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PERSPECTIVE ESSAY

Techno-natalism: Geopolitical and socioeconomic implications of emerging reproductive technologies in a world of sub-replacement fertility

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Abstract

Population is a key factor of national power. Declining fertility rates, especially in major economies, are reshaping global power dynamics by shrinking workforces amidst aging populations. In response, more nations are adopting techno-natalist policies, promoting reproductive technologies ("reprotech") like IVF to increase birth rates. Advances in genetic embryo selection, gene editing, in vitro gametogenesis, and artificial wombs could further enhance these policies by improving birth rates, health, and human capital. This article examines current and emerging reprotechnologies, the policy landscape, socioeconomic and geopolitical implications, and future research directions. By shaping national and global gene pools, reprotech policies and practices offer a paradigmatic case of gene–culture coevolution. If these technologies prove safe and effective, nations that embrace them are likely to gain geopolitical and evolutionary advantages over those that do not.

Keywords: geopolitics; natalism; IVF; reproductive technologies; sub-replacement fertility; gene–culture coevolution

Introduction

From Aristotle to Benjamin Franklin (Lianos, 2016; Franklin, 1993 [1751]), political thinkers have long been aware of population and reproductive trends as factors underlying the viability and power of states. Whereas traditional societies are typically marked by Malthusian reproductive patterns defined by high fertility and high childhood mortality, political developments in the 21st century are marked by two novel features: (1) The entrenchment of sub-replacement fertility. (2) The rise of reproductive technologies ("reprotech").

This article surveys emerging reprotech and the varied policies surrounding its use, highlighting the potential socioeconomic and geopolitical impacts of reprotech's ability to foster population growth, genetic health, and human capital. It argues that techno-natalism—defined here as policies promoting the use of reprotech to achieve population goals—can provide a competitive advantage to countries and populations. This is already the case to a moderate extent with current technologies:

1. Technologies like in vitro fertilization (IVF) enable more births, counteracting the effects of infertility and mitigating population aging, although this advantage must be qualified by health and (epi)genetic risks associated with IVF.
2. IVF can enable preimplantation genetic diagnosis of embryos, reducing the prevalence of debilitating monogenic disorders like Tay–Sachs disease and cystic fibrosis in the population.

Nations such as Israel and Denmark are already using reprotech in this fashion at a significant scale, accounting for around 6%–7% of births (Israeli Ministry of Health, 2023; NOMESCO, 2024). In the future, emerging reprotech such as in vitro gametogenesis (IVG), artificial wombs, polygenic embryo screening, and gene editing may significantly expand techno-natalism's impact, particularly in low-fertility nations.

The analysis begins by stressing the global prevalence of sub-replacement fertility and its challenges to the geopolitical competitiveness of nations. It then surveys current and emerging reproductive technologies. This is followed by an examination of the policy landscape, outlining the varying political stances nations have taken toward reprotech. The article then explores the potential socioeconomic and geopolitical impacts of reprotech, focusing on its ability to enhance population size, genetic health, and human capital. While acknowledging that the current macro-scale impact of reprotech is limited, the discussion emphasizes that this impact is growing and may reach a tipping point depending on technological breakthroughs and policies that enable broader adoption.

Finally, the article considers how the use of reprotech offers a paradigmatic example of gene–culture coevolution and how the effective adoption of these technologies can confer evolutionary advantages to groups that integrate them successfully. The conclusion raises key questions for further exploration, pointing to the broader implications of these developments for health policy and political and social organization.

The rise of sub-replacement and ultra-low fertility

All else being equal, population is a fundamental variable of national power (Eberstadt, 2019; Terranova, 2023). For a given level of human capital and socioeconomic organization, the working-age population defines the potential number of workers driving economic growth, of scientists and engineers driving innovation, and of soldiers available to fight wars. Population changes can critically contribute to fundamental changes in the international balance of power, such as the decline of France relative to Germany and other powers in the nineteenth century, the rise of the United States in the nineteenth and twentieth centuries, the decline of Greece and Armenia relative to Turkey, and the rise of Israel.

While population is a fundamental factor in a nation's economic, military, and geopolitical power, it is not the only one (Treverton & Jones, 2005). Population size alone does not guarantee national power, as its advantages can be nullified by political chaos, weak institutions, or poor human capital. To translate population size into international influence, a country must develop human capital, establish effective economic institutions—such as property rights and a reliable legal system—and maintain sufficient national cohesion and social trust. A large population is not a geopolitical asset if it is unproductive, especially if high consumption demands, such as food, healthcare, and social security, limit resources available for projecting power abroad (Beckley, 2018). Large, impoverished countries and those with a high proportion of retirees may face a mismatch between national production and population needs.

Small states, especially during periods of cultural and economic innovation, can exert a significant influence on world history—5th-century BC Athens against Persia and 18th-century England are notable examples. However, sustaining such leadership seems to require a larger population, as innovations eventually spread and more populous rival nations adopt and refine the institutional and technological advantages of the pioneers. Moreover, a nation's size sets inherent limits on its power potential. For instance, while Singapore is a global leader in economic development and exerts influence beyond its size (Chong, 2009), it cannot realistically attain great power status unless it develops military technology so advanced that even larger nations cannot emulate it—which is an unlikely scenario.

Policymakers and political observers are often aware of the importance of population for national power, for instance in predicting the rise of the United States (Franklin, 1993 [1751]; de Tocqueville, 1986 [1831], pp. 595–8). Increasing fertility has also been a longstanding concern of, among others, French and Israeli policymakers (Ogden & Huss, 1982; Sperling, 2010). A growing body of research is exploring the geopolitical impact of population trends (Goldstone et al., 2012; Jackson & Howe, 2008).

Most countries now have sub-replacement fertility rates, defined as a total fertility rate (TFR) below 2.1 per woman, and nearly a fifth of countries have what the United Nations calls "ultra-low fertility," defined as less than 1.4 per woman (United Nations, 2024b). As of 2023, ultra-low fertility affects major economies including China (TFR of 1.0), Japan (1.2), Italy (1.2), Canada (1.3), South Korea (0.7), Spain (1.2), and Taiwan (0.9) (United Nations, 2024a). There is an acute awareness that sub-replacement and ultra-low fertility will pose socioeconomic challenges due to shrinking populations and the need to support ballooning elderly populations with associated needs in terms of pensions and healthcare (e.g., Edmond & North, 2023 on Japan; Farineau, 2023 on Italy).

