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Published in:
Nature Climate Change

DOI:
10.1038/NCLIMATE3222

Published: 01/01/2017

Document Version
Peer reviewed version

Citation for published version (APA):
Lutz, W., & Muttarak, R. (2017). Forecasting societies' adaptive capacities through a demographic metabolism model. *Nature Climate Change*, *7*, 177 - 184. https://doi.org/10.1038/NCLIMATE3222

Forecasting societies' adaptive capacities through a demographic metabolism model

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Main text: 5,600 words

Number of reference: 107 references

Number of figures: 3 figures

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Abstract

In seeking to understand how future societies will be affected by climate change we cannot simply assume they will be identical to those of today, because climate and societies are both dynamic. Here we propose that the concept of demographic metabolism and the associated methods of multi-dimensional population projections provide an effective analytical toolbox to forecast important aspects of societal change that affect adaptive capacity. We present an example of how the changing educational composition of future populations can influence societies' adaptive capacity. Multi-dimensional population projections form the human core of the Shared Socioeconomic Pathways scenarios, and knowledge and analytical tools from demography have great value in assessing the likely implications of climate change on future human well-being.

Assessing the likely impacts of climate change on future human well-being requires a combination of two kinds of forecasts: how the climate of the future will be different from that of today; and how humans and there societies in the future will differ in terms of numbers, regional distributions, age structures and, most importantly, their capacities to successfully adapt to changing climatic conditions. This includes capacities at multiple levels from individual, to household, community and national level as well as the associated qualities of institutions and levels of economic development. Much work has been carried out in terms of modelling the future climatic conditions[1–3], but very little has been done for modelling the future socioeconomic conditions. Successful adaptation is also dependent on the qualities of institutions and levels of economic development. In this *Perspective*, we discuss recent progress in the latter field, especially in the demographic metabolism model and illustrate the potential of multi-dimensional demographic methods for forecasting societies' adaptive capacities to climate change.

The Working Group II contribution to the IPCC Fifth Assessment Report appropriately summarizes what was the state of the art on this issue: "Most scenario-based assessments superimpose biophysical 'futures' onto present-day socioeconomic conditions."[4]. While this statement is based on many studies that in fact did this – for example, the estimation of the likely increase in malaria deaths in Africa by matching the future climate conditions with today's social conditions[5] – this is a highly unsatisfactory, if not outright misleading, approach. The IPCC report continues saying: "This is useful for assessing how current socioeconomic conditions may need to change in response to biophysical impacts but raises inconsistencies when future socioeconomic states are out of step with biophysical states"[4]. While we agree with the second part of the statement we disagree with the first one because it is known with near certainty that socioeconomic and demographic conditions in the future will be different from today. Thus, we see little value in the purely hypothetical exercise of assessing potential impacts of the future climate on a society that will not exist in the future. This may even result in misleading assessments.

In fact, the IPCC report recognizes this problem by saying "An important challenge, therefore, is to construct impact assessments in which biophysical futures are coupled with socioeconomic futures. A new set of socioeconomic futures, known as Shared Socioeconomic Pathways (SSPs), which are storylines corresponding to the new Representative Concentration Pathways, is being developed to assist this process"[4]. In the following Perspective, we further pursue this approach and discuss the scientific basis for the human core of the SSPs – the demographic model generating the scenarios of changing population size and composition by age, gender and level of educational attainment. This has been designed to capture key dimensions of future adaptive capacity. We first address the temporal nature of human–climate interactions and describe the toolbox of multidimensional population dynamics and the concept of demographic metabolism that translates them into measurable social change. We then provide an example of educational attainment (as one important population characteristic) and its role in enhancing adaptive capacity. We conclude with illustrations of numerical applications of the approach and policy recommendations.

It is important to clarify right at the beginning that in this *Perspective* we will not address all possible consequences of climate change but only those that we consider most dangerous to human well-being. These include all threats to human life (death is irreversible), human health (in particular serious and lasting disability) and basic human subsistence (for example, the risk of absolute poverty which causes higher risk of death and disability). Economic losses that affect wealthy people but fall short of pushing them into poverty will not be considered in this analysis since they are caused by different mechanisms. For example, the destruction of expensive houses by storms that rich people built in highly exposed coastal locations is not considered in our approach to studying adaptive capacities. Moreover, there is no consistent measure of total economic losses[6] and the evidence on a negative impact of natural disasters, especially on indirect loss, remains inconclusive[7]. For this reason, our arguments do not relate adaptive capacity to potential economic loss. Instead they relate primarily to loss of life, health and basic livelihood.

