\text{yr}$, $y > \$7,000/\text{p}/\text{yr}$), and η is the income elasticity at the median income listed in Table 1. I_C is the indicator function, nought if C is false, unity otherwise; α_g is a rate of convergence parameter that equals 0.05; multiplied with the indicator function, this implies convergence for high income regions and no convergence for other regions. $F_{conv,a}$ is the age-specific equilibrium fertility; it is specified to add up to 1.6 (the convergent total fertility rate) while the age-profile equals the average age-profile of the countries in the highest income group. W is a weight specified as

$$(5b) \quad W_{r,g,t} = \frac{1}{W_{r,t}^*} e^{-\beta(\ln(y_{r,t}/\hat{y}_{g,t}))^2}$$

where \hat{y} denotes the median per capita income per group, $\beta=2.314$ is a smoothing parameter and $W_{r,t}^*$ is defined such that $\sum_g W_{r,g,t} = 1 \forall r, t$.

Equation (5a) was estimated separately for each income group using panel data analysis. Equation (5b) represents a kernel smoothing process to make continuous the transition of one income group to the next.

The interpretation of (5) is that the income elasticity of fertility is a weighted average of the income elasticity of three reference groups. The income elasticity for high income regions is zero; their fertilities evolve only through convergence to an exogenously specified profile. Total fertility at convergence is below replacement fertility (2.1 children per woman) in the base case; that is, population asymptotically goes to zero. The distribution of convergent fertility over the age groups equals the average distribution of the high income countries (see Table 1).

The above specification implies that fertility necessarily declines with economic growth except for the richest region. This is indeed what is generally observed, but in some poor countries, particularly China, fertility is artificially suppressed. According to Equation (5), fertility would fall even further as incomes rise. Equation (4) is therefore not applied to China as long as its income is below \$7000 per person per year.

Note that CHIMP deviates substantially from other demographic models. Lutz *et al.* (2004), for instance, assume future total fertility rates based on what seems trend extrapolation. The UN projections are based on expert judgement on the rate of decline and convergent total fertility (Bongaerts and Bulatoa, 2000, p. 63-64). The World Bank and US Census Bureau projections are based on autoregressive techniques (Bongaerts and Bulateo, p. 64). In contrast, we model fertility, based on two crucial variables: income elasticity and convergent total fertility.

2.3. Mortality

The growth rate of life expectancy g^{LE} follows

$$(6) \quad LE_{r,s,t} = LE_{r,s,t-1} \left[1 + \sum_g W_{r,g,t-1} \varepsilon_{g,a} \frac{y_{r,t} - y_{r,t-1}}{y_{r,t-1}} + \tau I_{g=2} \right]$$

where W is the same kernel smoothing weight as defined in (5b), y is per capita income, g income group, ε is the income elasticity at the median income listed in Table 2, τ is the rate of technological progress, and I_C is the indicator function, nought if C is false, unity otherwise. Note that life expectancy is projected to continue to increase with economic growth. Note also that medical technology is assumed to primarily benefit the rich.

Mortality is updated by assuming that all age-cohorts have the same *proportional* change in mortality rates, and hence by numerically solving

$$(7) \quad LE_{r,s,t+1} = \sum_{a \in A} \prod_{b < a} (1 - M_{r,s,b,t+1}) = \sum_{a \in A} \prod_{b < a} \left[1 - (1 + g_{r,s,t}^M) M_{r,s,b,t} \right] = (1 + g_{r,s,t}^{LE}) LE_{r,s,t}$$

where LE is life expectancy, M is mortality, and g^{LE} is the region-, sex- and time-specific growth rate of life expectancy, and g^M is the growth rate of mortality; g^{LE} is implied by (6); we numerically solve (7) for g^M .² The first part of (7) gives the definition of life expectancy, which is the ratio of the total number of people in a population over the number of people

² Note that we deviate from the original GTEM population model, which uses an analytical approximation of (7) and solves that numerically (see Pant, 2002); here we solve (7) numerically.

aged zero, under the assumptions that mortality rates and the absolute number of newborns are constant.

Note that CHIMP again deviates from other demographic models. Lutz *et al.* (2004), for instance, assume future life expectancy. The UN population projections are also based on expert judgement, including an assumed maximum life expectancy (Bongaerts and Bulatao, 2000, p. 129). The World Bank and US Census Bureau population projections use fitted logistic functions, with an assumed maximum life expectancy (Bongaerts and Bulatao, 2000, p. 129-130). In contrast, we model life expectancy based on two crucial parameters: income elasticity and technical progress.

2.4. Migration

An essential part of the migration model is the relationship between the international migration rate and variables that are generated within the population model or provided exogenously to it. Thus, achieving reliable estimates for the impacts of differences in GDP per capita (y) and GDP per capita growth rates as well as estimates for the influence of the age structure of the source country and the destination country, are of particular interest. Following Massey *et al.* (1993), theories on international migration based on neoclassical macroeconomics would suggest to include especially differences in wage rates and characteristics of the labour market together with government controls on migration of labor flows. Differences in GDP per capita can be seen as a rough proxy for wage differentials. The unemployment rate is the only information regarding the labor market that can be obtained for a broad base of countries in a relatively consistent way that can be used in estimation. Network theory, predicting the perpetuation of international movement due to sets of interpersonal ties that connect migrants with former migrants put forward to include lags of the dependent variable. Finally, the distance between the capital cities can be seen as an approximation of the individual costs of migration, where costs not only refer to the expenses on traveling but also to the problems of barriers between cultures.

Data on migration rates are scarce, as most countries provide data only on net migration. The Migration Policy Institute³ (MPI) offers numbers of immigrants into the USA, Canada, Australia, The Netherlands, Germany and the United Kingdom segmented by the source country, for the years 1990 to 1999. These data are converted into migration rates, using population numbers of the International Data Base (IDB) of the U.S. Census Bureau, International Programs Center (version May 2000). Data for GDP per capita and unemployment are taken from the World Development Indicators database (World Bank, 2002).

We estimate the migration to the above-mentioned regions⁴ separately. We tested a variety of functional forms, different variables concerning the age structure of the country that the people are leaving and several combinations of dummies for the emigration regions. Surprisingly, the unemployment rates in the destination country/region as well as in the source country are not significant. The following panel-regression was estimated for the different regions:

$$(8) \quad \ln(EMR_{i,j,t}) = \beta_{j,0} + \beta_{j,1} \ln(EMR_{i,j,t-1}) + \beta_{j,2} \ln(D_{i,j}) + \beta_{j,3} dy_{j,t} + \beta_{j,4} DY_{i,j,t} \\ + \beta_{j,5} S_{j,t}^{0-9} + \beta_{j,6} FSU + u_j$$

where EMR is the emigration rate, that is, the number of migrants from country j to country i divided by the population of country j ; dy denotes the growth rate in per capita income *in the*

³ <http://www.migrationinformation.org/GlobalData/>

⁴ The Netherlands, Germany and the United Kingdom are used together, representing "Western Europe".

source country, DY the difference in per capita income *between the source country and the destination country*;⁵ dy and DY together measure the expected improvement of living standard by emigrating; S^{0-9} is the share of the population of age less than ten years in the source country; FSU is a dummy that is equal to one, if the source country is part of the former Soviet Union; t indexes time, and u is white noise. We expect a fairly high persistence in migration patterns. If the income difference is high, migration would be high too; but if economic growth in the source country is high, migration would be low. The expected sign on the number of young children is unknown; on the one hand, a family with young children has a greater incentive to migrate; on the other hand, children make migration more cumbersome.

In addition to the four regressions, we put all destination regions together into one panel; that is, we estimate the emigration rate, without specifying the destination country. We use this to estimate migration to destinations for which we do not have specific data. Furthermore, we use the results of this additional regression to make the region-specific estimates more reliable by constructing a weighted estimate (Theil and Goldberger, 1961):

$$(9a) \quad \beta_c^* = COV_c^* (COV_g^{-1} \beta_g + COV_c^{-1} \beta_c)$$

with

$$(9b) \quad COV_c^* = (COV_g^{-1} + COV_c^{-1})^{-1}$$

where c denotes country and g denotes the global average. The regression results are in the appendix.

The fit is fairly good in all regressions. This is due to the inclusion of the lagged dependent variable, as migration rates are persistent. Furthermore, in the "world-regression", distance and the difference in per capita income have the expected negative and positive influence, respectively. The economic growth rate in the source country has the expected negative effect, as potential migrants compare their expected future income in the destination and source country. Countries with a higher share of young children (under 10 years of age) generate fewer migrants, as migration is more expensive and more disruptive for families with young children.

Above, we estimate how migration between *selected* countries evolves. To initialize the model, we need migration rates for *all* countries. We estimated these as follows. The evolution of migration rates follows from Equation (8), but is conditional on the starting point (1990 in our case). We estimate the 1990 migration rates so as to reproduce observed net migration rates⁶ in 1997 as closely as possible, minimizing the squared deviation of observed and predicted net migration rates.⁷ The minimization is forced to reproduce some known flows of migrants.⁸ The 1997 migration rates follow readily.

