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### Abstract

Modern fertility techniques like flow cytometry allow parents to carry out preimplantation sex selection at low cost, no medical risk, and without the ethical or medical concerns associated with late abortions. Sex selection for non-medical purposes is legal in many high-income countries, and social norms toward assisted reproductive technology are increasingly permissive and may plausibly become increasingly prevalent in the near future. While concerns over son preference have been widely discussed, sex selection that favors female children is a more likely outcome in high-income countries. If sex selection is adopted, it may bias the sex ratio in a given population. Male-biased populations are likely to experience slower population growth, which limits the long-term viability of corresponding cultural norms. Conversely, female-biased populations are likely to experience faster population growth. Cultural norms that promote female-biased sex ratios are as a consequence therefore also self-reinforcing. In this study, we explore the demographic consequences of a female-biased sex ratio for population growth and population age structure. We also discuss the technology and parental preferences that may give rise to such a scenario.

**Keywords:** sex selection, sex ratios, assisted reproductive technology, population growth, son preference, daughter preference



## 1. Introduction

Preimplantation sex selection (henceforth sex selection) is a practice in which individuals attempt to control the sex of their offspring *before* the fertilized egg has been implanted in the uterus. The motivation for sex selection can vary, but we will here focus on sex selection for non-medical reasons. In recent decades, post-implantation sex selection (i.e., abortions and infanticide) has contributed to bias in the sex ratio in certain countries; this phenomenon has been widely discussed (Sen, 1990). Most research on biased sex ratios at birth due to parental preferences has focused on “missing women,” often with a focus on Asian countries where sex selection against female children and excess child mortality among girls have been prevalent (e.g. Guilмото, 2012; Sen, 1990).

In this article, we discuss the potential impact of an increase in the use of sex selection technology from a different perspective, based on three recent developments:

- Sex selection technologies are now legal, non-invasive, and relatively inexpensive in many high-income countries.
- In high-income countries, prospective parents have, on average, a preference for female children.
- In most high-income countries, single women<sup>1</sup> and women in same-sex relationships have unprecedented legal and financial access to assisted reproductive technology (ART).

We note that unlike a male-biased sex ratio, which tends to depress population growth (Johnson, 1994), a female-biased sex ratio will increase population growth (*ceteris paribus*). In this article, we explore the demographic consequences of female-biased sex ratios at birth and show that they may be considerable under certain assumptions.<sup>2</sup>

## 2. Reproductive Technologies

Three techniques are currently used for the purpose of sex selection. The first two are relatively invasive, expensive, and associated with non-negligible medical risk. We mention these in contrast to the third technique.

**Ultrasound in combination with abortion** is a prenatal rather than a preimplantation technique for sex selection and is thus more invasive and associated with considerable medical risk. The sex of the fetus can be detected with ultrasound at week 11, at the earliest, which means that abortions may have medical risks, especially in low-income countries (Igbiniedion

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<sup>1</sup> By “single women,” we mean women that *choose* to procreate and rear a child as the sole caretaking parent.

<sup>2</sup> Here, we quote the prescient foreword by Nathan Keyfitz to the pioneering edited volume (Bennet 1983) exploring potential future consequences of how sex selective abortion may give male biased sex ratios: “Too often we have to wait until an invention has been in use for a long time for social science to investigate and explain its effect. We are fortunate in this instance that a group has taken the initiative to start the social investigation before the invention comes to technical maturity and long before it is actually adopted”

& Akhigbe, 2012).<sup>3</sup> While this remains the most prevalent technique for sex selection in low- and middle-income countries (mostly used to select male children), it is rarely used in high-income countries. We do not foresee this as a common or preferred method for sex selection in high-income countries in the future; thus, we will not discuss this technique in any further detail.

**Preimplantation genetic diagnosis (PGD)**, a practice where an embryo is screened in vitro before implantation in the uterus, is used to some extent for sex selection in high-income countries. PGD is highly accurate in determining the sex of the embryo (Harper & SenGupta, 2012; Sermon et al., 2004). However, since PGD requires in vitro fertilization (IVF), it is relatively expensive and invasive, as it requires hormonal ovarian stimulation and retrieval from the ovaries. Thus, PGD is typically motivated by medical sex selection: for example, if the parents have a hereditary medical condition that only affects one sex. However, as a larger share of parents use IVF for reasons other than sex selection (Kupka et al., 2014), more parents will be able, at little additional cost, to choose the sex of their child if they so desire.

