Opportunities and Challenges of a World with Negligible Senescence

A Report to the SENS Foundation from the Frederick S. Pardee Center for International Futures Josef Korbel School of International Studies University of Denver www.ifs.du.edu

DECEMBER 2014
In completion of work under contract from September 1 2012 through August 31 2014

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Executive Summary

This report comes from a project analyzing the broad global implications of extensions, some potentially dramatic, of longevity with alternative senescence patterns. In this report we explore the implications of rapid and extensive aging with very low senescence. Specifically, we consider how the world might evolve were there to be, over a 20-year period, a rapid development and deployment of technologies that nearly eliminated mortality and morbidity from communicable and most non-communicable causes. We consider the great benefits of such advance, of course, but we also look at some of the complex sociopolitical (as well as individual) rebalancing challenges that human societies would face.

The project uses the International Futures (IFs) long-term, multi-issue, global forecasting system as its central tool. The IFs system uniquely integrates demographic, economic, human development (education and health), physical (agriculture, energy, and infrastructure) and sociopolitical models, representing 186 countries with annual forecasts from 2010 through 2100. The fully integrated systems of IFs allow a coherent analysis of the interactions among the immediate demographic implications of negligible senescence technologies, related changes in health costs and government finance, changes in life-cycle patterns of participation in the labor force, resultant transformations of economies, and the ability of the biophysical environment to sustain the dramatically altered human demands that emerge. In short, there is a story to be told about the ripple effects of changing life expectancy and senescence.

We begin with the strictly demographic implications of aging with low senescence. We explore both the size and the structure of resultant populations. We also look, albeit briefly, at the additional issues that might face a world in which menopause age were pushed back, allowing for an extended period of childbearing. We find:

- The global population in 2100 could be as large as 19.5 billion rather than just over 10 billion in our Base Case scenario (Figure 3.7).
- Total fertility rates are the key uncertainty; although a TFR falling to 1 could hold population to about 11.6 billion, it would also yield an extremely old age structure, with 74% of population over age 65 and 39% over age 100 (page 21).
- Conclusion: We think a global fertility rate of 1.9 more likely and that would produce a global population of about 14.9 billion (page 18).

We turn next to the issue of medical costs and expenditures. Great reductions in mortality and morbidity would greatly reduce associated direct expenditures. Yet such life extension and health improvement technologies would almost certainly have their own associated expenses, potentially quite considerable ones at least at any early stage. A major challenge in such a world would be the ability of those of lower income, within and across countries, to pay the expenses of life extension and the demand for transfers or subsidies by those who could not. We find:

- Because traditional morbidity costs would plummet, health care expense would become primarily a function of the costs of life extension; we explore low,
medium (our core scenario), and high cost variations of $3,333, $5,000, and $10,000 per person-year of life saved (pages 26—27).

- If all humans were provided life extension at the medium cost of $5,000 per person-year, global health care costs would rise to at least 13 percent of GDP and as high as 28 percent during the transition to full coverage, before falling with the decline of traditional costs and those of life extension itself (Figure 4.5).

- Across the cost scenarios Low-income countries would require subsidies or transfers that would range from 45 to 143 percent of their GDP on top of locally borne costs of from 6 to 13 percent; local costs and subsidies/transfers for high-income countries would be 14 percent of GDP even in the middle-cost scenario (Figure 4.4).

Conclusion: A rapid and comprehensive transition to negligible senescence is not feasible for any nation at the high price of $10,000 per person-year and remains infeasible for low- and middle-income countries even at the medium price of $5,000 per year.

Greatly changed demographics would have major implications for economies. But the implications for economic growth would depend heavily on life-patterns of work and finance, our third focus. Alternative combinations of longer working lifespans with different patterns in the savings and spending decisions of both households and governments are possible, and we explore some of those. We conclude:

- With more and healthier workers, by 2100 the GDP per capita of the negligible senescence world would exceed that of the Base Case (Figure 5.8).

- The extent of gains would depend greatly on the cost of the negligible senescence treatment. We estimate that the global GDP per capita in 2100 would be $86,000 in the Base Case compared to $91,000 with high treatment costs, $99,000 with medium costs, and $102,000 with low treatment costs in $2011 PPP (Figure 4.9).

- The extent of economic impact would also depend heavily on life-cycle work and finances. Failure to effectively eliminate retirement would create impossible burdens on governments; responsibility for life-pattern finance would need shift primarily to individuals, most likely after a period of political conflict (page 41).

Conclusion: With relatively modest increases in government involvement and the total elimination of retirement, GDP per capita could reach $114,000, about 33% higher than that of the Base Case, though such a result would depend greatly on other inputs to growth including life-cycle financing, resource availability, and sustainability (page 45).

Finally, such major demographic and economic changes would have large-scale impacts on nearly all aspects of humanity’s struggle to live sustainably within its larger environment. Demand for energy and food would almost certainly rise sharply. We find that under the Negligible Senescence core scenario:

- Energy demand would increase by 51 percent above the Base Case in 2100 and cumulative energy consumption through 2100 would be 29 percent higher. Even if expansion of fossil fuel usage supplied only 36 percent of the extra
consumption, atmospheric CO2 could reach 634 PPM in 2100 relative to 588 in the Base Case (page 48; Figure 6.3).

- Meeting extra food demand (from population and income increase) would require increasing average crop yields in 2100 by 31 percent relative to the Base Case and doubling relative to current levels (page 52).

- Conclusion: The sustainability of a negligible senescence world would depend on the outcome of the long-running debate between those with great optimism for technological advance and those who believe humanity already lives in an increasingly unsustainable manner.

These analysis insights suggest several general conclusions about a world that had the miraculous technologies needed to achieve negligible senescence. First, population would almost certainly surge and fertility rates would become an issue of tremendous societal importance. Second, even a cost as low as $5,000 per person-year of treatment would pose unbearable burdens to individuals and societies below high-income levels, and would make issues of transfers within and across societies central political issues. Third, in the absence of simultaneous availability of transformative production technologies, life-pattern financing would require reshaping of work patterns that essentially eliminated retirement and that would greatly restructure government finances and their broader societal role. Fourth, pressures on the global environment would greatly intensify.

Each of these insights would benefit from further analysis. For instance, we have stressed that life-pattern work and financial arrangements could take very different forms, and it would be of considerable interest to consider a range of these in interaction with alternative assumptions about the unfolding of the broader technological capabilities of the economy and society (perhaps most humans will really not need to "work"). At the same time, we have not touched at all on the issues of continuing education/learning and the implications of that for a long- or indefinitely-lived humanity and its political-economic systems. Nor have we delved deeply into what we have sketched as rather profound implications of negligible senescence for the environment. And, of course, if we were to step back somewhat from the positing of movement to negligible senescence very rapidly and soon, there is a wide range of possibilities and scenarios to explore both the pace and diffusion of progress across and within societies.

We may have limited social choice control over how much life will be extended and the health of the aged—technological change will largely drive those—but we will have many social choices to make on the financing of health care (including life extension technologies), on incentive structures around work and savings patterns, and on how to address the sustainability issues that life extension could intensify. While these difficult decisions might be manageable, many societies would find them extremely challenging.

We recognize our portraits of the future and human choices within it to be inevitably and potentially greatly flawed. We hope that they can also be thought provoking.
1. Introduction

There is near certainty that the world will experience rapid population aging throughout this century, thanks primarily to widespread and very substantial reductions in fertility and secondarily to ongoing extensions of life expectancy. While current demographic trends make such a world almost inevitable, great uncertainties remain about (1) the prospects for continued extension of life expectancy and (2) whether aging will be characterized by additional years spent in good health or in increased frailty.

The longevity analysis field, while in general agreement that average life expectancies will continue to increase over the coming decades, has long debated whether the rate of increase will continue at its current pace of one-and-a-half to two years per decade (in high-income countries) for the foreseeable future, or whether the rate of future gains will slow and eventually cease as life expectancy approaches a fixed limit to the human lifespan (de Beer 2006; Bongaarts 2006). Olshansky et al (2009) and Coles (2004) argue in favor of diminishing gains and an ultimate statistical limit due to the need to reduce all-cause mortality by ever-greater amounts in order to keep increasing longevity. Because of this, Olshansky et al (2009) suggest that average life expectancy is unlikely to exceed 90 years by the end of the century. Thus, many past efforts to forecast longevity have foreseen diminishing rates of progress against mortality at older ages (Wachter 2003).

On the other side of the debate, Oeppen and Vaupel (2002), Christensen et al (2009), Howse (2009) and Vallin and Meslé (2010), among others, find little evidence for a limit to life expectancy, given that the age groups seeing the greatest mortality declines have been shifting older over time and the rate of mortality decline has been accelerating for the oldest old as well (Caselli and Vallin 2001; Strulik and Vollmer 2011; Willets et al 2004). Indeed, recent forecasting efforts, including the United Nations Population Fund, have dropped the imposition of diminishing returns (Howse 2009).

The second uncertainty, the health of those experiencing increases in life expectancy, will play a major role in determining the economic impact of population aging. Researchers like Klijs et al (2011), Stulik and Vollmer (2011), and Payne et al (2007) point to recent evidence showing a compression of morbidity even as life expectancies increase; that is, individuals are living longer and healthier lives. A continuation of this trend could prove a tremendous human welfare success story. In addition it might prove an economic boon as individuals remain productive workers longer (or even indefinitely) and need less expensive medical care for disabilities.

If, on the other hand, Olshansky et al (2009) and Fries (1980) are right, longer lifespans will expose more people to the diseases of old age, while continuing medical advances will allow for increased life expectancies by keeping sick individuals alive longer. In such a world, medical costs could be much higher. Christensen et al (2009) suggest that

1 Barring any major systemic disruptions such as global pandemics, large-scale wars, significant detrimental environmental feedbacks.
both sides are partially right, because the rate of the most severe morbidities has been decreasing while the rate of the least severe has been increasing.

The basic purpose of this paper is not to explore the uncertainties around extension of life and the health of the aged, but to pursue a topic less well considered, namely the broader implications of alternative longevity futures. Much writing on these topics focuses on the public-policy implications of aging and frail populations. Yet the possibility for game-changing medical advances, from telomerase-based treatments to growing new rejection-proof organs, makes it important that we also look at the potential implications of greatly extended and healthy life expectancies (Lucke and Hall 2006).²

In particular, we want to consider the issues that would be raised by a future of very rapidly expanding life expectancy coupled with very low senescence. Even more specifically, we want to consider how the world might evolve were there to be, over a 20-year period beginning as early as 2020, a rapid development and deployment of technologies that nearly eliminated mortality and morbidity from all communicable and most non-communicable causes. We label this world that of a Negligible Senescence scenario and use a large-scale, integrated forecasting system to explore it. We juxtapose this world with a Base Case scenario of more slowly progressing extension of life expectancy, accompanied by delayed but not ultimately reduced senescence (a more common forecast than that of Negligible Senescence).

It is not enough, however, to simply look at first order demographic consequences of the Negligible Senescence scenario, which we know would be greatly disruptive for societies as a whole (even if the individuals within them greatly desire it), resulting in large imbalances between the behavioral patterns of the old world and the requirements of the new one. We also want to begin the consideration of some of the social, economic and ecological changes and adaptations that societies might experience in such a world—in fact, changes that they might well find necessary.

Negligible Senescence would have huge implications. First, it would directly affect demographic change, the pace and extent of aging and the resultant population sizes and structures. Our Base Case forecasts anticipate the global median age rising from 29 in 2010 to 45 in 2100 with the most rapid rise in low-income countries (from 20 to 41). Our Base Case forecasts, including population reaching a global total of about 10 billion, are largely consistent with those of the United Nations Population Division. Our Negligible Senescence scenario adds nearly 5 billion people to that total and the median global age in 2100 climbs to 76 (71 in low-income countries). If the technologies also extended or even restored fecundity and women used the extra years to bear more children in total, the implications for total population might be much larger. Thus, a key social issue we explore is the pattern and total level of childbearing.

² See Appendix 5 for a more extensive literature review concerning the uncertainties, forward linkages, and other issues surrounding longevity extension.
Second, greater health of aging populations would dramatically shape the size and pattern of health care expenditures, public and private. Already in the Base Case we anticipate those expenditures to rise from 10 to nearly 12.5 percent of global GDP. Yet, that portrayal of global growth suffers from the income-weighted averaging of low- and middle-income countries having relatively low expenditures and rapid GDP growth with high-income countries that illustrate the reverse. Expenditures in currently lower-middle-income countries could rise from 4 to 8 percent of GDP, those of upper-middle income countries from 6 to more than 12 percent, and those of high-income countries from less than 12 to more than 26 percent. What would they be in the case of Negligible Senescence? Although they might ultimately drop dramatically in the face of new technology, the costs of achieving and maintaining such healthy extended life could also be very large, at least initially, perhaps outweighing the cost reductions associated with current morbidity and mortality patterns. Could societies, especially low-income ones, afford the costs? If at least ultimately the technologies were to greatly reduce total health expenditures, how might their diversion to other uses benefit societies? We will need to consider variations on the Negligible Senescence scenario to map such possibilities and their consequences.

Third, the extent and health of aged populations already greatly concerns governments and corporations, particularly those committed to defined-benefit pension plans. Governments globally already direct about 6.5 percent of GDP to pensions and the Base Case forecast is for that to rise to 8.5 percent in 2100. Again, those numbers conceal composition effects. In high-income countries, that percentage could rise from nearly 8 to more than 14 in 2100. In the case of healthy and very long life, governments, corporations and households themselves would need to fundamentally reconsider what working life means and how to finance both it and periods during which work-related income might be disrupted or foregone. In the absence of such reconsideration, the pension payouts to increasingly large global populations continuing to retire near 65 and not changing their savings patterns would rise to 16.5 percent of GDP in 2100 and still fall far short of covering the consumption needs of the elderly (spending would be constrained by shortages of funds), an imbalance that would demand changed patterns of behavior. Again, there are multiple possible unfoldings in the adaptation of the financial and work lives of humans in a world of Negligible Senescence, but greater personal responsibility for life pattern finance and a greatly extended working life would be highly probable results. (A world with robotic provision of human needs could, of course, change the work/leisure balance.)

Finally, larger economies (and possibly higher GDPs per capita), which we find likely to be associated with the larger populations of Negligible Senescence, would have major implications for the use of resources such as energy and water and for the release, often harmful, of pollutants back into the environment. Ceteris paribus, a world of 47 percent more people than our Base Case, each with incomes also higher than the average of our Base Case, would have a proportionately larger impact. We know, of course, that a variety of feedback processes, some equilibrating and some potentially accelerating, would likely somewhat dampen that impact. This paper will not attempt an elaborated exploration of this issue, but it will begin to set some foundations for such analysis.
This report will proceed by first briefly introducing the International Futures forecasting system that, adapted for this project, is our principal analytical tool. We will then devote subsequent sections to the issues introduced above, namely to the implications for and possible adjustments to Negligible Senescence in the areas of immediate demographic size and structure, health costs and expenditures, the life pattern of work and financing, economic growth, and sustainability.
2. The International Futures (IFs) Tool and Scenarios

The International Futures (IFs) forecasting system has been developed over more than 30 years and is widely used for long-term analyses of human, social, and environmental system development (see Appendix 1 for more detail on the IFs system and its use). This section provides a brief survey of it with particular attention to the modules of special interest to this project, sketches the extensions made for this project, and introduces the scenarios developed for this analysis. The IFs system, with all changes made for this project and files to generate the scenarios discussed in this report, is available for free use at Pardee.du.edu. For this report we used Version 7.09.

2.1 International Futures (IFs)

The International Futures (IFs) forecasting system of the Frederick S. Pardee Center for International Futures at the University of Denver is a large-scale, multi-issue, long-term global forecasting tool. IFs includes detailed models of demographic, economic, sociopolitical, education, health, infrastructure, energy production, and agricultural subsystems for 186 countries interacting in the global system. Each of these models is comparable to, and sometimes more fully developed and advanced than other stand-alone models in each of the issue areas represented. Extensive linkages connect the separate models of the IFs system, providing the ability to analyze the issue area interactions desired in this report.

The models within IFs that are of special interest for this paper include those of demographic, health, government finance, and economic systems. Some of the key characteristics of the population model (prior to extensions for this project) are that it:

- represents 22 age-sex cohorts to age 100+ in a standard cohort-component structure (but computationally spreads the 5-year cohorts initially to 1-year cohorts and calculates change in 1-year time steps);
- calculates change in cohort-specific fertility of women in response to income, income distribution, infant mortality (from the health model), education levels, and contraception use;
- uses mortality calculations from the IFs health model; separately represents the evolution of HIV infection rates and deaths from AIDS;
- computes average life expectancy at birth, literacy rate, and overall measures of human development;
- represents migration (using exogenous forecasts from other sources)
Some of the key characteristics of the health model (prior to extension for this project) are that it:

- represents mortality from 15 causes across the groupings of communicable disease, non-communicable disease, and injuries and accidents;
- differentiates mortality by 5-year age category and for 186 countries;
- builds on distal driver forecasting formulations developed within the Global Burden of Disease project and on proximate driver formulations for selected variables from the Comparative Risk Assessment project;
- links change in morbidity to change in mortality;
- feeds mortality and morbidity patterns forward to economic productivity.

Some of the key characteristics of the model's representation of finance (within the broader governance and sociopolitical model) are that it:

- represents fiscal policy through taxing and spending decisions;
- identifies eight categories of government spending (military, health, education, R&D, two categories of infrastructure, foreign aid, and a residual category) plus transfer payments;
- represents the need to maintain some long-term equilibrium between government revenues and expenditures and enforces trade-offs across categories of government expenditures;
- integrates financial flows of governments with those of households and firms domestically and internationally in a social accounting matrix that assures balances and trade-offs.

Some of the most important characteristics of the economic model are that it:

- represents the economy in six sectors: agriculture, materials, energy, industry, services, and information and communications technology;
- computes and uses input-output matrices that change dynamically with development level;
- is a general equilibrium-seeking model that does not assume exact equilibrium will exist in any given year; rather it uses inventories as buffer stocks and to provide price signals so that the model chases equilibrium over time;
- contains a Cobb-Douglas production function that (following insights of Solow (1956 and 1957) and Romer (1990)) endogenously represents contributions to growth in multifactor productivity from human capital (education and health), social capital and governance (domestic security, low corruption, democracy), physical and natural capital (infrastructure and energy prices), and knowledge development and diffusion (research and development and economic integration with the outside world);
- uses a Linear Expenditure System to represent changing household consumption patterns as a function of income;
- utilizes a "pooled" rather than bilateral trade approach for international trade;
- is imbedded in a social accounting matrix (SAM) envelope that ties economic production and consumption to representation of inter-agent class financial flows.
2.2 International Futures (IFs) Extensions for This Project

Quite substantial changes and extensions were made to the IFs system in the course of this project in the modules identified above (see Appendix 2 for detail). Some of the changes of the population model were:

- extending the 22 age-sex cohort structure to 42 cohorts so as to represent population to age 200+ in a standard cohort-component form
- adding the ability to control the shape of the mortality J-curve in either or both of two ways: extending the age cohorts across which low mortality prevails and reducing mortality rates, especially at higher ages
- adding parameters to control the onset and duration of fecundity as well as the peak year of fertility and the pattern of rise to the peak an fall from it

Some of the key changes in areas of health and finance were:

- representing the cost of person-disease-years of morbidity (by cause) and of last life year; also representing the costs of life extension and of "other" health costs (e.g. administration and R&D) related to morbidity, mortality, and life extension (see Appendix 3 for details on this important model extension)
- adding representation of the interaction of bottom-up health costs related to demand for spending , of top-down government spending on health linked to costs, and of the ability to control the extent to which bottom-up costs or top-down fund availability respectively determine actual spending (Section 3 elaborates this)
- linking actual health care spending (the total of public and private) back to health outcomes
- allowing greater and more direct parametric control of work-start and retirement age
- adding parameters to control changes in household saving patterns and government pension spending as mechanisms for satisfying life-pattern financial needs

2.3 Scenarios for This Project

Two principal scenarios frame this project, the Base Case scenario and the Negligible Senescence scenario (upon which many variations were built for extended analysis).