⁵ Note that we assume that there is net migration from poor to rich regions only; DY is therefore always positive.

⁶ The net migration rates are derived from the difference between the population at time t and the population of the previous period augmented by the number of new born and reduced by the number of deaths according to the fertility and mortality rates in the following way:

$$nm_t = 1 - \frac{(P_{t-1} + F_{t-1}P_{t-1} - M_{t-1}P_{t-1})}{P_t}$$

where nm_t denotes the net migration rate at time t , P_t is total population, F_t is overall fertility and M_t is overall mortality.

⁷ We used the following procedure to derive a starting value for the 1990 estimates. First, migration rates in 1991 are assumed to be in a steady state thus following directly from Equation (8) (using the "world" parameter estimates). Estimates for the years 1992-1997 readily follow. Second, we fitted a linear trend to the country-specific migration rate for 1991-1997, and derived the 1990 value.

⁸ More than 150000 people move from Mexico to the United States, which is not adequately projected by the estimation process; only some 20000 people migrate between Canada and the United States; the number of

The obtained initial migration rates evolve from period to period according to changes of values in three of the independent variables of the regressions, that change over time within the model, namely the change in GDP per capita growth, in difference in GDP per capita between the emigration country and the destination country and in the share of people less than ten years old. Using the regression estimates of the log-linear formulation of the model, emigration rates change via:

$$(10) \quad EMR_{i,j,t} = EMR_{i,j,t-1} e^{\beta_{j,3}dy_{i,t} + \beta_{j,4}DY_{i,j,t} + \beta_{j,5}S_{i,t}^{0-9}} e^{-\beta_{j,3}dy_{i,t-1} - \beta_{j,4}DY_{i,j,t-1} - \beta_{j,5}S_{i,t-1}^{0-9}}$$

Note that there is not a one-to-one match between Equations (8) and (10). Equation (10) omits those factors of Equation (8) that do not change. Equation (10) also omits the autoregressive parameter (i.e., it is set to zero), which was included for estimation purposes only.⁹ Strictly, a further multiplier $(EMR_{i,j,t-1}/EMR_{i,j,t-2})^{0.95}$ should be added to the right-hand side of (10) (for a one-year time step). However, this term would dominate and would drive the emigration rate from i to j to zero, and from j to i to unity. This is hard to justify, but the results are reported below as a sensitivity analysis. Note that (10), in combination with the income scenarios, has a decline in migration as income gaps narrow and economic growth slows. However, the decline in the share of young children at first increases net migration from poorer to richer regions.

The computed emigration rates are related to the *total* population. However, there is a specific age pattern of migrants. For instance, following MPI statistics, people in their late 20s are most likely to migrate. Table 3, which is constructed using the MPI data, shows the percentage of each cohort within the total number of immigrants for certain regions. A few adjustments with respect to the age groups used in the model were necessary and the values for ROW are simply averages. So, after the absolute number of migrants is computed, the change of the cohorts in the emigration and the immigration region is calculated with the shares of this table. It is assumed that the shares do not change over time.

Once more, CHIMP deviates from other demographic models. Lutz *et al.* (2004) assume absolute migration numbers that are constant over time. The UN and US Census Bureau population projections hold some migration at their current absolute levels, and let other migration converge to zero. The grouping of countries and the rate of convergence is based on expert judgement (Bongaerts and Bulatao, 2000, p. 174.) The World Bank population projections have migration converge to zero in a few decades (Bongaerts and Bulatao, 2000, p. 175). We model migration, using income differences, economic growth and age structure as driving variables.

2.5. AIDS

The HIV model works with the following equation:

$$(11) \quad \frac{dHIV(t)}{Pop(t)} = e^{-1.97} (1 - \varphi)^t \left(\frac{HIV(t-1)}{Pop(t-1)} \right)^{1.09} \left(\frac{Y(t-1)}{Pop(t-1)} \right)^{-0.03}$$

where HIV denotes the number of HIV-infected people, and $dHIV$ the change in that number, Y denotes national income, measured in US dollar; φ is technological progress and

immigrants to the USA and Canada must exceed 650000 respectively 1800000 people, which have been lower bound values during the late 1990s according to MPI; the number of migrants from Central and Eastern Europe is limited to 1 million people (otherwise the flow of migrants would be overstated, because of the geographical proximity and large difference in per capita income).

⁹ Recall that including a lagged dependent variable is equivalent to including an AR(1) error structure.

behavioural change (e.g., abstinence, faithfulness, condom use). This model was estimated with OLS using data for 1999; there are not enough data for more appropriate panel data analysis. Equation (11) has that HIV is highly persistent, in fact explosive, but falls as income rises and technology progresses.

The number of AIDS deaths follows from:

$$(12) \quad AIDS(t) = dHIV(t-10)$$

as suggested by REFS.¹⁰ The number of HIV cases follows from

$$(13) \quad HIV(t) = HIV(t-1) + dHIV(t-1) - AIDS(t-1)$$

Starting values are in Table 4.

After the number of AIDS deaths is computed, the deaths are divided into age and sex groups using data for the USA from the *HIV/AIDS Surveillance Report, Vol.14* (<http://www.cdc.gov/hiv/stats/hasr1402.htm>) and data for Sub-Saharan Africa from REF. In the US, men are much more likely to be infected than woman. The age profile for other countries is derived from a linear interpolation using per capita income as a scalar.

CHIMP again deviates from other demographic models. Lutz *et al.* (2004), for instance, include AIDS by downward adjustment of life expectancy, based on what appear to be ad hoc assumptions. CHIMP models AIDS by its own momentum, economic growth, and technological progress.

3. Results

Figure 1 shows total population sizes for the 16 regions for the coming 200 years. Table 6 has some of the main characteristics. In the base case, the population peaks at 13.2 billion people around 2170 and falls to 13.0 billion people by 2200. Sub-Saharan Africa overtakes South Asia as the most populous region around 2070. In the next section, we compare the CHIMP projections to those of other demographic models. The crucial difference is our assumptions on fertility. We first discuss other sensitivities.

Above, the sex ratio of new-born children is kept as in 1997. If we let it converge to 0.5 in 2200, the peak population rise to 13.4 billion people and the 2200 population to 13.3 billion people. The 2200 population is 2.6% greater than in the base case. This is because, in the base scenario, there are more baby boys than baby girls. The effect is strongest in China and South Asia, where the 2200 population is 6.1% and 5.0% higher than in the base scenario. See Figure 1.

Without migration, the 2200 world population would be 13.5 billion people, 4.0% higher than the base case, because would-be migrants do not adopt the fertility and mortality of their would-be destination countries. This global aggregate hides large regional changes, however. The 2200 population of Western Europe would be 88.6% lower, while the population of North Africa would 186.2% higher. See Figure 1 and Table 6. We also investigate a case in which the migration rate increases by the ratio of the emigration rate in the previous period and the rate in the period before that, raised to the power 0.76, which corresponds to an annual auto-regressive parameter of 0.95; see Equation (10). In this high migration case, the 2200 population falls by 0.5% compared to the base scenario. Again the regional differences

¹⁰ Note that we could also introduce technological progress in (12). However, separate dynamics of HIV and AIDS would not influence the dynamics of the total population, our prime interest in this paper.

are stark. The 2200 population of the Japan increases by 88.4%, while the 2200 population of North Africa falls by 37.5%. See Figure 1.

Without AIDS, the 2200 world population would be 13.8 billion, 6.7% higher than in the base case. The 2200 Sub-Saharan Africa would be 12.9% higher, while the population of Western Europe would be 4.5% higher, largely the result of higher immigration. See Figure 2 and Table 6. Without technological progress in combating AIDS, the 2200 world population would 12.6 billion people, 3.2% lower than the base case; again, the effect is largely felt in Sub-Saharan Africa, where the 2200 population would be 5.8% lower. See Figure 2.

In the base scenario, the life expectancy increases by 20 years in the 21st century for Japanese men and by 23 years for Japanese women. Lutz *et al.* (2004) assume an increase by 21 years for both. In Sub-Saharan Africa, life expectancy increases by 5 year for men and by 6 years for women. Lutz *et al.* (2004) assume 19 and 21 years, respectively. The difference is explained by the fact that we assume that technological progress in medicine primarily benefits the rich, while the health status of the poor would improve through economic growth. If we assume that the middle income group would benefit from technological progress at the half the rate the rich do, the life expectancy in Sub-Saharan Africa would increase by 8 years for men and by 14 years for women. The 2200 world population would be 19.0% higher, the population in Sub-Saharan Africa 30.4%. See Figure 2 and Table 6. Without technological progress, life expectancy in the rich countries would hardly change, while life expectancy would increase by almost as much as in the base scenario until 2100, but slower afterwards. The 2200 world population would be 11.2% lower, the US population 40.5%. See Figure 2 and Table 6.