Temporal associations between society and global climate

[FIGURE 1: ABOUT HERE]

Figure 1 illustrates the circular link between the human population including its size and structure, socioeconomic development and the global climate system. The two systems interact dynamically with a complex lag structure both on the mitigation and adaptation sides of the circle.

The left side of the diagram shows that humans have been causing changes to the climate system mostly through the burning of fossil fuels and land use change. This is a cumulative process that has been going on at least for a century and will likely continue over the coming decades. It is triggered by both the growing number of humans and increasing per person impacts, which in turn can be decomposed into income (consumption) and technology effects working in opposite directions. A decomposition of these effects is sometimes discussed in terms of the so-called I=PAT equation (Impact = Population x Affluence x Technology) which has been introduced by Ehrlich and Holdren[8] and also by Kaya[9]. It can be quantified in terms of the identity CO_2 = (population) x (GDP per capita) x (energy per unit of GDP) x (CO_2 per unit of energy use). Several studies have tried to assess the relative impacts of the three factors which turned out to be rather problematic because the three factors are not independent. Technology and affluence work in opposite directions and other factors such as household size were shown to be equally relevant[10,11]. There is however no doubt that in a synergistic way, all these human activities together are responsible for the increased concentration of greenhouse gases in the atmosphere contributing to global warming.

On the right hand side of Fig. 1, we see the impacts of the changed climate at time t + x on the human population. The changes in the climate can directly affect human health and mortality (due to natural disasters and changes in the disease environment), and impact on human livelihoods as they cascade through the entire economic production chain. In the context of our focus on basic subsistence, the effects on farming through changing agricultural productivity especially in the context of subsistence farming in less developed countries are of particular relevance. These impacts may also trigger migration flows either within countries or to other countries. Flooding and sea level rise can also directly drive populations out of certain territories. The actual push factors for out-migration will likely result from a complex interplay between environmental and economic reasons and political and security conditions.

The literature on possible climate change induced international migration abounds and tends to be rather speculative in nature[12]. A comprehensive assessment of the scientific evidence concludes that while one response to environmental change is to migrate (reflected on the right of Fig. 1)[13], populations who experience the impacts of environmental change may see a reduction in the very capital required to enable a move. In fact, millions of people will be *unable* to move away from locations where they are vulnerable to environmental change. If climate-driven migration does occur, it will likely be short distance, within national borders[14]. The net result of this on international migration thus is quite uncertain.

Figure 1 suggests that there are multidecadal lags in the system and the humans causing the change through their emissions (at time *t*) are typically of a different generation to those being affected by the consequences (at time $t + x$). Note, however, that these different generations may have different degrees of vulnerability and different capacities and options for adapting to climate change.

Adaptive capacity is not only linked to the capacities of social and economic systems: additionally, there is and will be substantial heterogeneity within populations. Population heterogeneity is captured by observable individual characteristics such as age, gender, education, income, and place of residence ,which determine a population's capacity to adapt[15]. In other words, similar to the risk of disease, people living in the same community or even within the same household are likely to have differential vulnerability depending on their characteristics. Moreover, the composition of the population with respect to these characteristics is not static but is changing over time.

When addressing societies' future adaptive capacities, we also need to take account of the complex interactions between human capital (knowledge and skills embodied in individuals) and social capital (institutions, regulations and public policies such as zoning that structure the individual adaptive decisions). While social capital facilitates the formation of human capital[16], it is enhanced human capital that will produce stronger social capital. Good institutions do not fall from heaven nor can they be imposed by other powers: they have to evolve from an increasingly self-empowered population. There is evidence on how increasing levels of education in a population help improve the quality of institutions and bring about democratic decision making processes through increasing civic and political participation[17–19]. While it is close to impossible to forecast the quality of specific institutions, there are tools to forecast societies level of aggregate human capital, which is a necessary prerequisite for the development of such institutions. Indeed, there is a strong statistical association with the causality clearly going from better education (comes years before) to higher adult human capital with a decadal-scale lag time and, subsequently, better institutions. In this respect, human capital, which is forecastable, can be treated as a proxy of institutional capacity, which is more difficult to forecast directly. Knowing the future composition of the population with its associated capacities will thus assist policy planning including those related to climate change.

