

Working paper

World Population Trends and the Rise of *homo sapiens literata*

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Abstract

World population has increased remarkably from one billion around 1804, to two billion by 1927, to the current 7.7 billion. While growth in absolute terms is still at record high levels, the rate of increase has declined over the past decades and there is a credible prospect of world population peaking during the second half of the 21st century before reaching the 10 billion mark. This prospect will largely depend on whether female literacy continues to spread in Africa and Western Asia as it already has in other parts of the world. While throughout history literacy has been limited to tiny and mostly male elites, it was only over the course of the 20th century that mass education of both men and women rapidly spread on the global scale, leaving only limited pockets of female illiteracy concentrated in Africa. In this paper I argue that this phenomenal rise in global literacy – and in particular female literacy – has been a primary driver of human development through the cognitive changes associated with learning to assign abstract meaning to a combination of signs and thus discouraged fatalism in favor of more rational planning in one’s behavior. Because of this overriding importance of female literacy for demographic and socioeconomic development in this paper I coin the notion of “homo sapiens literata” to highlight the decisive role of female education and point to the fact that educated humans tend to behave in a qualitatively different way from their illiterate counterparts. The paper concludes with discussing alternative scenarios for population and education trends, up to 2100, following the SSP (Shared Socioeconomic Pathway) narratives. The dramatically divergent paths illustrate how investments in the near future, particularly in the universal education of girls, will be highly relevant for future resilience of the human species and the adaptive capacity to already unavoidable environmental change.

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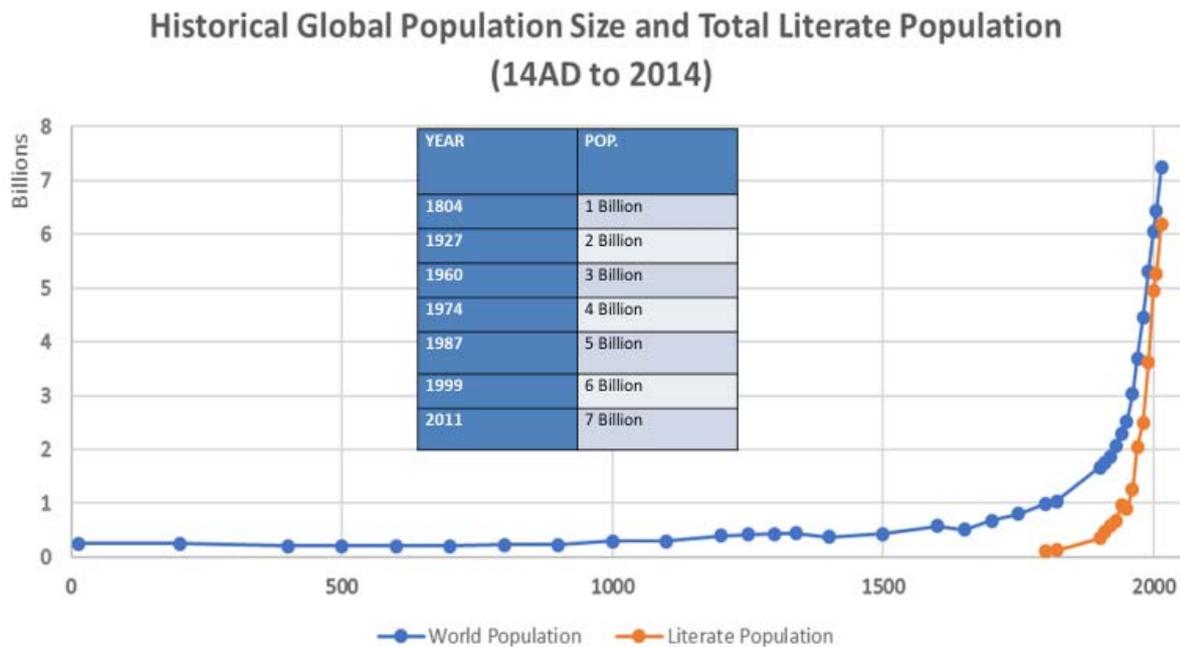
1. Introduction

The population of homo sapiens on our planet fluctuated at very low levels of population density throughout most of its history. There may even have been instances when our species was close to extinction. While the Neolithic revolution with the domestication of plants and animals starting some 12000 years ago lead to a marked increase of population sizes, world population up until around 1500 AD stayed below the size of 500 million, i.e. lower than the entire population of the European Union today. Over the last half millennium humankind has experienced many more revolutions in demographic, economic, social and technological terms. One of the hypotheses elaborated on in this paper is that these modern revolutions were to a large extent driven by the spread of literacy, and in particular female literacy, from being confined to elites to changing the lives of the general population. I will also argue that the future path of world population growth as well as adaptive capacity to already unavoidable climate change and other challenges will greatly depend on the speed of improvements in the education of women, particularly in the least developed countries. This decisive role of female education in improving the human condition shall be highlighted by introducing the new term "homo sapiens literata".

Figure 1 summarizes the big picture of the remarkable growth in the size of the human population on our planet over the past two centuries and the even more rapid increase in the literate population over essentially the last century. Estimates of past population trends show that the first billion of world population was only reached around 1804 and that it took another century and a quarter to reach the second billion. In contrast, the sixth and the seventh billion took only 12 years each to be added. By the beginning of 2020 the world population is estimated to stand at 7.7 billion and determining when the 8th billion will be reached depends on the projection assumptions made – probably around 2024. However, the growth rate has started to decelerate, and it is an open question – which is discussed towards the end of this paper – whether world population will ever reach 10 billion. As we will also discuss in this paper, both the acceleration of growth (through mortality decline) and the following deceleration (through subsequent fertility decline) are closely linked to and driven by the increase of literacy and basic education among broad segments of the population. Over the past millennia literacy skills have been limited to a small group of elites which at the global level stayed under one percent of the population until the rise of universal literacy started in Northern European countries in the 19th century. Over the first half of the 20th century most of Europe, Japan and the Americas became fully literate and during the second half most of the rest of the world, with some pockets of illiteracy only remaining in parts of Sub-Saharan Africa and Western Asia. This remarkable rise of literacy also was the key driver of remarkable social, economic and cultural changes.

In this paper I will first discuss demographic trends over the past two centuries and introduce the concept of cognition-driven demographic transition, i.e. how the declines in mortality rates and the subsequent decline in fertility were driven by improvements in the average levels of education of the population in interaction with medical and institutional innovations. Next, I will discuss how the increases in human capital turned out to be a key determinant for populations raising out of poverty and achieving economic growth and improvements in more broadly defined aspects of human wellbeing. This will be followed by scenarios about possible population and human capital trends over the coming century. In the conclusion I will discuss how the empowered *homo sapiens literata* has shaped the world, including a visible footprint on the natural environment which also threatens to undermine our own life support systems in the future. But I will also discuss how knowledge and education may offer opportunities for insight and foresight which can bring about a transformation towards sustainable development as well as strengthening our adaptive capacity to already unavoidable environmental changes.

Figure 1: World population size and size of the literate population over the past 2000 years



2. Cognition driven demographic transition

Demographic transition is the universal process of change from a pre-modern demographic regime of essentially uncontrolled high levels of birth and death rates to a modern regime of controlled and low levels of these rates. While in the context of fertility “controlled” refers essentially to the reproductive behavior of individuals/couples, in the context of mortality it also has a strong public health component. Intermediate stages of the demographic transition – when death rates have already fallen while birth rates are still high – are associated with high natural population growth, where “natural” refers to the balance of births and deaths not considering migration which in open populations is a third factor of population change.