Figure 3 shows the fraction of people of 75 years and older for selected regions for the base scenario. This fraction increases continuously everywhere for the next 200 years. By the end of the 22nd century, more than half of all Chinese is over 75 years of age, a situation that is hard to imagine. Figure 3 also shows the dependency ratio. For the OECD regions, this rises continuously. For the other regions, the dependency ratio first falls. In the case of the former Soviet Union, this has to do with the high mortality of the elderly. For the other regions, the dependency ratio falls with falling fertility, before rising with ageing. In Sub-Saharan Africa, the dependency ratio only starts rising in the 2nd half of the 22nd century. The dependence ratio exceeds 65% in China in 2200.

4. The importance of fertility

Of all the uncertainties around future population – migration, mortality, AIDS – the uncertainty around the evolution of fertility is the most important. In this section, we present a sensitivity analysis around the formulation of fertility in CHIMP.

4.1. Alternative convergence points

Above, we assume that fertility eventually converges to replacement level for all regions. Figure 4 displays population sizes for the alternative convergent total fertility rates of 1.1 and 2.1 (replacement). Until around 2075, the convergent behaviour of fertility has little influence. After that, it becomes very important. The population in 2200 is 10.1 billion for an eventual total fertility rate of 1.1, and 16.0 billion for 2.1, 16.9% below and 23.1% above the base case, respectively. The population of the currently high and middle income countries are more affected by the assumption on the convergent total fertility rate than are the currently low income countries, because the former are closer to convergence than the latter. Obviously, the

problems of an aging society and a growing dependency rate are less (more) pronounced the higher (lower) the convergent fertility.

4.2. Income elasticities

Figure 4 also shows what happens if we multiply the income elasticities of fertility by 1.5 and 2.0. With 50% higher elasticities, the 2200 world population would be 7.1 billion people, down from a peak of 9.9 billion people; this is 45.5% and 24.8% lower than in the base case; the population peak is much earlier, around 2090 rather than around 2170. With 100% higher elasticities, the world population peaks around 2050 at 8.8 billion people, and falls to 4.7 billion in 2200, 73.4% below the base case. The poor regions are most affected by this, particularly South Asia and Sub-Saharan Africa. With the (very) high elasticities, their 2200 populations are 33.1% (12.1%) and 36.1% (14.1%) of their 2200 populations in the base case. See Table 9.

Table 7 compares our population projections with selected other studies. Table 7 shows that, in order to reproduce Lutz *et al.* (2004), we would need to double our estimates of the income elasticity of fertility. In that case, both we and Lutz *et al.* project a world population of 8.8 billion people in 2050, while we project a population of 8.2 billion in 2100 against 8.4 billion by Lutz *et al.* Although income elasticities are hard to estimate, doubling them seems unjustified.

4.3. Alternative income elasticities

In the base specification, the income elasticity of fertility is the weighted sum of the elasticities at median income for low, high and middle income regions. The result is that the income elasticity falls as countries grow richer. Eventually, the income elasticity goes to zero and fertility reaches its convergence point.

Alternatively, we could specify this as

$$(15) \quad F_{r,f,a,t} = \begin{cases} F_{r,f,a,t-1} \left[1 + \left(\frac{y_{r,t} - y_{r,t-1}}{y_{r,t-1}} \right)^{\min(0, \kappa + \lambda y_{r,t})} \right] & y_{r,t} \leq 7000 \\ \alpha_g \left(\frac{F_{conv,a}}{F_{r,a,t-1}} - 1 \right) & y_{r,t} > 7000 \end{cases}$$

The convergence process is the same as above. The parameters for Equation (15) were estimated with OLS for 1997 data with 148 observations.¹¹ Table 8 shows the results. Interestingly, the income elasticities of fertility for low and high age groups fall if income grows (implying that fertility falls ever faster), while the income elasticity of fertility rise with income for middle ages (implying that fertility falls ever slower).

Figure 5 shows the resulting population sizes if fertility follows Equation (15)¹² and if fertility follows Equation (15) without the drift term. With the drift term, the 2200 world population is 10.9 billion people, 15.9% below the base case. North Africa is most affected; its 2200 population falls by 22.3% compared to the base case. Without the drift term, the 2200 world population is 8.3 billion people, 35.9% below the base case. China is most affected, its 2200 population falls by 80.7% compared to the base case; for Japan and South Korea, the drop is

¹¹ We estimated income elasticities of the form $\kappa + \lambda y$ as well as κy^λ , but the latter could not be reliably estimated.

¹² Again, China follows the drift term from 1997 onwards.

52.6%. Table 7 shows that, although the world population is less, it does not come near the projection of Lutz *et al.* (2004). See also Table 9.

4.4. Equilibrium fertility

The fertility models above take observed fertility as a starting point, perturb it with changes in age structure and per capita income, and then gradually let it converge to an equilibrium point. In the alternative presented here, we omit the second step, letting fertility converge to an equilibrium value, which is itself changing with age structure and per capita income.

$$(16a) \quad F_{r,f,a,t} = (1 - \rho)F_{r,f,a,t-1} + \rho F_{r,f,a,t}^N$$

where

$$(16b) \quad F_{r,f,a,t}^N = \max \left\{ \alpha y_{r,t}^\beta, F_{conv,a} \right\}$$

where $F_{conv,a}$ is as above; α and β are parameters, obtained from one cross-sectional regression for each age group, using 1997 data of 148 countries; the values for α and β are given in Table 8; ρ is also a parameter, measuring the convergence from observed to “natural” fertility; ρ is set to 0.03 to roughly reproduce the base model.

Figure 5 shows the resulting population sizes if fertility follows Equation (16). The 2200 world population would be 10.5 billion people, 29.0% below the base case. The effect is largest in China, where population falls by 61.6%. Without the cap on fertility, the global and regional results would be very similar. Table 7 shows that this configuration of CHIMP does not bring it closer to Lutz *et al.* (2004); in fact, the deviation from the baseline comes only after 2100. If we set $\rho = 0.06$, 2200 world population would be 2.2 billion people, 82.7% below the base case. The effect would be largest in Sub-Saharan Africa, with a drop in 2200 population of 88.3%. With rapid convergence to “natural” fertility, the CHIMP population projections fall below those of Lutz *et al.*; see Table 7 and Table 9.

5. Global change scenarios

Above, we use the FUND scenario of economic growth, which is close to the IS92a scenario developed in the context of the IPCC. More recent IPCC work generated the SRES scenarios. The SRES population scenarios were developed independently from the SRES economic scenarios. Here, we investigate what population scenarios are consistent with the SRES economic scenarios.

Figure 6 shows the resulting population sizes for the base model and the four basic SRES scenarios of per capita income according to the IMAGE model. In the A1 scenario, the 2200 world population would be 9.3 billion people, 18.0% below the IS92a scenario. The regional distribution would be very different, with the Middle East having 35.8% more people and North Africa 56.7% less. In the A2 scenario, the 2200 population would be 14.9 billion people, 15.3% higher than in IS92a. The regional pattern is again very different, with Sub-Saharan Africa seeing an increase of 41.1% and South Asia a decrease of 11.2%. In the B1 scenario, the 2200 population would be 10.1 billion people, 11.9% below IS92a. Eastern Europe would see its 2200 population increase by 22.1%, South Asia a decrease of 38.6%. In the B2 scenario, the 2200 population would be 12.6 billion people, 2.8% below IS92a. However, under IS92a, the world population is falling in 2200 whereas, under SRES B2, it is still rising. Sub-Saharan Africa would see its population rise by 10.4%, South Asia fall by 32.0%.

Table 10 shows more detailed results, and includes the SRES projections according to IMAGE as well. In both cases, A2 is the most populous scenario, followed by B2. A1 and B1 are close together, with A1 more populous according to IMAGE, and B1 according to CHIMP. Note that CHIMP has a much narrower range of results as only per capita income differs, while the SRES storylines indicate that other parameters should change as well.

Population is a major driver of global change, but global change may also affect population. One example is through the impact of climate change on human health. We here consider malaria only, which is a major disease that is sensitive to climate change. In contrast to cardiovascular and respiratory disorders, which affect the elderly, malaria mainly affects the young and potentially productive.

We use the health module of FUND to generate a scenario of climate-change-induced malaria mortality for the same population, economic, and emissions scenario as in our base case here. In order to better demonstrate the effects, we assume a high sensitivity of malaria to climate change (a 1°C global warming leads to a 14% increase in malaria), and a low income elasticity of malaria (a 1% increase in GDP per capita leads to a 2% decrease in malaria mortality); see Link and Tol (2004) for the model and its parameters. We assume that all malaria mortality is under-five mortality. We add climate-change-induced malaria to baseline mortality in CHIMP.