Population dynamics and demographic metabolism

In the following, we present a new approach for modelling and forecasting socioeconomic change for decades into the future based on the changing composition of populations by relevant characteristics (for example, age, gender, level of education, and other stable individual characteristics) that matter for future adaptive capacity both at individual and societal levels. Unlike economic forecasts and predictions of human behaviour that are rather volatile and within a few years can move in totally unexpected directions, demographic forecasts are remarkably inert. Population forecasting is reliable over decades because it refers to the slowly changing stocks of people with life expectancies of well above half a century and many characteristics established at young age (for example, education) that remain unchanged over the life course.

While the tool is demographic in its approach and origin, the applicability goes far beyond what are conventionally thought to be demographic questions. To our knowledge, this is the only existing tool for relevant quantitative social forecasting at a timescale that is applicable for climate change-related analyses.

Demography studies the changing size and composition of populations. As this scientific discipline developed out of what used to be called ‘political arithmetic’, there has been a long tradition of forecasting future population trends for all kinds of government policies ranging from military to health and education systems. Originally, the approach was to consider the population as homogeneous and projection was simply done by applying an assumed growth rate to a given initial population size. Although birth and death rates vary strongly with age, under conditions of rather stable age structures, this was a useful approximation and it is still widely used, for example, in animal demography. For human populations, however, age structures in Europe became irregular due to fertility declines and the strong fluctuations in births and deaths associated with World War I, the Spanish Flu and the Great Depression.

Therefore, since the middle of the twentieth century, most population projections have been based on an age-specific model, called the cohort-component model which projects populations along cohort lines (for example, the cohort aged 20-24 in 2015 becomes 25-29 in 2020) adjusting for the three principal components of population change: fertility, mortality and migration. While the model differentiating population by age and gender has been widely used, multi-dimensional population models can actually sub-divide populations by further observable characteristics that are considered relevant and whose distribution can influence population dynamics. In terms of methods, projection is similarly done along cohort lines (e.g. the proportion of women with high school graduation aged 25-29 in 2015 is a good predictor of women aged 60-64 with high school graduation in 2050 after accounting for mortality and migration). Since in most countries both fertility and mortality tend to vary greatly by level of education, explicitly accounting for educational differences also changes the population forecasts[20] .

This model of population change along cohort lines has also been generalized to a model of social change with predictive power called demographic metabolism[21]. Building on the earlier work of the sociologist Karl Mannheim[22] and the demographer Norman Ryder[23], this concept operationalizes the age old view that societies change as a function of new generations, that are different in relevant ways, successively replacing older ones. The notion of "demographic metabolism" was introduced by Ryder who saw this replacement through new generations with different perspectives and characteristics as the only mechanism of social change. In his view "a population whose members were immortal would resemble a stagnant pond"[24]. The generalization by Wolfgang Lutz[21] further allows for individuals to change over their life cycle and thus model the combined effects of new and different cohorts moving up the age pyramid as time passes while certain proportions within each cohort change from one sub-population to another (such as from secondary to tertiary education). Capturing these movements between different sub-categories of each cohort through a set of age- and gender-specific transition probabilities allows for the application of the powerful methods of multi-dimensional mathematical demography mentioned above[25,26]. Hence, the model of demographic metabolism can describe and forecast under certain assumptions how societies change as a consequence of the changing composition of their members with respect to certain relevant and measureable characteristics.

[FIGURE 2: ABOUT HERE]

This social change through successive generational replacement can be illustrated in the form of three-dimensional age pyramids. For the case of the Republic of Korea, Fig. 2 shows in different colours the proportions of men and women in different age groups who have different levels of education. In 1970, the Republic of Korea was still a poor developing country with a very young population structure and only the younger age groups benefitted from then recent education expansions. Virtually all women above the age of 50 had never attended any school. For the pyramid in 1990, we clearly see that the entire education pattern has essentially moved up the age pyramid by 20 years. By then, the better educated younger cohorts had reached the main working ages which also was a factor driving the rapid economic growth of that time[27]. By 2010 the education structure had moved up another 20 years and as a consequence of improved female education, birth rates strongly declined. This mechanism of cohorts moving up can be extended into the future as the pyramid for 2030 shows. By then, even the elderly in Korea will have some education and the uneducated population will essentially disappear.

