Opportunities and challenges of a world with negligible senescence

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ABSTRACT
The development of anti-aging technologies could have dramatic implications for a world already challenged by population aging. We explore how the world might evolve given the development and deployment of technologies capable of nearly eliminating mortality and morbidity from most causes. We consider both the great benefits and some of the complex sociopolitical rebalancing resulting from such advances. We use the International Futures (IFs) long-term, multi-issue, global forecasting system in our analysis of the interactions among demographic changes, the related changes in health costs and government finances, shifts in labor force participation, resultant economic transformations, and the environmental sustainability of the dramatically-altered human demands that emerge. We find that the widespread deployment of anti-senescence technologies would cause populations to surge—making fertility rates an issue of tremendous social import—while a much larger, healthier, labor force would spur economic growth. But this is not a given; the cost of treating entire adult populations could prove unbearable to non-high-income economies without significant transfers within and across societies. In the absence of new transformative production technologies, life-pattern financing would require the virtual elimination of retirement and a major restructuring of government finances. Pressures on the environment would also greatly intensify.

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1. Introduction
There is near certainty that the world will experience rapid population aging throughout this century, thanks primarily to widespread and substantial reductions in fertility and, secondarily, to ongoing extensions of life expectancy.1 Even as debate persists on biological limits to human longevity, we may even be accelerating at older ages (Willets et al., 2004; Strulik and Vollmer, 2013; Vallin and Meslé, 2010). At the same time, new breakthroughs in regenerative medicine and anti-aging therapies point to the possibility of improvements in longevity that are dramatic rather than incremental, and that reduce morbidity along with mortality (Lucke and Hall, 2006, 2010). Yet, forecasts produced by government and intergovernmental organizations continue to assume a fairly narrow range of upside longevity variation, amounting to at most 10 years of added life expectancy.

In this study, we take the opposite approach, exploring a future of very rapidly expanding life expectancy coupled with very low senescence. Using International Futures, a large-scale, long-term, integrated forecasting system, we explore the demographic, socioeconomic and ecological consequences of, and necessary adaptations to, such a world. There has been continued debate on whether longevity will continue to increase at its current rate of one-and-a-half to two years per decade (in high-income countries) for the foreseeable future, or whether future gains will slow or cease as we approach potential limits to the human lifespan (de Beer, 2006; Bongaarts, 2006). Olshansky et al. (2009) and Coles (2004) argued 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—and, in fact, many past efforts to forecast longevity built in diminishing rates of progress against mortality at older ages (Wachter, 2003).

On the other side of the debate, Oppeen and Vaupel (2002), Christensen et al. (2009), Howse (2009) and Vallin and Meslé (2010), among others, found little evidence for a limit to life expectancy, given that, over time, the greatest declines in mortality have occurred in older and older age groups, and also that the rate of mortality decline has been accelerating for the oldest old as well (Caselli and Vallin, 2001; Strulik and Vollmer, 2013; Willets et al., 2004). Indeed, more recent forecasting efforts, including that of the United Nations Population...
Fund, have dropped the imposition of diminishing returns and introduced a set of Bayesian forecasts that consider the possibility of far more rapid increases in longevity (Howse, 2009; Raftery et al., 2013).

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 Klips et al. (2011), Strulik and Vollmer (2013), 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 life spans 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. Indeed, the continued accumulation of morbidity at older ages and the resultant increases in health expenditures are assumed in most baseline forecasts of demographic and health change (Goldman et al., 2013).

While these uncertainties loom large now, they could be obviated by the advent of game-changing medical advances, including stem cell therapies, telomerase-based treatments, tissue engineering, gene therapy, and growing rejection-proof organs (Longo et al. 2015; Kennedy and Pennypacker 2015; Moskalev and Pasyukova 2014). Thus, it is important to consider the implications of greatly extended healthy life expectancies (de Grey et al., 2002; Lucke and Hall, 2006, 2010). Few studies, however, have explored the long-term consequences of breakthroughs resulting in dramatic and widespread mortality reduction. This study imagines a world in which such medical advances occur in the near future and examines their likely consequences.

In a short paper in 1959, Ansley Coale, the intellectual father of modern demographic research, used Alfred Lotka’s Stable Population Model (Lotka, 1998) to demonstrate the surprisingly modest effects of longevity on population size by envisioning a world of immortality with fertility unchanged. Coale noted that a shift toward immortality would just have the same long-term impact on population growth as a 10% increase in fertility rates. More recently, Caselli and Vallin (2001) computed the population implications of a world with a life expectancy of 150 years instead of 85. Assuming a convergence of the global total fertility rate (TFR) to replacement level, their high longevity scenario produced a population of 14 billion in 2100 instead of 11.8 billion, a sizable increase, though in relative terms it would pale in comparison to the population growth of previous centuries. In models assuming a convergence to a TFR of 1.0 child per woman, the extension of life expectancy from 85 to 150 would merely delay the inevitable path toward inexorable population decline by 100 to 200 years, depending on the age structure of longevity changes. Both the earlier and later studies noted that the more dramatic changes resulting from extreme longevity would lie with the aging of the population.