All else being equal, ultra-low fertility societies will grow less due to shrinking working-age populations and innovate less because of a declining pool of scientists, engineers, and entrepreneurs. These societies will also need to allocate more resources to pensions and healthcare to support growing elderly populations—putting pressure on governments to pass painful reforms to ensure fiscal sustainability—and will generally have fewer resources to project power on the international scene. There is a growing recognition that the "longevity shock" and shrinking working-age populations associated with ultra-low fertility have significant geopolitical implications for affected countries (Fuxian, 2023; Nivoix & Rey, 2023).

Working immigration, especially of highly skilled workers, can mitigate the economic effects of population aging, although this may pose challenges in terms of political acceptability, social cohesion (Dinesen et al., 2020; Putnam, 2007), and ethnocultural identity (Kaufman, 2019). Immigration is no solution to the problem of sub-replacement fertility as a *global* phenomenon, as the majority of nations can no longer provide a surplus supply of immigrant workers. There is already zero-sum competition to attract highly-skilled workers, entailing debilitating brain drain for nations and territories experiencing emigration.

In short, the rise of sub-replacement and ultra-low fertility will have profound socioeconomic and geopolitical consequences. Nations that are better able to sustain their fertility rates will, all else being equal, enjoy more economic growth, be better able to manage population aging, and maintain geopolitical capacity. Rapidly falling birth rates may also lead to a decline in global innovativeness and provision of global public goods such as foreign aid. Artificial intelligence (AI) could certainly mitigate and perhaps reverse declining innovation, although the ability of nations to develop AI will itself depend on the availability of high-level human capital in the form of AI researchers and developers.

There are serious environmental arguments against natalism in general, particularly on a planetary scale (Hedberg, 2020). A smaller global population would have a more modest environmental footprint, potentially benefiting humanity and life as a whole. However, there remains the coordination problem of asymmetrical or asynchronous population decline, leading to potentially dangerous power imbalances for individual countries. The case of France mentioned above is emblematic. Achieving a coordinated, symmetrical global population decline would likely be extraordinarily difficult. In an international system characterized by anarchy and, as we have seen in recent years, capable of reverting to brute power politics, there is always the risk that nations selflessly limiting their own fertility will find themselves enfeebled and vulnerable in the face of less scrupulous rivals.

In addition, the environmental argument against natalism should be qualified insofar as progress toward decarbonizing economies will depend on further scientific advances and technological innovations. It is relevant in this regard that virtually all of the most scientifically and technologically advanced nations of the world, concentrated in North America, Europe, and East Asia, have sub-replacement or ultra-low fertility. With the exception of Israel, all of the top 25 nations of the Nature Index, which ranks countries and institutions by publications in leading science journals, have sub-replacement fertility (Nature Index, 2024).

Current and emerging reproductive technologies

Before outlining current and emerging reproductive technologies that may help nations manage demographic aging and decline, it is important to clarify that reprotech is not the only solution to sub-replacement fertility and its consequences. Adaptive cultural norms fostering early family formation can promote both genetic health and higher birth rates. Various policy measures that facilitate family formation, such as affordable housing, economic incentives, and work–life balance, can also play a role. However, insofar as shaping culture is difficult and demographic trends are "sticky," the current and potential contribution of reprotech should also be considered.

Recent decades have seen tremendous biotechnological breakthroughs with significant implications for reprotech. Such breakthroughs include affordable whole genome sequencing, the digital collection of environmental and phenotypic data (especially health-related), the use of AI and other tools to better understand the complex interaction between genes and environment, and affordable and precise gene editing tools.

Biotechnological progress has also enabled novel reproductive technologies. Reprotech is increasing the ability of individuals and nations to procreate and to do so in novel ways, notably through assisted reproductive technologies and embryo selection. New technologies like cloning, genomic selection, and gene editing are also being applied to non-human species—for example, to improve livestock health and quality (Mueller & Van Eenennaam, 2022), and to support wildlife conservation and biodiversity (Bolton et al., 2022; Mastromonaco & Songsasen, 2020).

If some of the emerging technologies below seem like science fiction, that does not necessarily make their development and use implausible in the coming decades. After all, conception in the lab, cloning, genome sequencing, genetic transposition, and gene editing—technologies which, to paraphrase Arthur C. Clarke, for previous generations would have been indistinguishable from magic—are now routinely used in human, animal, and/or plant settings.

In vitro fertilization

IVF involves the fertilization of an egg with sperm in the laboratory before implantation in the womb. IVF has been practiced since the birth of Louise Brown in the United Kingdom in 1978. As of 2019, over 8 million children had been born thanks to IVF worldwide and over 500,000 more deliveries were being performed every year (Fauser, 2019).

IVF is currently the single most powerful technology in terms of expanding reproductive choice. IVF is chiefly intended to treat infertility, which affects around 17.5% of people worldwide (WHO, 2023a). A recent study found that the global age-standardized prevalence rate for infertility had risen over 18.7% between 1990 and 2021 (Huang et al., 2025). The procedure can more broadly enable reproduction beyond the traditional biologically viable category of fertile premenopausal heterosexual couples to infertile or fertility-challenged people, older women, single women, and lesbian and gay couples.

In combination with early egg freezing or use of donor eggs, IVF can markedly expand women's fertility well beyond their 30s, which may be particularly significant in developed societies where family formation is delayed by studies and professionalization (Chen, Kuo, et al., 2024b; Seshadri et al., 2020). IVF enables gestational surrogacy, where a woman other than the genetic mother carries the embryo to term. It also makes possible the selection of donor sperm and eggs, as well as preimplantation genetic testing and embryo selection.

Monogenic and polygenic embryo screening

IVF typically involves creating multiple embryos and selecting the most viable one for implantation based on visual and genetic indicators. Embryos are often tested for chromosomal anomalies and monogenic disorders such as sickle cell disease, cystic fibrosis, and Tay–Sachs disease. This allows for the implantation of an embryo that is free of these conditions.

Polygenic embryo screening (PES) involves evaluating embryos based on their genetic likelihood of developing conditions or traits influenced by many genes, known as polygenic traits or conditions. Polygenic disorders include Alzheimer's disease, depression, bipolar disorder, schizophrenia, some cardiovascular diseases, breast and prostate cancer, celiac disease, inflammatory bowel disease (IBD), and diabetes. Polygenic traits include mental and physical characteristics, such as height, eye and hair color, intelligence, and most, if not all, major personality traits (Plomin et al., 2016).