This model does not only hold for the changing educational composition. It can also be applied to other relevant characteristics that tend to be persistent along cohort lines. For instance, the entry of new generations who have grown up being exposed to environmental education and post-materialistic values[28] can influence environmental attitudes and environmental behaviour at the societal level. The concept of demographic metabolism has already been applied to modelling and forecasting the changing prevalence of attitudes towards gender roles[29,30], homosexuality[31] and European identity[32,33] where younger and older birth cohorts differ mainly because younger generations were socialized in different social environments.

There are also relevant cohort effects with respect to health. Owing to social and economic development over the second half of the twentieth century, there is strong evidence showing that younger cohorts, especially those born after 1960 are healthier than the older ones at any given age. This pattern is particularly discernible in old age both for physical capability and cognitive function[34–36]. Although the elderly are particularly vulnerable to certain weather extremes such as heat waves and population ageing is expected to amplify the risks associated with heatwaves[37], the process of demographic metabolism suggests that older people in the future will not only be better educated but will likely be healthier and have better cognitive function than those of today. This implies that the healthier and better informed subsequent cohorts will be able to cope better with the health challenges associated with climate change. The central role of the changing composition of human populations in socioeconomic development thus has significant implications for the ability to cope with the changing climate.

In fact, adaptation practices have been categorized along different dimensions such as by spatial scale, sector, type of action, climatic zone, baseline development level and actor[38]. Furthermore, adaptations involve anticipatory and reactive actions and include adaptation to short-term weather variability and extreme events and to longer-term climate change including sea-level rise. While heterogeneity in the populations' characteristics of today determine coping responses to current weather variability, anticipating the future population composition through the process of demographic metabolism allows for forecasting societies' capacity to adapt to climate change in the longer-term. For instance, changing educational composition in the population is highly relevant to societies' adaptive capacity as explained below.

Education changes our behaviour and reduces vulnerability

Regarding how precisely education contributes to vulnerability reduction, we build the argument upon a well-established causal link between education and health[39–42]. Education influences our cognitive function, attitudes and behaviours and equips us with better social and economic opportunities. Schooling enhances cognitive development through increasing the synaptic density in relevant parts of the brain. Not only experimental and observational studies have provided confirmation of a robust effect of education on executive functioning and cognitive abilities[43–45]: neurocognitive and neuroimaging studies have also shown strong associations between adaptive changes in the brain and learning experience in classrooms[46,47]. Abstract cognitive skills such as categorization and logical deduction acquired through schooling enhance the way educated individuals reason, solve problems, assess risks and make decisions[48,49] – those skills and qualities that are highly relevant for adapting to climate change. Similarly, since education improves knowledge, understanding of complex information, efficiency in allocation of resources and capacity to plan for the future[50–52], this can help in making better choices on adaptation options such as what insurance to take or how to reinforce building structure.

Furthermore, education indirectly reduces vulnerability through mediating factors such as improved socioeconomic status and social capital. The increased income, for instance, allows people with higher levels of education to make not only the right but also costly strategic investments to reduce vulnerability. With greater social capital and larger social networks[53,54], the more educated also have better access to information and social support which facilitate coping responses and undertaking of adaptation measures. Through these direct and indirect mechanisms, there is sufficient ground to assume that education plays a role in reducing vulnerability and enhancing adaptive capacity.

A cautionary note is required on the interplay of the effects of education and income on vulnerability. There is a widespread view that income or GDP per capita is the most important aspect of socio-economic development and also that it is directly related to vulnerability and adaptive capacity. Many empirical studies indeed find an association between the two[55–57]. The alternative hypothesis, however, is that the cognitive enhancement associated with education is the common cause of both higher income and economic growth[27,58,59] and lower vulnerability. The association between income and vulnerability thus is spurious. Testing these contradictory hypotheses is beyond the scope of this *Perspective*. There is however evidence based on a study of disaster-related mortality in 167 countries over the period 1970-2010 confirming that female education is the most significant factor resulting in fewer deaths from climate-related disasters after controlling for the effect of income[60]. Most extant studies on human loss from climate hazards nevertheless commonly consider either only GDP[55–57] or a composite indicator such as Human Development Index[61]. In fact, when the latter is decomposed into its three elements (income, education and health)[62], the results show that countries with higher level of education on average did experience lower disaster mortality while income did not play a significant role[60].