**Flow cytometry** is a relatively novel technique that is far less invasive and costly than the other two. Here, semen is labeled with a fluorescent dye that binds to the DNA of each spermatozoon (Sharpe & Evans, 2009). As the X chromosome is larger (i.e., contains more DNA) than the Y chromosome, “female” (X-chromosome bearing) spermatozoa will absorb a greater amount of dye than their “male” (Y-chromosome bearing) counterpart. Consequently, when exposed to UV light, “female” spermatozoa fluoresce brighter than “male” spermatozoa. As the spermatozoa pass through the flow cytometer in single file, each spermatozoon is encased by a single droplet of fluid and assigned an electric charge corresponding to its chromosome status (X-positive charge or Y-negative charge). The stream of X- and Y- droplets is then separated using electrostatic deflection and collected into separate collection tubes for subsequent processing (O’Neill, 2013; Reubinoff & Schenker, 1996). This method does not require IVF and can be used in combination with insemination. While this method is less invasive than PGD, it is also (somewhat) less accurate. In a study from 2014, 95% of babies born were females after sorting for X- spermatozoa and 85% were males after sorting for Y-bearing spermatozoa (Karabinus et al., 2014). The technique is more accurate when selecting female children than male children (Karabinus et al., 2014).

Sex selection is legal and in use in some high-income countries, including the U.S. (Bhatia, 2018). However, the most prevalent technique for sex selection in high-income countries, PGD, requires IVF, and the extent to which this is available for non-medical purposes varies. The U.S. has a very permissive regulatory regime, allowing so-called “fertility tourism” from other countries where sex selection is only allowed for medical purposes (Whittaker, 2011). However, with the increasing popularity of flow cytometry, access to sex selection is also likely to increase. No high-income country has banned flow cytometry, and a ban on insemination of sorted sperm is likely to be difficult to enforce. The company MicroSort, which uses flow

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<sup>3</sup> Although possible, such early attempts at sex determination are prone to a high degree of false negatives.

cytometry, and offers non-medical sex selection services, already operates in Mexico, Malaysia, North Cyprus, and Switzerland, attracting fertility tourism (MicroSort, 2020).

Since the first IVF procedure in 1978, ART has become widespread and widely accepted. In the U.S., more than 55,000 women per year give birth to a baby conceived through ART (IVF or insemination; Dusenbery, 2020). Moreover, public support for this technology has also increased considerably, with ART now subsidized by public healthcare systems in many high-income countries for infertile different-sex couples, single mothers, and female same-sex couples.

### **3. Sex Preferences in High-income and Middle-income Countries**

Recent research in sociology and demography has found increasing preferences for female children in high-income countries. This has mostly been expressed through parents more often having higher-order births if their previous children were either lacking sons or daughters, but there is also increasing evidence for parents explicitly wanting daughters when they have more direct choice over their reproduction. Below, we summarize the recent research on sex preferences in high-income countries.

Most of the existing research on sex preferences and fertility outcomes has focused on countries with strong son preferences. In particular, in East and South Asia, where patrilineal kinship systems are common, parental preferences for male children have been commonplace in both contemporary and historical societies (Arnold & Zhaoxiang, 1992; Drixler, 2013; Guilmoto, 2012; Mungello, 2008; Sen, 1990). Such preferences have historically been associated with elevated female child mortality and infanticide, with major demographic impact (Arnold & Zhaoxiang, 1992; Drixler, 2013; Guilmoto, 2012; Mungello, 2008; Sen, 1990). In the 1990s and 2000s, the availability of ultrasound combined with abortion led to elevated male sex ratios across East Asia, South Asia, and Caucasia (Guilmoto, 2009). A preference for male children has also been historically common throughout Western Europe, but with only limited effects on child mortality or fertility outcomes (Kolk, 2011; Sandström & Vikström, 2015; Tsuya et al., 2010).