PES can therefore be used to select embryos that are more likely to have healthy or enhanced traits. The effectiveness of preimplantation genetic testing depends on the number of embryos created through IVF and the genetic variation contributed by the parents or by sperm or egg donors.

Germline gene editing

Heritable human genome editing is currently feasible with CRISPR-Cas9 gene editing technology. The first gene-edited human babies were born in China in November 2018, leading to global controversy and moratoria on the practice. He Jiankui, the head researcher, was sentenced to 3 years in prison for forging ethical review documents and misleading doctors into unknowingly implanting gene-edited embryos (Normile, 2019). He modified a gene thought to confer resistance to HIV.

Since then, editing has become more precise and promises to continue to advance along with our understanding of genetics. Germline editing is most relevant for preventing monogenic disorders and potentially for targeting a few variants that affect cognitive development or the health of the immune system. In principle, germline gene editing could also be used for human enhancement. However, given the polygenic character of most relevant traits, the feasibility of this is unclear.

In vitro gametogenesis

IVG refers to the creation of human eggs or sperm in the lab. This is achieved by taking embryonic stem cells or somatic cells, such as skin or blood, and reprogramming them to become stem cells. Stem cells can become any kind of cell, including eggs or sperm. Although technical barriers remain, human gamete reconstitution has been partially achieved for both males and females (National Academies, 2023). The technology has significant implications for basic research into mammalian developmental biology, animal breeding, and potentially human reproduction.

If safe, effective, and approved, such technology would allow both males and females to generate sperm and eggs. The implications for family formation are profound (e.g., gay couples would be able to have children genetically related to both parents). IVG could also greatly expand access to reprotech by eliminating the need for ovarian stimulation to obtain eggs. This would also enable the production of many more embryos to screen before implantation, significantly increasing the power of polygenic embryo selection. Instead of choosing among a dozen embryos with the lowest risk score for diabetes or the highest polygenic score for IQ, one could select from a much larger pool (Bourne et al., 2012).

Artificial wombs

An artificial womb or uterus is a device that would allow extracorporeal pregnancy, bringing a fetus to term without requiring a gestational mother. Technology increasingly approximating artificial wombs is being developed as part of the effort to create neonatal incubators able to support ever-more-premature infants. Artificial wombs would massively facilitate the ease of procreation by removing the need for consenting human females to undergo the burdens and risks of pregnancy. It is unclear whether and when artificial wombs will be viable, although regulators have been considering clinical trials for them (Kozlov, 2023). Artificial wombs would also facilitate the use of donor eggs or sperm, as well as genetic screening and/or modification of embryos without the use of IVF.

The reprotech policy landscape

The international landscape for reprotech capacities and policies varies wildly. Reprotech procedures are more likely to exist in developed countries with advanced life science and medical sectors. Different

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jurisdictions may restrict, allow, or promote (e.g., through awareness-raising and/or subsidies) the use of particular reprotechnologies, reflecting different policy choices and values (see Table 1).

Values and objectives that commonly shape policy decisions on reprotech include:

- **Empowering reproductive choice:** Reprotech may be supported on liberal grounds, such as enabling reproduction for infertile heterosexual couples, single women, gay couples, or people more broadly, for example, in the case of elective surrogacy for a heterosexual couple.
- **Boosting fertility:** Expanding access to and use of reprotech may be supported as a way to increase fertility rates and overall population, with potential socioeconomic and geopolitical benefits for the nation.
- **Promoting genetic health:** Access to and uptake of genetic screening may be supported on the grounds of promoting the health of newborns, thus reducing the burden of genetic diseases for individuals and the population as a whole. This is especially relevant in populations with high consanguinity due to high rates of cousin marriage and may grow in importance more broadly as the burden of polygenic non-communicable diseases rises.
- **Guaranteeing equality:** States may support reprotech by raising awareness and providing subsidies to ensure more equal access. This can include expanding access for lower-income individuals or same-sex couples, and allowing more people to benefit from technologies that promote genetic health or enhancement. Conversely, some forms of reprotech—especially those involving genetic enhancement—may be restricted in the name of social equality.
- **The sanctity of (embryonic) human life:** This value may be used to justify restricting reprotech such as IVF—due to the creation and disposal of surplus embryos—and germline gene editing. Arguments may be framed in religious terms (e.g., humans created “in the image of God”) or in secular terms (e.g., certain conceptions of human dignity).

Different nations may or may not adhere to all of these values and objectives, and each nation will have different ways of interpreting and balancing them.

Interest in reprogenetics is rising, particularly in wealthy nations with populations suffering from a high burden of genetic illnesses, typically due to a history of endogamy leading to unique genetic characteristics and a higher load of recessive genetic disorders. This is evidenced by the rise of genetic counseling and screening for reproductive purposes in Israel (Sagi & Uhlmann, 2013) and the Gulf Arab

Table 1. Summary table of different approaches to reprotech

Concept	Definition	Policy example(s)
Negative bioliberty	Legal ability to use reproductive technology.	Legality of IVF; legality of polygenic screening for various traits.
Positive bioliberty	Actual ability to use reproductive technology.	Mandatory insurance coverage for IVF treatments; awareness raising and reimbursement of genetic screening of parents based on ethno-genetic background; awareness raising and reimbursement of elective screening for Down syndrome.
Bioconservatism	Principled (not prudential) opposition to reproductive technologies.	Religious opposition to abortion and IVF; egalitarian opposition to polygenic embryo selection or gene editing.
Restrictive bio-paternalism	Restrictions on the use of reprotech for the good of the children and/or society.	Bans on polygenic embryo screening or germline gene editing on the grounds of inadequate safety or efficacy.
Prescriptive bio-paternalism	Requiring the use of reprotech for the good of the children and/or society.	When using IVF, requiring genetic screening of preimplantation embryos for aneuploidy; requiring genetic screening of prospective marriage partners; various forms of mandatory eugenics.

states (Malik et al., 2022). Other historically endogamous nations, such as India, have massive unmet demand for genetic counseling (Shah et al., 2023).