In this context, it is also enlightening to look at the rich body of literature studying child mortality as an aspect of vulnerability. Multivariate (controlling for many relevant factors) and multi-level (stratified by household, community, national level) studies have clearly come to the conclusion that for child survival, mothers' education matters more than household wealth as measured by various indicators[63,64]. Another series of studies has tried to explicitly test the importance of education with respect to disaster vulnerability after controlling for income and vice versa, asking what matters more, income or education? Generally, the result was that for vulnerability, mind matters more than money[62,65–68].

With all this evidence at the micro level, it is not surprising that the vulnerability reducing role of education also dominates at the macro level. Recent empirical studies have demonstrated consistent evidence showing that countries and communities with higher average levels of education experience lower vulnerability to natural disasters[69]. This applies to both developed and less developed countries as well as different dimensions of vulnerability including preparedness and responses to disasters, mortality, morbidity, coping strategies, recovery from disasters and other relevant outcomes. With respect to disaster preparedness (measures taken to prepare for and reduce the impacts of disaster such as having family evacuation plan, emergency supply kit, and disaster insurance), undoubtedly, direct experience of a disaster is one key driver of disaster risk reduction efforts. However, in the absence of disaster experience, it has been reported that the highly educated exhibit higher level of disaster preparedness thanks to their better abstraction skills in anticipating the consequences of disasters i.e. thinking about the counterfactual that has not yet been experienced[66,70]. Indeed, better disaster preparedness among more educated communities can provide protective effects when a disaster strikes. Not only were educated individuals more likely to survive and had a lower risk of injuries e.g. from the 2004 Indian ocean tsunami[71,72], communities and countries with higher average levels of education also experienced much lower losses in human lives from climate-related disasters[60,62,65,73]. The protective role of education further extends to morbidity associated with natural hazards, especially mental health with more highly educated individuals showing a lower prevalence of distress, depression and post-traumatic stress disorder following a disaster[71,74–76].

Likewise, since education facilitates decision making related to disaster risk reduction measures such as construction practices and location decisions, damages to residential property and economic losses are found to be lower in communities and countries with higher mean year of schooling or higher literacy rate[65,77,78]. Furthermore, with better access to loans and credits as well as larger assets and social networks which provide a wider portfolio for coping strategies, households or communities with higher level of education on average are better able to maintain their welfare and level of consumption after being affected by disaster shocks[79–83].

With respect to adaptation to the changing climate, education is indeed highly relevant since individuals with higher level of education are also more likely to have better awareness of climate risk[84]. Given that climate change is a relatively new form of risk and a rather sophisticated scientific subject, education facilitates the understanding of new ideas and concepts related to climate variability. Accordingly, a wide range of studies reported a higher likelihood of carrying out adaptation actions such as changing crop types, planting and harvesting dates, methods of farming and using improved type of seed among better educated households[85–87]. Education also increases options to diversify livelihood and sources of income when facing climate pressure[88]. For instance, migration as an adaptation strategy to cope with livelihood disruptions due to environmental change often involve more educated members[89].

With the focus of this review on "dangerous" climate change, given the consistent evidence on the protective role of education in reducing disaster vulnerability [69], we can conclude that better educated societies are more resilient and hold greater adaptive capacity to climate change. This insight is relevant when deciding what qualities/characteristics of populations shall be forecasted when assessing future adaptive capacities in the context of global socioeconomic scenarios used in the analysis of climate change. Because these qualities go far beyond the mere consideration of population size – as has been done in earlier work based on the Special Report on Emissions Scenarios (SRES)[90] – the new Shared Socioeconomic Pathways (SSPs) approach has the populations fully stratified by age, gender and level of education.

Scenarios of future adaptive capacity

The qualitative narratives of the SSPs describe alternative future worlds with respect to socioeconomic development that matters for both mitigation and adaptation challenges. These narratives have been translated into consistent quantitative scenarios covering future trends in areas ranging from population and education[91], to GDP growth[92], urbanization[93], energy and land use. Here we will only focus on what has been termed "the human core of the SSPs"[94] because it directly addresses the future of human beings, including their changing numbers and regional distributions as well as their health and empowerment through education.

The calibration of the SSPs was carried out in tandem with a major new effort to summarize the international state of the art with respect to the drivers of future fertility, mortality, migration and education trends. Over 550 international population experts participated in an attempt to assess alternative substantive arguments that pertain to future demographic trends. The results were subsequently translated into alternative demographic assumptions for all countries of the world until 2060[95]. The specifications of these demographic scenarios followed the general narratives of the SSPs[94]. More specifically, the medium scenario of these new expert argument based projections – which is considered the most likely in terms of future fertility, mortality, migration, and education trends – was set to be identical with SSP2 which reflects a “middle of the road” scenario.