While declines in mortality are almost always an object of universal aspiration, high fertility norms are often deeply rooted within cultures and typically take longer to change. Only after birth rates fall below the so-called “replacement level” of two surviving children per woman and a period of time passes when a young age structure results in an increase of women entering reproductive age (positive momentum of population growth) does population growth come to a halt. The precise timing of this process varies from one population to another, but the general process of the demographic transition is considered universal and essentially irreversible.

At the moment, various populations around the world are at very different stages of the demographic transition. While the process has been completed in Europe decades ago, it is now also complete in most countries in Asia and the Americas, but still under way in large parts of Africa, where most countries are still in the phase associated with high population growth. The striking differences in demographic patterns currently observed in different parts of the world are essentially a consequence of different populations being at different stages of this universal process.

The concept of demographic transition was originally triggered by the observation of declining birth rates in many European countries over the first decades of the 20th century. In the early writings, the words

“demographic transition” and “demographic revolution” were used interchangeably. Warren Thompson (1929), Adolphe Landry (1934) and Frank Notestein (1945) were the first to classify countries as being at different stages of a universal process that brings them from a condition of high birth and death rates to one that is ultimately characterized by low birth and death rates. In this early literature, the driver of this process was simply called “modernization” without a deeper specification in terms of the relevant causal mechanisms involved. But what they likely had in mind was general socioeconomic development as the reason for a decline in crude death rates (CDR) that was typically followed by a decline in crude birth rates (CBR) after a time-lag of varying length – these rates give the number of births and deaths per 1000 in the population and are called crude because they do not adjust the age structure. As a consequence of the difference between CBR and CDR, the rate of natural increase (RNI) was rising in the process. Disregarding migration, this difference is the reason for population growth in all populations around the world.

Figure 2 illustrates this process for Finland, which has the world’s longest national level demographic time series with annual data on death and birth rates since 1722. After strong fluctuations until the middle of the 19th century, in the 1870s a lasting decline in death rates started while the birth rates only entered a steeper decline at the beginning of the 20th century. During this period the population grew at around 1.3-1.4 percent per year. Figure 3 shows the pattern of demographic transition for Mauritius which has long and reliable time-series data and is the country in the African region that is today most advanced in this process. While up until the 1930s birth and death rates were at roughly the same level, death rates first started to decline with a particularly steep fall right after WWII while birth rates stayed high or even increased due to women being in better health status. From the early-1960s to the mid-70s Mauritius then experienced one of the most rapid fertility declines observed in human history with the mean number of children declining from above 6 to below 3 in less than 15 years (Lutz 1994). This comparison illustrates that the demographic transition of late comers can be much more rapid than the rather gradual historical transitions experienced in Europe. Consequently, the population growth rates in today’s developing countries can rise much higher than they ever were in historical Europe. In Mauritius they were over 3 percent per year in the 1950s which is equivalent to a doubling time of the population of just 23 years.

Figure 2: Crude birth and death rates in the territory of today’s Finland 1722-2017

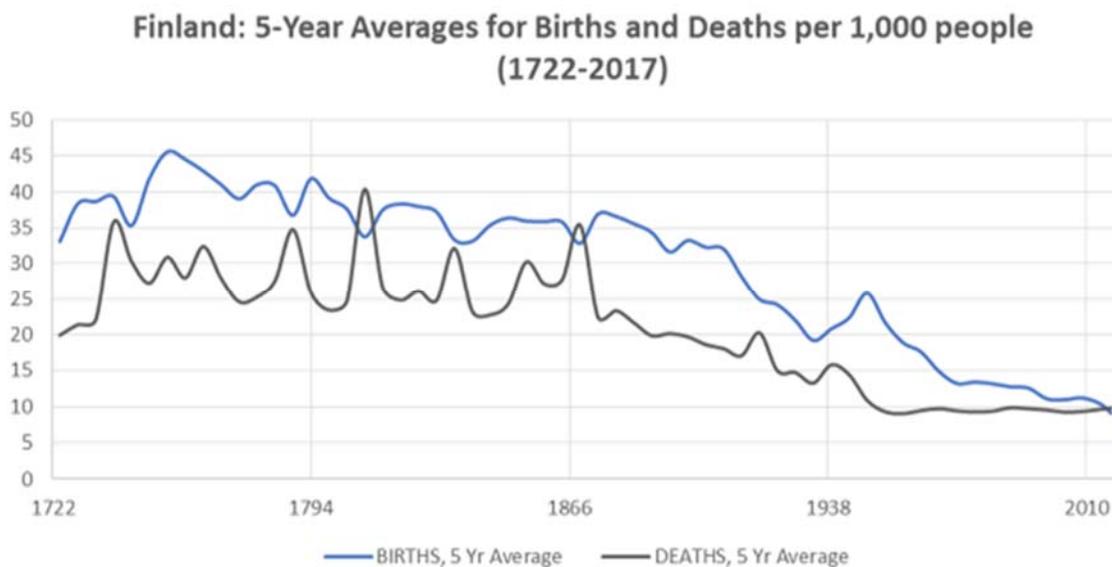
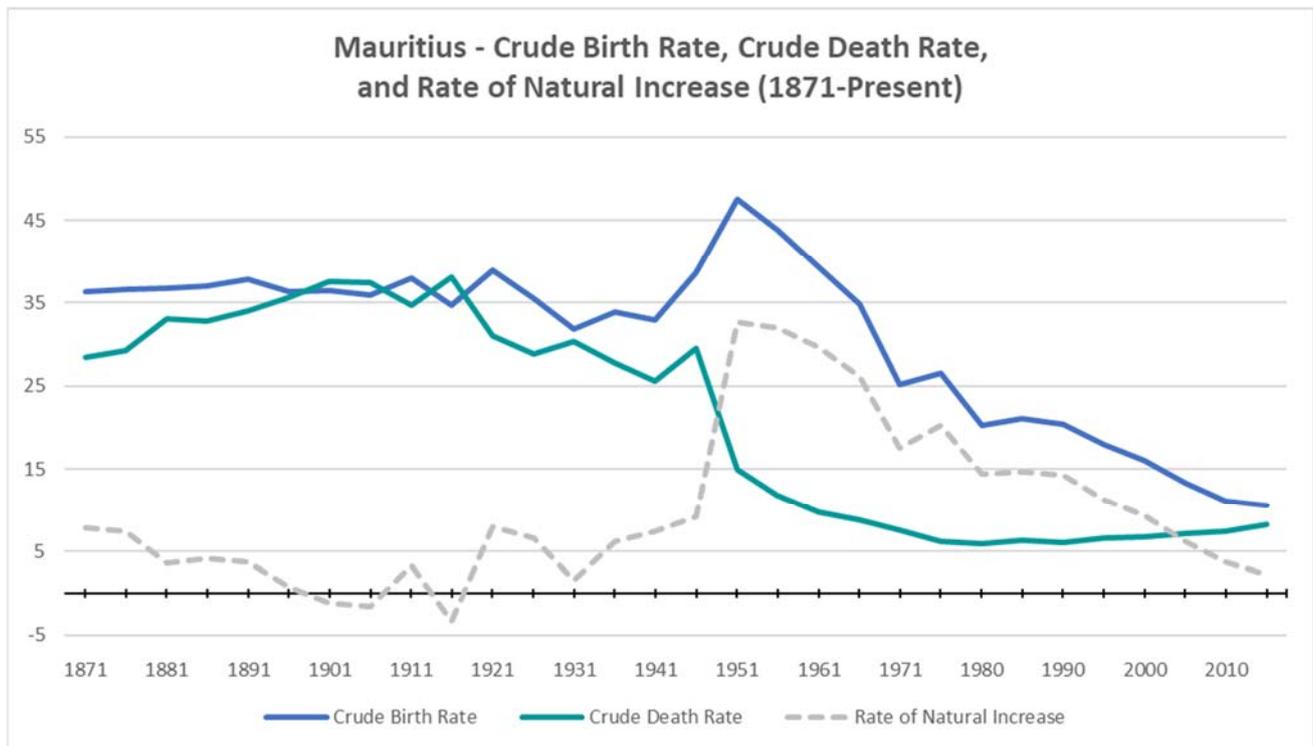