Genetic counseling can help prospective parents assess the risk of passing on genetic disorders and encourage the use of reprotech to prevent them. Israel has had a national carrier screening program since 1978, initially targeting Tay Sachs disease among Ashkenazi Jews and later expanded to β-thalassemia among Arabs and affected Jewish subgroups (Zlotogora, 2019). The Israeli carrier screening program is unique in offering free genetic testing for several diseases tailored to ethno-religious background and appears to have yielded significant results in terms of reducing the burden of spinal muscular atrophy, Tay–Sachs disease, and other disorders (Israeli Ministry of Health, 2020; Singer & Sagi-Dain, 2020).

Israel and Germany can in many ways be taken to represent opposite poles on the spectrum of reprotech policies. Israel, motivated by the need for the Jewish population to regrow after the Holocaust and create a secure majority-Jewish state in the Middle East (Rosenberg-Friedman, 2015), has enthusiastically embraced the potential of reprotech to foster population growth and genetic health. This includes promoting genetic screening tailored to different ethno-genetic groups, as well as broad access to and reimbursement for IVF (Birenbaum-Carmeli, 2016). Israel also supports posthumous sperm retrieval of fallen soldiers. The share of children born via IVF in Israel rose from 1.7% in 1995 to 5.8% in 2021 (Israeli Ministry of Health, 2023).

Jewish religious authorities have generally been supportive of the use of reprotech on the grounds of respecting God's natalist command to be "fruitful and multiply" (Silber, 2010). Israeli genetic counselors are much less likely than their German counterparts to view reprogenetic interventions as problematic "eugenics" (Hashiloni-Dolev & Raz, 2010; see also Simonstein & Mashiach-Eizenberg, 2015 and Bentwich et al., 2019). Israel can be considered a techno-natalist and largely bioliberal jurisdiction.

In contrast to Israel, Germany has drawn nearly opposite lessons from the Holocaust. It rejects nationalistic natalism, restricts reprotech that could be viewed as "eugenic," and affirms the (alleged) human dignity of embryos, arguing that they must not be used as a means to other ends. As such, Germany limits the overproduction of embryos during IVF, rejects genetic selection of embryos except for severe diseases, and restricts stem cell research (Jasanoff & Metzler, 2018). Germany is a bioconservative jurisdiction.

Among more bioliberal jurisdictions, there may be significant differences in the degree of positive and negative bioliberty. Negative bioliberty may be defined as the freedom from restrictions on using reproductive technologies. Concerning polygenic embryo selection, the United States enjoys an especially high level of negative bioliberty given that the procedure is legal for both health and personality traits.

Positive bioliberty may be defined as the actual capacity to access and use reproductive technology. Governments can promote positive bioliberty through awareness campaigns, direct subsidies, or medical insurance mandates, such as requiring insurers to cover part of the cost of IVF or preimplantation genetic testing for embryos. Many nations are facilitating access to IVF and genetic screening on the grounds of promoting reproductive freedom, including by promoting equal access to innovations such as prenatal testing for Down syndrome (Bunnik et al., 2019; Ravitsky et al., 2021).

Americans have relatively bioliberal attitudes concerning embryo selection for polygenic traits. One survey found that, if already undergoing IVF, 77.7% of Americans would be interested in embryo selection for physical health conditions, 72% for psychiatric health conditions, and 36% for behavioral traits (Furrer et al., 2024). A majority (around 55%) of respondents also expressed concerns about PES promoting false expectations and/or promoting eugenic practices. Another survey found 38% of Americans were "mostly willing" to engage in genetic testing of IVF embryos if it would increase the chance of their child attending a top-100 university (Meyer et al., 2023).

European jurisdictions and scientific/medical associations have often had more bioconservative positions. The European Society of Human Genetics (ESHG) has deemed polygenic embryo screening "an unproven, unethical practice" and called for a moratorium until there is further debate (Forzano et al., 2021). The European Union's (EU) Charter of Fundamental Rights, which applies to Member States when implementing EU law, prohibits "eugenic practices, in particular those aiming at the selection of persons" on the grounds of respecting the "right to the integrity of the person" (European Union, 2000). It is unclear whether "persons" would include embryos, as forms of embryo selection for genetic health are practiced in EU countries such as France (Doudna & Sternberg, 2017, p. 236).

Human germline editing is perhaps even more controversial. Since the experiments of He Jiankui, research into human germline editing appears to be on hold in most or all countries. UNESCO has urged caution, warning of germline editing's potential to violate human dignity and the genetic unity of the human species (IBC, 2015; UNESCO, 1997). Yet, some have argued that germline editing can be compatible with respect for human dignity (Gurcan, 2024). Moreover, scientists and governance professionals hold differing views on the acceptability of germline editing (Cadigan et al., 2024). In the United States, federal legislation bans the Food and Drug Administration (FDA) from reviewing any therapies modifying the heritable human genome. In the EU and the United Kingdom, the legal landscape governing human germline editing is complex and fragmented, lacking clarity on the prohibition of eugenics and the distinction between therapy and enhancement (Nordberg & Antunes, 2022).

Research into human germline editing to prevent genetic diseases (as opposed to for human enhancement) is allowed in Belgium (Pennings, 2019) and is foreseen under certain conditions in recent South African research guidelines (National Health Research Ethics Council, 2024). Jennifer Doudna, the principal codeveloper of CRISPR-Cas9 gene editing with Emmanuelle Charpentier, has argued that "[i]t's almost certain that germline editing will eventually be safe enough to use in the clinic" and has been critical of the "nebulous language" of policy documents governing germline editing (Doudna & Sternberg, 2017, pp. 222, 236).

Geopolitical and socioeconomic implications of emerging reprotech

With the emergence of sub-replacement and even ultra-low fertility in many nations, governments are increasingly recognizing reprotech's potential to increase birth rates. Governments in different regions, chiefly in the developed world, are embracing varieties of techno-natalism to foster the socioeconomic sustainability of aging societies and geopolitical capacity in general. As reprotech advances and more nations face sub-replacement fertility and projected population decline (United Nations, 2024b), it is likely that more governments will promote reprogenetic services to foster population growth and genetic health.

As previously mentioned, reprotech has long been a key component of Israel's demographic strategy to maintain a large and secure Jewish-majority nation-state in the Middle East while helping to prevent genetic diseases. Driven by largely Jewish immigration and natality, Israel's population has steadily risen from 2.1 million in 1960 to 6.3 million in 2000 to almost 10 million in 2023 (World Bank, 2024). Against many expectations, Jewish fertility in Israel has overtaken Muslim fertility (Weinreb, 2023).