[FIGURE 3: ABOUT HERE]

Fig. 3 shows the global population and education trajectories for the three SSPs. The scenario story lines in SSP1 envisage a rapidly developing world with more education, lower mortality, and a more rapid fertility decline in countries with high fertility. For today’s rich OECD countries this scenario, based on economic prosperity, assumes medium fertility as couples are likely to be better able to realize their childbearing aspirations. SSP3, in contrast, assumes increasing global inequality in the context of social and economic stagnation leading to stagnant school enrolment rates and retarded demographic transition. For the rich OECD countries, the picture is different with adverse economic conditions assumed to result in low fertility. As Fig. 3 illustrates, by 2050 SSP1 and SSP3 already differ greatly in terms of resulting population size and education structures. Total population size will differ by as much as 1.5 billion over the coming four decades (8.5 billion for SSP1 and 10.0 billion for SSP3 in 2050). Given the very different educational compositions of the world population, it is indeed plausible to assume that these scenarios refer to very different future levels of human well-being. By the end of the century, SSP1 depicts a world of less than 7 billion people with a relatively well-educated and therefore healthy and wealthy population, who will be better able to cope with the consequences of already unavoidable climate change. In contrast, SSP3 shows a world of almost 13 billion people who are less educated, less healthy and less wealthy making them more likely to be much more vulnerable to environmental change.

These differences in total population size are mainly due to a different educational composition for women of reproductive age because fertility rates differ by level of education, with more educated women in developing countries wanting and having better means to actually have fewer births. Lutz and KC[20] recently showed that by 2050, different education scenarios alone result in a difference of about one billion. The SSPs also alter the levels of education-specific fertility and thus produce an even larger inter-scenario difference. As can be expected, the middle-of-the road SSP2 scenario which essentially assumes a continuation of current trends (as they look most likely from today's perspective) results in an intermediate picture with the world population reaching a peak of around 9.4 billion during the second half of this century, followed by a slight decline to 9 billion by the end of the century.

A recent study of disaster fatalities translated estimated determinants of disaster vulnerability including education to the SSP1 and SSP3 scenarios for the rest of the century[60]. It was shown that due to the educational expansion under the rapid social development path in SSP1, disaster mortality will be much lower – even in the case of increasing climate related hazard –than in the SSP3 scenario where underinvestment in education leads to high population growth and heightened vulnerability.

Discussion and policy implications

Despite the theoretical argument and solid empirical evidence showing that ensuring universal education can potentially be a powerful measure for reducing "dangerous" impacts of climate change on human life, health and basic subsistence, in practice public and internationally driven adaptation efforts have been concentrating on hard structural adaptation measures[96,97]. Hard adaptation such as reinforcing buildings or dykes and seawalls are often capital-intensive, large, complex and inflexible technology and infrastructure. On the contrary, a soft adaptation path involves behavioural changes or planning and policy adaptions, empowering of local communities, simple and modular technologies owned by local people as well as natural infrastructure such as ecosystems and forests[98]. Soft adaptation measures hence are less expensive and are relatively more flexible to respond to alterations in climate change projections. While it has been argued that optimal adaptation paths require synergies between hard measures and non-technological adaptation options[99,100], being more tangible and visible, hard structures remain prominent. Subsequently, analysis of adaptation costs or estimation of adaptive capacity typically only consider economic capacity to install hard structural measures since this is easier to quantify[101,102]. Instead, empowerment through education in order to enable flexible and informed adaptive decisions in the future should be made a priority in this field.

Given that investing in human capital not only has a large number of social, economic and health benefits but also is an efficient adaptation strategy, knowing the educational distribution also implies understanding adaptive capacity of a society to a certain extent. Indeed, we have shown that multi-dimensional population projections have a forecasting property, which can be incorporated into climate change modelling. Stratification by age, gender and level of education is necessary not only because these characteristics matter for population dynamics (that is, fertility, mortality and migration) but they are also relevant to vulnerability and adaptive capacity. Besides differential vulnerability by education, mortality from extreme climate events and natural disasters, for instance, differs substantially by age. For example, with lower capacity to adapt coupled with limited ability to thermoregulate body temperatures, the majority of 70,000 deaths in 12 European countries during the heat wave in summer 2003 comprised older persons aged >65 years[103]. Likewise, in certain hazard events such as tsunami where physiology plays a key role in survivorship, women, children aged<5 and older persons aged>70 years had a clear mortality disadvantage[104]. Mortality risk from flood events, on the other hand, is higher for males than for females[105,106]. Such demographic differential vulnerability needs to be taken into account in projections of climate change vulnerability and adaptive capacity. The above described SSPs offer a valid way for explicitly incorporating these aspects into assessments of future adaptive capacity.