Figure 6 shows the results for Sub-Saharan Africa, the most vulnerable region. The fraction of people dying of climate-change-induced malaria is small. This is because in the first half of the century, climate change is modest, while in the second half of the century, people in Africa are sufficiently rich to protect against this infectious disease (Tol and Dowlatabadi, 2001). Qualitatively, the pattern of malaria deaths on the one hand and the pattern of population change on the other hand are very different. The latter is also not just the integral of the former, because of the indirect effects of changes in mortality. Particularly, even as climate-change-induced malaria goes to zero, the scenarios with and without climate change continue to diverge. This is due to the fact that there are less parents around to have children.

6. Discussion and conclusion

We present a new model for making long term projections of the world population. The model has several crucial features: (1) it is freely available; (2) it responds to economic growth and climate change; and (3) many of its parameters are estimated from data. Other models are hidden, non-responsive, and based on expert guesses.

The long term population projections and sensitivity analyses reveal a number of things. Some conclusions were known before. The growth of the world population is likely to slow, and the number of people may start to fall in the future. The average population will get older and older. In other respects, our results differ substantially from previous work.

We can reproduce previous results on total population numbers, but we need to force the model hard. Fertility is the variable that is most important for the future number of people. The rate at which fertility falls determines whether the world population will peak at 8 billion people (as other studies contend) or at 12 billion people (as our results indicate). In order to have our population peak at 8 billion, we need to let fertility fall twice as fast as the empirical evidence suggests.

However, as we force our model reproduce the total number of people from other studies, we cannot simultaneously reproduce other parameters, such as longevity. The reason for this is that, in our model, these variables are not independent. The sensitivity analysis show that,

although long-term equilibrium fertility is the main driver of the eventual population size, the rate of fertility change is at least as important for the population of the 21st century.

On integration, the results presented here clearly show that the IPCC was wrong to make population independent of income. Projecting population independently of economic growth is inappropriate in principle and may lead to substantial errors in practice. Projecting population independently of climate change is wrong in principle, but the bias is minimal.

When starting this project, our prime aim was to develop a population model that would fit in our integrated assessment frameworks. The model was primarily intended for our own use, but as we are civil servants on public money, the model would be available to others as well. Building the model to the best of our knowledge and ability, we found that our projections differ from those of other researchers, and we stumbled on the many questionable assumptions that have to be made in population projections. The divergence of the projections, and their sensitivity to reasonable variations in parameters and assumptions demonstrate how little we know. Although we do not claim that our projections are “more right” than those of other researchers, our projections are not obviously “more wrong” either. The sizeable uncertainty about such a fundamental driver of global change requires substantial additional research into the determinants of the population growth.

Acknowledgements

We are grateful to Malgorzata Zbylut for help with the data. The Volkswagen Foundation, through the ECOBICE project, and the Michael Otto Foundation for Environmental Protection provided helpful financial support.

References

- Bongaerts, J. and Bulatao, R.A. (eds.) (2000), *Beyond Six Billion – Forecasting the World’s Population*, Panel on Population Projections of the National Research Council, National Academy Press, Washington, D.C.
- Link, P.M. and R.S.J. Tol (2004), ‘Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of *FUND*’, *Portuguese Economic Journal*, **3**, 99-114.
- Lutz, W., Sanderson, W.C. and Scherbov, S. (2004), ‘The End of World Population Growth’ in W. Lutz, W.C. Sanderson and S. Scherbov (eds.) *The End of World Population Growth in the 21st Century – New Challenges for Human Capital Formation and Sustainable Development*, EarthScan, London.
- Massey, D.S., Arango, J., Hugo, G., Kouaouci, A., Pellegrino, A., Taylor, J.E. (1993), ‘Theories of International Migration: A Review and Appraisal’, *Population and Development Review*, **19** (3), 431-466.
- Pant, H. M., 2002, *GTEM: The Global Trade and Environment Model*, Australian Bureau of Agricultural and Resource Economics, Canberra.
- Sanderson, W.C. (1998), ‘Knowledge Can Improve Forecasts: A Review of Selected Socioeconomic Population Projection Models’, *Population and Development Review*, **24**, S88-S117.

Tol, R.S.J. and H. Dowlatabadi (2001), 'Vector-borne Diseases, Climate Change, and Economic Growth', *Integrated Assessment*, **2**, 173-181.

United Nations (2003), *World Population Prospects: The 2002 Revision, Highlights*, United Nations, New York.

US Census Bureau (2003), *International Data Base*, US Census Bureau, Washington, D.C.

World Bank (2002), *The 2002 World Development Indicators*, CD-ROM, World Bank, Washington, D.C.

Table 1. Income elasticities of birth rates at the median annual income.

Age	Low	Middle	High	Conv. Fert.
15-19	-0.5127	-0.2162	0.0000	0.0196
20-24	-0.2749	-0.2060	0.0000	0.0809
25-29	-0.1730	-0.1545	0.0000	0.1438
30-34	-0.1703	-0.2271	0.0000	0.1168
35-39	-0.2506	-0.3534	0.0000	0.0479
40-44	-0.4912	-0.5652	0.0000	0.0101
45-49	-0.8190	-0.6820	0.0000	0.0008
Med. Inc.	\$315	\$1414	\$20843	

Table 2: Income elasticities of life expectancy.

Gender	Low	Middle	High
Male	0.1400	0.0754	0.0120
Female	0.1418	0.0848	0.0233

Table 3. Age and sex profile of immigrants (percent of total immigrants).

	USA		CAN		WEU		ANZ		FSU		ROW	
	male	female	male	female	male	female	male	female	male	female	male	female
0-4	2.33	2.67	2.67	2.92	3.83	3.84	4.92	4.64	3.22	3.05	3.39	3.42
5-9	3.28	3.14	3.77	3.43	3.27	3.06	4.18	4.02	3.81	3.56	3.66	3.44
10-14	4.66	4.36	5.35	4.77	2.82	2.55	3.71	3.59	3.32	3.11	3.97	3.68
15-19	5.28	5.12	3.10	3.75	3.36	4.08	3.22	3.68	3.87	4.03	3.76	4.13
20-24	4.16	5.23	3.78	4.32	5.82	8.13	3.51	5.51	6.48	6.42	4.75	5.92
25-29	5.66	7.24	7.60	7.91	10.02	9.43	6.34	8.02	7.21	5.76	7.37	7.67
30-34	5.29	6.30	7.11	6.88	7.90	6.30	6.74	7.20	6.24	4.90	6.65	6.32
35-39	3.75	4.70	5.04	5.13	5.19	4.02	5.06	5.22	5.00	4.00	4.81	4.61
40-44	2.79	3.71	3.74	4.05	3.24	2.44	3.31	3.35	3.56	3.01	3.33	3.31
45-49	2.22	2.88	1.92	1.87	1.94	1.55	2.22	2.06	2.49	2.35	2.16	2.14
50-54	1.64	2.22	1.42	1.44	1.24	1.02	1.28	1.32	1.33	1.37	1.38	1.47
55-59	1.39	2.03	1.20	1.32	0.70	0.70	0.94	1.20	1.67	2.29	1.18	1.51
60-64	1.22	1.70	1.05	1.11	0.45	0.61	0.92	1.02	1.06	1.41	0.94	1.17
65-69	1.01	1.29	0.56	0.74	0.52	0.61	0.64	0.65	0.88	1.52	0.72	0.96
70-74	0.59	0.79	0.33	0.45	0.27	0.41	0.37	0.40	0.43	1.00	0.40	0.61
75-79	0.29	0.37	0.26	0.22	0.13	0.20	0.18	0.19	0.20	0.54	0.21	0.30
80+	0.30	0.40	0.37	0.38	0.10	0.25	0.19	0.20	0.19	0.75	0.23	0.40

Table 4. Number (thousands) of people with HIV, people with newly acquired HIV and people dead by AIDS per regions.

Region	HIV 1997	dHIV 1997	AIDS 1997	AIDS 2002
USA	820.0	38.2	28.0	12.5
CAN	44.0	2.8	0.7	0.3
WEU	474.7	29.8	159.7	7.7
JPK	9.9	1.6	0.4	0.8
ANZ	12.3	1.6	0.7	0.1
EEU	31.2	2.0	1.9	1.9
FSU	208.2	12.1	0.9	50.0
MDE	86.8	16.7	0.2	1.4
CAM	293.2	151.0	21.5	19.3
LAM	1002.5	37.1	60.5	24.0
SAS	4293.5	47.7	149.7	32.0
SEA	1591.7	202.7	104.8	93.0
CHI	411.5	49.8	4.2	36.0
MAF	21.6	4.1	1.9	2.2
SSA	22333.5	3794.3	2008.3	2400.0
SIS	405.1	63.4	24.7	61.0

Table 5. Age and sex distribution of HIV.