Figure 3: Crude birth and death rates on the island of Mauritius 1871-2017



Sources: Lutz (1994) and Wittgenstein Centre (2018)

Much research has been conducted on trying to understand the drivers of the global demographic transition and the specific mechanisms that have caused the mortality and fertility declines. There have also been studies trying to unpack the rather vague notions of modernization and development into its more specific components relating to material/economic changes and cognitive changes related to expanding literacy and general education. There is no space here for a full record of the very extensive literature which has recently been summarized elsewhere (Lutz, Butz, et al. 2014). Instead, I will only give a brief sketch of some of the main arguments. As to the onset of the modern mortality decline in the 19th century in Scandinavia and England, as well as in today's developing countries, there have been two schools of thought associated with the names of McKeown (1976), who puts the emphasis on improving economic circumstances including better food supply, and Caldwell (1976), who emphasizes education and in particular female schooling. Other authors have stressed additional factors, such as medical progress and public health policies that brought down death rates and subsequently helped reduce fertility through declining demand for children (Easterlin 1983; Cleland & Wilson 1987). A recent comprehensive reassessment of the evidence concerning the drivers of global increases in life expectancy since the mid-20th century across all countries of the world shows that improvements in education seem to lie at the root of these increases in terms of improving knowledge and behavioral patterns and can explain the observed changes much better than increasing income, with public health interventions also playing some role, particularly in child mortality decline (Lutz & Kebede 2018). The study of the drivers of fertility decline has been even more controversial. But there are some generally agreed insights. While in a few cases, such as historical France, the mortality and fertility declines happened only gradually and at about the same time, in most countries there was a distinct time lag of several decades between the observation of falling death rates and falling birth rates. This lag is explained by the fact that in virtually all cultures, norms and institutional settings favoring high fertility are deeply embedded in the

normative systems of societies and change only slowly, whereas everybody readily accepts the possibility of higher survival chances as soon as it is attainable. Also widely accepted is the framework of the three basic preconditions for a lasting fertility decline as specified by Ansley Coale (1973):

1. Fertility must be within the calculus of conscious choice, i.e. move from the realm of fatalism to that of consciously planned behavior,
2. Lower fertility must be advantageous, and
3. There must be acceptable means for preventing births.

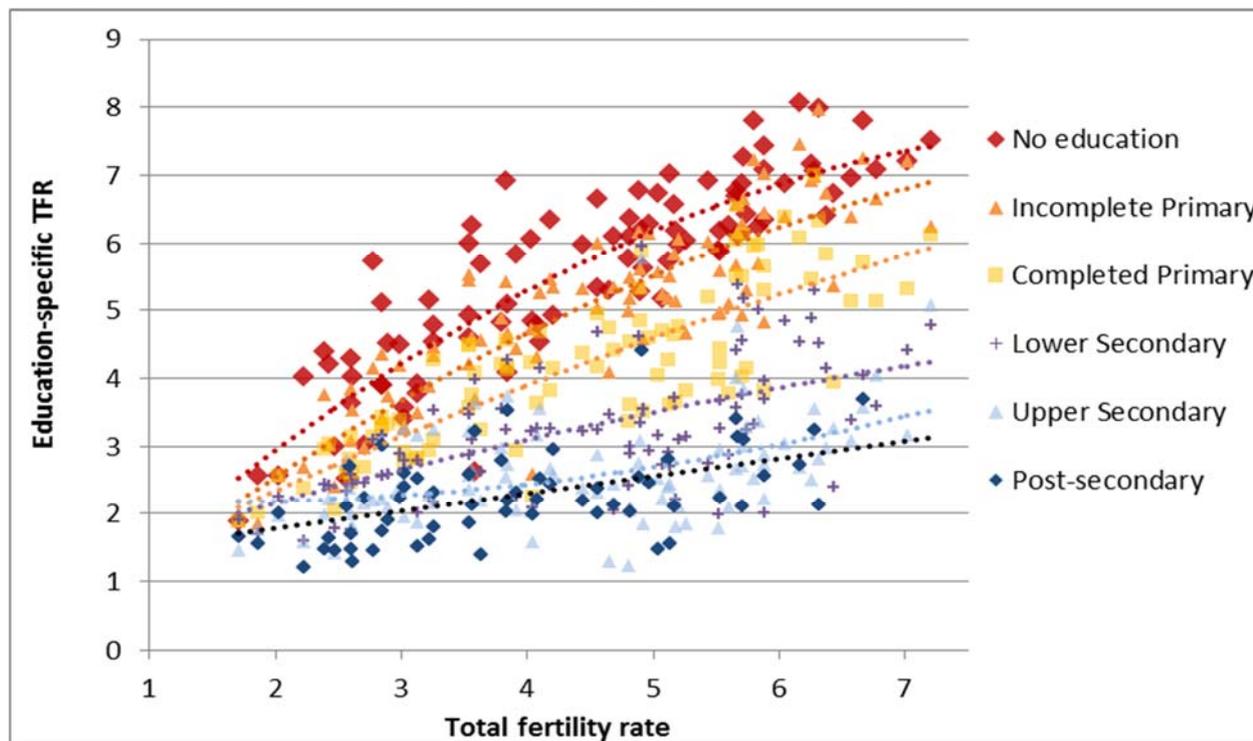
This framework nicely shows that there is no one-dimensional causation and the cognitive (education-related), economic (also urbanization-related) and contraception-related factors all need to come together in order to result in a lasting fertility decline. This was the case in historical Europe in the same way as it is in today's African populations. While perceived benefits of having fewer children (precondition 2) and the availability of culturally acceptable methods of family limitation (precondition 3) are also necessary for triggering a lasting fertility decline to low levels the basic precondition 1 of moving from a more fatalistic attitude ("I have as many children as God gives me") to a conscious choice of a specific family size is closely associated with female education, as will be discussed in the following.

Girls' education and fertility decline

Consistent patterns of fertility differentials by mothers' education have been found from medieval times to the present in virtually all countries and at very different stages of economic developments (Skirbekk 2008). The differentials are particularly pronounced in countries during the process of demographic transition when death rates have already fallen and birth rates start to fall after a certain time lag (Fuchs & Goujon 2014). Only in recent years in the Nordic countries does the gradient seem to flatten or show a mild U-shape because more educated women can arrange their lives better in a way to actually achieve the two-child norm which is still almost universal in Europe (Sobotka & Beaujouan 2014). More generally, the empowering effect of education brings women in high fertility settings to want fewer children and find effective ways to have fewer children. They generally want fewer children for health reasons, as many births at short intervals can be a major risk in the absence of effective health services, and because of value change preferring fewer children who each will have better life chances, and possibly because of higher opportunity costs. Also, better educated women can better resist the traditional pro-natalist norms in their societies and resist the often higher fertility desires of their husbands (Lutz 2014).