The Base Case is not a simple extrapolation of variables in multiple issue areas, but rather the dynamic, nonlinear output of the fully integrated IFs system. Among the most obvious consequences of this integration are that changes in assumptions concerning health result in changes in demographics, economics, and all other systems in IFs; similarly changes in those other systems affect health. Feedback loops can mean that interventions may accelerate further beneficial or detrimental change in human development.
The forecasts that other IFs system models produce of key drivers, such as GDP per capita and education attainment of adults, are foundational underpinnings of its Base Case health forecasts. Hughes et al. (2009: 56–71) explored those forecasts, comparing them to others, such as those of the United Nations Population Division and the World Bank. As a general rule, the IFs Base Case produces behavior quite similar to medium variant or base forecasts of such analyses (see also Hughes and Hillebrand 2006).

Relative to the Base Case, the Negligible Senescence scenario and its variants are all characterized by:

- a 20-year phase-in of negligible senescence between 2020 and 2040. Model parameters allow variations in the starting point of and period of phase-in (see Appendix 2) and specification of a pattern of delays rather than near elimination of senescence. We have chosen this pattern because it illustrates a particularly sharp and dramatic break with the Base Case. We did not reduce mortality and morbidity for mental illness, but did place limits on the extent to which the burden of mental illness would rise with age. We did assume a great reduction in injuries and accidents, positing that individuals and societies with low levels of other mortality would make special efforts to decrease these.

- universality in this phase-in within and across countries. Although we recognize that this is unlikely given the presumably high costs of necessary medical treatments, again this assumption allows most extensive exploration of implications. Section 3 will turn to the issue of cost subsidies that such universality would require, within and across countries.

- Life extension treatment costs of $100,000 per person-year, assumed to be re-occurring on 20-year cycle for country-years with GDP per capita as high or higher than that of the US in 2010 (or, equivalently, an assumption of costs of $5,000 per person-year). Assuming the necessity of subsidies or cost-shifting by providers, treatment costs are scaled down with GDP per capita for countries below that of the US in 2010 (to 5 percent of high-income country levels as a minimum).

- a changed relationship between mortality and morbidity from CVD; in the Base Case morbidity changes only at a rate of 50 percent of the change in mortality, while in the Negligible Senescence scenarios the association is 100 percent. Note: the link in the Negligible Senescence scenario is thus less than 100 percent only for injuries/accidents (75 percent) and mental health (no link).

For the analyses described in each of the subsequent sections of this report, we built variations on the Negligible Senescence scenario so as to explore alternative possible implications of the scenario and possible social adaptations that might arise to address imbalances the scenario might create. The sections will describe those variations on the basic long-lived, negligible senescence world.
3. Population Size and Structure

The technical advances of Negligible Senescence have the potential for substantially increasing global population and for reshaping its structure. How much larger might global population be at the end of the century than in the Base Case? The changes made to the IFs structure for this project facilitate the treatment of population in discrete age categories through 200+. Although our displays represent this in 5-year age categories, the underlying model represents it in 1-year age categories, consistent with the 1-year time steps of the IFs forecast computations.

In this section we will explore the demographic consequences of the Negligible Senescence scenario relative to the Base Case. We will then turn to a few variations that we considered to the basic Negligible Senescence scenario, considering alternative mortality and fertility patterns.

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3 Personal communication with Samir K.C. indicates that the demographic forecasting of the International Institute for Applied Systems Analysis (K.C. and Lutz. 2014) represents age categories up to 120+ and that in some analysis the United Nations Population Divisions extends that to 130+. We know of no project other than ours that has developed the capacity to represent still older age categories.
3.1 The Base Case and Negligible Senescence

Figure 3.1 shows the J-curves with age-specific mortality rates for the Base Case and Negligible Senescence scenarios. In the Base Case the pattern of senescence shifts to the right between 2010 and 2100 and flattens very slightly. In 2100 the life expectancy of 115-120 year-olds (2.5 years) is the same as that of 105-110 year-olds in 2010. In the Negligible Senescence scenario the parameters both shift the curve the right and, most notably, flatten it.

![Figure 3.1 J-Curves of mortality globally in 2010 and 2100](image)

*Note: Mortality is summed across death causes and aggregated across sexes.*

Although it may look like it in Figure 3.1, the result of the Negligible Senescence scenario is not to eliminate mortality totally. Appendix 2 explains the analytical functions used to shift the system to Negligible Senescence. These affect individuals 15 and older with respect to communicable disease and those 25 and older for other mortality causes. That leaves some extent of infant and youth mortality in Negligible Senescence, but the numbers, especially by 2100, are very small and could be seen to be related to very severe genetic problems for communicable. Moreover, we have not reduced mortality and morbidity from (non-physiological) mental illness. The tiny numbers do not affect the general results of this paper's analysis.

We can see the crude death rates for the two scenarios in Figure 3.2. In the Base Case, the continuation of population aging is beginning to reverse the long-term global decline in crude death rates. The shift towards negligible senescence shifts crude death rates close to zero, with no eventual rise. Since crude death rates are a principal contributor to population growth rates, the relative decrease in crude death rates from 9-11 deaths per
1,000 (or 1 percent per year) to near zero would add an extra 1 percent to population growth each year.

Figure 2. Crude death rates globally, Base Case and Negligible Senescence scenarios

Note: 1960–62 omitted because the Great Leap Forward in China distorted the mortality pattern.

Figure 3.3 shows the resultant sizes of global population in the two scenarios. The Base Case produces a total global population in 2100 of 10.1 billion, very slightly down from a peak reached in 2090. Compare this with 10.8 billion (and still rising slowly) in the median variant forecast of the United Nations Population Division's 2012 Revision and with a range in forecasts of the International Institute of Applied Systems Analysis (KC and Lutz 2014) from 6.9 to 12.6 billion (9.0 billion in its centrally-oriented Shared Socioeconomic Pathway 2 scenario). In sharp contrast, Negligible Senescence produces a population of 14.9 billion in 2100 that is still rising. This last forecast assumes no changes in either migration patterns (which would have a very small impact by altering the fertility and mortality of migrants) or fertility patterns (which we shall see below could have a major impact).
Along with a larger global population in 2100 in Negligible Senescence, Figure 3.4 suggests that the overall age-sex structure would also be significantly affected. First, the peak of the age-sex distribution would be much higher, second, those in the middle-aged categories (not just the very much older ones) are more numerous because of their survival with Negligible Senescence, and finally, the global convergence toward a total fertility rate of 1.9 sees a notable decrease in the size of younger cohorts compared to the Base Case.
3.2 Additional Explorations: Senescence Variations and Fertility

The discussion of demographic and health implications of new technologies to rejuvenate aging bodies is subject to huge uncertainties. The two primary ones are the rate and extent of senescence reduction and its implication for fecundity and thus fertility patterns. We consider each in turn.

3.2.1 Senescence Variations

The Negligible Senescence scenario assumes rollout of dramatic reductions in mortality and morbidity (in essence near immortality) over a 20-year period beginning in 2020, and either the ability of almost all societies to pay the associated costs or to benefit from subsidies. It is thus on the very most optimistic end of the literature with respect to medical advance (see a review of that literature in Appendix 5).

The IFs system allows any combination of speed, extent, and cost of senescence reduction. We have explored alternative scenarios including a Delayed Senescence scenario in which life expectancy globally reaches approximately 110 in 2100 rather than...
the indefinite life expectancy of Negligible Senescence. Delayed Senescence is also available for users to analyze at our website (Pardee.du.edu), but we will not address the scenario here. In-between scenarios have, of course, mostly in-between results.

3.2.2 Fertility Variations
Negligible Senescence technology could also potentially delay or even eliminate age-related infecundity. Such change to fecundity could lead to

1. an extension of childbearing at more or less constant rates per fertile year of female life (a scenario we call NS with Extreme Fertility because total fertility rate would soar; we have explored this but do not present it here because it seems so unlikely)

2. an extension of childbearing years with a reduction in rates per year but an overall rise in TFR (we call this NS with High Fertility and our variation in this report produces a TFR of about 3)

3. a continuation of the global trend toward a TFR of about 2, just below current replacement levels (we call this NS with Middle Fertility and the variation we explore here simply maintains the global trajectory to a TFR of 1.9; it is the core scenario we use in most analysis of the report)

4. potentially reduced fertility overall because of some combination of reduced risk-taking propensity, a reduced sense of self "replacement" and "old-age care" needs, and societal needs to limit fertility substantially to slow the rapid population growth of the underlying scenario (we call this NS with Low Fertility and our variation here moves TFR to 1; only a value near 0 would allow population to fully stabilize, but a value of 1 would lead to a gradual and constant slowing of population growth)

Any of the scenarios above other than the first could include a possible interim period of higher TFR given the initial opportunities of extended fecundity for older women and then a reduction to lower rates (as shown in the Low Fertility scenario of Figure 3.5).
Figure 3.5 Total fertility rate globally by scenario

Although significantly limited by the fact that the model is crudely age-specific in its representation rather than cohort-specific (important because women born before, during, or after the transition to Negligible Senescence would have different histories and decision-orientations), the IFs system allows some exploration of such variations through direct manipulation of the total fertility rate. Figure 3.5 shows the TFR patterns of the High, Middle or Core (which is nearly identical to Base Case), and Low NS scenarios.

These alternative fertility scenarios, in interaction with their mortality patterns produce rather shockingly different age-sex structures in 2100 (Figure 3.6). The High Fertility scenario produces a general shape much like that of the world today, although its overall size is much larger. The Low Fertility scenario produces an almost inverted pyramid (or child's top) form, one that would become substantially more pointed over still more time. Although total population would be much smaller than in the Low Fertility scenario, 74% of the world’s population would be over age 65 (compared to 58% in the Middle Fertility scenario) and 39% of the world’s population would be over age 100 (compared to 29% in Middle Fertility).
Figure 3.6 Population globally in 2100 by mortality and fertility scenario

Figure 3.7 shows the resultant global population sizes. The so-called High Fertility scenario would lead to what most observers would consider a demographic and sustainability nightmare, with population nearly doubling relative to the base case. Were annual rates of births to women not to change at all with extended fecundity (the Extreme Fertility scenario, now shown in our figures), it would add yet another 20 billion by 2100. The Low Fertility (1-child scenario) would hold global population below 12 billion in 2100, and growth would be indefinite but steadily slowing. Given our skepticism that the world would adopt a 1-child policy or that individuals would make it a practice, however, we will carry forward to subsequent analytical sections of this report the assumptions of the Middle or Core Fertility Negligible Senescence scenario, a continued progression to fertility rates of about 1.9.
Figure 3.7 Population globally by fertility scenario

*Note: All fertility scenarios are combined with the Core Negligible Senescence scenario.*
4. Health Care Costs and Expenditures

The technical advances of Negligible Senescence have the potential for substantially reducing, even eliminating many health care costs associated now with morbidity and the last year of life. At the same time, however, the treatments associated with reducing senescence, particularly if reductions are very great, cannot be costless. What might the net impacts with respect to health costs and expenditures be and how might those affect larger governmental and economic performance?

The changes made to the IFs structure for this project facilitate our analysis of the trade-offs of health cost reductions and increases within and across years, as well as within and across countries. Specifically, we:

- introduced data on the costs of each morbidity-person-year and each mortality-person-year for all of our 15 mortality causes, using a mixture and mostly average of 2010 data from the U.S. and the Netherlands as our guide to the costs and scaling those downward for country-years with lower GDP per capita (see Appendix 3);

- used the data we collected or updated on public and private health expenditures with the morbidity and mortality levels and costs across countries to estimate, as a residual, total Other Healthcare costs (including administrative and R&D ones);

- added parameters to represent the costs of treatments to largely eliminate senescence and represent the number of years on average between such treatments—and we added a variable to track the resultant life extension costs;

- scaled the costs of treatments and therefore life extension costs downward across country-years when GDP per capita is below the GDP per capita of the US in 2010 and added a variable to track the implicit subsidies associated with such scaling;

In this section of the report we will explore the health cost and expenditure consequences of the core Negligible Senescence scenario relative to the Base Case. We will then turn to a few variations that we considered to the basic Negligible Senescence scenario, considering alternative life extension cost levels. Finally, we will consider the more extended economic and demographic implications of the Negligible Senescence scenario.
4.1 Dramatically Changing Health Cost Structures with Negligible Senescence

The difference in morbidity and last-life-year costs between the Base Case and Negligible Senescence scenarios (see Figure 4.1) is dramatic. On a global basis morbidity-associated costs in the Base Case would approximate 8.4 percent of GDP by 2020, and would be continuing to rise; mortality-associated costs would be just under 1 percent of GDP. Thus the near elimination of these would reduce the economic burden of health care by roughly 9 percent. The small remaining levels of morbidity costs in the Negligible Senescence scenario (and even smaller mortality costs) reflect mental health illness and deaths/illness among children.

Figure 4.1 Morbidity and mortality costs globally as percent of GDP, comparative scenarios

The change in morbidity and mortality costs would only occur, however, if technology to extend life with very low senescence were available. Leaving aside the costs of developing such technology, there would be costs associated with using it. The level of such costs is, of course, completely uncertain, as is the required frequency of treatments. As we shall see, the assumptions one makes around these costs is, beyond the potential of developing the technology itself, the greatest uncertainty we faced in our analysis. Consistent with the use of sensitivity analysis or more broadly integrated scenarios to

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4 For high-income countries (using the World Bank's definition), the percent of GDP spent in 2020 is 11.6 and rises in the Base Case to 22 percent in 2100; the curve in the graphic is held down by the increasing GDP weight of much lower-spending low- and middle-income-countries.
map alternative futures under conditions of uncertainty, we developed three alternative sets of assumptions. The first is the basic or core Negligible Senescence scenario (used also elsewhere throughout our analysis). Its key assumptions are:

- Per-person treatments cost for very high-income countries of $100,000 at 20-year intervals (equivalent to $5,000 per person-year). The $100,000 is based on the average cost per patient for a number of advanced medical treatments that potential life extension therapies might resemble, including: molecularly targeted cancer drugs, gene therapy treatments, a recent protease inhibitor treatment, and the cost of the telomerase supplement TA-65.achen

- Downward scaling of those treatment costs for country-years in which GDP per capita is less than that of the United States in 2010, to a minimum of 5 percent of the costs in high-income countries. This downward scaling in price is influenced by the complex pattern of subsidies and transfers that pharmaceutical companies, nongovernmental organizations, and governments currently employ to produce variable cost structures for antiretroviral therapies to treat HIV. Based on data from the President’s Emergency Plan for AIDS Relief (PEPFAR), the current mean cost per patient-year for lower- and lower-middle income countries in 2013 was $642 when taking into account all sources of support, while for upper-middle-income countries the mean cost was $941. When compared with average person-year treatment costs in the US of $20,000, low-income and lower-middle-income countries pay 3.2% of the US cost while upper-middle-income countries pay 4.7%.

- Decline in person-year costs in real terms to one fourth of initial cost (to $1,250 in constant 2005 dollars) over 80 years to 2100, a rate of 1.7 percent annually. Relative to growing GDP per capita, this would mean a quite rapid and very substantial decline in economic burden.

- Cost-determined spending on health. We recognized that bottom-up calculations of total health costs with our full set of assumptions (in the Base Case as well as Negligible Senescence) will not be equal to top-down calculations of what governments and private citizens have historically been willing or able to actually expend. Although these are relatively well balanced in the Base Case, they can be very different in variations of Negligible Senescence. We therefore demand in Negligible Senescence that the public and private expenditures be equal to the bottom-up cost structures, an assumption that allows us to see the implications for government finance of alternative costs.

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5 The annual cost of the selected molecularly targeted cancer therapies ranges from $60,000—$240,000 US$2010 (Sikora 2011; Christian Torres, “Cancer drugs can cost an arm and a leg… or a car,” Spoonful of medicine blog, Nature Medicine, January 22 2010). The annual cost of the selected gene therapy treatments range from $30,000—$340,000 (Nicholas Wade, “Treatment for Blood Disease is Gene Therapy Landmark,” New York Times, December 10th 2011; “Europe approves high-price gene therapy,” Reuters, November 2nd 2012). The protease inhibitor treatment cost $57,200 per year (Liu et al 2012), and the annual cost of the TA-65 supplement is $8,000 (Jesus et al 2011).

6 2013 Report on Costs of Treatment in the President’s Emergency Plan for AIDS Relief

The two variations on this basic Negligible Senescence scenario change the treatment re-occurrence interval to 10 years and 30 years, respectively. For analysis purposes this is equivalent to leaving the treatment interval at 20 years and raising (by 100 percent) or lowering (by 50 percent) per treatment costs. On an annual basis the cost of a $100,000 treatment every 10 years would be $10,000 and that of a treatment every 30 years would be $3,333. Throughout most of this paper we refer to these three variations as the core or medium cost variation (20-year intervals or $5,000 per year), the high-cost variation (10-year intervals or $10,000 per year), and the low-cost variation (20-year intervals or $3,333 per year).

Figure 4.2 shows the impact of these alternative cost assumptions on the global cost as a portion of GDP associated with the life extension treatments themselves. It makes clear that even this relatively narrow variation of cost assumptions can generate life extension costs that either exceed or fall short of the savings generated by collapsing morbidity and mortality costs. The peak global cost of 5.3 percent of GDP in the medium cost (core assumption) variation of Negligible Senescence is somewhat less than the reduction in morbidity and mortality costs in the same scenario. In the high-cost variation, however, the costs would double and obviously put substantial upward pressure on total healthcare costs (perhaps a price that societies would be very willing to bear given the prospect of very long and healthy lives, but a substantial price, nonetheless).

![Figure 4.2 Life extension costs globally as percent of GDP, three negligible senescence variations](image-url)
There are, however, two additional aspects of total health costs. The first is "other" healthcare costs (such as administrative and R&D). Given all but non-existent data, we estimate these in 2010 as the residual of reported health expenditures by country and our calculations of morbidity and mortality cost—in the process we find that such other costs are a much higher percentage of GDP in high-income countries than elsewhere in the world. For forecasting we assume a constant ratio of such costs to the sum of morbidity, mortality and life extension costs. Ranging from approximately 1 to 3.5 percent of GDP globally (much higher for the US), they are a much less significant element of the total global cost structures than are morbidity or life extension costs. We therefore do not focus on them in this analysis.

The final remaining health care cost is that of the implicit subsidies or transfers involved in the lower prices for poorer countries. One could speculate that lower prices should reflect effective transfer of costs and profit opportunities by pharmaceutical companies from poor-country to rich-country clients (covered within the cost to the rich), or that government or private assistance programs would cover the costs (adding to the overall health-care bill), or that it would be some combination. Such speculation runs up against the problem indicated by Figure 4.3. At the year of peak cost in the core Negligible Senescence scenario, the subsidies/transfers would require an additional 7 percent of global GDP on top of the 5 percent for life extension costs. Realistically, almost all of these costs would be borne in some manner by high-income countries. Since the collective GDP of those countries would be approximately half of the global total at the peak of the subsidy/transfer expense rate, supporting all paid and unpaid costs would consume something near one-third of the GDP of the high-income countries. This raises very serious questions about whether high-income countries would, indeed, pick up a substantial share of, much less all of such costs for those in lower-income countries.