	SSA ^a		USA ^b	
	male	Female	male	female
0-4	0.0243	0.0452	0.0017	0.0005
5-9	0.0021	0.0049	0.0017	0.0005
10-14	0.0020	0.0027	0.0017	0.0005
15-19	0.0112	0.0344	0.0140	0.0044
20-24	0.0599	0.1067	0.0140	0.0044
25-29	0.1060	0.1009	0.1115	0.0351
30-34	0.1026	0.0839	0.1115	0.0351
35-39	0.0776	0.0519	0.1555	0.0489
40-44	0.0508	0.0299	0.1555	0.0489
45-49	0.0296	0.0214	0.0705	0.0222
50-54	0.0169	0.0107	0.0705	0.0222
55-59	0.0089	0.0035	0.0197	0.0062
60-64	0.0090	0.0042	0.0197	0.0062
65-69	0.0000	0.0000	0.0132	0.0042
70-74	0.0000	0.0000	0.0000	0.0000
75-79	0.0000	0.0000	0.0000	0.0000
80+	0.0000	0.0000	0.0000	0.0000

^a 529/capita

^b \$28,662/capita

Table 6. Maximum and final population sizes (millions) in the base scenario for the 16 regions, and the ratio of maximum and final population size in the alternative cases to the bases case.

	base		no migr.		no AIDS		no tech.		broad tech.	
	2100	2200	2100	2200	2100	2200	2100	2200	2100	2200
USA	460	660	0.645	0.346	1.008	1.020	0.824	0.595	1.008	1.042
CAN	55	79	0.448	0.192	1.007	1.019	0.826	0.606	1.012	1.057
WEU	773	1286	0.334	0.114	1.019	1.045	0.851	0.668	1.021	1.103
JPK	266	349	0.472	0.203	1.003	1.012	0.814	0.606	1.015	1.059
ANZ	33	40	0.694	0.399	1.007	1.025	0.824	0.620	1.008	1.055
EEU	77	118	0.752	0.207	1.021	1.046	0.867	0.673	1.033	1.119
FSU	265	310	0.491	0.149	1.011	1.031	0.910	0.686	1.121	1.228
MEA	613	613	1.032	1.126	1.006	1.022	0.951	0.711	1.062	1.156
CAM	318	279	1.320	1.963	1.011	1.017	0.897	0.667	1.041	1.052
LAM	600	570	1.114	1.207	1.010	1.016	0.851	0.570	1.023	1.041
SAS	2390	1277	1.265	1.819	1.010	1.016	1.000	0.801	1.062	1.184
SEA	1018	868	1.005	1.033	1.011	1.015	0.941	0.696	1.070	1.089
CHI	1177	670	1.206	1.561	1.002	1.006	0.950	0.717	1.059	1.096
NAF	267	181	1.608	2.862	1.005	1.024	0.964	0.745	1.060	1.083
SSA	3441	5365	1.029	1.150	1.126	1.129	0.999	0.927	1.043	1.304
SIS	192	295	0.360	0.172	1.036	1.058	0.966	0.751	1.062	1.133
World	11947	12960	1.016	1.040	1.043	1.067	0.951	0.788	1.049	1.190

Table 7. World population (in million people) according to various studies and various configurations of CHIMP.

Study	2050	2100
IIASA	8,797	8,414
UN	8,919	-
WB	8,806	-
USCB	9,084	-
This study, base case	9,546	11,947
This study, low convergence	9,508	11,661
This study, high convergence	9,585	12,258
This study, high elasticities	9,146	9,873
This study, very high elasticities	8,792	8,238
This study, alternative elasticities	9,521	11,613
This study, alternative elasticities, no convergence	9,281	10,669
This study, natural fertility	9,529	11,828
This study, natural fertility, fast convergence	8,724	7,881

Table 8. Parameters for Equations (15) and (16), and their goodness-of-fit.

Age	κ	λ	R_{adj}^2	α	β	R_{adj}^2
15-19	-0.2751	$-3.27 \cdot 10^{-6}$	0.53	1.2763	-0.4455	0.50
20-24	-0.2261	$-1.31 \cdot 10^{-6}$	0.52	1.2691	-0.2944	0.51
25-29	-0.2144	$7.78 \cdot 10^{-7}$	0.36	0.6091	-0.1739	0.36
30-34	-0.2806	$2.03 \cdot 10^{-6}$	0.24	0.4634	-0.1751	0.22
35-39	-0.3838	$1.81 \cdot 10^{-6}$	0.28	0.5856	-0.2894	0.27
40-44	-0.5160	$6.07 \cdot 10^{-7}$	0.38	0.8764	-0.4884	0.38
45-49	-0.7748	$-8.28 \cdot 10^{-7}$	0.38	1.5264	-0.8163	0.38

Table 9. 2100 and 220 population sizes (millions) in the base scenario for the 16 regions, and the ratio of maximum and final population size in the alternative cases to the base case.

	base		high elas.		v. high elas.		alt.elas.		Nat. fert. fast	
	2100	2200	2100	2200	2100	2200	2100	2200	2100	2200
USA	460	660	0.976	0.866	0.957	0.782	0.991	0.941	0.634	0.205
CAN	55	79	0.963	0.825	0.933	0.723	0.993	0.945	0.668	0.242
WEU	773	1286	0.933	0.706	0.880	0.548	0.990	0.918	0.665	0.225
JPK	266	349	0.981	0.886	0.966	0.824	0.999	0.975	0.665	0.239
ANZ	33	40	0.974	0.835	0.954	0.744	0.997	0.958	0.655	0.227
EEU	77	118	0.897	0.677	0.816	0.509	0.973	0.901	0.689	0.219
FSU	265	310	0.861	0.676	0.752	0.498	0.955	0.895	0.771	0.237
MEA	613	613	0.858	0.657	0.743	0.452	0.927	0.820	0.629	0.173
CAM	318	279	0.868	0.732	0.756	0.545	0.909	0.798	0.607	0.134
LAM	600	570	0.940	0.859	0.885	0.751	0.894	0.796	0.566	0.122
SAS	2390	1277	0.730	0.331	0.551	0.121	1.000	0.839	0.793	0.271
SEA	1018	868	0.809	0.600	0.666	0.377	0.937	0.815	0.736	0.227
CHI	1177	670	0.996	0.957	0.992	0.932	1.000	0.990	0.619	0.188
NAF	267	181	0.796	0.542	0.645	0.316	0.935	0.777	0.661	0.160
SSA	3441	5365	0.750	0.361	0.579	0.141	0.977	0.792	0.573	0.117
SIS	192	295	0.823	0.588	0.694	0.384	0.952	0.844	0.748	0.247
World	11947	12960	0.826	0.545	0.704	0.363	0.972	0.841	0.660	0.173

Table 10. Population sizes (millions) for the 16 regions in 2100 for five alternative economic scenario for our projections (CHIMP) and the IPCC projections (IS92a and SRES).

	IS92a		A1		A2		B1		B2	
	CHIMP	IS92a	CHIMP	SRES	CHIMP	SRES	CHIMP	SRES	CHIMP	SRES
USA	460	291	448	333	447	450	445	334	440	278
CAN	55	33	53	38	54	52	53	38	52	32
WEU	773	394	715	458	751	619	713	459	713	383
JPK	266	227	265	207	256	279	259	207	254	172
ANZ	33	31	32	28	32	38	32	28	32	23
EEU	77	121	74	94	75	200	77	93	78	110
FSU	265	291	276	226	264	481	279	224	285	264
MEA	613	544	571	202	610	521	574	197	571	364
CAM	318	217	297	215	321	432	310	206	319	341
LAM	600	541	588	536	592	1080	589	514	599	852
SAS	2390	2623	1724	1135	2294	2922	1902	1102	1937	2039
SEA	1018	1062	920	459	1014	1183	932	446	949	826
CHI	1177	1687	1303	1035	1119	2664	1265	1005	1232	1859
NAF	267	408	225	228	267	459	237	219	259	362
SSA	3441	1903	2633	1064	3630	2143	2849	1020	3255	1691
SIS	192	67	172	66	190	133	179	63	188	105
World	11947	10438	10298	6323	11915	13655	10695	6155	11163	9701