While a preference for sons seems to be the major determinant of childbearing decisions globally (Arnold, 1997; Guilmoto & Tove, 2015), in high-income countries, the picture is notably different, with increasing evidence of a preference for daughters and for a mixed-sex composition (Kolk & Schnettler, 2013; Miranda et al., 2018). This trend is not only prevalent in Western countries but has also been observed in Japan (Fuse, 2013). Also, in middle-income countries traditionally dominated by strong son preferences, such as rural China, there is some novel evidence that some parents are developing a preference for daughters over sons (Shi, 2017). In high-income countries, sex preferences are not expressed through biased sex ratios at birth; however, the sex composition of previous children has a strong impact on parity progressions (the decision to have a subsequent child). Across Europe and the U.S., research has shown that transition to higher order births is influenced by the sex composition of previous children (Blau et al., 2019; Hank, 2007; Hank & Kohler, 2000). A pattern in which parents prefer children of each sex is increasingly common; it is strongest for the transition to a third

child, where a transition to a third child is least prevalent for parents with a son and a daughter (Hank & Kohler, 2000; Miranda et al., 2018).

Interestingly, in Nordic countries, while a preference for mixed-sex composition remains the dominant pattern, evidence points to more parents displaying daughter preference over son preference (Kolk & Schnettler, 2013; Miranda et al., 2018). For parents with one child, 35% of parents who had a son preferred their second child to be a girl, whereas only 23.4% of parents who had a daughter preferred their next child to be a boy (Miranda et al., 2018). For parents with a daughter, 74% said the sex of the next child did not matter, compared to 58% for those with a son. Demographers have previously speculated that high gender equality would lead to parental sex indifference, whereby the sex composition of previous children would not affect the decision to have subsequent children (Pollard & Morgan, 2002). In reality, however, this seems not to be the case; instead, we find that in countries that are the most equal, it appears more common for parents to prefer female children (Andersson et al., 2006; Miranda et al., 2018). It is thus conceivable that increasing gender equality will, if anything, lead to daughter preference becoming more widespread. Moreover, in Japan, traditionalism and adherence to traditional gender roles among women have also been predictive of daughter preferences (Fuse, 2013), suggesting that—with increasing female agency over fertility—we may also see greater daughter preference in less gender egalitarian contexts (see also Shi, 2017). It should be noted here that, while they are a clear marker of parental sex preferences and the distribution of sons and daughters within families, sex-biased parity progressions (as described above) do not affect the overall sex ratio in a population.

Evidently, although most heterosexual parents in Western countries have not acted to deliberately affect the sex of their children, their behavior following the (random) allocation of previous births has a clear impact on their subsequent behavior. In the less prevalent contexts where potential parents already have direct agency over the sex of their children, we find stronger evidence of parental preferences for daughters. For several decades, adoptive parents have, on average, shown a strong preference for female children, an interesting illustration of a scenario in which parents to some extent can choose the sex of their children (Högbacka, 2008). However, sex and other aspects, such as the ethnic match of the child and the parents, interact in complex ways in international adoption (Högbacka 2008). In a sample of infertile women considering ART treatment, 40% responded positively about choosing the sex of their child if the option to do so was offered at no additional cost (Jain et al., 2005). Among women who wanted to select the sex of their future child, 39% wanted a male child, and 61% wanted a female child (Jain et al., 2005). Of women considering ART treatment, it was much more common to express a daughter preference than a son preference, although women who already had children had a preference for a mixed-sex composition (Jain et al., 2005). Lamberts et al. (2017) found higher rates of vasectomy among men with more sons than daughters. Overall, it seems that when more choice, technology, and agency are associated with the process of having a child (as opposed to children conceived through intercourse in heterosexual unions), the more parents accept and consider the option of choosing the sex of their children. When parents explicitly consider the choice of sex of their future children, a daughter preference seems more common.

Most children are reared by different-sex couples. In the research on sex preferences of partnered men and women, prospective mothers are seen to have a relatively higher preference for female children, whereas prospective fathers have a relatively higher preference for male children (Higginson & Aarssen, 2011; Lynch et al., 2018). This sex-biased pattern is found in societies with both son preference and daughter preference on average (van Balen, 2006). This suggests that the preference for children of one's own gender is a relatively general pattern across cultures. There is little research knowledge about sex preferences among single women and same-sex female couples, although some studies indicate that heterosexual single women and women in same-sex couples more often exhibit daughter preference (Gartrell et al., 1996; Goldberg, 2009; Leiblum et al., 1995). If women across all union types have a preference for daughters one would expect single women and female same-sex couples to be able to act on this preference without negotiating with a male partner and therefore on average engage more readily in sex selection. In general, groups who are more likely to use ART for non sex-selective reasons, such as people with fertility concerns, single women, and women in same-sex relationships, may more often choose sex selection, because sex selection (either via PGD or flow cytometry) is a relatively straightforward addition to ART procedures (van Balen 2006).