8 In scenario analysis not reported here we have also structured an alternative to the constant ratio assumption, namely a convergence across countries to a common value such as the 12 percent of total health costs that we find in lower-cost high-income countries; such convergence would be especially important for a country such as the United States, where our estimate of those costs in 2010 is 43% of total costs and 8 percent of GDP.
Figure 4.3 Subsidy/transfer and paid life extension costs globally as percent of global GDP, core Negligible Senescence scenario (20-year treatments at $100,000 or $5,000 per year)

Figure 4.4 elaborates the essential impossibility of such transfers by showing the percentage required as portions of the GDP in recipient countries (by income category). In the core Negligible Senescence scenario richer countries and peoples would be subsidizing the average low-income country at close to 80 percent of its GDP. By comparison, in 2012 direct overseas development assistance (ODA) accounted for just 7.4 percent of GDP in low-income countries and 0.8 percent in lower middle-income countries (World Development Indicators 2014). Only a few conflict-affected states have received ODA of 80 percent or more of GDP for even a single year (e.g. Liberia received 127 percent in 2010, but only 36 percent in 2012; Afghanistan received 50 percent in 2007, but only 33 percent in 2012) (World Development Indicators 2014).
4.2 Total Health Costs and the Difficulty of Paying Them

The IFs Base Case forecasts for total health spending are quite close to existing forecasts in the literature. The OECD, for example, forecasts total public spending on health by the group to reach 13 percent of GDP by 2050. In the IFs Base Case, OECD spending reaches a slightly higher 14 percent of GDP by 2050. At the country level, Keehan et al. (2011) forecast total health spending in the United States to reach 19.8 percent of GDP by 2020. In IFs, spending in the US in 2020 is a similar 20.1 percent of GDP. Similarly, Besseling and Shestalove (2010) forecast public health spending in the Netherlands to be 10 percent of GDP in 2015 while IFs has it reaching 10.8 percent GDP (see Appendix A4.4 for a more in-depth comparison of results with existing forecasts).

Would the world be able to cope with the additional health care costs of Negligible Senescence, particularly in the early years? Figure 4.5 helps us address that question. It shows the total costs of health care as a percent of GDP in the Base Case and all three Negligible Senescence scenarios, assuming that all of the subsidy/transfer costs to cover lower-income regions of the world are incremental to the paid life-extension costs (and therefore adding them into the total). In the core or medium-cost Negligible Senescence scenario the costs during the phase-in period peak in 2030 at 16.3 percent of GDP,
relative to 11.5 percent in the Base Case—perhaps theoretically bearable in a world struggling (and with the technology in sight, presumably desperately struggling) to end sickness.

![Figure 4.5 Global total health care costs assuming subsidies/transfers are incremental to paid life extension costs (adding them into the total)](image)

Figure 4.5 Global total health care costs assuming subsidies/transfers are incremental to paid life extension costs (adding them into the total)
The key problem within and across societies would almost certainly be distributional. Within high-income societies it could be quite manageable. Figure 4.6 shows the same information for high-income countries only. Were the effective cost per person-year of treatment to be no more than $5,000 it should, in fact, be relatively easy, with the declining costs of morbidity and mortality offsetting the incremental costs of life extension. Given that morbidity costs are already heavily assignable to the poor and significantly subsidized, the redirection of expenditures should be eased.

Figure 4.6 High-income country total health care costs, not including any possible subsidies/transfers to lower-income countries
The political realities of the world would, however, make addressing costs beyond the high-income countries an incredible challenge, all but impossible to meet, especially for countries in the World Bank's low-income country category. Figure 4.7 turns attention to those countries. It shows that, even if the subsidies and transfers discussed above (see Figures 4.3 and 4.4) were forthcoming to allow residual costs to be scaled down with GDP per capita to as low as 5 percent of the amount paid in high-income countries, the remaining domestic burden would be very large for several decades. In the core Negligible Senescence scenario peak expenditures would still be several percentage points higher than in the Base Case, with the subsidies and transfers. And in the high-cost variation they would nearly double. In societies especially challenged to mobilize revenues and use them effectively, success in paying the costs beyond a very elite sub-population seems improbable.

![Figure 4.7 Remaining low-income country health care costs even after receipt of subsidies/transfers](image)
Were, however, low-income countries actually able to meet the burden of their relatively small share of treatment costs, would high-income countries be forthcoming with the necessary subsidies and transfers? Figure 4.3 showed the magnitude of those needed globally, covering low- and middle-income countries. The peak level in the core Negligible Senescence scenario was just short of 7 percent of global GDP, which would be about 17 percent of the GDP of high-income countries. During the Marshall Plan the United States managed to mobilize about 1.25 percent of its GDP for assistance in rebuilding Europe for a four-year period. Expecting all high-income countries to mobilize something close to 17 percent of their GDPs, on top of their own high health care expenditures and distributional issues is not reasonable. On this fundamental life and death issue, the world would almost certainly face great divisions—after several decades over which life expectancies of lower-income countries have converged toward those of higher-income countries, divergence would be highly probable and most likely substantial.

4.3 Forward Implications of Negligible Senescence and Health Costs

Barring constraints that cause Malthusian-like collapses (Section 6 returns to this issue), a world with Negligible Senescence should have a larger economy than that of the Base Case for at least two reasons: more people should mean more workers; a longer and healthier lifespan could potentially and most probably mean longer working lives (Section 5 returns to this issue). Figure 4.8 indicates that to be the case in our own forecasts. Note, however, that variation across the three Negligible Senescence scenarios, obviously related to the difference in health-care costs (treatment costs divided by the interval over which they are spread) that constitutes the only different assumption of the scenarios.
Figure 4.8 GDP globally, Base Case and Negligible Senescence scenario variants
Figure 4.9 helps show the interaction of the extra labor force and the health care costs by displaying GDP per capita across the scenarios. Were the life extension costs equivalent to $10,000 per year (the high cost variation), those costs would keep GDP per capita closer to the Base Case through most of the century, with a slowdown in growth towards the end of it—a small trade-off between extra life and economic well-being per year of it. If the costs were lower (as in the Core NS and Low Cost NS scenarios), the GDP per capita would rise by as much as $16,000 per capita above that of the Base Case, a result of that larger and especially healthier work force (all Negligible Senescence scenarios to this point assume retirement at 65 and no change in participation rates through that age, an issue to which Section 5 returns).

![GDP per capita (PPP) globally, Base Case and comparative Negligible Senescence scenario variants](image_url)
Figure 4.10 shows more directly the kind of trade-offs that life extension and associated healthcare costs can create. It focuses on public formal education spending as a portion of GDP. In the Base Case that stays in the 3.5 to 5.0 percent band (the early erosion is a result of decrease in higher-income countries, mostly related to declining youth portions of the population and high current spending levels; rates of spending in lower- and middle-income countries are rising). The High Cost Negligible Senescence scenario takes so much health spending that it squeezes out a portion of the education spending during the first part of the century, contributing to the pressure on GDP per capita seen above because it would lower worker productivity. The other two scenarios actually allow an expansion of education spending (and the positive productivity contributions of it) for much of the century, until the decreased portion of population at younger ages brings spending rates down again relative to the Base Case.

Figure 4.10 Education spending as percent of GDP, globally, Base Case and comparative Negligible Senescence scenario variants

4.4 Conclusion

To this point we have considered two major challenges that a world of healthy, very long life would face. The first, addressed in the previous section of the report, is a burgeoning population. This would occur even without delay of menopause and extension of fecundity with a possible increase in total fertility rates. It would occur, in fact, even in a world that attempted to adapt with a TFR dropping to 1.0. In the absence of substantial deaths, almost all births become population increasing.

The second challenge, addressed in this section, is paying the costs of life extension, especially in the early years during and immediately after phase-in and most especially for lower-income countries. Even with great reduction in the costs of treatment for those
in low-income countries, subsidized by those in higher-income ones, the ability of societies to deliver consistently the benefits of healthy long-life is questionable.

We turn now to a third potential challenge, reconceptualizing the financing of life spans.
5. Life Pattern Financing and Economic Implications

The contemporary world already struggles with financing of old age. Many developing countries, including giants like China and India, have yet to set up pension systems that fully cover aging populations that once relied upon children for support but are becoming relatively more numerous. High-income countries tend to have such systems, but many are based on defined-benefits rather than defined-contributions and are proving inadequate in the face of even current rates of longevity increase and growth in proportions of the elderly. Richer countries have not seen average retirement ages rise as people live longer and healthier lives; instead, higher life-time incomes and healthier retirement plans have encouraged younger retirement ages. Efforts to delay eligibility for public benefits have been only partially successful in the face of often substantial protests and the voting power of the elderly and their supporters (Ebbinghaus and Hofäcker 2013; Komp 2013; Preston 1984).

How then might life patterns and related financing systems evolve in a world of Negligible Senescence? The evolution would necessarily involve some combination of three elements: changes to the working-life pattern, increased household savings to allow new patterns of lifetime flexibility and sustained or increased public spending for those who would retire, periodically interrupt work, or work fewer hours (it is not clear what retirement would mean in such a world). Not surprisingly, we shall see that the first element, in rather dramatic form (essentially the elimination of the concept of retirement), would be necessary to finance lifetimes in the world of Negligible Senescence. Yet individual and societal patterns would likely unfold in surprisingly and interestingly complex fashion.

We made changes to the IFs structure for this project to facilitate our analysis of the trade-offs and combinations of the three interacting options. These included:

- allowing parametric redefinition of work starting age and retirement age in replacement of the fixed values earlier in the IFs system;
- computing the annual consumption needs of the elderly, both in terms of annual flows and long-term stocks (assuming a finite life expectancy); also computing household assets as a stock and the potential for sustained flows from them;
- building mechanisms to compute endogenously the needed retirement age, savings pattern, or government transfers to meet retiree needs (assuming no substantial change in contributions from the other two contribution sources);
- creating a mechanism to allow exogenous specification of a balance of contributions from the three sources, so as to allow experimentation with different combinations that might suit different societies.

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9 It is possible that continued progress in technologies including artificial intelligence, robotics and production processes such as additive manufacturing could provide an abundance of not just material goods but also services (even knowledge advancement) and increasingly eliminate the need for humans to work. In that case, the challenge of societies would not be that of extending work life, as discussed here, but of socializing assured access to increasingly inexpensive goods and services.
In this section of the report we will build our analysis cumulatively on the core Negligible Senescence scenario (with fertility rates, health cost and expenditure patterns as discussed in the previous sections). That scenario did not, however, extend the working lifetime or address associated household and societal changes in financial behavior. A purpose of this section is to develop an elaborated variation of the core NS scenario that reflects at least one possible path into and through those changes.

5.1 Financing Needs

In the contemporary world as captured in our Base Case scenario, increasing life spans and growing elderly populations as a share of the total are already putting much upward pressure on the various mechanisms for meeting the basic consumption demands of retirees (using those over 65 years of age as an estimate of their number). Figure 5.1 shows our Base Case estimate of the portion of GDP needed to do so in different country income categories. It is rising for countries at all income levels and will at least double its share for each grouping by the end of the century (more than tripling for lower-middle-income countries).

![Figure 5.1](image)

Figure 5.1 Portion of GDP needed to meet consumption needs of retirees in different income categories of countries, Base Case scenario
Note: Using World Bank Country-Income Categories.
If we turn from different country income groupings in the Base Case (Figure 5.1 above) to global comparison of the Base Case and Core Negligible Senescence scenario, Figure 5.2 shows that the substantial global rise in global consumption needs of those over 65 in the Base Case is nearly insignificant compared to the 3-fold rise that long life would produce. In the Core Negligible Senescence scenario, the fertility rate of 1.9 would be continuing to produce a relatively constant number of workers; yet they would be hard pressed to keep satisfying the growing consumption demand of more and more retirees. Were fertility rates to decline substantially with Negligible Senescence (see again Section 3.2.2 and the red line of Figure 5.2), the GDP would be lower as the labor force shrank and the share of that GDP demanded by those above 65 would rise still faster.

**Figure 5.2 Portion of GDP needed globally to meet consumption needs of retirees, three scenarios**

*Note: In the Low Fertility NS scenario TFR trends to 1.0.*

### 5.2 Meeting Life-Long Financial Needs: The Nearly Inevitable Challenge

It is obvious from Figure 5.2 that current pension systems (government and presumably also corporate) could not meet the consumption needs/demands of a long-lived population that might contractually insist on retiring at ages close to those common today. During a major transition to low senescence (and in the early years of adaptation to it) there would likely be a combination of confusion, denial, and inertia across even high-income, technologically advanced societies with respect to what was actually happening, in part because the transition would occur in stages and unequally across society. Moreover, the already strong political position of the elderly would become increasingly and fairly rapidly even stronger as mortality and senescence were forced back.
5.2.1 The Push to Protect Retirement "Rights"

The clamor to protect entitlements would most likely be very strong and the first push would likely be to strengthen existing pension systems and protect the perceived right to benefitted retirement. Figure 5.3 suggests government pension spending paths that might result from such a push. The lines in that figure represent endogenous IFs calculations in the Base Case and Core Negligible Senescence scenarios, with expenditures driven by the number of retirees and their consumption demands (as indicated in Figure 5.2), but very substantially constrained by competing expenditure demands and revenue rise limitations calculated in the model. To put the resultant pension expenditures in context, current total global government expenditures are about 40 percent of GDP, and the Negligible Senescence scenario in Figure 5.3 allows pension spending alone to rise to more than one-third of that.

The question cannot really be whether the current pattern of substantial governmental provision of retirement funding in high-income countries would continue and spread globally in a negligible senescence world without inter-generational conflict, but only when the social patterns and the trend toward higher government spending would break. Corporate systems might more easily move to defined contribution programs and shift the burden back to the retiree, but many old-line corporations would, like General Motors in recent years, be taken into bankruptcy in large part by unsustainable pension payment requirements of defined benefit programs. Other existing forecasts tend to agree with the IFs Base Case that population aging and increasing longevity will likely drive up spending on public pensions as a percent of GDP by several percentage points over the next several decades (see Appendix 6 for more on other forecasts of pension spending).

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10 Global pension spending as a portion of GDP is fairly flat in the Base Case in part because the line combines the rising global GDP share of lower-income countries with lower pension spending rates.
Figure 5.3 Expansion of government pension transfers globally in attempt to meet retiree needs
Even as progression down that path of increased government (and to some extent corporate) spending unfolded, however, the gap between what retirees needed to keep up with their traditional consumption patterns and the income they could actually have from all sources would grow. Figure 5.2 showed the 52 percent plus share of GDP demanded by those over 65 (as does Figure 5.4). Figure 5.3 indicated the 8 percent that governments might actually supply and Figure 5.4 augments that with income from savings to raise actual consumption potential to just over 21 percent. Thus Figure 5.4 indicates that by 2100 the remaining gap between consumption demand and all sources of support and therefore actual consumption would be about 30 percent of GDP or about $300 trillion dollars in our Core Negligible Senescence scenario. The push to protect retirement as we know it today would fail both from push-back against the high share of government expenditures required and the inadequacy of them combined with personal savings in any case.

Figure 5.4 Remaining gap globally in retiree consumption needs even after major pension expansion, Negligible Senescence scenario

*Note: Actual consumption is calculated in IFs based on ongoing income from work, pensions, and earnings of assets accumulated during working years; the last is especially hard to estimate, but IFs does so using its representation of life pattern savings and interest rates.*
5.2.2 The Push to Effectively Eliminate Retirement

While many in societies would argue for more of the same historical pattern and therefore especially for increased government support, others would call for waking up, recognizing the dramatic changes taking place, and taking the big step to adapt with a large-scale adjustment of retirement age, eliminating government support in all but exceptional and bridging circumstances (e.g. to allow for retraining as the economy changed). Those others would supportively argue that all humans would "want to work" much longer or indefinitely if given healthy old age. A bit of thought about such a change, however, suggests that it would be as politically impossible suddenly to eliminate retirement (or at least to the push it out to such an old age that the average person could accumulate assets that would then support life indefinitely) as it ultimately would be to protect traditional retirement rights.

5.3 Meeting Life-Long Financial Needs: How it Might be Unfold

So how might changes in the balance between retirement age (or more generally the character of working life), personal savings, and government support work out? There are, of course, an infinite numbers of combinations and they would vary over time and across societies. We cannot pretend to forecast that unfolding. But we can explore patterns that may illustrate and help frame the possibilities. Figures 5.5—5.7 below, and the discussion around them, collectively constitute such a pattern and illustration; we know it to be one of minimal likelihood, but believe it also to have a basic logic.

Rather than being defined by a big policy push for either government support or official retirement elimination, and rather than taking clear form quickly, new societal patterns around life pattern financing are likely to emerge gradually and iteratively from the cooperative and competitive interactions of households, firms, and governments.

On the retirement side, most people living indefinitely in good health would ultimately likely work in some fashion across their lifetimes, probably dropping out periodically for recreation or retraining, and very likely cutting back the intensity of work life (and often eschewing paid employment when finances allowed). But the changes to old patterns would likely happen gradually as people began to adjust to the new reality, many "retiring" and then re-entering labor, many scaling back, others savoring the ability to jump rapidly into new opportunities. One subpopulation of considerable importance, however, would be those who are already in retirement when the technology-based gift of long and healthy life arrived—many would have left careers and employment in high positions and would find it extremely difficult to reclaim those slots; they would to some degree be starting over.
Figure 5.5 shows one of the infinite number of possible paths toward what might be considered a kind of average years working life as the various adjustments and extensions were made across society as a whole. Such an adjustment might well involve some significant and substantial extensions of working life near the end of the negligible senescence phase-in period (2040), motivated in part by financial exigency of governments and households that begin to run huge pension plan deficits paying for the transition and by the increasing social comprehensive of the changed health and ability of population at all ages. The initial adjustment might be followed by longer-term continuing adjustments. The reason it has a somewhat irregular pattern in Figure 5.5 is because it is a global summary of that unfolding and because the endogenous working of the model produces ongoing adjustments within and across countries in the balance of retirement age, savings, and government support.  

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The model uses parameters to control the contribution of each leg of that triangle to meeting the gap between retiree consumption needs or demands and actual consumption levels (see Figure 5.4): workerageretirendpctuse for the weight given to retirement age change, cpenduse for the weight given to reduced consumption and higher savings, and govhpentinndpctuse for the weight given to government contributions to pensions. In the analysis here these have been set from 2020 at 50, 10, and 40 respectively, but it is difficult to give these values substantive interpretation. Given any set of parameter values the model's computations of actual retirement age, savings rates, and government spending and the interactions among them are very complicated, because they involve a combination of flows (such as income, consumption, government spending) and stocks (such as household assets accumulated and government debt levels) and because a variety of equilibrating systems (such as production and consumption of goods and services; government revenues and expenditures) involve lags and feedbacks that dynamically affect still other systems (including economic productivity and growth). Thus the setting of parameters to establish a scenario involves substantial iteration and trial-and-error. Again, we do not pretend the variation presented here it is one of high likelihood, because the range of feasible alternatives is very great.
Figure 5.5 Phase-in globally of work life extension in Negligible Senescence adjusted for life-pattern changes

Note: Figures 5.5-5.7 collectively represent the unfolding of one possible pattern of life-pattern finance changes by households and government.