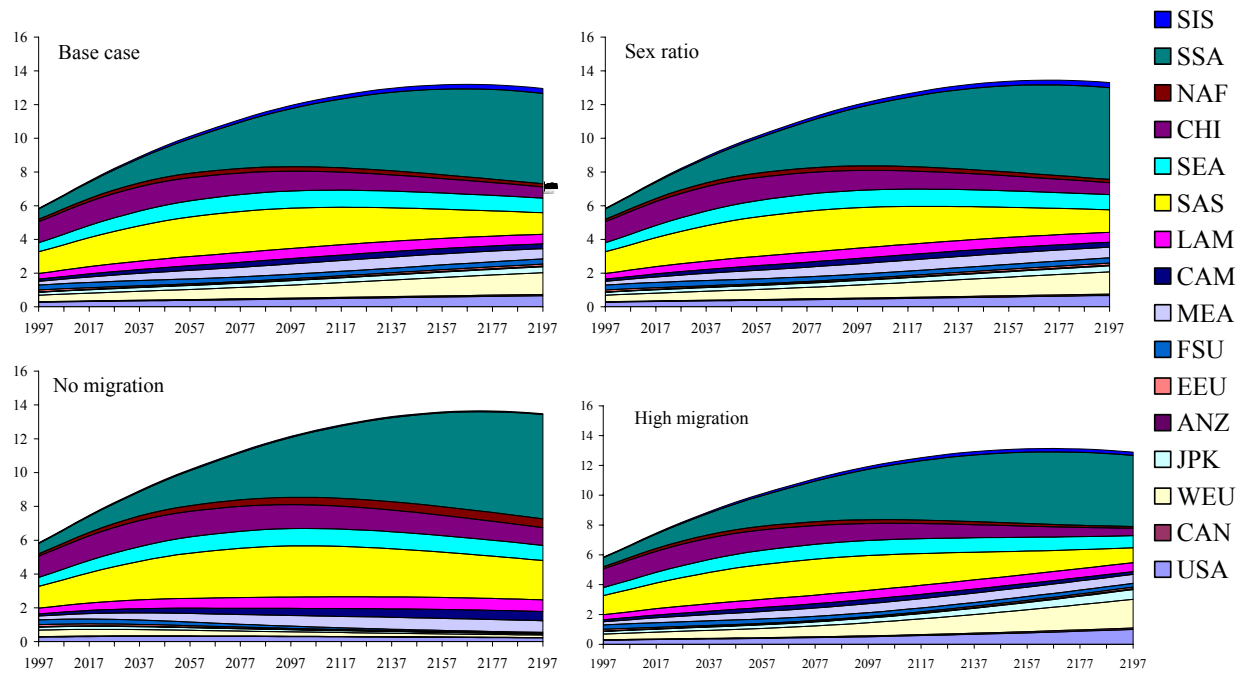


Figure 1. Projected population sizes (billion people) for 16 world regions for the period 1997-2197, for the “base case”, for the case in which the “sex ratio” of new-born children converges to 0.5 in 2200, for the case with “no migration” and for the case with “high migration”.

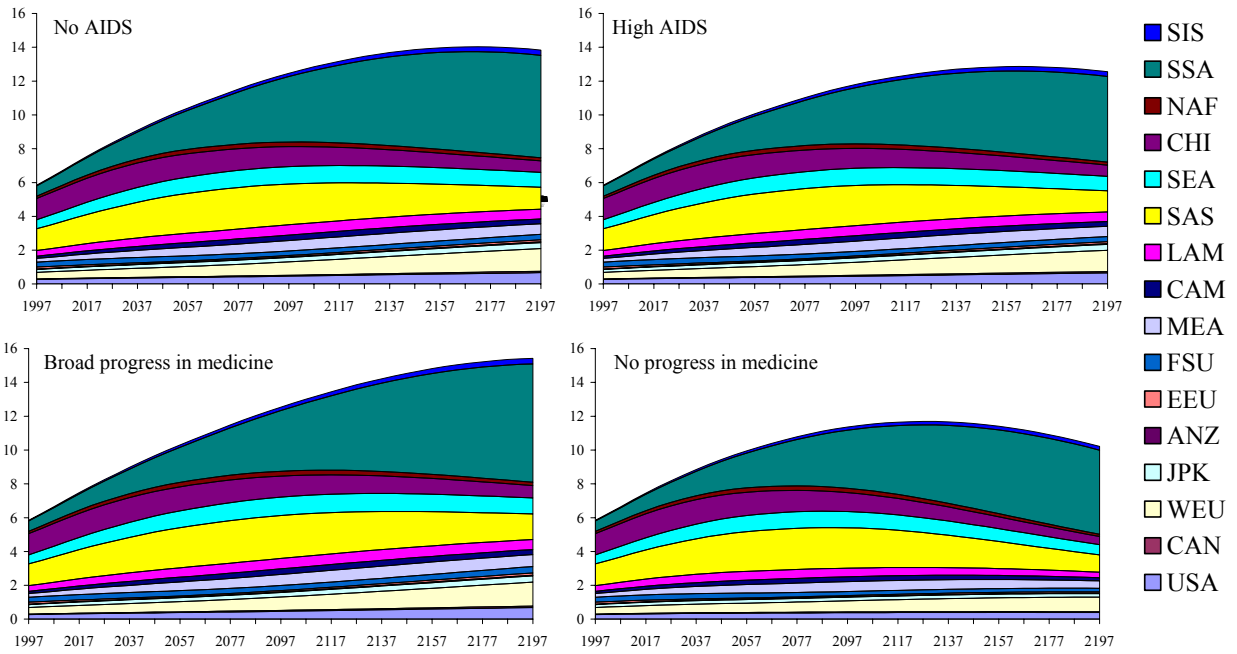


Figure 2. Projected population sizes (billion people) for 16 world regions for the period 1997-2197, for the case with “no AIDS”, for the case in with “high AIDS” because of lack of technological progress, for the case with “broad progress in medicine” and for the case with “no progress in medicine”.

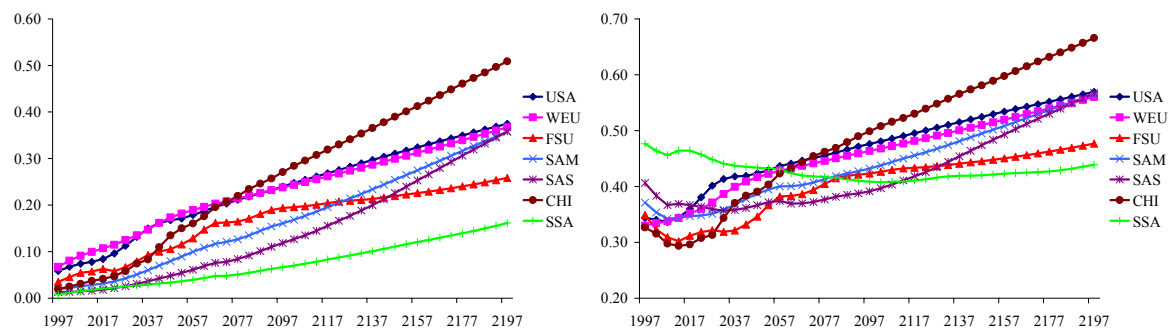


Figure 3. The fraction of people over 75 years of age (left panel) and the fraction of people under 15 and over 65 (right panel) in the total population for seven regions.

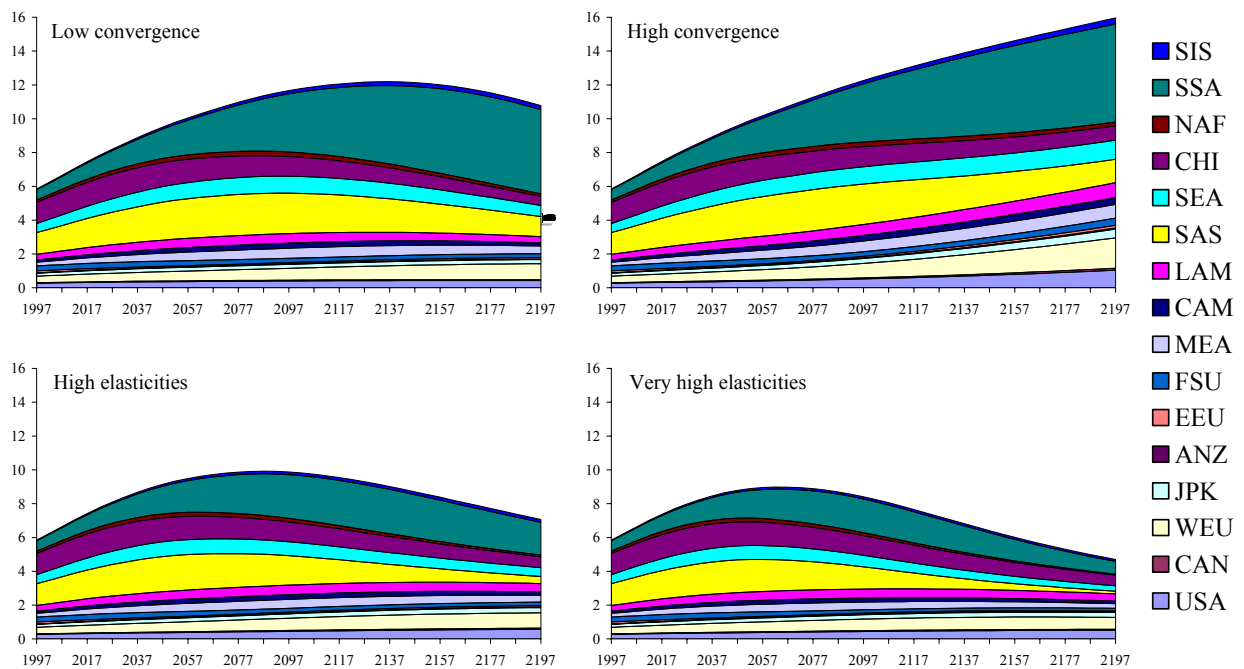


Figure 4. Projected population sizes for 16 world regions for the period 1997-2197 for the case in which the total fertility rate converges to a low level of 1.1 (“low convergence”), to a high level of 2.1 (“high convergence”), for the case in which the income elasticities of fertility are 50% higher (“high elasticities) and 100% higher (“very high elasticities) than in the base case. In the last two cases, as well as in the base case, total fertility converges to 1.6 children per woman.