None of the aforementioned studies addressed the possibility that a dramatic increase in longevity might be accompanied by an extended fecund span, with the potential for further population growth. Given continued increases in the effective reproductive age through assisted reproductive technology (ART), any forecast of the long-run consequences of extreme longevity must also consider potential scenarios for fecundity extension, including the possibility of eternal reproductive capability.

The purpose of this paper, then, is to consider the issues raised by a future of very rapidly expanding life expectancy coupled with very low senescence. More specifically, we want to look at 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 disease as well as eliminating infecundity. We label this world that of a Negligible Senescence scenario and use the International Futures (IFs) 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). Our goal is not to model a likely future world, but rather to frame our understanding of the potential consequences of negligible senescence by evaluating the effects of a rapid and universal transition to such a regime. We thus do not address the rather obvious likelihood that a rollout of such technologies would be both more incremental and less universally available than our scenarios suggest. We also do not address the specific technologies or policies that might lead to such a scenario.

It is not enough 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). We also want to begin 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.

The next section describes the IFs modeling system, the Base Case scenarios, and the negligible senescence intervention space. In modeling necessary adaptations to a world of negligible senescence, we introduce additional scenario variations relating to fertility, financing of life extension, and financing of retirement, as described in Section 2.3.

Section 3 presents results on the comparison of the negligible senescence scenario to the Base Case and comparisons of different scenario variations within the negligible senescence space. We first present possible impacts on population size and age distribution, exploring three alternate fertility scenarios. We next address health finance, exploring three potential cost per life saved scenarios and illustrating the necessity of subsidies from rich to poor countries to ensure global access. We then consider the costs of financing the general consumption needs of an older but healthier population. Having addressed these potential sources of variation, we model the impact of a rebalanced Negligible Senescence scenario on economic output environmental sustainability.

2. Materials and methods

The IFs forecasting system used in our explorations has been developed over the past 35 years and is widely used for long-term analyses of human, social, and environmental system development. This section provides a brief survey of the system, sketches the extensions made for this paper, and introduces the scenarios developed for this analysis. The IFs system, with all changes made for this paper and files to generate the scenarios discussed here, is available for free use at www.Pardee.du.edu.

2.1. International Futures (IFs)

The International Futures forecasting system is based at the Frederick S. Pardee Center for International Futures at the University of Denver’s Josef Korbel School of International Studies. IFs includes detailed models of demographic, economic, sociopolitical, education, health, infrastructure, energy production, and agricultural subsystems for 186 countries interacting in the global system (see Fig. 1).2 Most of these models are comparable to, and sometimes more fully developed and advanced than, other stand-alone models in 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 paper. The models within IFs that are of special interest.

2 We only touch on some key impacts within the large and highly integrated IFs system; for a complete mapping of individual variables and their connections, see the expendable diagram at http://pardee.du.edu/understand-interconnected-world or documentation of all IFs models at http://pardee.du.edu/working-papers.
for this paper include those of demographic, health, government finance, and economic systems. Roll-ups of forecasting results to world regions or income-category groupings reflect the aggregation of country-level results, following aggregation rules appropriate to the variables (e.g., sums, simple averages, population- or GDP-weighted averages).

IFs represents population using a standard cohort-component structure. Five-year cohorts are computationally spread to 1-year cohorts, and population change due to birth, death, and migration is computed in 1-year time steps. In order to study extreme longevity, we extended the previously existing 22 age–sex category structure (up to age 100) to 42 age–sex categories so as to represent population to age 200+. The native IFs mortality estimates and forecasts build on the World Health Organization’s Global Burden of Disease (GBD) project (Mathers and Loncar, 2006), including representation of mortality and morbidity due to 15 causes across the groupings of communicable disease that can be transmitted from person-to-person (e.g. HIV/AIDS, diarrheal disease, malaria), noncommunicable disease (e.g. cardiovascular diseases, cancers), and injuries and accidents, and endogenous forecasts of mortality change based on distal drivers (i.e., GDP per capita, education, and time as a proxy for technological advance) and proximate risk factors (e.g., obesity, smoking, air pollution). Following the methodology of the GBD study, IFs represents initial morbidity as a fixed product of mortality for each cause of death. Subsequent changes in the level of morbidity relative to mortality are controlled by a multiplier that allows for greater or lesser accumulation of morbidity among survivors. Mortality and morbidity then impact economic growth through pathways of labor force participation, productivity, savings, and health expenditure. All model initializations, including age–sex structures, fertility and mortality rates are specified separately for 186 countries with IFs project estimations to fill data holes as necessary.

In the current study, for adults we introduced parametric control over the mortality J-curve for each cause, using a logistic expression to control the timing of mortality (moving the J-curve horizontally) and the pace of mortality increase with age (making the J-curve steeper or flatter) for each mortality cause as follows:

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

On the fertility side, IFs calculates change in age-specific fertility of women in response to income, income distribution, infant mortality, education levels, and contraception use. To account for the potential extension of fecundity well past the typical onset of menopause in current populations, we added a parametric structure that builds age-specific fertility as a function of the age of menarche, age of menopause, peak age and level of fertility, and the pattern of rise and fall from the peak.