In conclusion, this *Perspective* shows that the model of demographic metabolism can be used to meaningfully produce forecasts of human and associated socio-economic capabilities for several decades into the future. This long time horizon is very different from economic or technological forecasts which have much higher uncertainty, even in the shorter term. The reason for the longer time horizon of the demographic metabolism model lies in the fact that the human life span is now seven to eight decades in most countries. Given that many relevant characteristics of people (such as educational attainment and basic attitudes) are formed at young ages and tend to be stable over the rest of the life course, we are able to predict adaptive capacities associated with these characteristics for many decades ahead. Taking aggregate future human capital projected in this way as a proxy for future socio-economic and institutional capacity, the demographic metabolism model thus offers a meaningful way to quantitatively forecast societies' future adaptive capacity to climate change. This offers the possibility for analyses that actually match future climate conditions with future socio-economic conditions, thus avoiding the misleading assumption that the climate of the future will meet the societies of today. This is an essential prerequisite for trying to assess how dangerous climate change will be for future human well-being.

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Acknowledgements

Partial support for this work was provided by the European Research Council (ERC) Advanced Investigator Grant focusing on "Forecasting Societies' Adaptive Capacities to Climate Change" (ERC-2008-AdG 230195-FutureSoc). We would like to thank Samir KC and Nadia Steiber for their comments and input in the preparation of the manuscript.

Author Contribution

WL and RM contributed equally in the conception of the work, drafting and revising the manuscript. Author names are listed alphabetically.

Competing Financial Interests statement

The authors declare no competing financial interests.