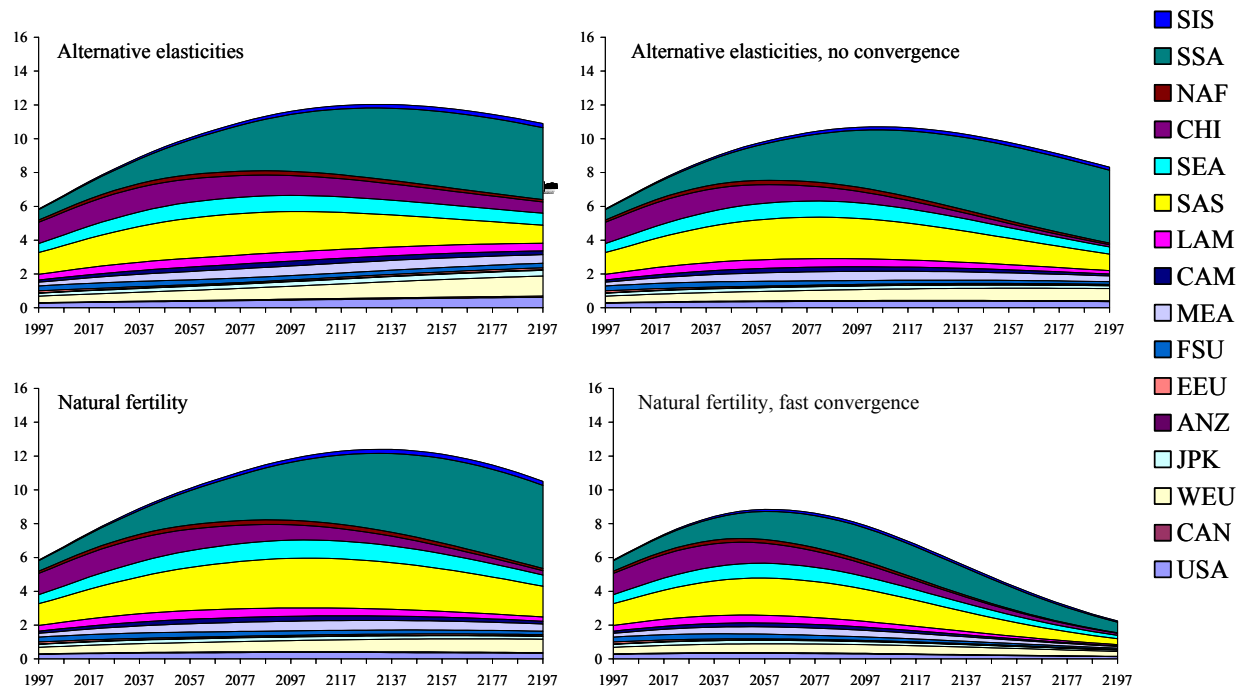


Figure 5. Projected population sizes for 16 world regions for the period 1997-2197, for the “alternative elasticities” of fertility, with and without convergence to a total fertility rate of 1.6, and for convergence to “natural fertility” at a rate of 3% per five years and 6% per five years (“fast convergence”).

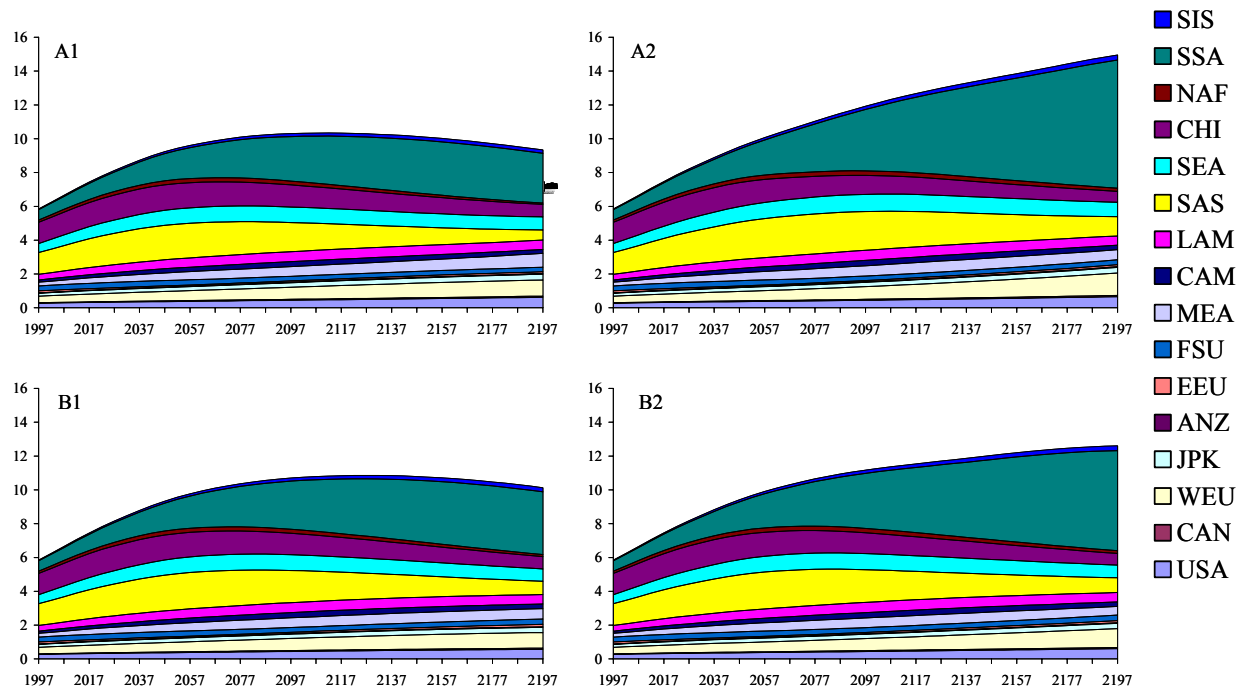


Figure 6. Projected population sizes for 16 world regions for the period 1997-2197 for the four SRES scenarios of per capita income.

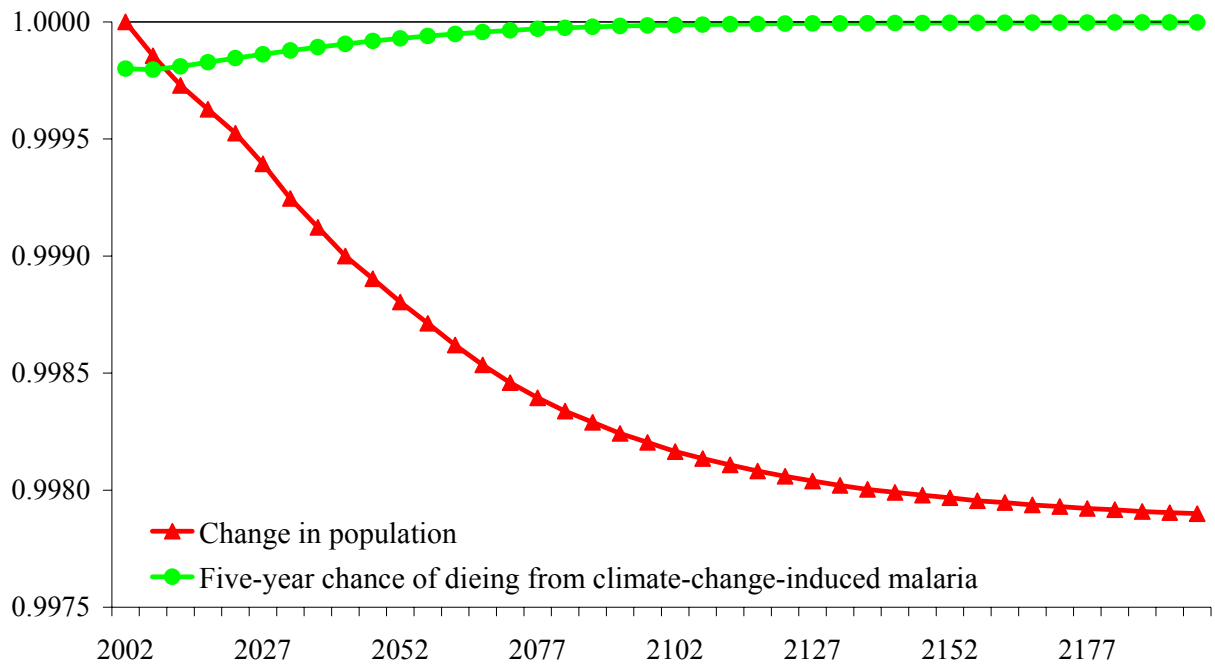


Figure 7. The effects of climate-change-induced malaria on the population of Sub-Saharan Africa as a fraction of the baseline simulation without climate change. The figure also show the climate-change-induced malaria mortality per five years.