The empirical evidence for a strong fertility reducing effect of education in today's high and medium fertility countries is overwhelming, although there are some country-specific peculiarities. Figure 4 shows comparable data based on recent Demographic and Health Surveys (DHS) for 58 developing countries with fertility levels (TFR) given for six different groups of women according to their highest educational attainment ranging from no formal schooling at all to post-secondary education. It shows that within the same countries there is a wide spectrum with in some cases uneducated women having on average six or more children while highly educated women have less than two children, levels similar to Europe today. Averaged across all countries (dotted lines) there is a consistent ordering of fertility levels according to the level of education. The highest fertility levels today are in Africa where studies on the causes of educational fertility differentials consistently show that better educated women want fewer children, have greater autonomy in reproductive decision-making, more knowledge about and access to contraception, and are more motivated to practice family planning (Bongaarts 2010).

Figure 4: Fertility by level of female education in high fertility countries. 58 DHS (Demographic and Health Survey) countries (multiple time points), sorted by aggregate TFR in country



These pervasive education differentials have also been incorporated into models of population dynamics that stratify populations not only by age and sex but also by levels of education (Lutz & KC 2011). Because female education is associated with lower fertility at the individual level, populations with higher proportions of better educated women have lower overall fertility rates. This fertility factor by far outweighs the higher child survival rates associated with better education of mothers which works in the direction of higher population growth. Combining both forces, better female education will lead to a sizable long-term reduction in the population growth rates. A quantification of the pure education effect has shown that assuming identical sets of education-specific fertility trajectories for all countries a scenario assuming constant school enrollment results in a world population size by 2050 that is one billion higher than under a scenario of rapid school expansion. (Lutz & KC 2011)

In concluding this section, the above brief survey of the literature and the data on the drivers of the demographic transition has made it clear that both for the onset of the mortality decline that resulted in ever increasing life expectancies around the world and for the onset and the further course of fertility decline from uncontrolled high to low levels education – and for the case of fertility, in particular female education – has been the essential driver, with many other factors also contributing in a more secondary role. But the real driver is not the fact that children spend a certain time in school, but it is what this schooling does to their brains, how it changes their synaptic structure and thus affects their cognition. And such empowering cognitive changes can in principle also be acquired outside the formal school system. For this reason, I prefer to speak of cognition driven demographic transition rather than education driven demographic transition.

3. Literacy and development

Few people in developed countries would dispute the importance of education in our lives and those of our children. We need education in order to be professionally successful, to broaden our horizons, to be able to question the status quo and to choose what kind of life we want to lead. Education even allows us to influence our health. Indeed, education is what enables us to lead a self-determined existence at all. It is fundamental for the complex organisation of modern societies and it serves higher goals such as freedom and justice. Better-educated people become more involved in political decision-making processes, thus helping to further democracy. In most countries across the globe extending education to broad sections of the population by following the principle of "education for all" and seeking the attainment of ever higher qualifications has brought about a marked improvement in living conditions over a period of decades or even centuries. All over the world the prosperity of nations is closely connected with their citizens' level of education. For this reason, modern societies are also called knowledge societies.

For most of the 5000 years since writing was introduced in Mesopotamia and Egypt to keep simple accounts about stocks of grain delivered and other administrative purposes, literacy skills tended to be restricted to a tiny elite. For the first millennia, literacy was primarily limited to religious leaders, state servants, far-travelling traders, members of specialized guilds, and certain nobility (UNESCO 2016). There are two known exceptions to this: In ancient Athens in the 5th century B.C.E. and in 15th century towns in Tuscany. In both cases, there were interesting interactions with democracy in the way in which being able to write (e.g. the name of a person who should be ostracized by the assembly of the demos of Athens) was a prerequisite for exerting democratic rights, and conversely. The rights were an incentive to acquire basic literacy (Missiou 2011). It should be noted, however, that in both cases the skills and rights were limited to the male population that held rights of citizenship, a minority of the total population. But the reformation took this a step further. In spring 1524 Luther wrote his pamphlet "To the Councilmen of all cities in the German lands, that they should establish and maintain Christian schools." (Aland 1990, p.70) In it he called for children to be taught more than was necessary for earning their daily bread. This is a very important foundation for the later spread of literacy in the Protestant territories where it preceded economic growth, thus challenging the frequent assumption made by economists that the spread of education was a consequence of responding to economic incentives. It can be shown that almost universally the spread of literacy for non-economic reasons preceded economic growth. It was for religious and not economic reasons that Luther and his closest associate Melancton wanted every boy and girl – including "das geringste Mägdelein" ('the lowest level maid') – to be able to read the bible.

As a consequence of this emphasis on universal literacy, the Protestant territories in Northern Europe gradually became the most literate populations of the world, though there were some interruptions, such as the Thirty Years' War. In fact, one could argue that the rise of the Netherlands and England as colonial powers and the parallel decline of the powers of Spain and Portugal with much less educated populations were in part due to this factor (Klingholz & Lutz 2016). Statistics from the Netherlands show that already around 1600, two-thirds of men in the cities could read and write. Around 1850, about 80 percent of the population, including those in rural regions, were literate. The same happened in England, where around 1800, 60 percent of all men and 40 percent of all women could read and write (Broadberry & O'Rourke 2010). Looking at a map of Europe around 1870, the clear association between literacy and religion is evident (Broadberry & O'Rourke 2010). The Protestant territories of Sweden, Germany, the Netherlands and Great Britain are undisputed leaders with literacy rates of around 80 percent at this time. They are followed by France, which after the French Revolution managed to raise its literacy rate to 69 percent. Austria and Ireland

rank after France. Italy and Spain lag a long way behind with rates below 35 percent. Russia reaches 15 percent literacy and Turkey 9 percent.

This ranking by level of literacy in 1870 matches almost exactly the degree of economic development at that time. Interestingly, recent research suggests that this association of religion and development is not so much attributable to Max Weber's famously hypothesized effect of "Protestant Ethics" but that the economic head start of Protestant regions can be more easily and more directly explained by their better educated populations (Becker & Woessmann 2009). In fact, the French sociologist Emmanuel Todd (1987) describes the progress of humankind as a direct function of the spread of literacy in populations. Comparing the evolution of literacy rates around the world, he suggests that a critical threshold for socio-economic change and even political revolutions is reached around the point when 50 percent of male adults are literate. He sees the progress of human history as driven by the progress of the human mind with the slow rise of literacy being even more influential in the long run than the industrial revolution.

Human capital – defined as the combination of education and health - is a fundamental prerequisite for economic progress and good institutions – key components of sustainable development. At the level of individuals, empirical evidence shows beyond any reasonable doubt that, more years of schooling on average lead to higher income. This pattern can be found in virtually all countries, and discussions only concern the specific patterns or changes over time in this so-called education premium. At global macro-level economic growth regressions, however, until recently did not find the same significant positive effects of education due to the education data used (Barro & Lee 1996; de la Fuente & Doménech 2006; Cohen & Soto 2007; Benhabib & Spiegel 1994; Pritchett 2001). Indeed, the usual human capital indicator in the form of mean years of schooling of the entire adult population does not adequately reflect recent improvements of the education of younger cohorts. Under conditions of very rapid education expansion the young adult cohorts who are decisive for economic growth can already be highly educated while the mean years of education indicator can still be depressed through the still uneducated older cohorts. In analyses that explicitly consider the age structure of human capital growth, regressions unambiguously confirm the key role of human capital in economic growth (Lutz et al. 2008). In addition, utilizing in economic growth regressions the full range of the educational attainment distribution by age results in findings of great policy relevance: For poor countries with very low levels of education, only the combination of universal primary education with broadly-based secondary education results in the kind of rapid economic growth that has the potential to push countries out of poverty. (Lutz et al. 2008) This important new insight is also reflected in the SDGs (Sustainable Development Goals): While the earlier MDGs (Millennium Development Goals) only called for universal primary education, SDG4 calls for universal high-quality primary and secondary education (Lutz & Muttarak 2017).