Migration rates for the IFs population model are drawn from exogenous forecasts provided by the International Institute for Applied Systems Analysis, but IFs maintains global balances in population flows (KC and Lutz, in press-a,b). The rates generate fairly stable foreign populations as a share of total populations, the pattern of recent decades.

The IFs economic model represents the economy in six sectors, as illustrated in Fig. 1: agriculture, materials, energy, manufacturing, services, and information and communications technology. The model computes and uses input–output matrices that change dynamically with development level. It is a general equilibrium-seeking model that does not assume exact equilibrium exists in any given year; rather, it uses inventories as buffer stocks and to provide price signals so that the model adjusts equilibrium over time. A Cobb–Douglas production function (following insights of Solow, 1956, 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). Finally, a Linear Expenditure System represents changing household consumption patterns as a function of income.

Our analysis of the implications of longevity and aging depends heavily not just on the demographic and economic models included in IFs, but also on the representation of financial flows. IFs represents eight categories of government spending (military, health, education, R&D, two categories of infrastructure, foreign aid, and a residual category) plus transfer payments. The model represents the need to maintain some long-term equilibrium between government revenues and expenditures and enforces trade-offs across categories of government expenditures. It also uses a social accounting matrix to integrate government financial flows with those of households and firms domestically and internationally so as to assure system-wide balances and tradeoffs.

2.2. IFs Base Case scenario

All scenarios build on the IFs Base Case scenario. 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. For example, IFs forecasts of key drivers, such as GDP per capita and education attainment of adults, are foundational underpinnings of its Base Case health forecasts. Further, changes in assumptions concerning health result in changes in demographics, economics, and all other systems in IFs. Feedback loops across many components of the IFs system mean that interventions may accelerate further beneficial or detrimental change in health and other modeled aspects of human development.

Hughes et al. (2009: 56–71) explored the key IFs 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 et al. (2011) for health model results).
This makes IFs an ideal integrated platform for exploring the far-reaching consequences of a systemic shock like the introduction of a Negligible Senescence scenario.

2.3. Negligible senescence scenarios

Fig. 2 describes the scenario tree for subsequent analysis. Relative to the Base Case scenario described above, we first introduce a core negligible senescence scenario (hereafter referred to as “NegSens”) in which all mortality and most morbidity (with the exception of mental health) is reduced to near zero. We then build variations on the NegSens so as to explore alternative possible implications of the scenario and social adaptations that could arise to address imbalances the scenario(s) might create. Specifically we address variation relating to intervention cost, fertility adaptation, and life cycle work/finance patterns. We then explore the implications of our combined scenarios on economic growth and sustainability outcomes.

2.3.1. Negligible senescence scenario

NegSens and its variants all include a 20-year phase-in period between 2020 and 2040 during which all noncommunicable disease (NCD) and communicable disease (CD) mortality is reduced to close to zero, as is morbidity due to all of these causes except mental health. We chose this pattern because it illustrates a particularly sharp and dramatic break with the Base Case. Although we did not reduce mortality and morbidity for mental illness, we placed limits on the extent to which the burden of mental illness would rise with age. We also assumed 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. In addition, model parameters allow variations to the core NegSens scenario with respect to starting point, period of phase-in, magnitude of reduction in mortality and morbidity, geographic scope of changes, costs of associated treatments, and much more.

In our NegSens scenario set, we assumed universality in the phase-in within and across countries. Although we recognize that this is unlikely given the presumably high costs of necessary medical treatments, this assumption again allows the most extensive exploration of implications. Rather than impose a particular structure of technological diffusion across countries or income groups, we instead explore the cost subsidies that such universality would require, both within and across countries. Fig. 3 illustrates the extent of this mortality reduction relative to the Base Case. In the Base Case, continued aging of the global population into ages of higher mortality will begin to reverse the long-term global decline in crude death rates, thereby slowing population growth. The negligible senescence scenario instead drives crude death rates close to zero, with no eventual rise, effectively eliminating rather than delaying death. Since crude death rates are a principal contributor to population growth rates, the relative decrease in crude death rates from 9–11 deaths per 1000 (or 1% per year) to near zero would add an extra 1% to population growth each year, with substantial economic implications. Population growth and aging could increase competition for resources in the social accounting matrix, particularly relating to retirement. The reduction of morbidity would increase the economic productivity of individuals and reduce health costs. The ultimate extent of these effects would depend in large part on changes in fertility behavior, costs of the negligible senescence intervention itself, and possible adjustments to life cycle work/finance arrangements.

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4 The link of mortality change to change in morbidity in the NegSens scenario is less than 100% only for injuries/accidents (75%) and mental health (no link).
The protease inhibitor treatment cost is $57,200 per year (Liu et al., 2012). The cost per person-year of healthy life is $5000 per person-year (in the 2011 constant dollars of the model). We also introduce alternate scenarios in which the treatment instead guarantees 10 or 30 years of negligible senescence, thus implying costs per person-year of healthy life amounting to $3333 and $10,000. 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-65.5

Assuming the necessity of subsidies or cost-shifting by providers, treatment costs are proportionately scaled down for countries with GDP per capita below that of the US in 2010, to 5% of high-income country levels as a minimum. In current programs such as the global antiretroviral treatment (ART) campaign for HIV/AIDS, this downward scaling in effective price for poor countries is generated by a combination of direct transfers from donors; discounts from innovators to buyers; and voluntary, and compulsory licenses of innovator property to lower-cost producers.