Table A1.

World

Number of observations 2481
Adjusted R2 0.9428

	Coefficient	Std. Error	t-Value
log(emigr.(t-1))	0.9476821	0.00536	176.8
log(distance)	-0.0867437	0.015167	-5.72
gdppc	-0.454691	0.194734	-2.33
diffGDPPC	0.0029703	0.001184	2.51
share0_9	-0.4273436	0.187164	-2.28
fsu	-0.1134654	0.047501	-2.39
_cons	0.2416427	0.130064	1.86

Weighted estimates**Australia**

Number of observations 1087
Adjusted R2 0.9034

	Coefficient	Std. Error	t-Value	Coefficient	Std. Error	t-Value
log(emigr.(t-1))	0.9013555	0.012103	74.48	0.942628	0.004801	196.354
log(distance)	-0.2403432	0.053994	-4.45	-0.10223	0.014098	-7.2517
gdppc	-0.650616	0.362611	-1.79	-0.52942	0.171357	-3.0896
diffGDPPC	0.0016859	0.002303	0.73	0.003292	0.001029	3.19837
share0_9	-1.231078	0.360566	-3.41	-0.56065	0.16262	-3.4476
fsu	-0.1612506	0.094716	-1.7	-0.12096	0.04242	-2.8515
_cons	1.30249	0.475412	2.74	0.341539	0.120543	2.83333

Canada

Number of observations 31
Adjusted R2 0.9772

log(emigr.(t-1))	0.9112322	0.056362	16.17	0.948205	0.005152	184.038
log(distance)	0.1235917	0.144609	0.85	0.079435	0.014197	5.59526
gdppc	4.996796	1.802019	2.77	-0.3478	0.192514	-1.8066
diffGDPPC	-0.0196873	0.01354	-1.45	0.003295	0.001142	2.88634
share0_9	3.326834	1.384513	2.4	-0.41424	0.184177	-2.2491
fsu	(dropped)			(dropped)		
_cons	-2.544648	1.683802	-1.51	0.174407	0.123473	1.41252

Western Europe

Number of observations 715
Adjusted R2 0.9428

log(emigr.(t-1))	0.9499063	0.010513	90.36	0.949327	0.004685	202.62
log(distance)	-0.0166239	0.021934	-0.76	-0.06864	0.011554	-5.9406
gdppc	-0.4328525	0.299416	-1.45	-0.45269	0.163145	-2.7747
diffGDPPC	-0.0012822	0.001874	-0.68	0.002171	0.000987	2.19839
share0_9	-0.0721259	0.299602	-0.24	-0.29355	0.157932	-1.8587
fsu	-0.0836907	0.076452	-1.09	-0.11332	0.039927	-2.8383
_cons	-0.2934721	0.174033	-1.69	0.086892	0.099041	0.87733

USA

Number of observations 639

Adjusted R2 0.9459

log(emigr.(t-1))	0.9495672	0.012106	78.44	0.95159	0.004536	209.809
log(distance)	-0.1178772	0.043011	-2.74	-0.08774	0.014073	-6.2351
gdppc	-0.0491059	0.303473	-0.16	-0.3404	0.163846	-2.0776
diffGDPPC	0.0022006	0.002361	0.93	0.003016	1.039721	0.0029
share0_9	-0.2513813	0.324668	-0.77	-0.37386	0.161198	-2.3192
fsu	-0.0858835	0.068922	-1.25	-0.10325	0.038985	-2.6484
_cons	0.544956	0.334606	1.63	0.284097	0.119296	2.38145

Working Papers
Research Unit Sustainability and Global Change
Hamburg University and Centre for Marine and Atmospheric Science

- Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), *CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change*, **FNU-69** (submitted)
- Rehdanz, K. and R.S.J. Tol (2005), *A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India*, **FNU-68** (submitted)
- Zhou, Y. and R.S.J. Tol (2005), *Water Use in China's Domestic, Industrial and Agricultural Sectors: An Empirical Analysis*, **FNU-67** (submitted)
- Rehdanz, K. (2005), *Determinants of residential space heating demand in Germany*, **FNU-66** (submitted)
- Ronneberger, K., R.S.J. Tol and U.A. Schneider (2005), *KLUM: A simple model of global agricultural land use as a coupling tool of economy and vegetation*, **FNU-65** (submitted)
- Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of FUND*, **FNU-64** (submitted)
- Röckmann, C., M.A. St.John, F.W. Köster, F.W. and R.S.J. Tol (2005), *Testing the implications of a marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions*, **FNU-63** (submitted)
- Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), *Triple Dividends of Water Consumption Charges in South Africa*, **FNU-62** (submitted)
- Zandersen, M., Termansen, M., Jensen, F.S. (2005), *Benefit Transfer over Time of Ecosystem Values: the Case of Forest Recreation*, **FNU-61** (submitted)
- Rehdanz, K., Jung, M., Tol, R.S.J. and Wetzel, P. (2005), *Ocean Carbon Sinks and International Climate Policy*, **FNU-60** (submitted)
- Schwoon, M. (2005), *Simulating The Adoption of Fuel Cell Vehicles*, **FNU-59** (submitted)
- Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58** (submitted)
- Bosello, F., R. Roson and R.S.J. Tol (2004), *Economy-wide estimates of the implications of climate change: Human health*, **FNU-57** (submitted, *Ecological Economics*)
- Hamilton, J.M. and M.A. Lau (2004) *The role of climate information in tourist destination choice decision-making*, **FNU-56** (forthcoming, Gössling, S. and C.M. Hall (eds.), *Tourism and Global Environmental Change*. London: Routledge)
- Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (submitted, *Climatic Change*)
- Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54** (submitted)
- Susandi, A. and R.S.J. Tol (2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53** (submitted)
- Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52** (forthcoming, Schlesinger et al. (eds.), Cambridge University Press)
- Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51** (submitted)
- Link, P.M., U.A. Schneider and R.S.J. Tol (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50** (submitted)
- Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49** (submitted, *Tourism Management*)
- Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of FUND*, **FNU-48** (submitted, *Mitigation and Adaptation Strategies for Global Change*)

- Erdil, Erkan and Yetkiner, I. Hakan (2004), *A Panel Data Approach for Income-Health Causality*, **FNU-47**
- Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of FUND*, **FNU-46** (forthcoming, *Energy Journal*)
- Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of FUND*, **FNU-45** (submitted, *Climatic Change*)
- Gaitan, B., Tol, R.S.J., and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44** (submitted)
- Rehdanz, K. and Tol, R.S.J. (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43** (submitted)
- Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of FUND*, **FNU-42** (*Portuguese Economic Journal*, **3**, 99-114)
- Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport*, **FNU-41** (forthcoming, *Water Resources Research*)
- Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg*, **FNU-40** (submitted, *Coastline Reports*)
- Rehdanz, K. and Maddison, D. (2004), *The Amenity Value of Climate to German Households*, **FNU-39** (submitted)
- Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38** (submitted, *Environmental and Resource Economics*)
- Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO₂-abatement with socio-economic inertia and induced technological change*, **FNU-37** (submitted, *Energy Journal*)
- Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism*, **FNU-36** (forthcoming, *Climate Research*)
- Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35** (submitted)
- Heinzow, T. and R.S.J. Tol (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach*, **FNU-34** (submitted, *Climate Research*)
- Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods*, **FNU-33** (submitted, *Environmental Science and Policy*)
- Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32** (submitted)
- Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study*, **FNU-31** (forthcoming, *Global Environmental Change*)
- Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (submitted)
- Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)
- Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (submitted)
- Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series*, Issue 6, pp. 120-124; <http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf>)
- Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (forthcoming, *Integrated Assessment*)
- Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**
- Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions*, **FNU-24**
- Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23** (submitted)
- Zhou, Y. and Tol, R.S.J. (2003), *The Implications of Desalination to Water Resources in China - an Economic Perspective*, **FNU-22** (*Desalination*, **163** (4), 225-240)

- Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**
- Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU-20** (*Ecological Economics*, **52** 111-125)
- Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (*Energy Policy*, **33** (16), 2064-2074).
- Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).
- Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).
- Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of FUND*, **FNU-16** (forthcoming, *Climatic Change*).
- Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists*, **FNU-15** (revised and submitted).
- Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of FUND*, **FNU-14** (forthcoming, *Climate Policy*).
- Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (forthcoming, *Climatic Change*).
- Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of FUND*, **FNU-12** (forthcoming, *Environment and Development Economics*).
- Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (forthcoming, *Ecological Economics*).
- Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (*Resource and Energy Economics*, **27**, 1-17).
- Tol, R.S.J. and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).
- Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).
- Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).
- Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted, *International Environmental Agreements*).
- Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).
- Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l’Air Propre?*, 155-179).
- Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).
- Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics*, **1** (4), 179-206)
- Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).