While the historical macro-level evidence described here tells a convincing story about how literacy and education of broad segments of the population drive development, one also has to ask what are the individual level mechanisms through which literacy changes our brains and in consequence our perceptions and behaviors. In this paper I can do no justice to the vast amount of research in cognitive science and neuropsychology as well as experimental economics that tries to understand these mechanisms. Instead I will highlight a few key findings that I found myself to be helpful in explaining how education influences our cognitive function, attitudes and behaviors as well as equips us with better social and economic opportunities. Directly, 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 (Blair et al. 2005; Baker et al. 2012; Brinch & Galloway 2012), neurocognitive and neuroimaging studies have also shown strong associations between

adaptive changes in the brain and learning experience in classrooms (Lewis et al. 2009; Welberg 2009). 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 (Bruine de Bruin et al. 2007; Peters et al. 2006) – those skills and qualities that are also 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 (Cutler & Lleras-Muney 2010; Kenkel 1991; van der Pol 2011), this can help in making better choices in a broad spectrum of choices affecting one's health, income and other aspects of one's personal life as well as the functioning and thriving of society and economy at large.

4. Demographic scenarios and sustainable development

World population currently – at the beginning of 2020 – stands at around 7.7 billion people. While the absolute increments per year still are at a peak level of about 83 million per year – it takes about 12 years to add another billion – the rates of growth have been already declining in the past decades as the demographic transition progresses around the world. World population growth peaked in the late 1960s at a level slightly above 2 percent per year. This kind of growth, if maintained, implies that the population would double roughly every generation. On a planet with limited resource of food, fossil fuel and fresh water this gave rise to a number of highly influential alarmist studies ranging from the "Population Bomb" and the "Population Explosion" of Paul Ehrlich (Ehrlich 1968; Ehrlich & Ehrlich 1990) to "The Limits to Growth" by the Club of Rome (Meadows et al. 1972). But there were also opposing voices mostly by economists who believed in the substitutability of resources and the innovative capacity of humans. Prominently among them was Julian Simon whose book "The Ultimate Resource" (1981) stressed that there could never be too many people because there always would be enough geniuses who would come up with solutions for all problems. These two opposing views on future world population growth remained essentially unreconciled until it became clear that focusing on simply the number of people without considering their heterogeneity and differential human capital and adaptive capacity was unproductive and misleading (Lutz 1994; Lutz 2014). Once educational attainment was explicitly factored into the population models a new paradigm could be developed that could reconcile both seemingly opposing views: Innovations tend to come from more educated people and not from starving illiterate ones (Simon) and without sufficient education population growth rates are likely to stay high and limits to food supply and other feed-backs from the environment may well result in increasing misery and death rates (Malthus and Ehrlich). A key to overcoming this unproductive polarization of the discussion thus lies in the fact that female education is a main determinant of lower fertility rates and that education enhances the adaptive capacity to environmental change (Lutz & KC 2011; Lutz & Muttarak 2017).

World population projections for the 21st century as produced by the United Nations Population Division and by IIASA (International Institute for Applied Systems Analysis) have changed quite a bit over time as a function of different long-term fertility and mortality assumptions and the incorporation of most recent observed empirical trends and analysis. While the UN uses the conventional cohort-component method which models the populations by their age and sex structures, IIASA has developed the methods of multi-dimensional population dynamics which in addition to age and sex also explicitly models the changing educational composition of populations in each age and sex group (Lutz & KC 2011). In their most recent assessments the UN (2019) in their medium variant projects continuous growth of world population reaching

10.9 billion people by the end of the century whereas IIASA (Lutz et al. 2018) in its medium scenario (SSP2) projects a peak population being reached at around 9.7 billion in 2065-75 followed by a slight decline to 9.3 billion by the end of the century (see Figure 5). This difference is mostly due to different methods of deriving long-term fertility assumptions for the different parts of the world where the UN relies primarily on statistical models that derive assumptions from the experience of other countries whereas IIASA gives more weight to expert arguments and region-specific scientific reasoning about the drivers of these trends. While the two sets of projections are quite similar for the coming decades, toward the end of the century they differ in an important qualitative way, with the UN suggesting continued population growth whereas IIASA anticipating the end of world population growth during this century.

The notion of an “end of world population growth” was first introduced in an article in the pages of “Nature” presenting the first set of fully probabilistic world population projections (Lutz et al. 2001). Based on empirical information up to the late 1990s these projections showed that there was a high probability of over two thirds that world population would peak and then start to decline over the course of the 21st century. This was qualitatively not so different from the UN medium projection at the time which also saw a levelling off of world population over the last decades of the century. The main difference was in the level of assumed ultimate fertility which for the UN was around replacement and for IIASA a bit lower. Subsequently, an unexpected stall in the fertility declines of some important African countries was observed where around 2000-2005 fertility rates interrupted their earlier declines or even increased somewhat. While the exact measurement and explanation of this stall is still controversial one plausible hypothesis is that it is a late consequence of the interruptions of the education increases of female cohorts born around 1980 in the context of the so-called structural adjustment programs (Goujon et al. 2015; Kebede et al. 2019). More recently, demographic surveys show that the declining trend has picked up again which is also associated with a continued increase in the education levels of young women in most African countries.

Figure 5 shows the results of the 2018 IIASA projections carried out in the context of CEPAM (Centre for Population and Migration Analysis, a joint venture between IIASA and the Joint Research Centre of the European Commission). While the long term fertility and mortality assumptions of these projections were derived from the major 2014 assessment of the scientific state of the art in terms of drivers of fertility, mortality and migration (Lutz, Butz, et al. 2014), the baseline data were updated and a specific focus was on the long-term impact of alternative migration assumptions which matter significantly for national populations but are irrelevant at the global level. Figure 5 also compares this projected trend (SSP2) to the UN medium variant as well as to two alternative high (SSP3) and low (SSP1) scenarios that were developed in the context of the Shared Socioeconomic Pathways (SSPs) widely used in the climate change research community (KC & Lutz 2017).

The SSP3 scenario assuming stalled social development and thus lower female education and higher fertility rates for each education group already reaches the 10 billion mark around 2045 and then continues to grow over the rest of the century reaching 13.4 billion in 2100. According to the narrative underlying this scenario this will be a very unpleasant future in which the world will be strongly fragmented, there will be widespread poverty, mortality will be rather high and the adaptive capacity to already unavoidable climate change will be very weak. This pretty much resembles a Malthusian scenario as described above.

The SSP1 scenario assuming rapid social development results in markedly lower population growth showing a peak population of around 8.9 billion in 2055-60 and a decline to 7.8 billion by the end of the century. This is just a bit higher than the population estimated for today and the same as expected for 2020. In terms of the underlying narrative this resembles a global development under which the sustainable development goals are met in most countries and significant progress in education and poverty reduction is made. As has been

shown elsewhere (Abel et al. 2016) meeting SDG4 (on education) and SDG3 (on health including reproductive health) will help to bring the SSP2 scenario closer towards the SSP1 scenario in terms of the total world population growth resulting from these trends.