2.3.2. Fertility variations

Within the NegSens scenario we explore three fertility patterns and compare them to our Base Case fertility assumptions. In the Base Case, global total fertility rate (TFR) declines to 1.9 children per woman, all births occur to women between ages 15 and 49, and the mean age of childbearing rises only slightly to 32, compared to 29 today. For biological and behavioral reasons, this pattern would be unlikely to hold in a world of negligible senescence. Instead, negligible senescence technologies could also potentially delay or even eliminate age-related infecundity, leading to increased fertility at older ages, particularly in the initial post-intervention years. At the same time, the age of initial and peak fertility would likely be pushed back substantially in anticipation of longer life.

Our primary or core scenario of interest is a Middle Fertility NegSens scenario in which TFR temporarily rises (as a result of extended fertility without intentional behavioral changes) before ultimately falling to 1.9 children per woman, but with a much delayed age pattern in which the mean age of childbearing rises to 58 (see Fig. 4). Our subsequent analysis also explores a Low Fertility NegSens scenario in which TFR declines to 1.0 children per woman (with a mean age of 51) due to some combination of a reduced sense of self ”replacement” and ”old-age care” needs and of societal needs to limit fertility substantially to slow the rapid population growth of the underlying scenario. Finally, we explore the possibility of a more substantial increase in fertility due to rising fecundity; the NegSens with High Fertility scenario assumes a gradual rise to a TFR of 3.0.

2.3.3. Health expenditure estimation and variations

In the core NegSens scenario, we assume that life extension treatment costs of $100,000 per treatment and provide, on average, 20 years of negligible senescence; assuming subsequent treatments on the same schedule, the cost per person-year of healthy life is $5000 per person-year (in the 2011 constant dollars of the model). We also introduce alternate scenarios in which the treatment instead guarantees 10 or 30 years of negligible senescence, thus implying costs per person-year of healthy life amounting to $3333 and $10,000. 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-65.5

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Based on data from the President’s Emergency Plan for AIDS Relief (PEPFAR), the current mean cost of ART 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 (PEPFAR, 2013). When compared with average person–year treatment costs in the US of $20,000 (Maxmen, 2012), low-income and lower-middle-income countries pay 3.2% of the US cost while upper-middle-income countries pay 4.7%. All of these cost reductions effectively constitute transfers from wealthy to rich countries.

We further posited decline in person–year costs in real terms to one fourth of the initial cost (to $1250 annually in constant 2011 dollars in the core scenario) over 80 years to 2100, a reduction of 1.7% annually. Relative to growing GDP per capita, this would mean a quite rapid and very substantial decline in economic burden. All in all, our cost assumptions appear quite optimistic and higher ones would exacerbate the issues we raise below.

For the purposes of this study, we further enhanced the IFs financial model by explicitly representing the financial cost of person–disease–years of morbidity (by cause) and of last-life-year and also by representing the costs of life extension and of “other” health costs (e.g., administration and R&D) related to morbidity, mortality, and life extension. These bottom-up calculations of total health costs will not be equal to top-down calculations of what governments and private citizens have historically been willing or actually able to expend. While the model is capable of allowing societies to over- or underspend relative to potential costs, with consequences for health outcomes, our analysis assumes that top-down expenditures will match bottom-up costs, allowing us to assess the implications of alternative cost structures for government finance and societal financial flows more generally.6

2.3.4. Life-pattern financing

Additional structural extensions and new parameters allow us to control changes in household work and saving patterns and in government pension spending as mechanisms for satisfying life-pattern

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5. The annual cost of the selected molecularly targeted cancer therapies ranges from $60,000–$240,000 in US 2010 dollars (Sikora, 2007; Torres, 2010). The annual cost of the selected gene therapy treatments ranges from $30,000–$34,000 (Wade, 2011; Hirschler, 2012). The protease inhibitor treatment cost is $57,200 per year (Liu et al., 2012), and the annual cost of the TA-65 supplement is $8000 (de Jesus et al., 2011).

6. The alternative to balancing bottom-up costs and top-down expenditures would be to allow societies to fall short of spending needs, resulting in some functionally specified reduction in societal health. Since this paper focuses on a society in which negligible senescence has been achieved, we assume the costs are met by expenditures and evaluate the consequences for the social accounting matrix.
financial needs. These include: allowing parametric redefinition of work starting age and retirement age in replacement of the prior fixed values 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 horizon); and building mechanisms for the balancing of life course finances through endogenous adaptations and exogenous adjustments to retirement age, private savings rates, and government transfers to retirees. Due to the complexity and interdependence of these interventions, we describe them iteratively in Section 3.3.

3. Results

3.1. Population size and structure

We first explore the demographic consequences of NegSens relative to the Base Case to illustrate the quantitative nature of the intervention and its consequences for population change. The Base Case produces a total global population in 2100 of 10.1 billion, very slightly down from a peak reached in 2090 (see Fig. 5). 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 from the International Institute of Applied Systems Analysis (KC and Lutz, in press-b) from 6.9 to 12.6 billion (9.0 billion in its centrally-oriented Shared Socioeconomic Pathway 2 scenario).