In February 2024, French President Emmanuel Macron announced an upcoming "great plan" against infertility, not only to enable more people to have children but also as part of a general "demographic rearmament" of France (Damon, 2024). This plan would include more child benefits, early screening to prevent infertility, and enhancing access to reprotech. IVF is reimbursed by French health insurance, with 2.9% of children in France were conceived via IVF in 2019 (Rochebrochard, de la, 2022).

In ultra-low fertility China, central and local governments have been scaling up efforts to boost the birth rate. In October 2024, the central government's State Council issued a directive calling for numerous measures to shift toward a "birth-friendly social atmosphere." This includes expanding medical insurance reimbursement to cover assisted reproductive technology services (Xinhua, 2024).

Emerging reprotechnologies have the following three potentially positive geopolitical and socioeconomic implications for the nations adopting them:

1. Insofar as reprotech enables *higher fertility*, nations boost their future working-age population, mitigate population aging, and sustain or increase their general socioeconomic sustainability and geopolitical capacity.

2. Insofar as reprotech enables *genetic health*, nations reduce the burden of diseases, entailing reduced disease-related healthcare costs and productivity losses. This may concern the burden of monogenic diseases (e.g., Tay Sachs disease, sickle-cell disease …) and polygenic diseases (many cancers, cardiovascular diseases, diabetes …). Noncommunicable diseases—the big four being cardiovascular diseases, cancers, chronic respiratory diseases, and diabetes—are a major worldwide health burden responsible for 74% of deaths (WHO, 2023b) and are often polygenic.
3. Insofar as reprotech enhances *human capital* through genetic enhancement of traits such as conscientiousness or intelligence, nations benefit from higher productivity. Human capital has a fundamental role as a driver of economic development (Keeley, 2007) and technoscientific innovation. Intelligence, in particular, which has both genetic and environmental foundations, powerfully influences both individual outcomes and collective outcomes (Anomaly & Jones, 2020; Burhan et al., 2014; Meisenberg, 2012; Wai, 2015).

Conversely, we can identify at least two potentially negative geopolitical and socioeconomic implications for nations adopting reprotech:

1. Increased risk of birth defects, epigenetic disruption, and/or reduced genetic health, the latter due to the accumulation of harmful mutations caused by the use of reprotech. These factors (discussed below) could increase the burden on healthcare systems and economies.
2. Sociocultural polarization, either due to opposition by segments of society to specific uses of reprotech or because of genetic stratification due to unequal access to genetic enhancement technologies (discussed further in the section on gene–culture coevolution).

The macro impact of reprotech is negligible in most nations today. However, the socioeconomic and geopolitical impact of reproductive technologies will grow as their adoption and capabilities increase (as summarized in Table 2).

The key reproductive technology today is IVF. Uptake of and policies toward IVF vary significantly. While publicly available statistics are patchy, in most Western countries IVF seems to enable 1%–3% of all births, rising to 5.8% in Israel and up to 7% in Denmark (U.S. Department of Health and Human Services, 2024; Israeli Ministry of Health, 2023; NOMESCO, 2024; Rochebrochard, de la, 2022). In 2018, annual IVF cycles per million people ranged from 5,711 in Israel to 3,603 in Japan, 3,573 in Denmark, 1,368 in Europe (continent-wide average), 922 in the United States, and 759 in China (Peipert et al., 2023).

Table 2. Summary table of the (potential) impact of current and emerging reprotechnologies. Increased births, health, and human capital positively impact nations' socioeconomic sustainability and geopolitical competitiveness

Reprotech	Status	(Potential) Impact
Genetic counseling	Practiced	May prompt the use of reprotech to avoid genetic diseases.
IVF	Practiced	Increases births and enables monogenic screening, polygenic screening, and gene editing.
Monogenic embryo screening	Practiced	Increases health (eliminates monogenic disorders).
Polygenic embryo screening	Practiced (limited)	Increases health and human capital.
Germline gene editing	Feasible, but restricted	Increases health (eliminates monogenic disorders).
Artificial wombs	Being developed	Like IVF, but potentially with much higher adoption.
In vitro gametogenesis (IVG)	Being developed	Increases the ease of IVF and the power of polygenic embryo screening.
AI and big data	Practiced	Increases understanding of genotype–phenotype relationship and the power of polygenic embryo screening.

The European Society for Human Reproduction and Embryology (ESHRE) estimates demand for IVF treatment at around 3,000 cycles per million people, implying significant unmet demand (Ferraretti et al., 2017). IVF is then already a significant contributor to births in certain jurisdictions and has the potential to contribute significantly more.

One study estimated that if the number of babies born via assisted reproduction every year stagnates around 400,000 per year, this would contribute to 157 million live people by the end of the century (Faddy et al., 2018). However, if one assumes the number of such births increases by 30,000 every year, this would lead to 394 million additional living people by 2100 (3.5% of the global population). As the authors note, "[t]he chief variable driving growth is access to fertility services." While the upper bound projection is based on naïve assumptions—though consistent with past IVF growth—it provides a sense of reprotech's rising potential for demographic impact. The geopolitical impact of almost 400 million reprotech babies would also be significant insofar as these births would likely be concentrated in aging developed countries with reprotech capabilities and disproportional international clout.

The cost of the IVF procedure is prohibitive for many people. In the United States, out-of-pocket cost of IVF treatment has been estimated at over US$19,000 (Wu et al., 2013), and insurance coverage for infertility treatment is an uneven patchwork of federal and state policies (Peipert et al., 2023). IVF and other assisted reproductive technologies in low- and middle-income countries (LMICs) are considerably cheaper than they are in the United States, but they are not accessible to most infertile couples due to the relatively high cost of treatment and to cultural, religious, and legal barriers (Chiware et al., 2021).

The potential of IVF to mitigate global fertility decline is increasingly recognized (Fauser et al., 2024). By actually increasing the number of children born, facilitating access to reprotech may foster intergenerational socioeconomic sustainability more effectively than other pronatalist policies, which often have uncertain results (Connolly et al., 2023). Several health economic studies suggest that government subsidies for IVF can generate a significant return on investment. A US study found that public funding for IVF could produce a sevenfold return in lifetime fiscal gains per child (Connolly et al., 2008). Similarly, a Taiwanese study of a real-world subsidized fertility program estimated a 5.6-fold return for the government (Chen, Kotsopoulos, et al., 2024a).