The second possible leg of life-pattern financing is one's own or the household's assets, accumulated via saving (and inheritance might be a disappearing concept). Recognizing that there might be a very long traditional retirement ahead would probably, at least in the early stages of Negligible Senescence, lead to increased savings for that future; as healthy future life came to be taken for granted, the calculus could change and people might come to believe that savings were less important. At the same time, in the earlier transition stages, many people would be very hard pressed to pay for the new medical technologies and treatments. Given the truly life-and-death stakes attached to being able to do so, savings would quite possibly surge (see Figure 5.6)—often such shifts away from consumption might follow the borrowing of money to pay for treatments (such lending inevitably becoming huge business) and then enforced savings to pay the debt.

Figure 5.6 Household savings globally in Negligible Senescence adjusted for life-pattern changes

Note: Five-year moving average used to smooth behavior. Figures 5.5-5.7 collectively represent the unfolding of one possible pattern of life-pattern finance changes by households and government.
Early in the transition and post-transition period, as we saw in Section 4, government resources would be hard pressed by the demands for health spending to pay for new medical options (much less more pensions) and debts are likely to accumulate. And if the phase-in of longer working life began early enough, as suggested in Figure 5.5 and household savings surged as in Figure 5.6, government retirement spending as a portion of GDP might even dip a bit during and after Negligible Senescence phase-in as in Figure 5.7. (This is a very different pattern than in Figure 5.3 where there was no change in retirement years and the model therefore pushed governments much harder for additional pension spending.) In early years such spending would likely continue to be conceptualized as pension payments, but ultimately it would morph into something more like life-pattern bridging support as people temporarily left the work force for either revitalizing leisure or redefinition with retraining. In the longer run it might be recognized that such important social support merited higher spending levels, and long working lives and taxes on them could generate considerable resources for re-interpretation.

Figure 5.7 Government support globally for pensions and rebalanced life-pattern bridging support

*Note: Five-Year moving average used to smooth behavior. Figures 5.5-5.7 collectively represent the unfolding of one possible pattern of life-pattern finance changes by households and government.*

The story of Figures 5.5—5.7 is, to say it again, only one possible unfolding of life-pattern behavior and financing in the new world of Negligible Senescence. It is, however, one story that within the International Futures system is able to balance the savings and consumption patterns over the long term, and it will become our Rebalanced Life-Pattern
Negligible Senescence scenario for further analysis in this report. How such adjustments might unfold will, of course, have large impacts on economic growth and we turn next to that topic.

5.4 Conclusion and Economic Impact

In short, adjustment of the life pattern and its financing would be both necessary and beneficial in a new world of healthy long life. It would be a wrenching transformation of existing patterns and likely subject to substantial social conflict as it proceeded. Some adjustment would clearly be necessary, however, because traditional patterns of retirement and associated financing would become impossible. Adjustment would be beneficial at the individual level because it would take advantage of the opportunities provided by healthy long life, and it would be beneficial at the collective societal level because of the income growth it would help generate.

As with societal choices around the funding of health care costs, those around financing of life pattern would have broader economic consequences. Among the consequences of both the longer working life and the higher savings rate would be both higher GDP and higher GDP per capita, relative to both the Base Case and the Core Negligible Senescence scenario. Figure 5.8 suggests a global GDP that could grow from 89 trillion (2011 constant) dollars today to about 1,700 trillion in 2100 (compared to 866 trillion in the Base Case).

![Figure 5.8 GDP globally in three scenarios](image)

Figure 5.8 GDP globally in three scenarios

Similarly, GDP per capita (at PPP) could grow from less than $13,000 to $114,000 by 2100, well above that in either the Base Case ($86,000) or the core Negligible Senescence scenario ($99,000). In other words, about half of the potential economic
gains associated with negligible senescence would only emerge if economies adapted to accommodate the new rhythm of the expanded human life course.

Figure 5.9 GDP per capita (at Purchasing Power Parity) globally in three scenarios

These estimates of potential GDP growth should be interpreted with great care and consideration of the underlying assumptions, recognizing the possibility that societies will be unable or unwilling to pursue some of the choices we have described above. Among the infinite number of potential life course financing scenarios noted above, those involving more dramatic increases in government expenditure or reduced working lives would entail considerably less economic growth. There is also the possibility that the consumption needs of some elderly simply might not be met by emerging adjustments to the state and market, introducing an unaddressed burden of poverty with attendant consequences for growth and social cohesion. By eliminating retirement, our estimates assume that populations will generally work at the participation rates of current high-income societies. In practice, populations living without retirement might experience periods of economic dependency by extending the period of adolescent dependency, by pursuing retraining in mid-life, or by simply choosing to retire anyway. Any reduction in the rate of economic participation would cut directly into our estimates of productivity.

Furthermore, the incredible additional growth in GDP and GDP per capita would occur in a world and in a century characterized by environmental sustainability issues that are already increasingly and belatedly taking center stage. We must consider the sustainability implications of the huge transformations that we have been discussing.
6. Economic Growth and Sustainability

Although there is a tremendous range of interface points between human systems and our broader environment, there are three that have special importance and on which we will focus here. Two of these draw energy from the environment, a variety of energy forms for our economies and food energy for our bodies. The third puts an output back into the environment, namely carbon into our atmosphere. Each of these three has interacting secondary environmental implications for land use, exhaustion of non-renewable resources, and global warming. How might the world of Negligible Senescence (with Rebalanced Life-Patterns as explored in Section 5) complicate or possibly enhance our ability to address key environmental and sustainability issues?

It was not necessary to make changes in the International Futures (IFs) forecasting system to initiate exploration of this question. There are, however, many levels of exploration that could unfold and lead us into areas that would require model development. This section of our report should be viewed as early stage analysis.

6.1 Energy Demand and Supply

In the IFs Base Case, global energy demand more than quadruples between 2010 and 2100 (see Figure 6.1). In the Rebalanced Life-Pattern Negligible Senescence scenario that increase becomes close to a factor of nearly 8 (4-fold in per capita terms). Given that Figure 5.8 had indicated GDP growth in that scenario by a factor of 19 by 2100, it should be obvious that the 8-fold increase in energy demand assumes great reductions in the use of energy per unit of GDP as a result of efficiency increases and demand pattern changes. In fact, the barrels of oil equivalent used per thousand dollars of GDP falls from 1.2 to 0.38 at a rate faster than the historical decline—there is no shortage of efficiency improvement in this scenario.

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12 This is in line with the Baseline scenario in the recent Global Energy Assessment (Johansson et al 2012) using the MESSAGE model. The Baseline scenario in the GEA using the IMAGE model projects somewhat slower growth, with only around a doubling of global energy demand over this period.
How might the world meet such a sustained and large increase in demand? Figure 6.2 provides possible answers to that question, focusing on carbon-based fossil fuels (oil, gas, and coal in the absence of carbon sequestration) on one hand, and all other energy forms in the aggregate (including hydroelectric, new renewables like wind and solar, and nuclear energy from fission and potentially fusion) on the other hand. The first scenario in the figure is our Base Case, which shows a peaking of fossil fuel use in the 2030s and a steady climb in non-fossil fuel sources throughout the century, overtaking fossil fuels just before mid-century.

In our examination of the energy supply patterns of the Rebalanced Life-Pattern NS scenario we found a very similar fossil fuel pattern but a dramatic and perhaps implausible increase in non-fossil fuels. Thus Figure 6.2 substitutes a variation to the Rebalanced Life-Pattern Negligible Senescence scenario that cuts growth in non-fossil production back somewhat and adds somewhat more fossil fuel production; the additional fossil fuel is assumed to be coal because the resource constraints on coal are much less than those on oil and gas. Even in this rebalanced scenario, non-fossil fuels sources overtake fossil fuels in contribution to meeting demand shortly after 2050. Our forecasts of non-fossil fuel supply are aggressive in the context of recent energy literature, as is our Base Case anticipation of the continued growth of non-fossil sources to as much as 9.2 times the contribution of fossil sources by 2100.¹³

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¹³ By comparison, in the Baseline scenarios of the Global Energy Assessment, non-fossil fuel sources contribute only 20-25% of total global primary energy in the year 2100 (Johansson et al 2012). The MESSAGE model does produce a fossil/non-fossil breakdown similar to that seen in IFs, but only in
Figure 6.2 Energy supply globally from fossil and non-fossil sources in two scenarios

Are such changes in the global energy production pattern feasible? We should remember that the global energy system in the 20th century was transformed from primary reliance on coal and wood to one dominated by oil and gas. Yet this report cannot drill down into the capacity constraints that might affect such expansion of non-fossil sources in the absence of break-through resources such as fusion power. Such transformation to non-fossil sources certainly appears extremely challenging.

scenarios with a strong sustainability focus. At the same time, total energy use is significantly lower in these scenarios, so the absolute growth in energy from non-fossil sources is much less than in the IFs Base Case.
6.2 Carbon Emissions and Global Warming

Because of the close linkage between energy and carbon emissions, we turn next to those emissions before returning to the other inputs required from the environment around agriculture. Given the fossil fuel forecasts shown in Figure 6.2, one might expected the story of our analysis around global warming in the face of Negligible Senescence not to be too challenging. In fact, the model structure and parameterization for the Base Case and most scenarios with IFs fundamentally assume that non-fossil alternatives will become sufficiently cost-effective and remain sufficiently plentiful (even if using them requires alternatives such as solar farms in North Africa to feed the energy needs of Europe) that markets and political systems will logically shift away from increasingly hard to access oil and gas supplies and highly polluting coal (absent sequestration). And, as we will discuss below, to meet global food needs in our agricultural scenario we (perhaps over-optimistically) posit relatively minor increase in cropland at the expense of forests. Yet the scale of Figure 6.2 conceals the fact that we still forecast total production and use of 15 percent more fossil fuel across the century in the Negligible Senescence scenario than in the Base Case and 60 percent more fossil fuel in the Rebalanced Life-Pattern Negligible Senescence scenario with high coal use.

It is quite far from good news that we see in Figure 6.3. In the Negligible Senescence with high coal use we see a rise to over 800 parts per million. Even the Base Case scenario in Figure 6.6 takes atmospheric levels well above the 450 parts per million that has been posited as an important target level so as to limit global warming. Carbon sequestration might prevent the coal production from having such consequence, but the technology is still very uncertain, especially at the scale it would be required in the high coal scenario.

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14 By comparison, the Baseline Scenario in the Global Energy Assessment forecasts atmospheric carbon dioxide to approach 1000 parts per million by 2100 (Johansson et al 2012). This is closely tied to the differences in projections of the share of energy coming from non-fossil fuel sources discussed in the previous footnote.
Figure 6.3 Carbon dioxide in the global atmosphere

*Note: The Negligible Senescence scenario includes life pattern rebalancing*

### 6.3 Food Demand and Supply

The situation with respect to food is similarly challenging. Perhaps it is even more challenging because the initial analysis with the model suggested that the world of Negligible Senescence with adjusted life patterns would markedly fail to experience a continuation of the steady growth of global calorie consumption per capita that has characterized the last 50-odd years and that continues in the IFs Base Case (Figure 6.4). The oscillations in the NS Rebalanced Life-Pattern scenario reflect sharply rising prices in interaction with efforts of the model to increase crop yields in the face of model constraints such as assumptions about maximum realistic expansion of crop land and yields per hectare. That is, we could expect stress and instability.
What would it require in terms of changes to agricultural systems in order to feed the nearly 15 billion people in 2100 of Negligible Senescence in contrast to the 10 billion of the Base Case (see again Figure 3.3)? The analysis of Section 5 suggested that those people would on average actually have incomes higher than in the Base Case, thereby demanding more calories per person, and wanting to shift the origin somewhat from crops to meat and fish. Some expansion of cropland is feasible, but since much of that would come from forest as well as from grazing land, we decided not to presume still further conversion of land for crops beyond the increment of about 8 percent in cropland that the model already generates for Negligible Senescence. Further production could and almost certainly will come from innovative new technologies such as vertical or high-rise farming in urban environments. There are, of course, limits to natural light in such locations (and are energy costs for synthetic light), and therefore photosynthesis capacity may be limited. Therefore most additional production would most probably come from yield increases on cropland.

What would it take in terms of assumptions about yield to maintain with negligible senescence the growth of calorie consumption that we see for the Base Case in Figure 6.4? There are two parameters in IFs that allowed us to explore yield increases. The first pushes upward our assumptions about potential maximum realistic yields per hectare—there has to be such a limit and almost all forecasts of food production assume a saturating yield curve. In our Base Case that limit is parametrically set at 15 metric tons per hectare, somewhat above the current crop-land values for high-yielding countries like the Netherlands and Egypt (with fertile alluvial soil, good water supplies, and/or multi-cropping opportunities). The second parameter is a brute-force multiplier on yields that can increase the rate of their growth over time (implicitly assuming advanced technology, better infrastructure including irrigation, and other potential positive factors).
With experimentation we determined that if increased the limit per hectare to 22 million tons and intervened in brute force fashion to try doubling yields by 2100, we were able to keep total yields rising steadily until near the end of the century (see Figure 6.5). The figure shows historical global yield increases so as to put that in context. The Base Case forecast represents the pattern of slow saturation that most forecasters expect. The Negligible Senescence Life-Pattern Adjusted scenario shows the struggle of the model to endogenously react to the higher demand it and to increase yields. The Negligible Senescence scenario with both life patterns adjusted and exogenously forced higher yields maintains a near linear profile until the 2090s when the model begins again to hit constraints such as the relaxed yield limit.

Figure 6.5 Crop yield per hectare globally in three scenarios

*Note: Yield adjusted scenario created so as to maintain Base Case calorie per capita levels.*

Unfortunately, even these interventions are not the end of the story of adaptation of Negligible Senescence. Figure 6.6 shows that because of the new yield growth limitations in Figure 6.5 the global calories per capita begin to fall behind their growth in the Base Case. And more important, we saw in Figure 3.7 that with an ongoing fertility rate of about 1.9 the world's population would continue to grow indefinitely—we were reluctant to drop fertility to 1.0 and begin stabilizing it by the end of the century.
6.4 Conclusion

The world of the IFs Base Case in the twenty-first century is one that moves toward sustainability in some respects (a shift to the dominance of non-fossil fuels, a small reversal of deforestation, stabilizing population, and slowing economic growth even as incomes rise and human calorie needs are largely satisfied, even over-satisfied).

Relative to the Base Case, the world in 2100 of Negligible Senescence is one of an additional 4.7 billion people (46 percent) and $598 trillion dollars of GDP (69 percent). Moreover, both are still growing at significant rates in 2100, 0.6 percent for population and 2.1 percent for GDP (versus -0.07 and 1.7 percent in the Base Case).

It is possible that those 4.7 billion additional and richer humans, the new ones being increasingly well educated and the old maintaining their education, intellectual ability and accumulated wisdom indefinitely, will interact with advanced artificial intelligence and generate solutions to any imaginable problems associated with environmental sustainability. In many respects it is much more difficult to speculate about this issue in the world of Negligible Senescence than it was even with respect to demography, health costs and expenditures, and life and financial patterns.

We can say, however, that those "any imaginable problems" will require serious attention.
7. Conclusions

We are living in an era of growing lifespan and aging populations. Given near certainty concerning continuation of those important changes (only near, because plague or war could take it all away from us), there are at least three very large and immediately related uncertainties:

1. What will be the pace and to what level will lifespans be extended?
2. What will be the quality of health of the aged, including the fecundity of those beyond current childbearing ages?
3. What will be the costs of the treatment(s) providing life extension, especially if there were to be breakthroughs that significantly accelerated the pace of technology advance?

The answers to these questions will dramatically affect, *inter alia*, demographics (the size and structure of our populations), health care costs and expenditures, life patterns around work and finance, economic growth and average income, and environmental sustainability.

Using a large-scale integrated model of global futures, the International Futures or IFs system, we have built thought and modeling analysis experiments upon a basic scenario of a world with technological advance that between 2020 and 2040 moves morbidity from current patterns to one of negligible senescence. This is an arbitrary set of assumptions but ones that facilitate analysis and can be extended. We have explored the larger consequences of that scenario and, in the process, elaborated a *vision of a negligible senescence world*.

Our analysis suggests several general conclusions about a world that had the miraculous technologies needed to achieve negligible senescence. First, population would almost certainly surge and fertility rates would become an issue of tremendous societal importance. Second, costs of even $5,000 per person-year of treatment would pose burdens that individuals and societies below high-income levels could not themselves bear, and transfers within and across societies would be central political issues. Third, in the absence of simultaneous availability of transformative production technologies, life-pattern financing would require reshaping of work patterns that essentially eliminated retirement (but could build in leisure in many alternative ways) and that would greatly restructure government finances and the broader societal role in those life patterns. Fourth, pressures on the global environment would greatly intensify.

Each of these insights would benefit from further analysis. For instance, we have stressed that life-pattern work and finance patterns could take very different forms, and it would be of considerable interest to consider a range of these in interaction with alternative assumptions about the unfolding of the broader technological capabilities of the economy and society (perhaps most humans will really not need to "work"). Nor have not touched at all on the issues of continuing education/learning and the implications of that for a long- or indefinitely-lived humanity and its political-economic systems. Nor have we
delved deeply into what we have sketched as rather profound implications of negligible senescence for the environment. And, of course, if we were to step back somewhat from the positing of movement to negligible senescence very rapidly and soon, there is a wide range of possibilities and scenarios to explore both the pace and diffusion of progress across and within societies.

We may have limited social choice control over how much life will be extended and the health of the aged (technological change will largely drive those). But our analysis suggests that we will have many social choices to make around demography itself (including social approaches to fertility rates), on financing of health care (including the diffusion of life extension technologies to people within and across countries that cannot afford them), on incentive structures around work and savings patterns (including how to trade off working live, savings, and government support), and on the sustainability issues that more and richer people would face (including how to move dramatically to non-fossil energy forms and to feed potentially billions more people).

We recognize our portraits of the future and human choices within it to be inevitably and potentially greatly flawed. We hope that they can also be thought provoking.
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Appendix 1 - The International Futures (IFs) Forecasting System

The International Futures (IFs) forecasting system of the Frederick S. Pardee Center for International Futures at the University of Denver is a large-scale, multi-issue, long-term global forecasting tool. IFs includes detailed representations of demographic, economic, sociopolitical, education, health, infrastructure, energy production, and agricultural subsystems for 186 countries interacting in the global system (see Figure 1). All of these subsystems are endogenized in the model, with a number of linkages and feedbacks among them.

Figure 1: Major modules in the International Futures system. Links shown are examples from a much larger set.

The project's purpose is to facilitate efforts to improve the global human condition, including that of human rights and human security. This requires attention to interacting developments in all of the system’s issue areas. The IFs project recognizes the close interaction of three dimensions of human activity:

- the development of individual human capabilities, including the achievement of improved health, extended education, and adequate material well-being;
- the evolution of social systems, including the advance of transparent, inclusive democracy and the protection and extension of the human rights;
- the interaction of human systems with the broader biological and physical environment, including the achievement of sustainability of physical inputs and the protection of natural systems from human outputs.

For general and technical documentation of the broader modeling system see Hughes and Hillebrand (2006), Hughes et al. (2009) and papers and documentation on each model component at Pardee.du.edu. For example research with the system see Hillebrand (2008) on income distribution, Hillebrand (2010) on globalization, Hughes et al. (2011a and 2011b) on health, Hughes et al. (2011c) on the environment and human development, Moyer and Hughes (2012) on ICT and the environment, and Birkmann et al. (2013) on
climate change and risk. For example use of the IFs system by organizations in applied analysis see the United Nations’ Human Development Reports for 2011 and 2013 (United Nations Development Programme 2011; United Nations Development Programme 2013), Shepherd et al. (2013; 2014) of the Overseas Development Institute (2013), and Chronic Poverty Advisory Network, and Burt et al. (forthcoming) for the World Bank. (sustainable human development), the World Bank, and others. See also our flagship volume series on Patterns of Potential Human Progress.