NegSens produce substantial increases in population size, growth, and aging relative to the Base Case, though the extent of change depends considerably on fertility patterns. The NegSens Middle Fertility scenario with a TFR moving to 1.9 (as in the Base Case) produces a population of 14.8 billion in 2100, with an annual growth rate of 0.6% in 2100. The NegSens Low Fertility scenario would slow population growth relative to the NegSens Middle Fertility scenario, though the population in 2100 would still be considerably higher than that in the Base Case at 11.6 billion, and population would still be growing at 0.2% in 2100. The so-called High Fertility scenario would lead to what most observers would consider a demographic and sustainability nightmare, with more than a doubling of population relative to the Base Case and continued rapid rise. Our subsequent analysis focuses on the NegSens Middle Fertility and NegSens Low Fertility scenarios.

These alternative fertility scenarios, in interaction with NegSens mortality patterns, produce rather shockingly different age–sex structures in 2100 (see Fig. 6). NegSens High Fertility produces a general shape much like that of the world today, although its overall size is much larger. NegSens Low Fertility produces an almost inverted pyramid (or child’s top) form, one that would become substantially more pointed over still more time, reflecting ever greater numbers of 100+ people. By 2100, 73.5% of the world’s population would be over age 65 in NegSens Low Fertility, compared to 58.5% in NegSens Middle Fertility, 25.7% in the

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7 We note that a TFR of 1.9 can be achieved through an endless variety of age-specific fertility patterns, with considerable implications for short-term population growth though not for long-run population growth rates. In the unlikely case that the age pattern remained the same as in the Base Case, the population in 2100 would rise to 16.7 billion.
the country level, Keehan et al. (2011) forecast total health spending as a percentage of GDP will reach 15% by 2050. At their peak in 2030, those subsidies or transfers add an additional 4.8% of GDP to the global total in the core NegSens scenario. Similarly, Besseling and Shestalova (2011) forecast public health spending in the Netherlands to be 10% of GDP in 2015, while IFs has it reaching 10.9% of GDP.

While disease-specific expenditures would decline in the NegSens set, all three scenarios would entail a high level of expenditure on regenerative treatments themselves, and these costs would be heavily front-loaded during the initial rollout period, peaking in 2040 at 5.4% of global GDP when priced at $5000 per person–year of healthy life (at 3.6% of global GDP using the $3333 price; at 11% of global GDP with the $10,000 price).

The time profile of net fiscal impact in NegSens would thus vary greatly depending on the intervention costs. Assuming the median or core cost estimate of $5000 per person–year, at the global level the negligible senescence treatment would become cost-neutral relative to the Base Case by 2022. If the cost were twice as high, however, the treatment costs on top of other ongoing health costs would rise to just under 14% of global GDP in 2034, an increase of 2.6% age points, and would only become cost neutral by 2044. In all of the NegSens scenarios, costs of mortality and morbidity would fall to near zero before seeing a gradual rise (beyond the time horizon of Fig. 7) due to the slow accumulation of mental illness among a continuously aging population.

As the four panel display by county-income level shows in Fig. 7, global analysis masks significant differences in the magnitude and temporal impact of treatment costs between high-income and developing countries. Upper-middle-income countries, for example, see their total health care costs as a percentage of GDP more than double, from just over 6 percent in 2020 to 14% in 2040, with a break-even point of 2060. Lower-middle- and low-income countries see costs triple over the same period, only becoming cost neutral toward the end of the century. In the medium-cost NegSens, most developing countries would see costs rise by 2 to 3 percentage points, and lower-middle- and low-income countries would see break-even points several decades after those of high-income countries.

The values in Fig. 7 are, however, misleadingly low because of the assumption that treatment costs in developing countries would be subsidized in some way, falling domestically to as little as 5% of those of high-income countries. At their peak in 2030, those subsidies or transfers add an additional 4.8% of GDP to the global total in the core NegSens with medium treatment costs, and 14.5% to the high-cost treatment scenario, while the low-cost scenario sees a modest increase of 1.6 percentage points even with the subsidies (Fig. 8 adds those subsidy costs back into the global total). That still makes the medium scenario appear potentially globally affordable with a peak of 16.2% of GDP directed to health in 2030. One might think that the world could rise to that challenge given the life-expectancy stakes. (The high-cost scenario would peak at 27.6% in 2035, and that is a challenge we would not expect to be met.)

The apparent affordability of the core or medium-cost NegSens scenario raises the question, however, of who would pay the subsidies and whether those payers would, in fact, view them as acceptable. In low-income countries, foregoing the subsidies would increase the

Fig. 6. Population globally in 2100 by NegSens fertility scenario. Source: IFs version 7.09.
scenario cost to 76.8% of their GDP in 2034, clearly not affordable. Obviously the world would look to the high-income countries. If those countries paid their own life extension costs plus the subsidies to the rest of the world, their costs would rise to 24.7% of GDP in 2034. Even paying their own costs would require political and social will to arrange substantial domestic transfers. Asking high-income countries to nearly triple the percentage of GDP spent on health so as to pay much of the cost in low- and middle-income countries would likely receive a negative answer.