Current reprotech procedures are not without health risks (Berntsen et al., 2019). Assisted reproductive technology has been associated with increased risk of major birth defects—18% higher for single-transferred embryos, for example, Luke et al. (2020) and Hansen et al. (2013). It is unclear to what extent this higher prevalence results from a selection effect, specifically, whether individuals with genetic or age-related reproductive challenges who use reproductive technology are already more likely to have children with birth defects. The biggest risk factor would appear to be multiple pregnancies due to the transfer of multiple embryos, a procedure undertaken due to the expense of IVF and the willingness to maximize the chance of pregnancy per procedure (Velde et al., 2017). IVF support programs can mitigate this risk by requiring transfer of single embryos, as is standard practice in some northern and western European countries.

The use of IVF, particularly to address genetically influenced infertility, may increase mutational load, that is, the accumulation of harmful mutations over generations. To mitigate this, some researchers have argued that reproductive technologies should be designed to mimic natural conception's selection mechanisms against harmful mutations (Evans & Garcia-Gonzalez, 2024; Van Oosterhout et al., 2022). Animal models and follow-up studies have found that assisted reproductive technology is associated with an increased risk of epigenetic errors. However, there is no conclusive evidence of a strong link between these errors and an elevated risk of disease in adulthood (Sciorio & Hajj, 2022). Studies have not found harmful social–psychological or cognitive effects on IVF-conceived children (Passet-Wittig & Bujard, 2021). Indeed, one study found IVF-conceived children overperformed their peers, although this may again be due to a selection effect as IVF users in the absence of a subsidy are likely to be from higher socioeconomic backgrounds (Mains et al., 2010).

The long-term and intergenerational health impacts, if any, of current reproductive technologies remain poorly understood and should be investigated through large-scale epidemiological studies. Reprotech procedures should also be developed to mitigate and counter any negative effects. To the extent that such effects are heritable, policies harnessing reprotech for pronatalist efforts may imply a lasting sacrifice of population quality in favor of quantity. However, this should also be weighed against the potential of interventions such as embryo screening—and possibly gene editing—to eliminate harmful mutations. Reprotech's health risks also point to the need for sociocultural interventions to raise birth rates and slow the rise of mutational load. These may include encouraging earlier family formation and increasing awareness of age-related fertility decline, as well as the genetic and health risks associated with delayed parenthood.

Turning to emerging reprotech, the environment for germline gene editing is generally restrictive. However, some governance bodies acknowledge that if this technology were safe and effective, it could be used to prevent serious monogenic diseases (National Academies, 2020), although any potential use would require further debate (European Group on Ethics, 2021). The potential to use germline gene editing for human enhancement appears limited, given that such traits are usually polygenic and would require numerous edits to have a significant impact.

Monogenic screening and germline gene editing's ability to prevent and virtually eradicate monogenic disorders is potentially very significant, especially in nations suffering from significant monogenic disease load, such as sickle-cell disease. Non-heritable gene therapies for sickle-cell disease exist but are extraordinarily costly (US$2.2 million to 3.1 million; Shaw, 2024). IVF coupled with either monogenic screening or germline therapy would likely be much cheaper, although at a minimum higher than the cost of regular IVF. By eliminating genetic transmission, such interventions would remove the need for treatment every generation.

Reproductive technologies often function as critical enablers of one another (see Figure 1). IVF makes possible gamete selection, monogenic and polygenic embryo screening, and heritable genome editing. Artificial wombs could eliminate the need for IVF or a gestational mother, potentially increasing reprotech uptake. IVG facilitates the creation of gametes without ovarian stimulation or egg retrieval, making it easier to conceive embryos and to produce more than would otherwise be biologically possible. Legal scholar Henry Greely has suggested that IVG could enable "easy preimplantation genetic diagnosis" (easy PGD), leading to the routinization of reprogenetic technologies, with the potential to reduce disease burden and allow for moderate enhancement within the normal range of human traits (Greely, 2018). Advances in genomics, large-scale biobanking, and AI are also expected to greatly increase the capabilities of reprotech, potentially to a transformative degree.

Breakthroughs in reprotech could then have far-reaching geopolitical and socioeconomic consequences, especially in an era of sub-replacement fertility. All else being equal, nations and populations adopting reprotech could have larger and healthier populations of greater human capital, giving them a geopolitical and evolutionary advantage. While adoption of reprotech today is low as a proportion of all

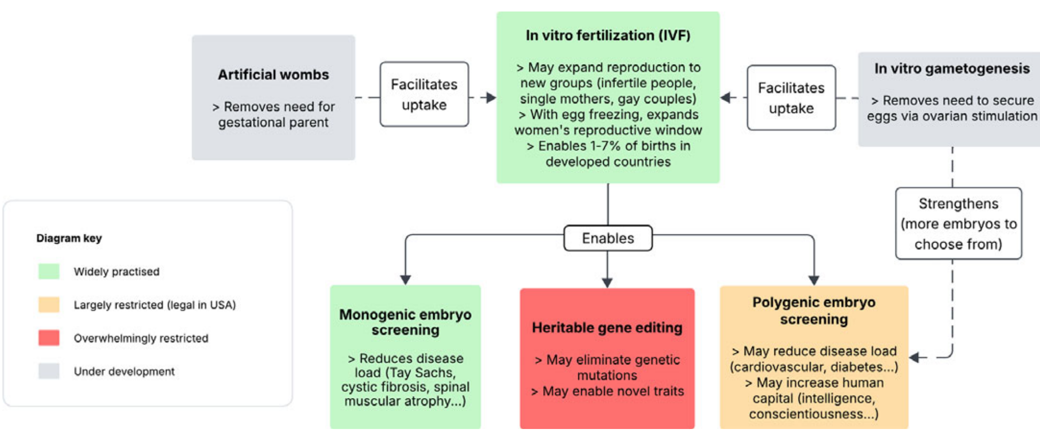

Figure 1. Demographic effects and mutually enabling relationships of selected current and emerging reproductive technologies.

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births, even moderate adoption could have significant demographic consequences, as already seen in Israel. The impact of reprotech could be especially significant in ultra-low fertility countries, where each birth has a relatively large impact on future outcomes.

When a technology proves viable and is adopted in one country, it can quickly shift public and political attitudes in other countries. "Preference cascades" can occur rapidly when individuals discover that respected figures are using a technology previously seen as taboo. A similar dynamic can unfold among political leaders, who may come to see that other countries are benefiting from a technology and that their own population could fall behind without access to it. IVF is a prominent example: once viewed by many as "unnatural," it has become widely accepted since its introduction in 1978.