In summary, previous research has found increasing evidence of a daughter preference in high-income countries. In situations where parents have more direct choice over the sex of their children, such as adoption and IVF, we also find stronger daughter preferences. Overall, we argue that a latent daughter preference is apparent in high-income countries, and that this is stronger among women than men.

#### **4. Results**

To estimate how female-biased sex ratios may affect population growth, we present calculations for different countries with different sex ratios and show how the sex ratio affects population growth rates and age structure.

Our calculations are based on two important assumptions. First, since we are interested in the long-term effects of changing sex ratios, we therefore show the long-term equilibrium effect of a change in sex ratios given a set of assumptions on fertility and mortality. This is what demographers refer to as a stable population (Wachter 2014, 218-249). It is worth stressing that we apply reductionist and commonly used demographic approximations to our demographic examples so they may be more easily followed, instead of more technical models. All our calculations refer to the long-term consequences for a population with the same fixed behavior over multiple generations; as such, they are only useful to illustrate the long-term implications of female-biased sex ratios. They are not useful for predicting actual demographic outcomes in the near future. Given the uncertainties in the extent of uptake (and timing of uptake) of the behaviors we discuss here, focusing on the large-scale demographic influence of these trends is more relevant than trying to forecast near-future empirical scenarios.

Second, our models follow the standard demographic methodology in which demographic analysis is based on female reproductive choice in a society. This is the approach used in most

standard demographic analysis (e.g., Wachter 2014, 79-89). However, certain assumptions in such models, such as the implicit assumption that (male) co-procreating and co-childrearing partners are unconstrained, are less realistic in cases with highly biased sex ratios. We discuss whether these assumptions can be analyzed independently of the overall sex ratio in section 5.3, as well as other factors that may stabilize the sex ratio given a preference for female births. We also analytically calculate the age structure implications (section 4.3) of different fertility scenarios with different sex ratios, showing that in some scenarios of high total fertility and highly biased sex ratios, it is relevant to assess demographic support ratios. Some previous demographic literature on male-biased sex ratios has created demographic models exploring how male preferences and male sex ratios affect population growth (Leung, 1994; Bennet, 1983; Mason & Bennett, 1977), finding that male-biased sex selection would decrease population growth.

#### ***4.1 Consequences of Biased Sex Ratios for Population Growth***

We begin by examining changes to population growth arising from different assumptions of fertility and share of female births. In Equation 1, we show the net reproductive rate based on a given sex ratio ( $\frac{B_f}{B_t}$ ), female births over all births), mortality pattern ( $l_x$ ), and fertility pattern ( $f_x$ ) for five-year life tables. The net reproductive rate can be interpreted as a multiplier of each subsequent generation; a value above 1 thus indicates a population where every generation is larger than the previous one, and a value smaller than 1 indicates a shrinking population. A value of 1.5 indicates that each new generation is 50% larger than the preceding one.

Equation 1:

$$NRR = 5 \frac{B_f}{B_t} \sum_{x=15-19, \text{ by steps of } 5}^{45-49} f_x l_x$$

In Equation 2, we show the Dublin-Lotka approximation, which shows how a given net reproductive rate translates into yearly population growth ( $r$ ) based on the mean age of reproduction in a population ( $T$ ), which can be calculated from  $f_x$ .

Equation 2:

$$r \simeq \frac{\ln(NRR)}{T}$$

Together, these two equations give a good approximation of how a given sex ratio, mortality pattern, and fertility pattern jointly determine long-term growth in a given population. We largely focus on sex ratios and fertility here, as different mortality assumptions make little practical difference to contemporary populations in high-income countries. We use a single mortality pattern in all examples, based on the pattern in the U.S. for 2017. Survival up to age



45 is today so high, even in lower-middle income countries,<sup>4</sup> that it plays only a minor role in generational reproduction, and we do not expect this to change in the foreseeable future.