3.3. Life pattern financing and economic growth

The contemporary world already struggles with the financing of old age. Many developing countries, including giants like China and India, have yet to set up pension systems that fully cover rapidly aging populations that once relied upon children for support of the elderly. 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 barely seen average retirement ages rise 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). Higher lifetime incomes and extensive retirement plans have often actually encouraged younger retirement ages.

Given the immense consumption needs facing aging populations, how might populations and insurance systems adapt during a major increase in longevity and health? At least in the early years of adaptation 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.

The top panel in Table 1 shows that the Base Case increases in consumption needs of elders would be trivial next to those observed in NegSens scenarios. In the Base Case, the share of GDP needed to support the consumption of retirees would double from 8.2% today to 16.8% in 2100. In that situation, even in the absence of increased retirement age, the model endogenously identifies a pathway to meeting future consumption needs—namely, the savings rate rises substantially from 22.4% today to 28.4% in 2100, and the share of global GDP devoted to government pensions climbs from 6.4% to 8.4%. The resulting solution for the Base Case yields a modest gap between old-age consumption needs and actual consumption, amounting to just 1.1% of GDP.

In contrast, no reasonable combination of increased government pensions and household savings could meet the retirement needs of a negligible senescence population unless retirement ages were to rise. In NegSens (shown also in the top panel of Table 1), the share of GDP needed to meet the consumption of retirees rises to 51.8% in 2100 with a 1.9 TFR and to 66.2% with a 1.0 TFR, largely in parallel with trajectories in the dependency ratio. The model partially adapts endogenously to these shifts by introducing a substantial increase in domestic savings rates (28.9% if TFR is 1.9 and 33.3% if TFR is 1.0) and the share of GDP devoted to government pensions (to 16.6% if TFR is 1.9 and 17.2% if TFR is 1.0). Both of these shifts are facilitated in part by a declining burden of health expenditures, but they nevertheless strain other aspects of public and private finance and push total government revenues in 2100 from 33.7% of global GDP in the Base Case to 49.5% of GDP. Even changes of this magnitude do little to close the old-age financing gap, which remains at 30.5% of GDP with moderate fertility and 43.6% of GDP with low fertility. In other words, it would be impossible to manage a world of negligible senescence in the absence of substantial increases in the age of retirement.

We therefore next introduced a rebalancing model in which the age of retirement was allowed to move up gradually in response to the gap between retirement consumption needs and availability of funds from accumulated savings and government transfers. Rather than impose a particular set of assumptions about a sudden jump in retirement age, we introduced one possible path toward a gradual increase in retirement age that was geared to balancing out the consumption gap. The transition identified by the model involves some substantial extensions of working life near the end of the negligible senescence phase-in period (2040), followed by longer-term continuing adjustments. We also assumed that people living indefinitely in good health might choose a work pattern less clearly shaped by the life course, dropping out periodically for recreation or retraining, very likely cutting back the intensity of work life, and often eschewing paid employment when finances allowed. As a result, we also introduced a gradual reduction in work force participation at all ages from 100% to 80%, phased in over the 20-year intervention period.

The resulting profile, shown in the bottom panel of Table 1, illustrates one possible path to closing the old-age consumption gap. Although solutions could be achieved through an infinite set of combinations of private savings, public finance, and delayed retirement,
we found that significant delay in retirement proved necessary in all successful cases. For the moderate fertility scenario, the age of retirement reached 114 by the year 2100, raising the workforce participation ratio from just 23.6% without rebalancing to 42.4%, basically in line with the Base Case. The lower proportion of retirees reduced the retiree consumption as a share of GDP from 51.8% to 15.7%, again in line with the Base Case. This particular solution saw savings rates remain quite high by historical standards (29.1%), though still barely higher than in the Base Case. The rebalancing reduced the share of GDP devoted to pensions from 16.8% to 13.7%, which was still substantially higher than the present-day share (6.4%) or the share for 2100 identified in the Base Case (8.7%).

Perhaps the most striking result of the rebalancing exercise is the relatively limited effect of fertility on the ultimate life-pattern financing solution, in contrast to our current era in which old-age financing needs are driven heavily by changes in fertility and the resultant size of the working population supporting the retired elderly population. In NegSens, the elderly would bear overwhelming responsibility for meeting their own consumption needs. In fact, it should be noted that by 2100 the retirement age would still be on a trajectory of linear increase, rising about 0.6 years for each calendar year. In essence the calculation of retirement age by that time is largely just an artifact of our financial balancing calculations, and the very concept would be steadily phased out as the population aged. Instead it would be replaced by changing participation rate patterns, reflective of alternative basic technological capabilities of society on the production side, of alternative life style consumption patterns, and of income and wealth distribution.

With the rebalancing of life-pattern financing in place for the medium cost or core NegSens scenario (see Fig. 2 for a review of the scenario development sequence of this analysis), we can consider resulting change in economic growth relative to the Base Case, as shown in Fig. 9. The Rebalanced NegSens scenarios (both medium and low fertility variants) would result in dramatically larger global economy sizes, largely because population would be so much greater. The Base Case has global GDP reaching $866 trillion by 2100 while in the Rebalanced NegSens scenario with medium fertility global GDP reaches $1697 trillion. The Rebalanced NegSens scenarios would also yield modest but positive effects on GDP per capita even with a much larger global population. Assuming no major environmental constraints, the Base Case would already see global GDP per capita rise from $12,900 to $86,000, while the Rebalanced
NegSens scenarios would yield a GDP per capita of $114,000 with moderate fertility and $119,000 with low fertility. In annualized terms, these gains relative to the base are quite modest.