Figure 5: Comparison of different scenarios for world population growth over the 21st century

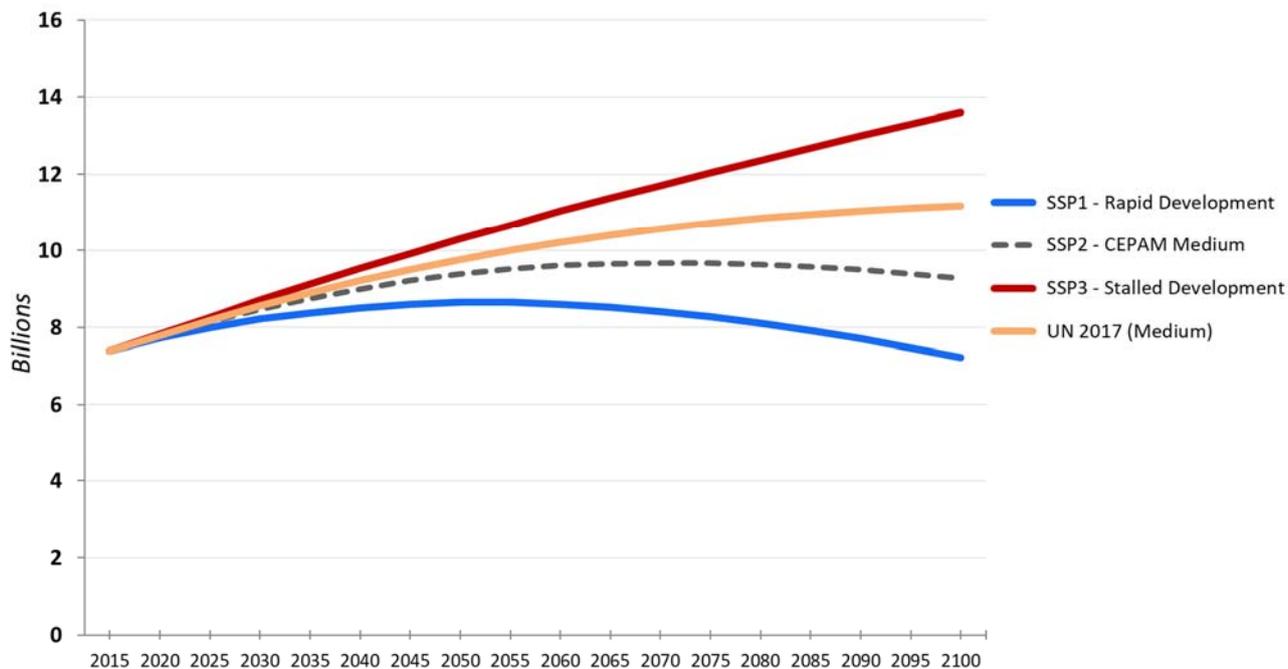
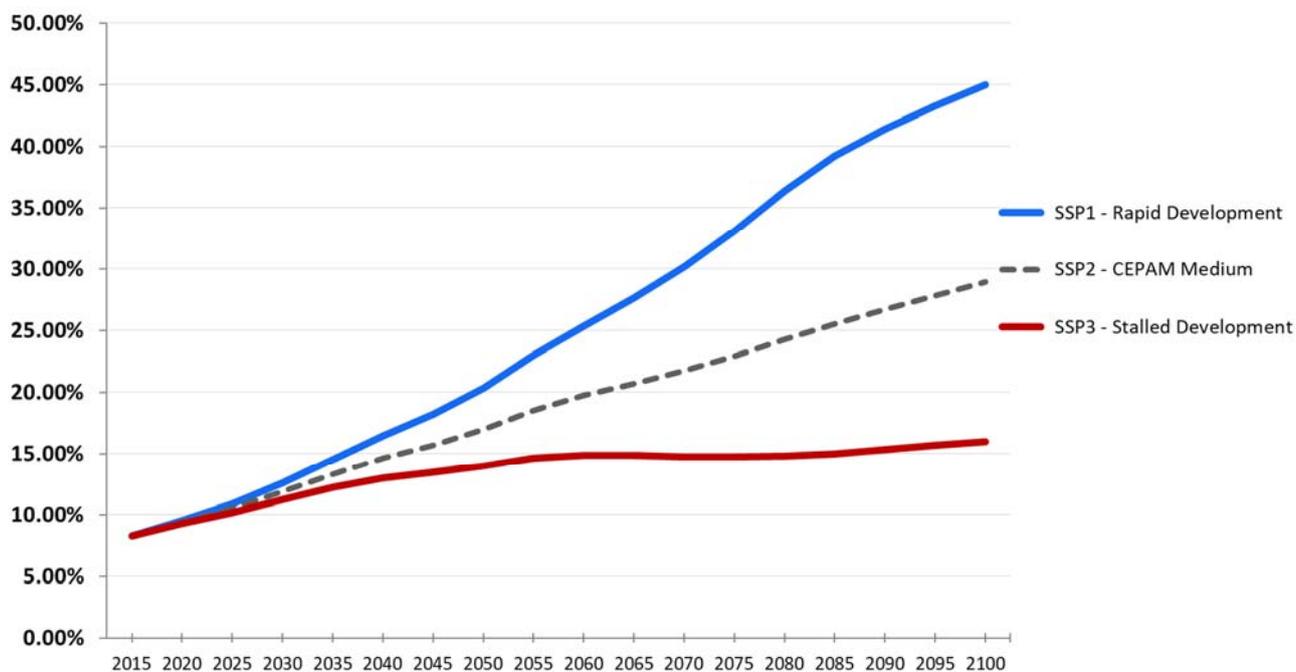


Figure 6: Global trends in the proportion of the population above age 65 according to different scenarios



Under all scenarios the world population will get significantly older as a consequence of low fertility rates and increasing life expectancy (see Figure 6). In the medium (SSP2) scenario the proportion above age 65 increases from currently 8.3 percent to 17 percent by mid-century and 29 percent by 2100. Under the rapid social development scenario (SSP1) which assumes faster increases in life expectancy this proportion of elderly reaches around 20 percent in mid-century and 43 percent in 2100. The stalled development scenario (SSP3) on the other hand will see a much slower increase reaching only 16 percent by the end of the century. When interpreting these different scenario results in terms of changing proportions of the populations above the age of 65 one has to keep in mind that a cut-off point at age 65 is rather artificial and reflects a static notion of being "old". The typical 65-year old in the 1960s had on average a much worse health status than the average 65-year old today. Also, in terms of the remaining life expectancy the 65-year old has many more years to expect today. This is also reflected in the saying "70 is the new 60" for which there is a lot of evidence. In terms of demographic ageing indicators this is also covered by new indicators such as the proportion of persons that have a remaining life expectancy of 15 or less years, an indicator that increases much more slowly than the proportion above age 65 plotted here (Sanderson & Scherbov 2019). This also needs to be taken into account when comparing the scenarios. SSP1 partly results in much more population ageing because it also assumes more rapid increases in life expectancy. And this is only likely to happen when at the same time disability-free life expectancy continues to increase. Hence, when thinking about a world population at the end of the century where possibly 40 percent of the population will be above age 65 we should not think in terms of the 65-year-olds we know today. If such a scenario should indeed materialize it could be expected that a majority of these people above age 65 would be not-so-elderly healthy and active people. But still it will pose challenges to adapting existing institutions including systems of social security.

In terms of educational attainment (Figures 7-9), in 2016 10.3 percent of the world population had no formal education at all and 10.9 percent had some sort of post-secondary education. Under the medium (SSP2) scenario significant progress will happen, with the proportion without any education declining to 5 percent by mid-century and on 1 percent by 2100, while at the same time the proportion with post-secondary increase to 20 and 38 percent respectively. Under the rapid development (SSP1) scenario the proportion with post-secondary education increases to 32 percent in 2050 and 65 percent in 2100.