The dynamics of reprotech adoption will be different depending on the policy landscape. Bioconservative nations—whether motivated by egalitarian, dignitarian, religious, precautionary, or other concerns—will have, ceteris paribus, lower population growth and potentially higher genetic disease load. These will be evolutionarily less competitive unless their bioconservatism is otherwise highly adaptive, for example, if the ultra-conservative Taliban in Afghanistan are able to maintain traditional marriage patterns and high fertility. The evolutionary adaptiveness of higher fertility in religious bioconservative jurisdictions must be weighed against the increased genetic disease load, which is particularly high in countries practicing cousin marriage, as in Afghanistan and many other Islamic countries.

Negative bioliberal jurisdictions are likely to see increasing adoption of the most advanced and cutting-edge reprotechnologies. While many in the general population will want to emulate such reproductive elites, actual uptake and access will be limited by economic costs. Positive bioliberal jurisdictions will see the broadest adoption as most parents opt for what comes to be seen as "best practice" procedures.

As reprotech capabilities expand, people may come to believe—based on procreative beneficence—that not using these technologies to promote the genetic health and well-being of children is irresponsible. (Savulescu, 2001). Henry Greely has argued that if "easy PGD" is achieved, meaning PGD without the current inconveniences of IVF, then this could eventually replace sex as the main mode of human reproduction (Greely, 2018).

We may also define state-prescriptive "bio-paternalist" measures as those that mandate the use of reprotech. China's "eugenic" Maternal and Infant Health Care Law, for instance, limits procreation if genetic screening finds either premarital couples or fetuses carry a serious genetic disease (People's Republic of China, 1994). While contemporary liberal democracies are likely to reject such measures as "eugenic" and authoritarian, some measures may still be accepted when framed as promoting infant health. One example is requiring screening for monogenic disorders in embryos conceived via IVF. Bio-paternalist legislation could be motivated by egalitarian or communitarian concerns, depending on whether genetic health is being promoted for the sake of individual newborns or the common good of the population as a whole.

Intentional gene–culture co-evolution and the competitive edge of reprotech

This discussion of national biopolicies offers only a glimpse of the varied national approaches to reproductive technologies. The key takeaway is that nations will differ not only in their capacity to develop and apply reprotech, but also in their policies and attitudes toward its use. These differences will shape how such technologies are adopted. Because the development, regulation, and uptake of reprotech directly affect the genetic makeup of national and global populations, these processes exemplify gene–culture coevolution: the process by which culture influences genetic selection, and genes, in turn, shape cultural development (Boyd & Richerson, 2008).

Gene–culture coevolution driven by reproductive norms is nothing new. Pronatalist beliefs and attitudes toward endogamy have had measurable genetic effects on various populations. For example, restrictions on cousin marriage among Western European Christians reduced consanguinity (Henrich, 2020), while high rates of endogamy among Ashkenazi Jews, Hindu castes, and Islamic populations practicing cousin marriage have had the opposite effect. However, reprotech now enables intentional gene–culture coevolution on an unprecedented scale and will influence the reproductive fitness of both individuals and nations (Anomaly, 2024).

Reproductive norms that persist over time tend to provide competitive advantages to certain groups, enabling them to outperform rival groups with less adaptive norms (Wilson & Wilson, 2007). This raises important questions about how reprotech will affect the fitness of groups with different reproductive norms. Whereas fertility rates have fallen below replacement level even in moderately developed countries with traditionally high fertility rates, such as Turkey, Mexico, Iran, and India, some nations like Israel and religious subcultures like the Amish have maintained pronatalist beliefs and marriage norms that sustain higher fertility (Colyer et al., 2017; United Nations, 2024a).

Reprotech will enable people in individualistic cultures to have more children by expanding reproductive options for those who want offspring. If artificial wombs become viable, the potential impact at the individual level could be immense—for instance, a billionaire could choose to bring any number of children to term using this technology. Insofar as reprotech increases a nation's population size, health, and capabilities, this nation will be more powerful on the international scene.

On the other hand, while reprotech can address specific biological limitations—such as infertility or predisposition to genetic disorders—it lacks the social mechanisms to create cohesive and adaptive groups. Traditional norms, by contrast, have evolved to structure behaviors that promote collective survival and long-term stability (Henrich, 2017).

Moreover, it is difficult to determine precisely which traits should be selected for societies to function harmoniously and cohesively. Groups require a diverse array of personality types and skills to work effectively, and traits that may seem beneficial individually might not translate into collective advantages. For instance, selecting for highly competitive or risk-taking traits might enhance individual success but could disrupt group cohesion. In such cases, groups skeptical of reprotech and reliant on well-tested traditional norms might outperform those embracing technologies that introduce untested social configurations.

Traditional cultural practices, such as pronatalism and endogamous marriage, provide a framework that integrates individual reproductive decisions into broader social strategies. Such norms can ensure that the benefits of increased reproductive fitness, whether biological or cultural, are distributed throughout the community in ways that foster cooperation and reduce internal conflict. For example, communities with strong familial or religious ties are more likely to coordinate resources for child-rearing.

Reprotech, while offering unprecedented opportunities, may also drive significant changes to traditional norms, marriage patterns, and gender roles. If the use of these technologies confers fitness advantages to groups adopting them over those that do not, cultural shifts may occur. For example, technologies like IVG or artificial wombs could redefine parental roles, challenging longstanding gendered responsibilities. Such transitions are inherently unpredictable and, as in many evolutionary processes, the most effective approach is likely to emerge through trial and error.

Reprotech will only benefit a nation geopolitically if its demographic gains do not come at the cost of social cohesion. Controversies over reprotech can fuel political and cultural divisions—for example, when secular and religious groups clash over whether artificial conception, embryo selection, or genetic modification is morally acceptable. If genetic enhancement proves effective, it could also lead to a biologically and psychologically distinct elite—the "genetic haves"—widening the gap with the "have-nots" (Doudna & Sternberg, 2017, p. 232).

With current technologies, such fears seem unwarranted. Since the 1970s, IVF has seen a steady increase in adoption across many jurisdictions (Fauser, 2019). Some people, particularly religious groups, oppose IVF and surrogacy as "unnatural" (Sariles, 2017). IVF is also subject to varying regulations across countries on bioethical grounds. Nonetheless, to our knowledge, IVF has not become a central culture war issue in developed countries, unlike abortion. Notably, the United States—often leading the bioethical culture wars in the West—has seen the national-populist movement embrace IVF.