A1.1 The IFs Health Model

The IFs global health model represents a hybrid and integrated approach to forecasting health outcomes. Hybrid because it uses both distal and proximate drivers to produce outcomes, and integrated because both drivers and outcomes are situated within the greater IFs system, allowing for the incorporation of forward linkages and feedback loops. Together, this approach enables users to explore dynamic age, sex, and country-specific health outcomes related to 15 individual and clustered causes of mortality and morbidity out to the year 2100.

The health model in IFs builds on previous modeling work done by Mathers and Loncar (2006) for the World Health Organization’s (WHO) Global Burden of Disease (GBD) project by integrating their formulations for the distal-drivers of health outcomes at the societal level, such as income and education, and GBD baseline estimates into the larger IFs system.\(^{15}\) The IFs model supplements, or hybridizes these formulations, some of which have been modified or replaced with more richly structural versions, with a set of proximate risk factors for mortality from the Comparative Risk Assessment (CRA) project and super-distal drivers from the larger IFs model (e.g. the environment and sociopolitical modules) in order to produce more complex, cause-specific behavior over a longer time horizon.\(^{16}\) The model also uses the regression models and associated beta coefficients prepared for the GBD project (Mathers and Loncar 2006) in forecasting cause-related mortality outcomes.

\(^{15}\) The distal-drivers of health at the societal level include: gross domestic product per capita, total years of adult education, the impact of smoking (lagged), and change in technology over time.

\(^{16}\) IFs models eight proximate risk factors, namely: childhood underweight, high body mass index, smoking, unsafe water and poor sanitation and hygiene, urban air pollution, indoor air pollution, global climate change, and vehicle ownership and fatality rate.
Figure A1.1 The hybrid structure of the IFs health model and its integration into the larger IFs system.

Integration with the larger IFs system provides the global health model further capability, because not only are the distal-drivers treated endogenously, but also mortality outcomes can be linked to population and economic change through a broad array of pathways, including linkages between mortality/morbidity and reduced fertility, increased human capital and productivity, and increased financial capital. The model’s integrated structure allows users to create custom scenarios by varying model assumptions and trace the impact of those changed assumptions throughout the entire system.

The public availability of the International Futures tool, in both its online and downloadable form without cost, and the analyses it makes possible, remain central to our mission. For more information and access, go to www.Pardee.du.edu. In addition to the project’s own website, the IFs system and forecasts are available through Google’s Public Data Explorer, the African Futures Project, the Atlantic Council’s Strategic Foresight Initiative, and country and issue-specific pages of Wikipedia.
Appendix 2 - Extensions of IFs for this Project: Formulations and Parameters for Scenario Creation

This appendix describes the basic implementation within IFs of extended mortality, changed fertility patterns, and reduced morbidity. It indicates both the parameters via which model users can control those demographic variables and some of the standard scenarios we have created for their exploration.

A2.1 Extended Mortality

The IFs model now includes an extended mortality logic used when handling age categories above 100 years of age (i.e. when the initialization parameter NCohorts is set to greater than 21), expressed in the following senescence mortality function:

\[ P(Mort) = \frac{\alpha \times e^{\beta \text{age}}}{1 + \alpha \times e^{\beta \text{age}}} \]

Where \( \alpha \) is a coefficient controlling the timing of mortality (moving the J-curve horizontally), and \( \beta \) is a coefficient controlling the rapidity of mortality increase with age (making the J-curve steeper or flatter).

In the Base Case, we assume \( \beta = 0.11 \), and \( \text{age} = 95 \). We then fit the observed age-specific death rates for individuals age 15+ (for communicable diseases) or 25+ (for other mortality causes) to the mortality equation to calculate \( \alpha \). We calculate \( \alpha \) separately for three main causes of death: communicable diseases (CDs), non-communicable diseases (NCDs), and injuries (INJs). We use the equation to re-express 5-year age-specific mortality rates for all categories by cause. For all ages above 95, starting with the 100—104 age category, these mortality rates are incorporated directly into the model. For age categories between 15/25 and 99, these estimated mortality rates would differ from those currently found in the IFs forecast. We therefore employ a convergence function that gradually replaces rates from the existing forecast with the next specification over a XX year period (20 years as a default).

Modeling extended longevity, however, also requires us to be able to control how mortality (total, and for each of the three main causes) changes over time. To accomplish this, we added four new parameters to the model that allow us to alter \( \alpha \) and \( \beta \) for the purposes of creating alternate mortality scenarios. These parameters are described in the table below.

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</tr>
</tbody>
</table>
The parameter *hlongvtyalpha*, with which users can customize the value of the Alpha coefficient, is also used as an off switch for our scenario logic; when left unchanged at the default value, the logic is off. The Alpha and Beta parameters are combined to compute a Target Mortality for all people older than the age indicated by the Start Age parameter. This allows for the convergence of the original mortality with the Target Mortality over a period of years defined by the convergence parameter. Given that the Alphas and Betas are only defined for the three main mortality causes (CDs, NCDs, and INJs), we then distribute mortality into the 15 above 100 age categories using existing proportions from the Health Model for each age category (these proportions are kept constant for people over age 95).

We then used these added parameters to create a series of basic scenarios in order to test extended mortality. Each scenario uses different Alphas and Betas in order to establish mortality patterns that will generate certain average life expectancies, while the convergence factor is kept at 20, meaning any changes in life expectancy will ramp up from the base year to 2030.

<table>
<thead>
<tr>
<th>Name</th>
<th>Region</th>
<th>$\alpha_{CD} \times 10^5$</th>
<th>$\beta_{CD}$</th>
<th>$\alpha_{NCD}$</th>
<th>$\beta_{NCD}$</th>
<th>$\alpha_{INJ}$</th>
<th>$\beta_{INJ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifex91</td>
<td>World</td>
<td>0.3</td>
<td>0.119</td>
<td>3.5</td>
<td>0.107</td>
<td>0.6</td>
<td>0.09</td>
</tr>
<tr>
<td>Lifex94</td>
<td>World</td>
<td>0.63</td>
<td>0.11938</td>
<td>2.024</td>
<td>0.10689</td>
<td>0.706</td>
<td>0.09263</td>
</tr>
<tr>
<td>Lifex110</td>
<td>World</td>
<td>0.4</td>
<td>0.092</td>
<td>2</td>
<td>0.092</td>
<td>0.06</td>
<td>0.092</td>
</tr>
<tr>
<td>Lifex150</td>
<td>World</td>
<td>0.4</td>
<td>0.065</td>
<td>2</td>
<td>0.065</td>
<td>0.06</td>
<td>0.065</td>
</tr>
<tr>
<td>Lifex200</td>
<td>World</td>
<td>0.4</td>
<td>0.047</td>
<td>2</td>
<td>0.047</td>
<td>0.06</td>
<td>0.047</td>
</tr>
</tbody>
</table>

We will explore some of the preliminary results from these scenarios below.

### A2.2 Reduced Morbidity

Since building full SENS scenarios will require more than just increased life expectancies, we have also added the capability to model major medical advances and interventions whereby diseases can be reduced or eliminated and fertility can be restored through regenerative medicine.

For morbidity, we have added two new parameters and enhanced an existing one. Of the new parameters, the first works as a multiplier switch, where the logic is only triggered when its value is changed from its default of -1. Once changed, the multiplier works as a portion of initial morbidity to compute a Target Morbidity, which in this case is either 1 for constant morbidity, or 0 for no morbidity. The second of the new parameters is used
to indicate convergence time from the morbidity rates used in the regular IFs Health Module to the desired Target Morbidity. The existing parameter controls the rate of change of morbidity. In the regular Health Module, the rate of change of morbidity, in terms of Years of Life Lived with Disability, is pegged to the rate of change in mortality, but this parameter allows the user to control the rate of morbidity independently.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Dimensions</th>
<th>Default Value</th>
<th>Time Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>hlmorbm</td>
<td>Target Morbidity Multiplier</td>
<td>None</td>
<td>-1</td>
<td>All years</td>
</tr>
<tr>
<td>hlmorbconv</td>
<td>Convergence to Target Morbidity</td>
<td>None</td>
<td>20</td>
<td>All years</td>
</tr>
<tr>
<td>hlmorbtomortgthport</td>
<td>Morbidity to Mortality growth portion</td>
<td>Disease subtypes (15)</td>
<td>1</td>
<td>All years</td>
</tr>
</tbody>
</table>

We have used these variables to produce two basic morbidity scenarios, one where we keep morbidity constant over time, and one where we gradually eliminate it over a 20 year period (2010—2030). Preliminary results of these scenarios can be found below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Morbidity Multiplier</th>
<th>Convergence Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Morbidity</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Wipe Out Morbidity</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>

A2.3 Changed Fertility

For fertility, we have added six new parameters to control extended fertility (fertility that goes beyond the standard menopause limit set in the regular IFs Health Module). Fertility in the IFs model follows a distribution schedule, with a start year, the age when women begin having babies, a peak level, the age when fertility rates peak, a half life, the age at which fertility rates have declined by half after reaching the peak level, and a menopause or stopping year, after which women no longer reproduce. The new parameters allow for greater control of this schedule, so that it can be lengthened, for example.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Dimensions</th>
<th>Default Value</th>
<th>Time Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>hlffrageinit</td>
<td>Initial Age to start fertility distribution</td>
<td>Regions</td>
<td>15</td>
<td>All years</td>
</tr>
<tr>
<td>hlffragepeak</td>
<td>Peak Age of fertility distribution</td>
<td>Regions</td>
<td>20</td>
<td>All years</td>
</tr>
</tbody>
</table>
The peak level parameter is used as a switch, turning on the extended fertility logic when its value is changed from its default of 0. In the first years, before the set convergence time is reached, the model finds the five values for the existing fertility distribution used in the regular Population Module, and then converges those values with the new values set via the five parameters detailed above. The number of years for convergence is set via the sixth parameter. After convergence, the model simply uses the values in the five parameters to build future fertility distributions.

A fertility distribution has the following parts:

1) before the Initial Age, all reproductive values are set to 0
2) a linear growth rate is used to move from Initial Age to the Peak Age
3) a compounded rate of change is used base on the Age of Half Life and is applied to all ages from Peak Age to Stop Age/Menopause
4) after Stop Age/Menopause, all values are set to 0

Once an extended fertility distribution is computed, the model then calculates an extended Total Fertility Rate and converges the TFR from the original Population Module to this new TFR over the same number of years specified by the sixth parameter.

We have used these new parameters to create a series of basic scenarios designed to test the new extended fertility capability. Initial results can be found below in the preliminary results section.

<table>
<thead>
<tr>
<th>Name</th>
<th>Region</th>
<th>Initial Age</th>
<th>Peak Age</th>
<th>Stop Age</th>
<th>Peak Level</th>
<th>Half Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak45Half75</td>
<td>OECD</td>
<td>15</td>
<td>45</td>
<td>120</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td>Peak25Half30</td>
<td>OECD</td>
<td>15</td>
<td>25</td>
<td>120</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>80Menopause</td>
<td>OECD</td>
<td>15</td>
<td>25</td>
<td>80</td>
<td>60</td>
<td>20000</td>
</tr>
<tr>
<td>NoMenopause</td>
<td>OECD</td>
<td>15</td>
<td>25</td>
<td>200</td>
<td>120</td>
<td>20000</td>
</tr>
<tr>
<td>HalfNoMenopause</td>
<td>OECD</td>
<td>15</td>
<td>25</td>
<td>200</td>
<td>60</td>
<td>20000</td>
</tr>
</tbody>
</table>
Appendix 3 - Fertility by Cohort

Section 4, and especially the two panels of Figure 4.3, showed the different profiles of fertility across our scenarios at two time points, 2030 and 2050. We have added the capability within the model to show also the varying profiles of women from different age cohorts within the same scenario. Figure A2.1 uses that capability for Japanese women born in three different years (1990, 2010, and 2030) in the Negligible Senescence with Moderate Fertility Scenario. Note that even women born in 1990 are affected by the movement to negligible senescence by 2030; their fertility declines over time, but persists even to 2100. Following 20 years behind them, the women born in 2010 reach their peak fertility about when senescence reduction is complete and the scenario assigns them a lower peak but a greater and even more extended period of fertility, one that the scenario specifies will also characterize women in subsequent cohorts.

Figure A2.1 Fertility Rates of Different Cohorts of Japanese Women (by Birth Year) in the Negligible Senescence with Moderate Fertility Scenario.

In contrast Figure A2.2 shows the patterns for cohorts of women across time in the Negligible Senescence with Low Fertility Scenario. In that scenario, women within the 1990 and 2010 cohorts both experience the more traditional fertility peak, plus reduced senescence allows them to continue childbearing throughout the time period. Those in the 2030 cohort have adapted still further and have a flatter pattern of childbearing across their lifetimes. The IFs model parameterization of fertility allows us to build a wide variety of scenarios for the lifetime fertility path.
We can also look at the cumulative childbearing of women across time, by age of their birth. See Figure A2.3 and the note explaining how to read it.

Notes: In understanding this graphic, consider women born in 2020. In the high fertility variant they will have had about 2.4 children by 2100, in contrast to about 1.5 for those in the moderate fertility variant and only .9 in the low variant. Women born in 2070 will,
of course be very early in their childbearing years by 2100 and have had very few children by 2100.
Appendix 4 - Health Costs and Expenditures

A4.1 The Drivers of Healthcare Expenditures

A number of factors can drive healthcare expenditure levels, including changes in income and demographics, government policies, and technology. This section focuses on what the existing literature considers the most impactful drivers: individual age and age at death, the nature of longevity gains (extended or compressed morbidity), and technological advance. Other drivers include: consumer behavior, changes in treatment practices, productivity, health prices, and institutional characteristics of health systems (Astolfi et al 2012).

A4.1.1 Health Expenditures, Age, Longevity and Time to Death

All other things being equal, older individuals tend to incur greater health costs, but what matters more for driving expenditures is whether the person lives (is a survivor) or dies at a given age (is a decedent). When it comes to survivors, the impact of age on health expenditures is mostly straightforward. After a brief peak in expenditure around birth, the costs for people who survive each year increases with age—the average expenditure in OECD countries for persons 65+ being two to eight times greater than for people aged 15 to 65—with the rate of increase accelerating for the oldest old (von Baal and Wong 2012; Payne et al 2007). Similarly, McGrail et al (2000) find that costs for survivors aged 90 and above were up to nine times greater than for survivors aged 65.

For decedents, the impact of age at death on expenditures is the inverse of what one might expect: while the costs for dying are much higher overall than costs for surviving, the costs for those in the last year of life are greatest for those at the very youngest (newborns) and youngest-old ages (65—75). In general, decedent expenditures increase significantly and more rapidly than survivor costs from ages 40 to 75, but after 75, actually decrease significantly. For example, Baker et al (1995) find the costs for decedents aged 101 and older were only 37% of those who died at age 70, and Polder et al (2006) find that those who died at 95+ consumed only about 40 to 50 percent of the medical services consumed by decedents aged 65-70.

Overall, the much higher level of decedent spending versus survivor spending leads to a concentration of spending among those individuals in the last year of their lives. Seshamani and Gray (2004), for example, in a 2002 UK based study found that while decedents made up only 1 percent of the population studied, they accounted for 28.9 percent of hospital expenditures during the study period. For the population aged 65 and over, the 5 percent of patients in the last year of their life accounted for nearly half of the population’s total hospital expenditures. Polder et al (2006) found that on average, medical costs per decedent in the Netherlands were 13.5 times higher in the last year of life than costs per survivor, with 11 percent of total health expenditures being associated with people in their final year.

Overall, the much higher level of per-decedent spending versus per survivor spending leads to individuals in their last year of life accounting for a much larger fraction of total
spending then the ratio of decedents to survivors would suggest. Seshamani and Gray (2004) in a 2002 UK-based study, for example, find that while decedents only made up 1 percent of the population studied, they accounted for 29 percent of all hospital expenditures during the study period. For those aged 65 and older, the 5 percent of patients who were in their last year of life accounted for nearly half of the study population’s total hospital expenditures. Polder et al (2006) find that on average, medical costs per decedent in the Netherlands were 13.5 times higher in the last year of life than costs per survivor, with 11 percent of total health expenditures being associated with people in their final year. Similarly, in the US, decedents aged 65 and older accounted for 22 percent of total medical expenditures (Hoover et al 2002).

There are three key findings to be gleaned from these studies. The first is that the cost of acute care in the last year of life is much greater than the cost of surviving. The second is that although individual decedents cost much more, they are greatly outnumbered by survivors, and so the majority of total spending still falls on the survivors. The third finding is that the age at which a person dies has an inverse impact on the cost of acute care, with younger-age groups seeing greater expenses than the oldest.

The nature of future longevity increases will also impact health expenditures going forward. If longevity gains are primarily from actual improvements in health, i.e. better diet, exercise, and medical prevention taken to avoid or reduce morbidity, costs will likely be delayed and reduced once they do occur. If, on the other hand, longevity gains are accompanied by increasing morbidity, costs could be significantly higher than otherwise (Thorpe and Philyaw 2012; Shang and Goldman 2007).

A4.1.2 The Impact of Technology and Other Non-Demographic Factors

Demographic changes certainly account for part of the rapid growth in health spending seen in much of the world, but most studies find such changes are only part of the picture; changes in epidemiology, technology, health policies, and ‘excess health price inflation,’ all impact health expenditures as well, and in many instances, have more of an impact than demographic changes (Astolfi et al 2012; Begg 2008; Vos 2007; Bryant and Sonerson 2006). Martins and Maisonneuve (2006), for example, find that demographic changes accounted for some .3 percentage points of total public health expenditure growth from 1981 to 2002 while 2.3 percentage points came from income effects.

Indeed, many studies are now finding that they cannot account for past growth in health expenditures without taking into account the impact of new medical technologies on spending (Payne et al 2007; Shang and Goldman 2007; Thorpe and Philyaw 2012; Fonseca et al 2013). Payne et al (2007) found that new medical technologies were responsible for an annual 1 percent increase in per capita expenditures in the US between 1975 and 1990, and used this 1 percent growth rate in their forecasts of medical costs. Similarly, the OECD (2006) found a residual 1 percent annual increase in expenditures that it too, associated with technology change for OECD countries. Borger et al (2007) found that medical innovation accounted for 2/3rds of the growth in per capita medical spending, while Thorpe and Philyaw (2012) put the percentage at close to 50 percent, as did a 2008 CBO report (Astolfi et al 2012). Sheshamani and Gray 2004 suggest that the
technology’s impact may vary by patient age as continued improvements might allow for more surgeries or other procedures at later ages than is commonly done now. Technology also tends to have two contradictory impacts on health spending over time. The advent of new, and usually more expensive technologies drives up health prices while the refining of existing technologies tends to lower unit prices (Przywara 2010).

A4.2 The Forward Linkages of Health Expenditures
Naam (2010) finds that while life expectancy goes up as health spending per person increases, above $3,000 dollars per person additional spending has little impact on longevity. The largest ‘bang for the buck’ seems to occur between 0 and $1,000 dollars per person per year in health spending. Additional spending will increase longevity further, but not at the same pace as the initial $1,000.

A4.3 Modeling Health Spending in IFs
Originally, the IFs model only produced forecasts for total health spending that could be broken down into public and private percentages. For this project, we expanded the model to include spending on for each of the 15 individual disease and injury types in the IFs Health Model broken down by morbidity and mortality. We did so by first assembling a new data set of health spending in the United States and the Netherlands, two sample countries to inform our own calculations.