But further long-term progress in education is not guaranteed, despite of the fact that today in virtually all countries the young generations are better educated than the older ones. As illustrated by the stalled development (SSP3) scenario in Figure 9 the combination of high population growth with little further schooling expansion can actually result in an increase of the proportion without any formal education from 10 to 22 percent by the end of the century. This scenario also shows a stall in the proportions with post-secondary education below 12 percent. This scenario will also result in a greatly polarized world. While the countries in today's developed world and the emerging economies where the young generations are already fairly well educated will continue to enjoy high levels of education the African and South Asian populations may actually become less educated because school expansion will not be able to keep pace with the rapid population growth.

Viewed together these population and education scenarios clearly illustrate that still two very different futures are possible: (a) One resembling the Malthusian trap which is captured by the SSP3 scenario in which low education investments and continued high fertility in Africa and parts of South Asia reinforce each other and lock the world into a trap of very high population growth and poverty and low adaptive capacity to environmental change; (b) another optimistic one captured by SSP1 where these feed-backs result in a virtuous cycle of further strong improvements in education together with lower fertility and an end of world

population growth and thus more healthy and wealthy people who are better empowered to adapt to already unavoidable environmental changes.

Figure 7: World population by level of educational attainment, Medium Scenario (SSP2)

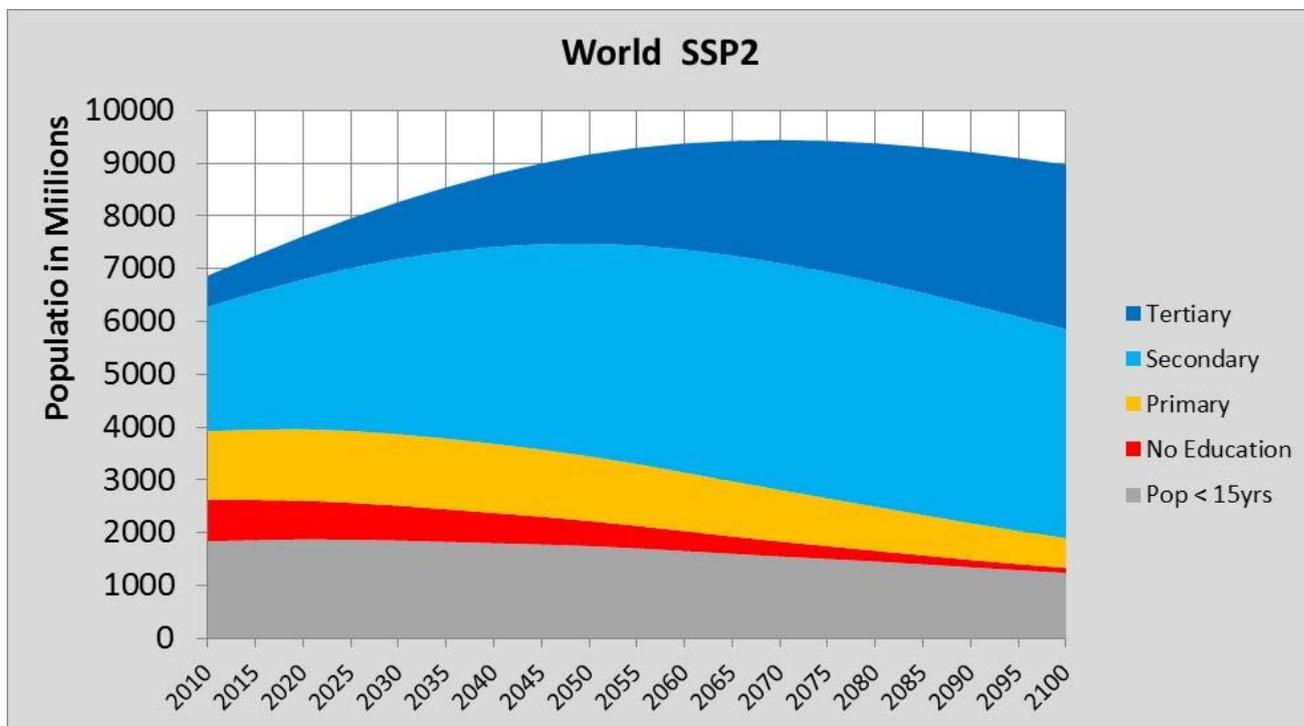


Figure 8: World Population by level of educational attainment, SSP1 Scenario – Rapid Development

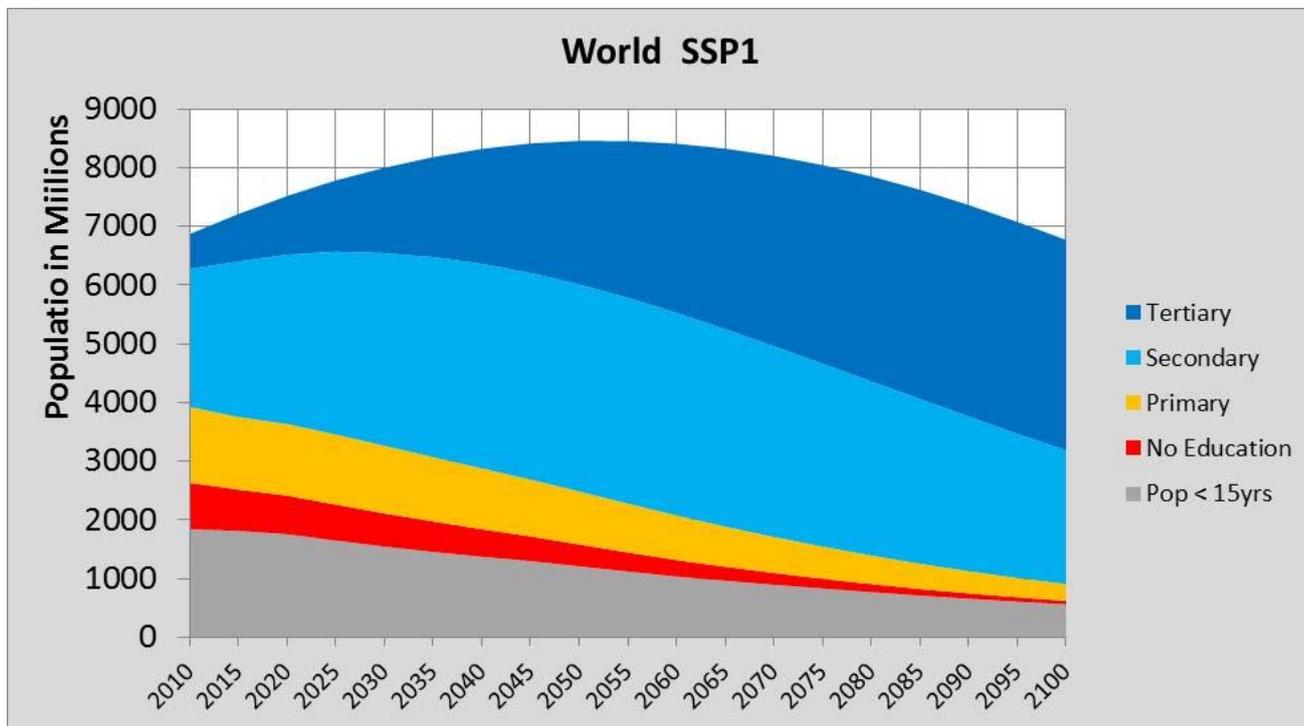
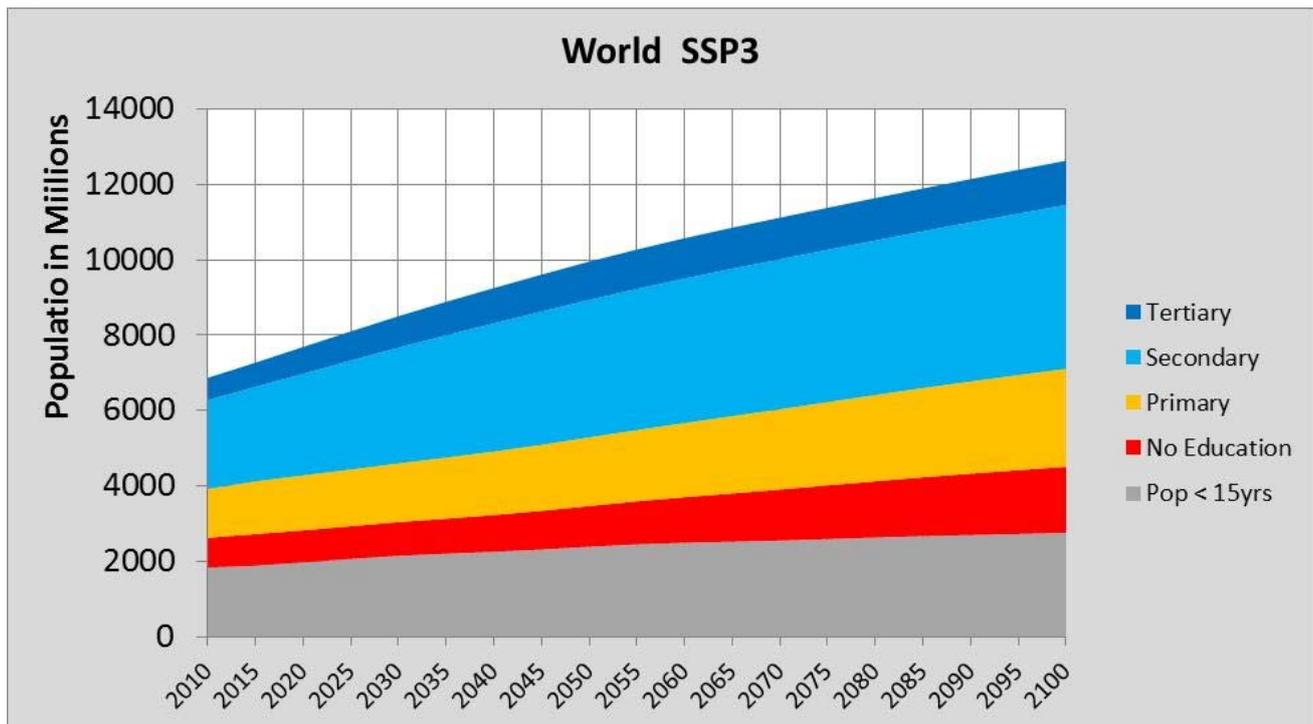