Figures and Figure Legends

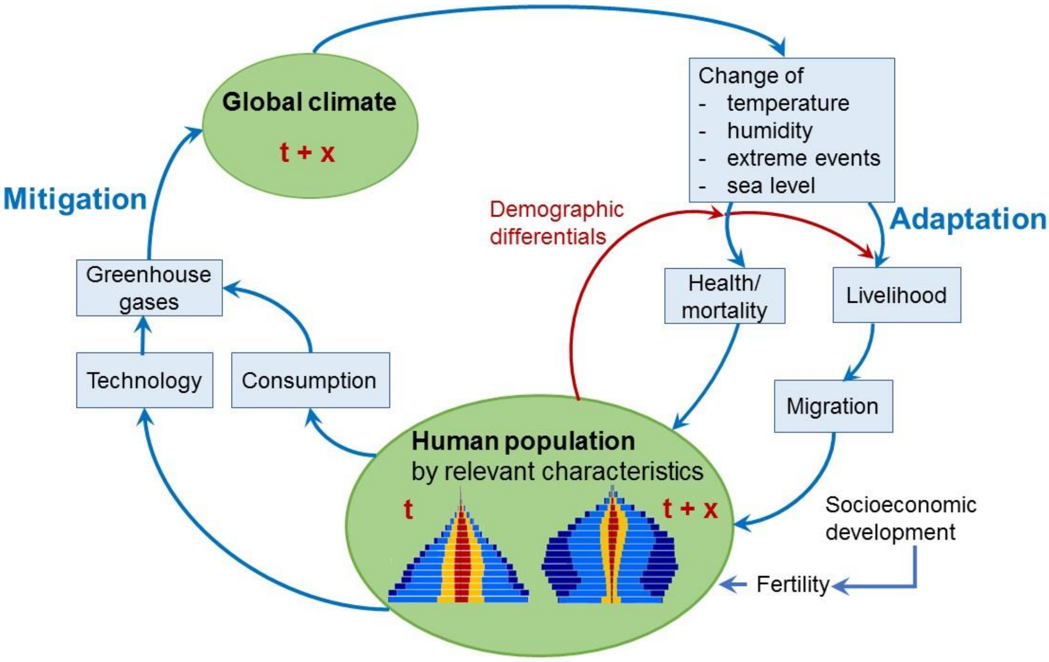

Figure 1: Circular link between human population and global climate systems

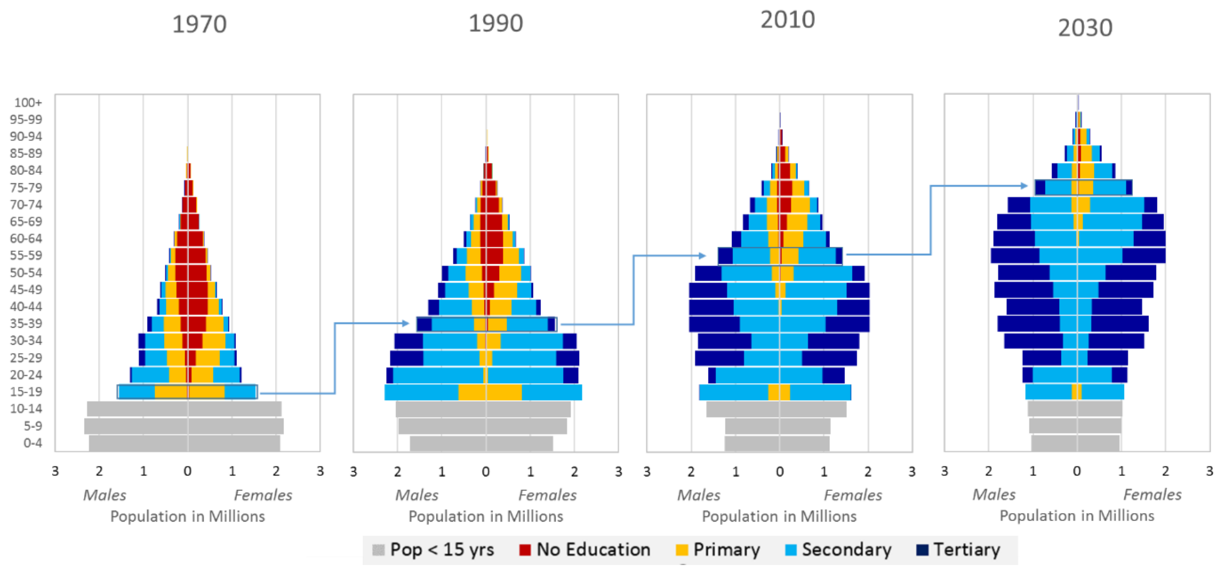

Figure 2: Age and education pyramids for Republic of Korea 1970-2030 in 20-year interval. Notes: Colours indicate highest level of educational attainment. Children aged 0 to 14 are marked in gray. The blue line links the identical birth cohorts at different points in time when they are of different ages but maintain their highest education attainment level as it is typically established before age 30.

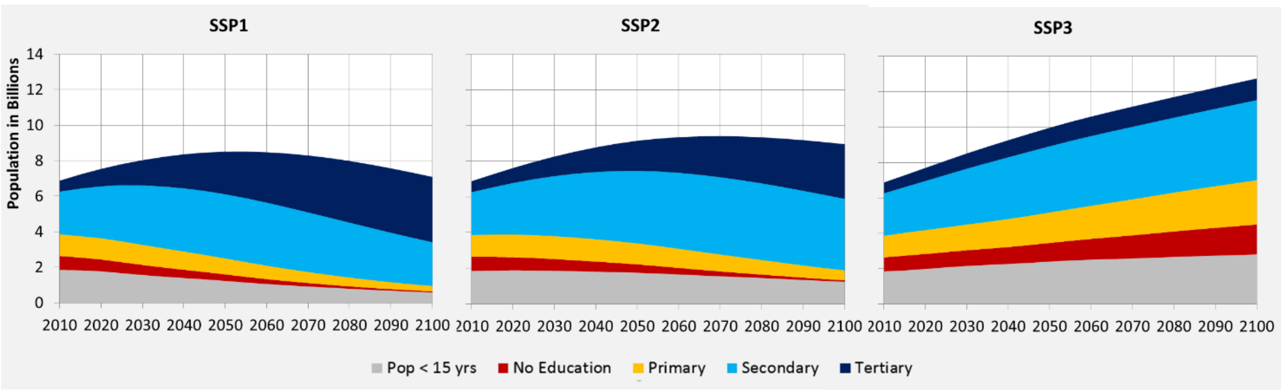

Figure 3: World population scenarios by level of educational attainment to 2100 on the basis of Shared Socioeconomic Pathways (SSP1, SSP2, SSP3). Source for base year[95] and for the scenarios[91].