For the US, we pulled prevalence and cost data by disease from the Agency for Healthcare Research and Quality’s Medical Expenditure Panel Survey (MEPS), the Center for Disease Control’s (CDC) WISQARS Injury and Mortality Reports, along with several data points gleaned from annual CDC reports. For the Netherlands, we used prevalence data from Statistics Netherlands (CBS), incidence data from the European Health For All Database and the European Annual Epidemiological Surveillance Report, and injury data from the Incidents and Costs of Injuries database from the Netherlands Central Government.

Building this data set also required us to consolidate the different disease categories used by each source into the 15 health categories in IFs. The MEPS, for example, uses 53 different categories and WISQARS 30. We followed the WHO’s Global Burden of Disease classification system in consolidating each category. Once consolidated, we calculated the percent of total spending for each disease category using total health spending from the CDC and GDP PPP data from IFs. In order to calculate the percent of total spending devoted to morbidity versus mortality, we also had to identify the proper cost ratio between decedent and survivors. Table A4.1 shows our calculated spending by disease type and decedent to survivor ratios by disease type for 2010.

Table A4.1 Unit cost by disease type and cost ratio of morbidity to mortality for the US and the Netherlands, 2010

<table>
<thead>
<tr>
<th></th>
<th>United States</th>
<th>Netherlands</th>
<th>Morbidity/Mortality Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morbidity</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Disease</th>
<th>IFs Base Case</th>
<th>US Base Case</th>
<th>OECD Base Case</th>
<th>2010-2020</th>
<th>2020-2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular Disease</td>
<td>35,643</td>
<td>2,012,321</td>
<td>19,538</td>
<td>783,338</td>
<td>56.46</td>
</tr>
<tr>
<td>Diabetes</td>
<td>136,080</td>
<td>1,357,320</td>
<td>56,839</td>
<td>441,172</td>
<td>9.97</td>
</tr>
<tr>
<td>Digestive Health</td>
<td>91,938</td>
<td>849,349</td>
<td>53,139</td>
<td>1,408,583</td>
<td>9.24</td>
</tr>
<tr>
<td>Malignant Neoplasms</td>
<td>82,865</td>
<td>361,619</td>
<td>69,029</td>
<td>338,557</td>
<td>4.36</td>
</tr>
<tr>
<td>Mental Health</td>
<td>10,705</td>
<td>44,325</td>
<td>31,620</td>
<td>168,305</td>
<td>4.14</td>
</tr>
<tr>
<td>Respiratory</td>
<td>103,719</td>
<td>327,315</td>
<td>45,143</td>
<td>114,616</td>
<td>3.16</td>
</tr>
<tr>
<td>Other</td>
<td>42,594</td>
<td>432,087</td>
<td>57,040</td>
<td>300,319</td>
<td>10.14</td>
</tr>
<tr>
<td>AIDS</td>
<td>257,862</td>
<td>736,366</td>
<td>252,573</td>
<td>1,161,876</td>
<td>2.86</td>
</tr>
<tr>
<td>Diarrheal diseases</td>
<td>88,169</td>
<td>49,273</td>
<td>40,273</td>
<td>36,736</td>
<td>0.56</td>
</tr>
<tr>
<td>Malaria</td>
<td>757</td>
<td>90,826</td>
<td>80,269</td>
<td>1,468,621</td>
<td>119.93</td>
</tr>
<tr>
<td>Respiratory Infections</td>
<td>57,059</td>
<td>2,177,898</td>
<td>43,946</td>
<td>747,132</td>
<td>38.17</td>
</tr>
<tr>
<td>Other</td>
<td>10,397</td>
<td>546,804</td>
<td>58,319</td>
<td>1,898,745</td>
<td>52.59</td>
</tr>
<tr>
<td>Intentional</td>
<td>9,470</td>
<td>139,921</td>
<td>159,453</td>
<td>4,732,131</td>
<td>14.78</td>
</tr>
<tr>
<td>Unintentional</td>
<td>47,282</td>
<td>2,574,521</td>
<td>8,191</td>
<td>244,141</td>
<td>54.45</td>
</tr>
<tr>
<td>Traffic Accidents</td>
<td>65,353</td>
<td>2,680,161</td>
<td>36,702</td>
<td>2,553,197</td>
<td>41.01</td>
</tr>
<tr>
<td>Total Noncom Diseases</td>
<td>57,380</td>
<td>342,955</td>
<td>45,449</td>
<td>270,505</td>
<td>5.98</td>
</tr>
<tr>
<td>Total Communicable</td>
<td>65,559</td>
<td>512,933</td>
<td>53,208</td>
<td>1,337,808</td>
<td>7.82</td>
</tr>
<tr>
<td>Diseases</td>
<td>38,286</td>
<td>2,205,260</td>
<td>59,996</td>
<td>612,011</td>
<td>57.60</td>
</tr>
<tr>
<td>Total</td>
<td>56,560</td>
<td>380,102</td>
<td>46,565</td>
<td>305,521</td>
<td>6.72</td>
</tr>
</tbody>
</table>

**A4.4 Comparing IFs output with existing expenditure forecasts**

A number of studies provide country-level forecasts for health expenditures. Most of these studies use similar methods, namely: decomposing the drivers of expenditures into demographic (using age-sex groups) and epidemiological impacts, as well as the impacts of technology or residuals; taking into account end of life costs; and using a similar set of scenarios, one scenario without any policy changes and one where policies are implemented to contain costs (with the particular policies chosen varying by study/country). Here we collect existing expenditure forecasts in order to help validate our own results.

In general, the studies reviewed here find that total healthcare expenditures under ‘no policy change’ scenarios tend to increase at a rate of 1 percentage point above the overall rate of GDP growth (ranging from 0.5 percentage points in Australia to 1.1 in the US), while most ‘cost containment’ scenarios see expenditure growth following that of GDP growth (Keehan et al 2011; OECD 2010; Begg 2008). In the IFs Base Case scenario, health expenditures in the US grow at an average annual rate of 1.3 percentage points above GDP growth from 2010 to 2020 and then 1.5 from 2020 to 2050, while for OECD countries as a whole, the average growth rate is 1.5 percentage points above GDP growth for the 2010 to 2050 period.
While the percentage of total expenditures devoted to individual disease types varies by country, they tend to follow a similar pattern of distribution (at least in high-income countries), with mental health, cardiovascular, digestive, and musculoskeletal (the ‘other noncommunicable disease’ category in IFs) diseases generally seeing the greatest expenditures and infectious diseases among the lowest (Vos 2007; Polder 2001). In IFs, OECD countries in 2010 spend the most on cardiovascular conditions, other noncommunicable diseases, digestive diseases and diabetes, and the least on communicable diseases.

**Health Expenditure Forecasts by Country**

**The Netherlands**

Besseling and Shestalova (2010) forecast that public health expenditures in Netherlands will reach just above 10 percent of GDP by 2015 in their no policy change scenario and just under 10 percent in their cost containment scenario. In the IFs Base Case, spending in the Netherlands reaches a slightly higher 10.9 percent of GDP by 2015. Polder (2001) forecasts that total health spending in the Netherlands will likely grow at an average annual rate of 2.4 percent from 2010 to 2015, similarly, in the IFs Base Case spending grows at an average 2.5 percent over the same period.

**United States**

Keehan et al (2011) forecast that health spending in the United States will likely reach 19.8 percent of GDP in 2020 (up from 17 percent in 2010). Overall, health spending is expected to grow at an annual average rate of 5.8 percent per year from 2010 to 2020, or 1.1 percentage points faster than GDP growth. In IFs, spending in the US reaches 20.1 percent of GDP in 2020 (up from 17.6 percent in 2010), though it grows at a slower rate of 3.1 percent per year over the same period.

Fogel (2008) finds that total health expenditure in the US has an income elasticity of 1.6, suggesting that health spending as a percent of GDP might very well reach 29 percent by 2040. The CBO, meantime, produces forecasts with much longer time horizons. The CBO forecasts spending on healthcare in the United States to reach over 31 percent of GDP by 2035 and 49 percent by 2082 if no changes to current laws are made, though such high ratios of spending to GDP seem slightly overblown (Astolfi et al 2012). In the IFs Base Case, health spending in the US reaches 28 percent by 2040 but only 38 percent by 2082.

**OECD**

The OECD’s report, Projecting OECD Health and Long-term Care, forecasts total public spending on health by the OECD countries as a whole out to 2050. They find that without cost controls, total public health spending will likely reach 13 percent of the OECD’s total GDP by 2050, up from 7 percent in 2005. In IFs, public spending reaches a higher but similar 14.9 percent of GDP in 2050.

**The EU 27**

The European Commission (EC) produced a similar report in 2010 looking at the long-range future of public health spending but also included a number of alternative scenarios
along with a reference case forecast (Figure A4.1). While the IFs Base Case starts at a higher level and remains significantly higher than the EC Reference Scenario, it is fairly close, over time, to the EC Technology Scenario, which takes into account the cost impact of continuing advances in technology.

![Figure A4.1 Public health expenditures by EU27 countries as a percentage of GDP, 2010—2060](image)

*Source: Przywara 2010, IFs model version 7.09*
Appendix 5 - Literature Review on Subject Matters of this Report

Even though this project’s exploration of extended longevity and its implications took us outside the level-of-comfort space established by existing longevity models, it remains well-grounded, drawing as it does on a wide array of existing literature. In this appendix we review the literature that undergirds our efforts, beginning with a review of past trends in and existing forecasts of mortality and longevity. We then look at the forward linkages from increasing longevity (and decreasing morbidity) to demographic, socioeconomic, and environmental change.

A5.1 Past trends and future limits
For most of human history, mortality was characterized by a strongly Malthusian pattern of high mortality with considerable deviation upwards in times of plenty and downwards in times of want. The first sustained population-level improvements in human life expectancy were only observed in Britain in about 1750. Since then, life expectancy has risen dramatically, both on a global average basis and among the longest-lived societies. From the 1840s to the 1960s, improved nutrition and control of infectious disease greatly reduced infant and child mortality leading to the fastest gains in world average life expectancy in human history (Sonnega 2006; Wilmoth 2011). Figure 3.2 illustrates that the life expectancy of the world’s longest-lived society has been rising at roughly 2.5 years per decade for over two centuries.

![Figure A5.1 Trends in maximum female life expectancy (1600-2000)](source: Oeppen 1999)

Source: Jamison (2006: 5) from original in Oeppen (1999); reprinted in Hughes, et al. (2011b) with permission of author.

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17 Earlier improvements could be observed among noble, landed, and educated populations in Britain as early as the late 17th century.
But these massive increases in life expectancy were largely due to the reduction of mortality among the young rather than increases in maximum lifespan. Up until the 1960s, rising life expectancy was driven primarily by successful reductions in infant and childhood mortality, which have a more substantial effect on life expectancy than reductions occurring at least ages.

Since the 1960s, improving living standards, medical technology, and healthy behavior have reduced mortality at older ages as well, beginning with reduced rates of cardiovascular disease but more recently reducing other causes of death as well. That life expectancies are still growing with infant mortality close to zero is due to accelerating mortality reductions at age groups above 45 (increasing from 0.44 years per decade prior to 1969 to 1.1 years per decade afterwards [Wilmoth 2011]) (Willets et al 2004). Today, 90 percent of all deaths in developed countries occur after the age of 65, and 30 to 50 percent occur after the age of 85 (Olshansky, Carnes, and Mandell 2009: 150). In recent years, the most dramatic reductions in mortality have come among the oldest-old (85 years old and older), which have of late outpaced reductions at younger ages, resulting in a dramatic increase in the population over age 100 (Caselli and Vallin 2001; Strulik and Vollmer 2011; Vallin and Meslé 2010; Willets et al 2004). Continued progress against the noncommunicable diseases of adulthood, particularly among the oldest age groups, have forced demographers and biologists alike to confront the senescence model and consider the possibility of continued or even accelerated longevity progress.

The question of whether there may be some fixed limit to the human lifespan has been a source of major debate in the longevity field for years. Researchers from Fries (1980) to Olshansky et al (2009; 2007) have argued that such a limit exists. Originally such arguments centered on a predetermined limit created by our genes. More recently, Olshansky and others have identified two major arguments for such limits. First, they see aging as the result of ‘evolutionary neglect’—aging and mortality only matter to evolution insofar as an animal or human 1) survives long enough to successfully reproduce, 2) dies at some point to make way for its progeny. Thus, while there is no genetic basis for a fixed lifespan, humans did not evolve to live indefinitely, eventually the body will simply break down due to biomechanical reasons, producing a biomechanical cap to lifespan. Medawar (1952) among others suggest that the absence of selection should render the post-reproductive years a “genetic dustbin” of abnormal genetic expressions predisposing individuals to a rising burden of disease that is increasingly more difficult and costly to treat.

The second argument in favor of a fixed maximum lifespan stems from the fact that mortality rates (in developed countries at least) are already very low. Olshansky et al (2009) suggest we are approaching a statistical limit on average life spans because past successes in reducing mortality rates of all age groups. They calculate it would take a further 85 percent reduction in all-cause mortality from 1985 levels to yield an average life expectancy of 100 years; thus, life expectancies in developed countries are unlikely to exceed 90 years, even by the end of the century. A number of studies argue that there should be an increasing compression of the distribution mortality as advanced societies push closer and closer towards the limits of the human lifespan.
At the same time, a growing number of researchers are challenging these arguments, especially as actual life expectancies have had the propensity of exceeding predicted maximums, usually within a few years of such predictions. (Bongaarts 2006; Howse 2009; Sonnega 2006; Vallin and Meslé 2010). Recently, a number of studies have identified two major trends that cast doubt on the existence of a fixed limit. First, the ages showing the greatest mortality declines have been shifting older over time, and second, the rate of mortality decline at the oldest ages has been accelerating (Caselli and Vallin 2001; Strulik and Vollmer 2011; Willets et al 2004)—life expectancy for those between the ages of 40 and 60 is increasing faster now than at any time in the past (Vallin and Meslé 2010). The challenging study of centenarians (age 100+) and super-centenarians (age 110+) reveals accelerating growth in the size of these populations. In advanced societies, the age at death for individuals 3 and 4 standard deviations above the mean age at death is rising considerably faster than the mean age at death (life expectancy), suggesting again continued progress against oldest-old mortality (Caselli and Vallin 2001).

Highly accurate data on age and timing of death among older populations has also revealed deviations from Gompertz’s pattern exponentially increasing life expectancy at older ages. It is now well documented in human populations and a number of other species that the pattern of exponential increase slows down considerably at the oldest ages. While a number of possible explanations for this trend exist, the most plausible points to the force of selection, namely that in a heterogeneous population, those individuals who have already survived to an advanced age such as 100 are selected from a pool of particularly robust individuals who therefore exist on some different mortality schedule. Better understanding of old-age mortality patterns, combined with new discoveries in gene sequencing, create new opportunities to understand the determinants of extreme longevity and identify new treatments.

Empirical evidence of continued longevity gains have led some biodemographers to posit a post-Darwinian theory of senescence in which humans transcend the supposed limits to life. Their argument is that while natural selection does not program humans to survive past the reproductive years, neither does it program them to fail. Instead, they argue that the high degree of systemic reliability require for humans to already survive well past the reproductive years mean could also allow us to survive for much longer periods. The gradual elimination of defects could propel humans into a stage of life in which the forces of senescence no longer hold. Although reliability theory is both highly stylized and detached from the mathematical realities of modern human mortality schedules, it does further establish that any assumptions about limits to human life must be carefully examined (Gavrilov and Gavrilov 2001). Furthermore, reliability theory points the way to an entirely new approach to human medical intervention focused on the perfectibility of imperfect bodies rather than the mere treatment or prevention of disease.

While the debate continues, the momentum appears to be in favor of considering the possibility of rapid progress against longevity. The UN has now removed the limit on maximum life expectancy from their forecasts, and the US National Research Council
has concluded that “if any limits exist, they are far above current levels, and that projections therefore should not impose ceilings” (Bongaarts 2006).

A5.1.2 Existing forecasts of mortality
In spite of the growing uncertainty about the limits of life, most existing forecasts explore a fairly narrow range of possible mortality outcomes. Kenneth Wachter (2003: 272) sums up the state of forecasting this way:

Official forecasts almost all impose assumptions of diminishing returns to progress against mortality at older ages. In contrast, researchers impressed by the long-sustained pace of progress extrapolate unabating gains. The policy ramifications are obvious, as the different forecasts put very different constraints on the political decisions required now to preserve the solvency of social insurance systems and the economic health of nation states. Choice between such forms of forecasts is not a technical issue. It is a matter of judgment, context, and plausibility, as are the ultimately subjective uncertainty bounds to be attached to all the forecasts... The relevance of underlying biology to future trends in mortality, however, is not incontestable.

Official government forecasts, including those of the US Social Security Administration, tend to impose limits on mortality gains, though it is unclear whether these forecasting decisions are driven by pessimistic assumptions or political imperatives to reduce apparent future pension burdens. A number of more actuarially-pure forecasts, including the widely employed Lee-Carter framework, generate considerably higher life expectancy outcomes, but these are still well short of the optimistic outlook. More recently, John Bongaarts pursued one of the more cogent efforts to remove extrinsic causes of mortality and deaths related to smoking out of a standard demographic forecasting framework in order to forecast based on intrinsic causes of death alone. The forecast best-case life expectancy outcomes were again quite high, with a life expectancy at birth of 97 in the longest-lived country by 2050. For high-income countries, forecasts range widely, from an average expectancy of 82 years (Bloom and Canning 2006) by 2050-2070, to 100 and above (Ahlburg and Vaupel 1990; Manton, Stallard, and Tolley 1991; Oeppen and Vaupel 2002; Vallin and Meslé 2010) before the end of the century.

The most prominent cross-country forecasts are those produced by the UN Population Division, which run to the year 2100. Previously, these provided a low-, medium-, and high variant for mortality. In the 2010 revision, the eventual life expectancy for females in Japan was 95 under the medium variant and 97 under the high variant. The more recent 2012 revision provided only one variant, arguing that

changes in fertility are more likely to have sizable impacts on future population size, growth and age structure than changes in mortality. Furthermore, whereas there is universal agreement that reducing mortality is a worthy goal, there are varied perspectives on what are the fertility trends best suited to satisfy the goals of different societies (http://esa.un.org/wpp/other-information/faq.htm#q19).

In the 2012 version, female life expectancy for Japan in 2100 had been upgraded to 98 years. More importantly, UNPD supported a series of probabilistic projections based on Bayesian Hierarchical Modeling (BHM) using 2010 data. Among their simulations, the
median female life expectancy for females in Japan in 2100 was 101 and the 80\textsuperscript{th} percentile life expectancy was 105.

It should come as no surprise that most existing forecasts of life expectancy do not take technological advances into account—forecasting them is notoriously difficult—what is surprising is the number of ‘conservative’ forecasts that suggest technological advances could result in much higher life expectancies. Even Olshansky et al (2009) acknowledge this:

\begin{quote}
What is known is that there is a concerted effort to find the means to slow aging in people and now there is reason to be optimistic that such developments will occur in this century... exactly how much of an impact such an advance will have on life expectancy is uncertain but should be encouraging to [all]... (744)
\end{quote}

Indeed, according to a 2001 article in The Scientist, Olshansky and Austad placed wagers on what the upper limit of human longevity might be.\textsuperscript{18} Olshansky bet 130 years and Austad 150.\textsuperscript{19}

Most studies dealing with extreme longevity tend to be quite qualitative in nature, discussing possible timelines of longevity enhancement interventions but not detailed longevity forecasts. Aaron and Harris (2004: 78) and Ahlburg and Vaupel (1990) produce some of the more ‘extreme’ forecasts. Both studies use an average 2 percent per year reduction in mortality as a ‘reasonable upper forecast’ with Aaron and Harris providing age specific mortality reduction rates: 2.8 percent per year for ages 0-14, 2.2 percent for 15-65, 1.9 percent for those older than 65. This produces an average rate of 2 percent with a drift towards 1.9 percent in later years due to almost all deaths occurring after 65 years of age. The 2 percent assumption produces cohort life expectancies of just over 100 years by 2030, just under 110 years by 2050, and 115 years by 2075. Mykytyn (2006), meanwhile, suggests that life expectancies of 120 to 150 years could be achieved by mid century through new technological developments.