Figure 9: World population by level of education, SSP3 Scenario, Stalled Development



Whether the world will move towards one of these two opposing directions or will end up somewhere in the middle will depend largely on policy choices made over the coming years.

These different population and education scenarios are highly relevant for different aspects of sustainable development. An important field of application is in assessing the likely future resilience and adaptive capacity to all kinds of potentially disruptive changes, including global environmental change. Recently, in the analysis of climate change, the attention has shifted from an earlier almost exclusive focus on mitigation to adaptation that will be necessary when coping with already unavoidable changes of the climate. However, much of the ongoing research in the field superimposes projected biophysical conditions for the end of this century onto present-day socioeconomic conditions (IPCC 2014), when we know that societies are also changing over time in dimensions such as public health capabilities that are essential for their adaptive capacity. Disregarding such future social change would be misleading. It has been demonstrated recently that education is a key determinant of differential vulnerability both at the individual and societal level (Butz et al. 2014). Hence, the above described SSP scenarios are an effective way for also forecasting societies' future adaptive capacities to climate change (Muttarak & Lutz 2017). Contrasting the SSP1 and SSP3 scenarios for the rest of the century (Lutz et al. 2014) it was recently 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. Given the uncertainty about the precise manifestations of climate change in specific areas, there is a strong case to be made for general empowerment through education which increases human and social capital to flexibly and effectively react to upcoming challenges rather than investing in massive concrete infrastructure projects.

More generally, for the interactions of humans with environmental change, education has been shown to matter for behavioral changes necessary to mitigate human impacts such as changing behaviors in terms of choosing greener technologies, switching to public transport or recycling waste (Muttarak & Lutz 2017). Since

education improves knowledge, understanding of complex information, efficiency in allocation of resources and capacity to plan for the future (Cutler & Lleras-Muney 2010; Kenkel 1991; van der Pol 2011) it is conducive for making better choices at the individual and societal level that will make a transition toward sustainability more likely.

5. Conclusions: Population growth and brainpower for sustainable development

The future trends in population and education greatly matter for many dimensions of sustainable development and all of its three social, economic and environmental pillars. With respect to trying to identify the impact of population growth on environmental change the combined effects of population growth (P), affluence (A) and technology (T) on environmental impact (I) has sometimes been expressed through the "I=PAT" equation. Called the Ehrlich-Holdren or Kaya identity, it lends itself to efforts to quantify the contribution of the individual components on environmental impact. The decomposition literature based on this identity has, however, been inconclusive due to the fact that the three components tend to work in different directions, are not independent from each other, and not all consumption can be meaningfully attributed to individuals. In particular, it has been pointed out that households and not individuals should be taken as the consuming units and that the consumption or impacts of big companies or the military cannot be meaningfully attributed to individuals. But despite some of these problems, the literature mostly agrees that population change and change in consumption patterns are both relevant aspects, even though the latter tends to dominate the picture (O'Neill et al. 2005).

The number of people on this planet not only matters with respect to their consumption and impact on the natural environment and thus the life support systems of future generations, it also matters in terms of human rights and basic needs to be met. It is clearly more difficult to leave no one behind and secure basic entitlements under continued rapid population growth associated with stalled development (SSP3) than under a scenario of rapid fertility decline together with fast socioeconomic development (SSP1). But while the human headcount on our planet clearly matters, the analysis summarized in this paper also shows that what is inside the heads matters more than the mere number.

Much more research is needed in this field, in particular to better understand the mechanisms by which enhanced cognitive abilities (brain power) can contribute to changes in our behavior at the individual and collective level toward achieving sustainable development. Many of the solutions are readily available on the table but they are not being implemented due to blockades at various levels, including the links between perception and behavior in our brains. Recognizing this, the German National Academy of Sciences Leopoldina has recently held two symposia in support of the Global Sustainable Development Report 2019 (Messerli et al. 2019) to explicitly address the cognitive preconditions for a successful sustainability transition. Under the heading "Brainpower for sustainable development" (Lutz et al. 2019) it has been affirmed that "brain power comprises the competences, abilities, traits and motivational skills that enable people to make sound decisions and adapt their behavior. Brain power is a key prerequisite for a successful transition towards sustainability. Individual brain power develops out of a continuous, lifelong interaction between genetic dispositions, maturation processes, environmental conditions and social experience. The most obvious way to strengthen brain power is to provide positive supportive environmental conditions in early childhood, both formal and informal high-quality education as well as lifelong learning. Furthering general cognitive and motivational competences proves to be more effective than specialized programs" (cited from Lutz et al. 2019, page.1). –

Again, this points to the overriding and fundamental importance of universal literacy and continued education for both women and men to assure future human wellbeing on this planet.

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