3.4. Sustainability

The demographic and economic shifts discussed above cannot help but affect the use of natural resources and the state of the natural environment. Although the effects would be widespread, we focus here on issues related to energy use and climate and crop production and undernutrition as examples of broader implications.

In the IFs Base Case, global energy demand increases by a factor of 5 between 2010 and 2100. In the Rebalanced (and medium-cost) NegSens scenario with a TFR of 1.9, that increase becomes close to a factor of 8 (and a factor of 7 with a TFR of 1.0), as shown in Fig. 10. Given that Fig. 9 indicated GDP growth in these two scenarios by factors of 19 and 15 by 2100, it should be clear that the model assumes dramatic reductions in the use of energy per unit of GDP as a result of efficiency increases and demand pattern changes.

The impact of increased energy demand on the climate system depends very much on how this demand is met. The IFs Base Case tends to be optimistic compared to other recent literature in terms of the shift to non-fossil fuel sources; it forecasts a plateauing of fossil fuel use in the 2030s followed by a steady decline after 2040, with non-fossil fuel sources overtaking fossil fuels just before mid-century and constituting 92% of all supply by 2100. Such reductions in fossil fuel use might be even more difficult to achieve given the much larger relative size of the economy in the NegSens scenarios. Thus, we explored a variation to the basic NegSens Rebalanced (and medium cost) scenarios in which growth in non-fossil production is cut back somewhat and more fossil fuel production is added; the additional fossil fuel is coal because the resource constraints on coal are much less than those on oil and gas. Even in this adjusted scenario, non-fossil fuel sources overtake fossil fuels in their contribution to meeting demand shortly after 2050, with just 18% of all energy coming from fossil sources by 2100.

Even the scenarios without higher coal production have substantial impacts on atmospheric carbon levels, as shown in Fig. 11. Although the levels are only slightly higher than those in the Base Case, they pass 600 ppm (ppm) in 2100—well above the 450 ppm that have been posited as an important target level so as to limit global warming. Forecasts of carbon concentration are, however, highly sensitive to the composition of increased energy supply. Just the modest shift from renewable to fossil fuel production laid out in the High Coal scenario variants of Fig. 10 would increase atmospheric carbon concentrations by about 30%, to 818 ppm in 2100 for the moderate fertility scenario and 791 ppm for the low fertility scenario, with little sign of peaking any time soon.

Of great concern also might be the demands on agricultural production in NegSens and the implications for undernutrition. Fig. 12 shows that, in the Base Case, global mean calories per capita rise from 2821 in 2010 to 3294 in 2100—not without some negative consequences for global obesity rates. In the Negligible Senescence scenario with moderate fertility, by contrast, calories per capita barely rise at all (2841) while even in the low fertility scenario the level only rises to 2910. Put another way, between 37% and 99% of all expected gains in caloric consumption could be eliminated as a result of NegSens. Since calories are not evenly distributed, the results for rates of undernutrition look even more striking. Whereas the Base Case sees the global rate of undernutrition declining from 13% in 2010 to 4% in 2100, the NegSens scenarios would see this rate only drop to 10% with moderate fertility and 9% with low fertility.

4. Conclusions

Using the International Futures system, a large-scale integrated model of global futures, we have built an experimental scenario of a world that, thanks to technological advances between 2020 and 2040, moves mortality and morbidity from their current pattern to one of negligible senescence. Our scenario and variations on it portray an arbitrary set of assumptions, but ones that facilitate analysis and can be varied using the International Futures system. We have explored the larger consequences of that scenario and, in the process, elaborated a vision of a negligible senescence world. We note that while any specific scenario that we or others present is highly unlikely, there is increased interest among biologists and economists in understanding the potential returns to health systems and societies from targeting aging itself rather than focusing on the physiological consequences of aging.

We find that a world of negligible senescence would pose a number of immense challenges that go well beyond increased population size. The most obvious and immediate challenge lies with disseminating and paying for the life-saving intervention itself. We estimate that rollout of such an intervention on a widespread basis would be infeasible even in the wealthiest countries if the initial price were set at $10,000 per year of healthy life added. At the price of $5000 per added healthy-life-year that we assumed through much of this paper, the initial financial burdens would be manageable for wealthy countries and would, over time, yield considerable reductions in disease-related expenditures that would more than offset the cost of the intervention. Yet poor and also middle-income countries would struggle to finance such an intervention even if, as we assumed, up to 95% of the costs in the poorest countries were defrayed through price reductions of the sort that have recently been observed for high-impact antiretroviral treatments.