A5.1.3 Timing and rollout of enhanced longevity

When might extreme longevity interventions come on the market, and who will have access to them? These are two of the more important uncertainties facing efforts to forecast extreme longevity and its repercussions. Whether such interventions arrive only a few years or fifty years from now and whether access to them quickly becomes widespread or remains only available to a select few will result in vastly different futures. Existing forecasts of when the first extreme longevity interventions might arrive vary greatly, from 2 to 4 years from now (originally 5-7 years from 2010 [Lucke et al 2010]), to sometime in the far future, i.e. not in this century, if at all. Church (2012), for example, provides a detailed near-term timeline for the interventions. He writes that genome engineering may become routine by 2014. By 2016, so may neuron regeneration and individual neuron stimulation and monitoring. By 2022, the brain itself could be

\textsuperscript{18} Maximum lifespan, not average expectancy

regenerated, enabling much longer lifespans by avoiding many degenerative diseases. Most forecasts, however, suggest a timeframe of 30 to 50 years from now (Bess 2008; Willets et al 2004). Others, like Hayflick (2000), argue that extreme longevity technologies are unlikely to arrive this century, if ever.

Of course, most forecasts treat the advent of extreme longevity interventions as a single discrete event—i.e. the technology arrives all at once. Bess (2008) suggests that longevity interventions are likely to arrive in ‘incremental packages, each offering a slight improvement… along a steadily increasing gradient of potency and sophistication.’ Over time, these interventions will add up to a major intervention, only the enhanced longevity will ramp up over time rather than appear immediately.

The question of rollout, who gets access to the interventions and how quickly, is perhaps easier to address, as we can look to the uptake patterns of similar technologies. Lucke et al (2010), for example, believe the dissemination of life extending technologies will likely mirror the development and spread of artificial reproductive technologies since the early 1960s. Such technologies were originally very expensive and limited to only upper-income families within developed countries. Today, the technologies are fairly accessible to middle-income families within developed countries and to the elite in developing countries. The spread has been slow and incomplete; even after being on the market for several decades, access to the technologies is still limited, but its cost continues to decrease and more and more people are able to afford it. Becker et al. (2005) makes a similar though more generalized case of looking at the time it has taken developing countries to absorb technologies developed in high-income countries.

### A5.2 Morbidity and Fertility

None of the longevity forecasts described above incorporated morbidity, yet many of the socioeconomic impacts of changing longevity patterns are as related to morbidity as to mortality. To the extent that mortality reductions lead to a rising burden of disabled survivors, the social and economic costs can be quite high, particularly in health systems where the last months of life can grow increasing costly. As a complex integrated system, IF's forecasts morbidity as a driver of workforce participation, productivity, and health costs, as we discuss below. More importantly, as we noted above, regenerative medicine raises the prospect of enhanced, extended, or restored fecundity, thereby requiring a fertility model that accounts for changing biological conditions (a product of reduced reproductive morbidity) and behavioral/social conditions.

#### A5.2.1 Morbidity Impacts

In general, disability rates over time have largely followed mortality trends, decreasing steadily since 1900 (Sonnega 2006), with significant declines in disability and deaths due to cancer and cardiovascular disease after the mid 1980s (Sierra et al. 2009). Within this general relationship, however, lie considerable variations that carry important implications for productivity and health costs. To the extent that a death is averted through palliative treatment of illness, the reduction in morbidity may be relatively small. If a disease is prevented, that may yield a considerably greater reduction in morbidity.
Since the goal of regenerative medicine is to prevent aging, success in this field implies an even more considerable reduction of morbidity, as we may observe the end not merely of recognizable causes of morbidity, but even of the degenerative sequelae of illness that may cause discomfort or dysfunction for the aged.

Existing evidence provides a complicated picture of the relationship between declining mortality and morbidity. For chronic diseases such as CVD, reductions in cause-specific mortality result from treatment as well as prevention, meaning that decreased mortality should be associated with relatively less decline in the incidence of the disease (Mathers and Loncar 2004). As a greater proportion of incident cases survive and continue to be affected by the disease, prevalence rates should rise (Michel and Robine 2004). In other words, the decline in incidence or prevalence of a disease associated with a mortality decline should be determined by the relative prominence of prevention (reducing all three in line) versus treatment (which should not affect incidence and should increase prevalence).

The simple logic described above does not, however, address changes in disease severity as mortality declines. While the survival of those who would otherwise have been most likely to die might increase the average severity of disease among surviving cases, it is also quite possible that the very treatments that reduce mortality would also reduce disease severity across the entire distribution of illness. In fact, most recent evidence points to reductions in morbidity, as measured by performance on the activities of daily living (ADLs) and self-rated health status, that outstrip the pace of mortality reduction, meaning that even as populations grow older, they spend a greater proportion of those extra years in good health (Crimmins 2004; Michel and Robine 2004; Payne et al. 2007). In other words, even as prevalence increases due to greater survivorship, reductions in the average severity of disease may be so great as to reduce the overall burden of morbidity (Crimmins 2004; Mathers and Loncar 2004). Recently, a number of studies have found evidence for compression in morbidity rates even as life expectancies increase (Klijs et al 2011; Stulik and Vollmer 2011). Klijs et al found that a ten-year increase in life expectancy, from 75 to 85 years, led to lower percentages of moderate and severe disability during the last five years of life and an increase in mild disability compared to average disability rates for 75-year-olds.

A5.2.2 Fertility Impacts

The shift from scenarios of delayed senescence to regeneration has profound implications for human fertility, and takes us into terrain not covered by existing models. Menopause and lesser forms of infertility can be easily construed as a form of morbidity, and thus regenerative medicine, to the extent that it involves the total replacement of organs or systems, may lengthen the reproductive span for men and women considerably, resulting in a total increase in lifetime fecundity. Almost all known research on mortality reduction and life extension has thus far assumed that mortality gains occurring in the post-reproductive ages will not alter the female reproductive life span. The potential boost to human fecundity must be set against the well-understood behavioral tendency towards fertility decline over time and across societies due to delayed marriage and the use...
of contraceptive technologies. While age-specific models of the fertility life course are numerous, most are focused on behavioral reductions in the timing or frequency of childbearing associated with family planning programs. To a lesser extent, some biological models have addressed variations in the onset of menarche due to long-term nutritional intake and patterns of premature infertility caused by sexually transmitted diseases.

No studies to our knowledge have explicitly modeled the consequences of an extended fecund life course. Far more current research in advanced societies is devoted to understanding the causes of early infertility than to understanding extension of the fertility. Recent decades have seen a substantial shift in the age-distribution of fertility towards later ages, yet most of this shift is explained by behavioral decisions to delay pregnancy, not by any biological extension of the reproductive span. Nevertheless, assistive reproductive technologies have already had a significant impact on extending the reproductive span through hormonal treatments, procedures to regenerate the uterine lining, and egg donations, among other interventions. Furthermore, historic evidence points to a relationship between an extended reproductive span and increased longevity. Using historic data from Quebec, Gagnon et al. (2010) report that after controlling for overall childbearing, women whose last birth occurred at later ages also had longer lifespans.

Given the lack of fertility models that account for reproductive extension, an approach to modeling fertility extension cannot have any specific parametric form, but rather must have the flexibility to capture a range of associations between a given longevity scenario, largely relating to the senescent component of mortality declines (see further discussion in Section 4 of this report). To the extent that a longevity scenario involves delayed senescence, we may imagine that the reproductive extension will be relatively limited. To the extent that longevity enhancement is regenerative, we may imagine elasticities linking life extension to fertility extension across a wide range from a total extension of the reproductive span to a relatively limited extension in the share of reproductive years.

The impact of the biological extension of reproduction will likely be heavily mediated by a series of compensating behavioral changes, though it is difficult to predict their exact nature. A few effects are at least important to consider. First, at the very least, reproductive extension might allow the large proportion of women in advanced societies who currently fail to reach their reproductive goals to now do so, bringing total fertility rates that are now below replacement level closer to that level. At the same time, women may delay the initiation of childbearing even more knowing that they have more time. Second, a profound extension of life including a return to youthfulness and reproduction might also lead many individuals or couples, particularly in the initial years, to return to childbearing after long ago completing their families. On the other hand, many societies have taboos often referred to as “grandmother rules” that discourage grandmothers...
from again becoming mothers, taboos that may be reinforced by genetic programming. Finally, an increased number of years of sexual activity might simply lead to an increased exposure to the risk of contraceptive failure and pregnancy over many years, though these pregnancies could be avoided through permanent sterilization procedures or through induced abortion. Finally, it is important to note that population growth is driven not just by the number of children a woman has in her lifetime, but also by the average age at which she has those children. A relatively modest rise in lifetime-completed fertility, particularly in countries now below replacement, could easily be spread out over the life course so that the effect on population growth is minimal. To summarize, extension of the reproductive lifespan clearly creates the mechanical conditions for a dramatic rise in fertility, yet a number of behavioral factors could mitigate those effects, particularly in the long run.

The impact of increasing longevity on fertility, particularly in cases of extreme longevity (including regenerative medicine) is another key uncertainty for forecasting the ramifications of longevity interventions. Under standard longevity scenarios (slowly increasing life expectancy with no change in age of menopause), the evidence points toward increasing life expectancies having a significant negative impact on fertility due to a set of reinforcing factors. Soares (2006) finds that a one-standard-deviation increase in adult life expectancies reduces lifetime fertility by 0.08 to .11 children, with 80% of this reduction coming directly from the increase in longevity and 20% from reinforcing factors like increased educational attainment.

The question is, why does living longer reduce fertility? In high-income countries, the reduction in fertility is primarily due to women delaying childbirth to ever-later ages (Sobotka 2010; Blackburn and Cipriani 2002). According to Sobotka (2010), the average age of first childbirth has now passed 30 in the majority of European countries and in Japan, and ever more women are having children even past the age of 40. Over the past 30 years (in developed countries), the probability of having a first child at the age of 20 has steadily decreased, while the probability of having the first child at the age of 35 has increased. Blackburn and Cipriani (2002) make the general conclusion that an increase in life expectancy implies a decrease in the demand for children early in life relative to the demand later in life, pushing back the timing of births. The result is slower overall population growth primarily due to delays in childbearing running into increasing rates of infertility at older ages (Sobotka 2010).

Similarly, Goldstein and Schlag (1999) find that delays in childbirth tend to offset any population growth from increased longevity of the old so long as the pace of childbirth delay is greater than the increase in longevity. They find that, on average, a doubling of longevity is accompanied by a 101 percent increase in the average age of childbearing. Thus, the authors forecast that even dramatic increases in human longevity are likely to have little impact on the population trajectory over the rest of this century (Goldstein and Schlag 1999). Bogojeciv, Balaz and Karapandza (2008) and Coale (2003)—who forecasted the impact of immortality on population growth—came to very similar conclusions.
Increased life expectancy also leads people to increase their education and associated human capital and to have fewer children overall (Goldstein and Schlag 1999; Sierra et al 2009; Soares 2006). Sierra et al (2009) raise the question of whether reproductive capacity will be impacted as longevity increases, i.e. will the maximum age at which a woman can give birth increase? This is especially a concern for rejuvenative scenarios like SENS. They note that increasing the capacity to have children later in life would impact the life cycle and family structure but do not address how this might impact population growth.

Interestingly, Marchetti, Meyer, and Ausubel (1996) suggest that, while increased longevity is much less important for population growth than fertility, developing countries might see a greater increase in population growth from increased longevity due to higher fertility rates and fewer delays in childbearing (more young adults surviving to have children). Of course, this assumes populations in developing countries would have access to life extension or at least see rapid gains in longevity without concurrent gains in human capital, which, as in developed countries, would delay childbirth.

**A5.3 Financing of Older Populations**

Population aging, particularly in developed countries, is seen as a major problem for those countries in terms of economic growth going forward. Under pessimistic scenarios, the proportion of the population in developed countries above the age of 65 will increase sharply, even as the proportion with disabilities remains the same or worsens, leading to an increased strain on welfare programs and a skyrocketing of health costs.

Bloom and Canning (2006) forecast that, as a result of fertility declines and increased longevity, the number of people aged 60 and above will likely number some 1 billion people worldwide by 2020—outnumbering the 5 to 24 age group—reaching 2 billion by 2050. In 2050, 32 percent of people in developed countries will be 60+, while 20 percent will be so in developing countries. Worldwide, the percentage of people 80+ will reach 4 percent.

The increasing number of elderly persons in such populations, coupled with decreasing fertility will also result in a proportionately smaller labor force that will be unable to generate enough new workers to counteract a rapidly growing ratio of workers to retirees (McConnel and Turner 2005). According to the Center for Strategic International Studies, in 2003 there were 30 elderly dependents for every 100 working adults in high-income countries. By 2040, they estimate the ratio will be closer to 70 elderly dependents for every 100 workers; with the fastest aging countries like Italy, Japan, and Spain actually seeing a ratio of 1 to 1 (CSIS 2003).

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20 The National Research Council (NRC) recommends using a retiree to worker ratio (RWR) in place of the standard old age dependency ratio. “The numerator of the RWR consists of the number of retirees (instead of the population 65+) and its denominator consists of all people in the labor force (instead of the population aged 20-64). The RWR typically exceeds the old age dependency ratio by a small amount because the number of retirees is exceeds the population aged 65+ and because the number of workers is somewhat smaller than the population aged 24-64.”
Aaron and Harris (2004) forecast what would happen to the age structure in developed countries under a scenario of rapid and sustained longevity increase. They find that countries like the US will age rapidly whether or not mortality declines sharply, and that any reductions in mortality beyond the base case will likely have little impact before 2030 and would not markedly change the percentage of people above 65 or 80 until after 2050 due to mortality rates for people under 65 being so low already and to the fact that it will take a number of years of gains in longevity before life expectancy advances at older ages. An extrapolation of past declines in mortality rates suggests that several developed countries will likely see the over-65 year old cohort make up around 30 percent of their populations by 2050 (Aaron and Harris 2004).

At the same time, several studies find that increase in old age dependency under pessimistic or even weakly optimistic scenarios is counteracted by the decrease in youth dependency ratios as fertility rates continue to decline (Bloom, Canning, and Fink 2009). Under strongly optimistic scenarios, both old age and youth dependency ratios should fall, making for a net positive economic impact (Aaron and Harris 2004; Bogojevic, Balaz, and Karapandza 2008).

A5.3.1 Changes in Retirement
The average age of retirement in developed countries has decreased for most of the 20th century, despite increasing health and longevity (Burtless 2004; NRC 2012), though this trend has begun to reverse; since 1995, the average age of retirement in the US has actually increased by 1.5 years (NRC 2012).

Thanks to increasing longevity and a slowly changing average age of retirement, the average time spent in retirement has increased by 5 years over the last 50 years in the US, from 10 years of retirement in 1962 (representing 15 percent of lifespan) to 15 years in 2010 (24 percent of lifespan), while average longevity increased by 8 years (NRC 2012). The National Research Council (NRC) projects this trend to continue, with average retirement time reaching 20 years by 2050 (but remaining at 24 percent of lifespan due to further increases in longevity), while working years only increase 9 years from 31 to 40 (a ratio of retired to working years of 41 percent). Thus, by 2050, the average American would work roughly 2 years for every year spent in retirement (a ratio of 52 percent) (NRC 2012).

The impact of longevity on retirement is still being debated, as is the direction of causality. Burtless (2004) notes that it can be difficult to tease out causality because longevity and average wage levels have increased simultaneously, and both can impact retirement. Burtless suggests that because retirement is a superior good, workers will increase the length of their retirement as their incomes increase. He would argue that since higher lifetime incomes are closely associated with increased longevity, it seems likely many people will opt for longer retirements.

Sierra et al (2009), on the other hand, suggest that increased life expectancy will push people to work longer in order to realize the economic benefit of longer life—assuming
the years of life added are healthy ones. Zhang and Zhang (2009) come to a similar conclusion, that increased life expectancy does lead people to work longer, but they also find that the magnitude of the increase depends on the current level of life expectancy; populations with lower life expectancies see a greater increase in the age of retirement than populations with high life expectancies.

Retirement patterns will likely vary greatly depending on the longevity scenario. Under scenarios of increased longevity and health it seems likely at least some workers will opt for multiple retirements and reentries to the workforce and or to the education system (Wheelwright 2010), especially under a SENS scenario, as it is hard to imagine a worker remaining in the same career for 100 years or staying in retirement for 50.

A5.3.2 Labor force participation

The response of labor force participation to increasing longevity in the past has been rather mixed. From 1950 to 1995, labor force participation by men 55-years and older in developed countries actually declined, with rates in the US declining from just over 70 percent in 1950 to under 40 percent by 1995, despite increasing longevity and increasingly compressed morbidity (Bloom, Canning, and Fink 2009; National Research Council 2012: 77). More recently, the participation rate among older men has begun to rise again even as total labor force participation remained flat, reaching just under 50 percent by 2011 (due in part to the Great Recession). For older women, the participation rate increased from 1950 to 1970, remained steady between 1970 and 1995 and increased again there after (NRC 2012: 78). Even with the recent increase, participation rates among seniors (ages 65+) remains very low, particularly in the US, with an estimated 85 percent remaining outside the labor force in 2001, in spite of the fact that a majority of people in their 60s and a substantial portion of those in their 70s do not have a functional impairment(s) keeping them from work (NRC 2012: 17). This low level of participation among the healthy old suggests that participation rates today have more to do with policy choices concerning retirement than with population aging (Bloom, Canning, and Fink 2009) and raises the question whether or not increased health-span will really lead to people working longer.

According to Burtless (2004), labor force participation rates among 65 year olds and older in the US are now so low that it will take more than simply increased longevity to change the make-up of the labor force. Given the low level of participation by the old seen today and the progression of population aging (and coupled with declining fertility), Bloom, Canning, and Fink (2009) project the global labor force participation rate to fall 4.3 percentage points from 2000 to 2040, from 66.4 percent of working age adults to 62.1 percent. Such a decline represents less than half a standard deviation in the cross-country distribution of the labor participation rate for 2000.

At the same time, declining fertility rates should also lead to an increase in female labor participation (and vice versa according to Bogojevic, Balaz and Karapandza 2008), which would also help to reinforce the post-1995 trend of increased labor force participation of the elderly. Bloom, Canning, and Fink (2009) find that for each unit decrease in the total fertility rate, female labor force participation increases by 5 to 10 percentage points. Also,
for each unit decrease in total fertility, women tend to work 2 years longer over the course of their working lives.

Burtless (2004) finds that increased longevity will have only a small direct impact on the age structure of the work force as reductions in mortality at younger ages increases the both the numbers of workers and their average age while increased longevity increases the fraction of workers who reach retirement age and increases the amount of time spent in retirement. Because the survival rates of young workers are already very high, increased longevity is only likely to have a major impact on the age structure of a given labor force if it causes people to change how they participate in the labor force (i.e. remaining in longer, partial retirement, or multiple exits and reentries).