During the 2024 presidential election campaign, then-candidate Donald Trump distanced himself from religious conservatives by advocating for reimbursing IVF treatments and, with characteristic hyperbole, even claimed to be "the father of IVF" (NBC News, 2024). This makes support for IVF a rare point of agreement—rather than division—between liberal progressives and national populists in the United States.

In the long term, genetic enhancement technologies could create distinct genetic castes, dividing nations into enhanced and non-enhanced groups. This risk can be reduced by ensuring broad, equitable access to reprotech—much like public subsidies for education and healthcare, which aim to promote equal opportunity and general well-being. In the United States, for example, the average cost of an IVF cycle is similar to the average annual cost of educating a public school student: $16,280 in 2020–2021 (National Center for Education Statistics, 2024; Peipert et al., 2022).

The risks of genetic stratification should not be overstated. Societies already exhibit genetic inequalities (Cochran & Harpending, 2009) and, in the foreseeable future, "enhanced" individuals would still fall within the natural range of human capabilities, although the long-term impact of technological advancements remains uncertain. Emerging reproductive technologies might increase the likelihood of exceptionally gifted individuals. However, both perceived and actual inequalities have long been sources of social conflict. To promote national cohesion, these technologies must be implemented in ways that minimize status-based divisions and prevent the rise of antisocial tendencies. A strong pro-social culture is essential.

Under gene–culture co-evolution, culture serves as a social technology that enables people to coordinate their actions and form cohesive, adaptive groups. It is also inherently flexible, allowing societies to adapt their collective behavior to changing circumstances and challenges. This adaptability is crucial for human survival and success, and any effort to shape genetic traits through reprotech must preserve this capacity for cultural innovation and transformation. Choosing genetic traits should not mean erasing the ability to produce and alter culture. Rather, it is the efficient balance between culture and genetic evolution that explains a significant part of humanity's success as a species. Disrupting this balance risks undermining the social adaptability that has historically allowed humans to thrive in diverse and dynamic environments.

As reprotech advances, the most reproductively fit communities may be those that combine its use for population growth and genetic health with pronatal cultural systems that emphasize early family formation, community, and intergenerational continuity. This would include high-fertility pronatalist religious communities favoring the use of reprotech, such as Orthodox Jews (Silber, 2010). The framework provided by traditional norms may also help ensure that these technologies complement, rather than disrupt, established social dynamics.

The adoption of reprotech will likely be most successful in societies that view it as an extension of adaptive values. For example:

- **Pronatalist Societies**: Nations that emphasize the moral or religious duty to procreate may see reprotech as a tool to fulfill these obligations, particularly in the face of fertility challenges.
- **Endogamous Communities**: Groups with traditions of genetic counseling to minimize hereditary diseases could readily integrate genetic screening and editing, viewing these tools as enhancements of established practices.
- **Bioliberal or Prescriptive Bio-Paternalist Jurisdictions**: Countries that prioritize innovation alongside social cohesion may foster broader adoption of reprotech, particularly if aligned with cultural narratives of progress.

By aligning technological innovation with cultural imperatives, nations and communities can amplify the benefits of reprotech, ensuring that its adoption supports not just individual outcomes but the collective health, stability, and competitiveness of societies.

Successfully integrating reprotech with cultural norms is not without challenges. Resistance may arise in bioconservative societies that view genetic interventions as threats to human dignity or natural order.

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Additionally, the economic barriers to accessing advanced technologies could exacerbate existing inequalities unless offset by government subsidies or cultural mechanisms that promote equitable distribution.

Nevertheless, the potential benefits of this integration are substantial. When deployed in tandem with adaptive cultural practices, reprotech can enhance not only reproductive fitness but also the cohesion and resilience of societies. This hybrid approach leverages the strengths of both traditional norms and cutting-edge science, creating a pathway for nations to thrive in an era of demographic and technological transformation.

Ultimately, while reprotech offers unprecedented tools for shaping the genetic future of populations, its true evolutionary potential lies in its ability to work alongside cultural norms. Together, they provide a synergistic framework that maximizes both individual and collective benefits, ensuring that societies can adapt and compete in the face of evolving global challenges. By preserving the flexibility and adaptability of culture while leveraging the precision of reprotech, societies can maintain the dynamic equilibrium that has been central to the success of human groups.

Conclusion and further research questions

As reprotech becomes more widely adopted and more capable, its geopolitical and evolutionary impact is likely to grow, especially over the long term. If there is sufficient uptake, bioliberal and prescriptive bio-paternalist nations are likely to become more competitive than bioconservative ones. Negative bioliberal jurisdictions may have limited uptake unless the cost of reprotech interventions falls dramatically. If costs remain relatively high, as in the case of IVF, positive bioliberal and prescriptive bio-paternalist nations are likely to see the greatest use of these technologies, and thus gain a competitive advantage.

The emergence of reprotech in the age of sub-replacement fertility raises many research questions of interest to demographic, science, and health policymakers, researchers, and practitioners, as well as to political scientists and evolutionary thinkers studying gene–culture coevolution. Relevant questions to be explored include:

- What explains the wide variation in reprotech policies and public attitudes across countries?
- To what extent does genetic counseling foster or inhibit the decision to have children?
- Does IVF encourage women to delay childbirth?
- What are the potential socioeconomic effects of different reprotech interventions in increasing birth rates and reducing disease burden? How might this shape policies to expand awareness and access?
- What negative congenital, genetic, or epigenetic outcomes are associated with reprotech procedures, and how might they be mitigated?
- How significant is the impact of polygenic embryo selection on health and human capital? Is this impact increasing?
- Can we forecast different demographic scenarios based on varying assumptions regarding the timing and nature of reprotech breakthroughs and policy developments? (e.g., affordable artificial wombs, IVG, and "easy PGD").

We are still in the early days of the age of reprotech. While reprotech has already enabled the births of millions of people and has meaningfully increased births in nations like Denmark, Israel, and France, the impact of these technologies is likely to rise in the years to come. Given the entrenchment of sub-replacement and ultra-low fertility, governments around the world are likely to focus more urgently on how to raise birth rates. This issue is certain to stay with us. By studying the emergence and potential impact of reprotech, scholars can deepen our understanding of reprotech's implications and inform debates to ensure its responsible and beneficial use.

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