Technological Forecasting & Social Change 99 (2015) 77–91

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

# Opportunities and challenges of a world with negligible senescence

Barry B. Hughes [a], Randall Kuhn [b,*], Eli S. Margolese-Malin [a], Dale S. Rothman [a], José R. Solórzano [a]

[a] Frederick S. Pardee Center for International Futures, Josef Korbel School of International Studies, University of Denver, Ben Cherrington Hall, 2201 South Gaylord Street, Denver, CO 80208, United States
[b] Global Health Affairs Program, Josef Korbel School of International Studies, University of Denver, Ben Cherrington Hall, 2201 South Gaylord Street, Denver, CO 80208, United States

ARTICLE INFO

*Article history:*
Received 18 December 2014
Received in revised form 23 June 2015
Accepted 25 June 2015
Available online xxxx

*Keywords:*
Negligible senescence
Longevity
Population aging
Forecasting
Futures
Sustainability

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.



## 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 life, a growing body of demographic evidence suggests that improvements in human longevity are not diminishing, and 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 governmental 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, Oeppen 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

*Abbreviations:* IFs, International Futures; SENS, Strategies for Engineered Negligible Senescence; NegSens, negligible senescence; TFR, total fertility rate; ART, assisted reproductive technology; GBD, the World Health Organization's Global Burden of Disease project; CD, communicable diseases; NCDs, noncommunicable diseases.

* Corresponding author at: Josef Korbel School of International Studies, Ben Cherrington Hall, 2201 South Gaylord Street, University of Denver, Denver, CO 80208, United States.
*E-mail address:* rkuhn@du.edu (R. Kuhn).
*URLs:* http://www.ifs.du.edu (B.B. Hughes), http://www.du.edu/korbel/health (R. Kuhn), http://www.ifs.du.edu (E.S. Margolese-Malin), http://www.ifs.du.edu (D.S. Rothman), http://www.ifs.du.edu (J.R. Solórzano).

[1] Barring any major systemic disruptions such as global pandemics, large-scale wars, or significant detrimental environmental feedbacks.

http://dx.doi.org/10.1016/j.techfore.2015.06.031

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 Klijs 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 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. 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 expandable diagram at http://pardee.du.edu/understand-interconnected-world or documentation of all IFs models at http://pardee.du.edu/working-papers.