With these caveats in mind, a world of negligible senescence would likely yield a still growing population of 14.8 billion by the year 2100, a considerable increase over the 7 billion today or the 10.1 billion forecast in our Base Case in 2100. Uncertainty in fertility, arising from the potential pronatalist impact of increased fecund spans and, on the other hand, the public interest in reducing fertility to check population growth, could yield a population with as many as 20 billion (with a global TFR of 3.0) or as few as 11.6 billion (with a TFR closer to 1.0). It is important to note that the 1.0 to 3.0 births per women implied in these scenarios would have to be spread out over 150+ years of fecund life span instead of the current 30-odd years. The societal burden of managing population size while also acknowledging the right to fertility at advanced ages would be great and pose considerable ethical challenges. In the absence of mortality, even incremental increases in TFR above the levels modeled in this paper would quickly generate unimaginably high levels of population.

A revolutionary jump in human longevity would require a comparable revolution in the meaning and timing of retirement. The IFs system can endogenously solve the problem of increased old-age dependency in the Base Case through a combination of increased savings and public pensions, even in the absence of any increase in the age of retirement. No such solution can be found in a world of negligible senescence. Instead we explore scenarios that would see the average age of retirement rising to 114 by 2100 if fertility remained moderate at a TFR of 1.9 children per woman, or to 118 if fertility instead dropped to 1.0. Even these relatively aggressive increases in retirement age necessitated a rise in savings from 22% today to 29% and doubling public pensions as a share of GDP, from 6% to something more like 14%. These increases would seem to be at the absolute edge of feasibility, and thus our

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8 This is in line with the Baseline scenario in the recent Global Energy Assessment (GEA) (Johansson et al., 2012) using the MESSAGE model. The Baseline scenario in the GEA, which uses the IMAGE model, projects significantly slower growth, with only around a doubling of global energy demand over this period.

9 This pace of transition to renewables is slightly more conservative than that of the expert panel tapped by TechCast (www.techcastglobal.com accessed 12/10/14), and it still results in non-fossil fuels contributing close to 90% of total global energy in 2100. 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 scenarios with a strong sustainability focus. At the same time, total energy use is significantly lower in those scenarios, so the absolute growth in energy from non-fossil sources is much less than in the IFs Base Case.
retirement age scenarios should probably constitute something of a lower bound. On a positive note, individuals would still be able to enjoy decades of post-retirement life if they so chose, or embark on new patterns of employment, education, and leisure that are less defined by imminent mortality than the current pattern.

Finally, our results point to perhaps the greatest challenge facing a world of negligible senescence, those relating to the sustainability of our natural resources and biosphere. Given widespread concern that our economic way of life is already unsustainable, the potential addition of billions of people would concern many, especially given that this population (in the absence of negative feedbacks from environmental constraints) would see a GDP per capita 30% above the already substantial economic growth built into our Base Case. Energy demand levels, even with quite optimistic assumptions about efficiency gains and renewable contributions, would drive atmospheric CO₂ levels above 600 ppm and, if coal were more heavily drawn upon without carbon sequestration, to 800 ppm or above. In the absence of food production technologies that are currently not on the forecast horizon, it might become nearly impossible to reduce the portion of the world’s population that is undernourished.

It is interesting to note that a massive reduction in fertility by nearly one-half (from 1.9 to 1.0 children per woman) would substantially reduce all of these environmental effects while having surprisingly little impact on old-age finance (retirement age would have to rise to 118 versus 114 in the medium fertility scenarios).

Given the preliminary nature of our investigation, we note several key limitations to address in further exploration. First, for the purpose of simplicity, we have assumed no variation over time in the effectiveness of the intervention, whereas a more complete study would explore a variety of rollouts with gradually increasing effectiveness. Second, although we run the model for every country, we explore few cross-country variations except to note that the global dissemination of the intervention would not be possible without considerable price reductions or other subsidies. A more explicit approach to representing dissemination would be to model the rollout of intervention coverage in each country, dependent on that country’s ability to pay for and deliver the intervention.
intervention. Such an analysis should also explore the potentially severe ethnical and political implications of the emergence of great life-expectancy inequality between populations receiving or not receiving the interventions. Third, our exploration of ecological challenges does not explicitly address the potential for the environment to put hard limits on growth of economies or overall well-being or to generate possible collapses in such growth. Fourth, our model and paper do not explore some of the more disturbing and difficult-to-quantify aspects of extreme longevity relating to ethics, the psychic burden of extreme longevity, or the potential consequences of disease pandemics. While our model does assume a gradually accumulating burden of mental health morbidity, there is much we cannot model or predict about such a fundamental change to the human experience. Finally, we have not considered the potential for billions of additional long-lived and healthy humans to help address any or all of the above challenges.

We may have limited social control over how much life will be extended and how healthy those extra years will be (technological change will largely drive these). But our analysis suggests that we will have many difficult social choices to make around demography itself (including social approaches to fertility rates), on global financing of and access to 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 life, savings, and government support), and on the sustainability issues that are already of concern today.

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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José Solórzano has worked with the IFs computer model since March of 2001 making substantive changes to the model’s code and converting the model to a web-based version. He has also made key improvements to the graphical user interface (GUI) including the development of specialized display features such as the Packaged Display, Poverty Display and SAM Display. José’s interests are in Financial Modeling and Financial Crisis Analysis. He can be contacted if you have technical or implementation questions on the use the IFs model. He lives in San Salvador, El Salvador and can be contacted in English, Spanish or French.