Burtless (2004) has developed four scenarios for how the US’s age structure might change due to increased longevity. The first two scenarios deal only with mortality based off the SSA’s mortality forecasts and the Aaron and Schwartz (2004) forecast (described above) respectively. Under the SSA forecast, 22 percent of the US population will be 65 and older in 2075 while 5.3 percent of the work force will be over 65. Under the Aaron and Harris forecast of accelerated longevity gains, 29 percent of the total population will be 65 or older, while 5.9 percent of the workforce would be (without any change in retirement). His second two scenarios use the same longevity forecasts but also assume increased participation rates (actually a return to participation levels in the 1950s when the average age of retirement was 70) by those above 65. Under the SSA and increased participation scenario, elderly participation in the workforce would be 35 percent in 2050 and reach 41 percent in 2075, increasing the 65+ share of the total workforce to 9 percent. Finally, under the Aaron and Harris scenario with increased participation, the 65+ share of the workforce would exceed 10 percent by 2075. Under the latter two scenarios, the total size of the workforce would increase.

Whether participation rates change largely depends, it would seem, on the longevity scenario. Aaron and Harris (2004) suggest that under an optimistic scenario, increased longevity could grow the labor force and shrink the number of dependents as morbidity rates drop and people are able to work longer. Of course, on the pessimistic side, it is also possible that as population aging increases the strain on existing safety nets, the elderly will be forced to work longer and or to reenter the labor force to support themselves. The big question with participation rates is what happens with the retirement age as longevity increases.

A5.3.2 Savings and consumption

Because an individual’s savings and consumption habits tend to vary over the course of his or her lifecycle, with most consumption occurring during youth and old age and most saving (and production) occurring during adulthood (working age), changes in a population’s age structure will affect the society’s consumption function, which is an important driver of economic growth. Lee, Mason, and Miller (1998) find that an older population (dominated by pension costs) tends to have reduced savings rates and a younger population (dominated by childrearing costs) tends to save more. Depending on what it does to a country’s age structure, increased longevity tends to be associated with
increased savings as people anticipate having longer retirements (Bloom, Canning, and Fink 2009; Zhang and Zhang 2009). 21

The NRC finds that, in general, as people tend to accumulate assets over their lifetimes, in an older population, the average household will likely have higher wealth relative to income than in a younger population. Because of this, the NRC forecasts that by 2050, the projected age structure and population of the US would yield a 25 percent increase in national net worth per person aged 20-64 due to population and asset accumulation. This increase in household wealth could in turn increase worker productivity.

The severity of the impact of population aging on savings and consumption once again appears to be contested. The NRC (2012) finds aging populations are more costly to societies as declining earnings combine with sharply increasing consumption at older ages. And the IMF (2012) paints a bleak picture of the cost of supporting aging populations. They estimate that a longevity increase of three years (globally) would cause the aggregate expenses of the elderly to society to double over the 2010 to 2050 period, with the annual cost rising from 5.3 to 11.1 percent of GDP for high-income countries and from 2.3 to 5.9 percent for developing countries.

On the other hand, a University of Torino commissioned study examining the linkages between aging and consumption patterns in the EU15 countries found that aging impacts on the size of the overall labor force will have a much stronger economic impact than changes in consumption patterns (elderly expense).

A5.3.3 Health care and other public spending
Healthcare spending, population aging, and longevity are tightly linked. All things being equal, as populations grow older, the amount spent on healthcare increases. But the exact impact depends greatly, again, on the longevity scenario, as, on an individual level, the amount of healthcare resources used increases dramatically after age 65, but much of the aggregate expense comes predominantly from individuals with disabilities (NRC 2012).

Bryant and Sonerson (2006) argue that population aging is not the main driver of rising health expenditures, rather that non-demographic factors within healthcare systems like wage increases for health workers, rising administrative costs, new medicines and treatments, and more comprehensive health coverage are the main culprits. But while population aging in and of itself may not be the main driver, it seems reasonable to expect that the particular longevity scenario will have an impact; a SENS scenario (depending on the cost of the longevity treatment itself, of course) will likely see much lower need for health spending then a pessimistic scenario where individuals spend a longer time in a state of frailty.

21Zhang and Zhang (2009) find that having a mandatory retirement age also helps raise saving rates as people are forced to live longer in retirement. But this increased saving comes at the cost of reduced human capital investment and long-run economic growth.
On the other side of the health spending equation, (Naam 2010) finds that life expectancy goes up as an individual's spending on health increases, but the gains undergo diminishing returns as spending increase. Above, 3000 dollars, additional spending has only a small impact on longevity. The largest bang for the buck appears to occur between 0 and 100 dollars per person per year in health spending, with additional spending increasing longevity, but not as much as the initial 100 dollars. See Appendix 4 for more on health spending.

A5.4 Broader Economic Implications

One of the key uncertainties regarding longevity in the future is whether its continued increase will prove a boon or burden to societies around the world, particularly those whose populations are already rapidly aging. Certainly, in the past, gains in longevity were a major driver of economic growth as more young people not only survived to enter the labor force but also remained healthy enough to continue working until old age. Sierra et al (2009) cite one estimate suggesting that increased longevity post-1970 in the US may have added as much as $3.2 trillion a year to the country's economy, primarily due to health gains among the working age population. Going forward, however, it is unclear whether such economic benefits will continue as increasing longevity is now leading to rapid population aging. Because mortality rates among the young in developed countries are already very low and are falling rapidly in most developing countries, the years of life gained will increasingly come later in life (after an individual’s prime working years or in retirement even for healthy individuals) (Bongaarts 2006).

Bloom, Canning, and Fink (2009), find that although population aging will have potentially profound implications for many macroeconomic issues, it will likely have only modest effects on economic growth due to concurrent declines in youth dependency and increases in female labor participation and human capital accumulation.

Whether the economic impact of increasing longevity and associated population aging will be positive or negative will largely depend on how dependency ratios, labor force participation rates and size, the average age and length of retirement, saving and consumption behaviors, human capital accumulation, and healthcare spending all change in response; each of these factors are closely tied to a country’s age structure. At the same time, the nature of future longevity gains, whether they fall along pessimistic, optimistic, or radical lines, will have a great bearing on how these factors change over time—a healthier, longer-lived population that is capable and willing to work much longer while needing little support in old age would likely be a major economic boon, while an older population plagued by long-term morbidity will likely prove a major burden. Aisa and Pueyo (2004) boils the economic impacts of longevity down into two main groupings, those stemming from the quantity and quality of the labor force and those that form the impact of mortality decline on savings and consumption rates.

A5.4.1 Economic output

Many studies have examined the connections between health, generally, and overall economic growth. For the most part, the findings have concluded that increased health
leads to greater economic growth, though the pathways and direction causality are not always clear. At the same time, some studies find increasing health can have a detrimental impact when it leads to greater population growth or an older population (Acemoglu and Johnson 2007; Chakraborty 2007). Many studies on the economic impact of health use longevity as a proxy for overall health, but few look specifically at the linkages between longevity and economic growth; those that do tend to find longevity has a greater impact on economic growth than health overall.

There are two main pathways by which increased longevity is thought to foster economic growth. The most direct pathway, perhaps, is that greater longevity increases personal savings and investment rates as it reduces the risk of long-term investments and increases the return on the same (Castello-Clement and Doménech 2008; Chakraborty 2007). Chakraborty also suggests that a similar mechanism may be at work in countries that have become stuck in ‘development traps,’ as high mortality rates would dissuade individuals from saving and investing, especially for the long-term. The accumulation of human capital (covered below) is the second main pathway, with increased longevity leading to longer schooling and delayed childbirth (Boucekkine et al 2007; Castello-Clement and Doménech 2008). Further, the additional human capital accumulation can also lead to a reduction in economic inequality (Castello-Clement and Doménech 2008). At the same time, as Boucekkine et al point out, increased longevity can also keep older un/undereducated individuals around longer which may act as a drag on economic growth—this assuming those older individuals are not able to re-enter education.

Finally, existing life expectancies can have a major impact on the magnitude of potential economic benefits from improving longevity. An increase in longevity when life expectancies are very low tends to have a greater impact on economic growth than a comparable increase when life expectancies are already high. Longevity increases at high levels of life expectancies can even have a negative economic impact when such increases lead to increased population aging and or fertility decline (Boucekkine 2007 et al; Chakraborty 2007).

Zhang and Zhang (2005) reach the conclusion that population aging and increased longevity will likely not have a major impact on the economies of developed countries as it will likely result in lower youth dependency, increased human capital accumulation, and perhaps lengthened working life. Their cross sectional analysis of 76 countries suggests that a 10 percent increase in life expectancy at birth raises the secondary education enrollment rate by 5.6 percent, increases the ratio of investment to overall GDP by 2.4 percent, increases GDP growth rate by nearly 1 percent and reduces fertility by 0.55 children. The authors ask the question whether further gains in life expectancy will have a similar impact or see diminishing returns. The identified elasticities may therefore be the strongest in developing regions, suggesting that as longevity treatments become widespread, developing countries may see a significant increase in economic growth. While Zhang and Zhang do not quantify the diminishing returns, they make the general statement that “rising longevity reduces fertility but raises saving, schooling time, and the growth rate at a diminishing rate.” For developing countries, such trends could prove an
economic boon by lowering mortality and fertility and increasing the demand for education and savings.

A5.4.2 Human capital and productivity
One of the implications of healthy life extension is that individuals will be able to accumulate much more human capital in terms of education, experience, and health. According to Sierra et al 2009, this could allow for an increase in efficiency even as a larger proportion of older people remain in, or rejoin, the labor force. Blackburn and Cipriani (2002) make a similar argument, suggesting that increased longevity lowers the opportunity cost of forgoing current work and reproduction to pursue human capital accumulation. They (along with Soares 2006) suggest that, with increased longevity, people devote more of their time to education and have fewer children when young, increasing productivity per worker and lowering population growth (reducing youth dependency).

The NRC notes that in the past, most human capital tended to be accumulated early in life, with formal education and on-the-job learning reaching a peak at 30 years of age, but that this is changing. With the advent of continuing education and people increasingly enjoying second or third careers, human capital accumulation is beginning to be smeared out along the life course (Carey and Tuljapurkar 2003).

Aisa and Pueyo (2004), too, find increases in life expectancy heightens the accumulation of human capital among older generations, but the author also finds that such accumulation can come at the expense of spending on younger generations as more older persons re-enter education, for example.

A5.4.3 Inequality
While increased longevity appears to have less of a negative economic impact (or even more of a positive one) than generally assumed, one area most studies seem to find less sanguine is longevity’s impact on inequality. Should the development of life extension technologies continue to follow the development path of most other technologies, life extension may be limited to only those of high-income for the first few years after initial roll out. This would have the potential to greatly enhance income inequality as the longer lived (and healthier) would be able to accumulate more human capital, work longer, and benefit more from long term interest rates than the shorter lived. McConnel and Turner (2005) worry that anti-aging products will go to those who are already better educated, wealthier, and healthier, amplifying the socioeconomic inequalities already present in developed countries. Naam (2010) and Lucke et al 2010 agree with this assessment, though they see increased inequality as being temporary, as the gap between rich and poor when it comes to life extension would operate as a time lag and diminish over time. As with most technologies, they argue, the price will come down rapidly over time, enabling the poor to catch up. At the same time, the greater the enhancement the harder it may be for the poor to close the gap (i.e. a SENS intervention may prove so game changing that those who initially get the treatment might have such an advantage that late comers simply cannot compete).
Changes in retirement can also be an important source of inequality going forward. A number of studies point to the problem of longer lived, healthier workers slowing down the rate of intergenerational turnover in the workplace (McConnel and Turner 2005; Stock and Callahan 2004). As Taubes (2010) suggests, the number of advanced or leadership positions in an economy are limited—most of these positions go to older persons, since there are already many more persons in older age groups than there are age-appropriate positions. This could have two detrimental impacts on inequality: first, many underemployed older workers and, second, many younger workers unable to advance as workers live longer and healthier. As Kenneth Boulding bluntly put it in 1965, “It is the propensity of the old, rich, and powerful to die that gives the young, poor, and powerless hope. When death is postponed, so is promotion.”

Interestingly, it is possible that increasing longevity—if access to the technology is widespread—could decrease economic inequality between high-income and developing countries. This finding (explained in Aisa and Pueyo 2004) is primarily due to the law of diminishing returns; developing countries still have relatively high levels or mortality and morbidity, thus technological interventions to increase life expectancies should be much cheaper or at least require fewer resources than similar interventions in developed countries, and the impact of these interventions is likely to be much larger in developing than developed countries. Aisa and Pueyo (2004) argue that since increasing longevity is a major driver of economic growth, developing countries might see a much larger economic boost, helping them to close the economic gap.

A5.5 Environmental Impacts

While studies specifically devoted to the implications of increasing longevity for the environment are not numerous, many studies briefly touch on the subject. Many existing analyses tend to focus on three main pathways from longevity to resource use and environmental quality: 1) changes in population size; 2) changes in population age structure; 3) changes in income from economic growth. The studies generally conclude that increasing longevity will have little to no, or even in some cases, a net positive impact on the environment. This is because such studies of longevity assume that: a) any population growth due to decreases in mortality will likely be counteracted by further slowing of fertility due to population aging (More 2004); and b) increasing longevity will likely increase concern for the environment as individuals will be more likely to "be around" when long-term environmental damage is forecast to occur (Mariani et al 2008; Ono and Maeda 2000). Aging populations are also seen as likely to prompt a greater shift in high-income countries away from personal vehicles to public transport, reducing emissions. Similarly, increasing longevity is associated with rising incomes, which can also spur greater environmental awareness and protection (while at the same time potentially increasing resource consumption) (Hunter 2000; Ono and Maeda 2000).

Contrary to such perspectives, however, are the implications of environmental analysis using the logic that environmental impact is a product of population size, affluence (and thus likely increase of impact per person), and technology (including the intensity of resource use per unit of the economy)—this is the I=PAT equation, often attributed to Commoner, Ehrlich and Holdren (Waggoner and Ausubel 2002). All else equal,
longevity increases would increase population and thus detrimental environmental impact. Fertility declines might with a delay re-equilibrate population, but probably at a higher level. Larger population would likely lead to greater total economic size, whether per capita values declined somewhat or advanced. Moreover, if low senescence also meant extended and perhaps higher fertility, at least on an interim basis, the impact of population growth itself would be exacerbated. If it also meant greater productivity in the developing world and more rapid convergence to high-income-level living standards, it would almost certainly strain the world’s resources. Low senescence scenarios of extended longevity might facilitate technological advance that would reduce impact per economic unit, but that is not at all clear.

In deciding between these two perspectives on the environmental impact of longevity, much would depend on the extent of mediating factors like changes in socio-political behavior (including fertility and consumption patterns) and the advance of technology (Hunter 2000; Max 2004).

A5.6 Conclusions and Takeaways
As noted in the introduction to this section, this project remains heavily informed by existing evidence despite its moving into the unknown realm of extreme longevity. Rather than pretending that known relationships between longevity, population, and other dimensions of human progress will persist in predictable ways, we informed our exploration of extraordinary uncertainty with a few basic assumptions drawn from the literature.

- Regardless of the scope of adaptation, a substantial amount of population growth and population aging is inevitable. Through the ability of individuals and societies to manage their fertility, humanity will face a significant and inevitable trade-off between slowed population growth with more aging, or reduced aging with more population growth.

- The shape of the human life course has undergone previously unimaginable changes due to past longevity gains, both in terms of the length of adolescence and the plasticity of age-specific roles. These shifts would no doubt accelerate with the end of senescence, yet certain activities like schooling and even family formation will remain focused in early life so long as humans are born biologically undeveloped.

- Working lives will grow longer, though there will be considerably more variation within society in the age of retirement, as some people will choose to use extra healthy years in the workplace whereas others may choose to extend their period of retirement (though it is unclear how public or private pension systems would finance it).

- Given the well-documented positive relationships between longevity, health and productivity, and given the new opportunities that long life would afford to return to pursue second and third careers, it seems likely that any model based in existing literature would predict an increasingly prosperous world, in spite of a
number of transitional challenges.

- While the laws of classical economics suggest that human technology and adaptation can accommodate any change in population or age structure, the true limits may relate to the laws of biophysics. If we indeed expect to forecast a more populous and prosperous world, what additional burdens will be place on our food, energy, and atmospheric resources, and what technologies will be needed to ease the stress on an already fragile ecosystem?

- The other limiting factor of interest is social. While we can imagine that a health intervention that could grant immortality would be disseminated widely through market and charitable mechanisms, such a move would be unprecedented. Even in today’s era of globalization and substantial philanthropic and multilateral global health action, health interventions like antibiotics, many vaccines, HIV/AIDS treatments, and safe delivery for mother and child remain unequally distributed between and within countries. Those interventions that are most widely disseminated in poor countries are those that present an economic or security benefit to wealthy societies, such as the polio vaccine. While no existing intervention would offer nearly the longevity gain as those underlying the scenarios we explore, it does not necessarily follow that a more effective intervention would be more widely disseminated. Beyond questions of price and profitability that might put the intervention out of reach to many populations, there would be many who would actively withhold the prospect of immortality from some groups on the grounds of overpopulation, environment, security, or power. Indeed, in science fiction, which offers perhaps the richest source of framing material on the consequences of extreme longevity, high impact longevity interventions are often restricted to a thin slice of humanity, placing a fundamental wedge between those with and without access and sowing dissent.

- One final constraint on the prospects for a bright and boundless future lies within the human body itself. While the end of senescence promises eternal survival, health, and youth, we must nevertheless ask ourselves what continues to decay even as we replace our organs, our cells, and our DNA? One natural concern lies in hidden vulnerabilities to infectious disease. A more mundane concern lies in the mind, where morbidity has risen unabated through decades of epidemiologic transition. While our brains and nervous systems may be subject to rejuvenation, people may be more protective of their thoughts and identities. So long as these remain unaltered, will the weight of so many years lead to the accumulation of memories, burdens, and habits that weigh on our motivation to work or indeed to live? These concerns may be especially salient for those of us who were born expecting relatively short lives.
Appendix 6 – Comparing IFs output with existing forecasts of public spending on pensions

How do IFs forecasts of public spending on pensions stand up to existing forecasts? At the country-group level, a baseline European Commission forecast from 2006 has public spending on pensions in the EU 27 reaching 11.9 percent of GDP by 2030 and 12.8 percent of GDP by 2050, compared to the IFs Base Case, which has pension transfers reaching 12.3 and 14.2 percent, by the respective dates (EC 2006). Similarly, an OECD forecast from 2013 has public spending on pensions reaching 13.1 percent in the EU27 and 11.7 percent in the OECD, both by 2050 (OECD 2013). IFs, by comparison, forecasts spending to reach 11.5 percent in the OECD and 14.2 percent in the EU27 (Figure A6.1 compares these forecasts over time).

Figure A6.1 Comparing public spending on pensions in IFs Base Case with OECD 2013 forecast
Source: OECD 2013, IFs model version 7.09

At the country level, the IMF provides forecasts of public spending on pensions for a number of ‘advanced’ and ‘emerging’ economies out to 2050 (IMF 2011). They find that for most of these countries, spending as a percent of GDP tends to increase by several percentage points over the next four decades as populations age and lifespans increase—the OECD comes to the same conclusion, suggesting both the OECD and EU27 will likely see pension spending grow faster than GDP growth over the 2010—2060 period (OECD 2013). For the US, the IMF forecasts public spending on pensions to reach 8.3 percent of its GDP by 2050, compared to 10.3 percent in the IFs Base Case. For the
United Kingdom, the IMF forecasts 7.6 percent in 2050 and IFs 6.7 percent. Figure A6.2 compares the IMF and IFs Base Case forecasts over time.

Figure A6.2 Comparing public spending on pensions in IFs Base Case with IMF 2011 forecast

*Source: IMF 2011, IFs model version 7.09*