We illustrate the consequences of changing sex ratios with a selection of different assumptions on the average number of births per woman in a population (or Total Fertility Rate, TFR). The different fertility scenarios are: very low (Taiwan 2014, TFR = 1.16); somewhat typical for an OECD country (U.S. 2017, TFR = 1.76); high (Kenya 2014, TFR = 3.90); and the traditional fertility schedule used for populations that are close to the highest observed fertility in human populations, the Hutterites in the U.S. in the 1920s (TFR = 10.31; see Henry, 1961, from where we get our fertility schedule). We collected mortality data for the U.S. (Human Mortality Database—U.S., n.d.), fertility data for U.S. and Taiwan (Human Fertility Database—U.S. & Taiwan, n.d.), and fertility data for Kenya based on the 2014 demographic and health survey (Human Fertility Collection—Kenya, n.d.).

In Table 1 below (upper panel), we show the consequences of female-biased sex ratios for population growth ( $r$ ) using the approximations from equations 1 and 2 with different fertility rates and sex ratios. We show fertility patterns for three different countries. We show a sex ratio for 48 daughters from 100 total births (which is close to what is naturally occurring in contemporary populations; see James, 1987), as well as sex ratios of 60<sup>5</sup> and 80 daughters per 100 births.

Equation 3 shows how yearly population growth ( $r$ ) corresponds to initial and final population size ( $P_0$  and  $P_n$ , respectively) over  $n$  years. We use Equation 3 to translate how the population growth rate in Table 1 (lower panel) translates into population growth over 50 years. This represents how much larger a population would be after 50 years of corresponding population growth, given that the fertility rates, mortality rates, population growth, and sex ratios would be fixed and at equilibrium.

Equation 3:

$$P_n = (1 + r)^n P_0$$

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<sup>4</sup> Survival to age 45 for a woman is around 95% for the US life table in our calculations, and above 90% for a country like modern-day Indonesia.

<sup>5</sup>For example, one conceptual scenario of a sex ratio of 60 could arise from a stratified population where (a) out of parents with two children, 50% of those with two sons choose sex selection for family balancing, but only 25% of those with 2 daughters do the same; b) within a group of single women and female same-sex couples, 45% choose to have only daughters; and c) out of everyone else, 20% choose to have only daughters. The effect on the population sex ratio can be meaningful even if only a minority of the population choose to use sex selection technology.

Table 1: Consequences of Varying Assumptions of Fertility Rates, Sex Ratios, and Mortality for Population Growth Rate (upper panel) and Population Change over 50 years (lower panel)

Population growth rate ( $r$ )			
Fertility schedule	Taiwan (2014)	U.S. (2017)	Kenya (2014)
Number of female births over 100 total births			
48	-0.0216	-0.0066	0.0217
60	-0.0136	0.0014	0.0296
80	-0.0034	0.0116	0.0398
Effect over 50 years (ratio to original population)			
Fertility schedule	Taiwan (2014)	U.S. (2017)	Kenya (2014)
Number of female births over 100 total births			
48	0.336	0.720	2.921
60	0.503	1.071	4.300
80	0.843	1.781	7.049
Total fertility Rate	1.16	1.76	3.90
Mean age of childbearing	31.08	29.39	28.13

*Note.* The table refers to the stable population equilibrium resulting from the different combinations of rates.

As we can see from the table, changing the sex ratio has a significant impact on population growth.<sup>6</sup> While the prevailing sex ratio and fertility schedule in the U.S. will lead to a reduction in the population by around 30% (the equilibrium consequences of contemporary demographic rates over 50 years), when we compare this to a population where an assumed 60% of all births are female, the population would instead surge by 7%. In turn, a population where 80% of births are female would increase by 78% over 50 years. With prevailing fertility rates and an unbiased sex ratio, Taiwan's current fertility schedule implies that such a population will contract by 66% over 50 years; given a sex ratio of 80% women, it would only contract by 16%. In Kenya, a sex ratio of 80% (rather than 48%) would result in an increase of over 600% (compared to the already considerable increase of nearly 200%) over 50 years. Note once again

<sup>6</sup> These numbers do not account for any demographic change related to migration, for example, or any forecasted change in demographic rates.

that these are equilibrium scenarios used to explore differences for changing sex ratios and not as demographic forecasts; here, we use constant demographic rates and contemporary constant U.S. mortality patterns to illustrate how changing sex ratios interact with different fertility assumptions. In the online appendix S1, we explore other demographic scenarios including very skewed sex ratios, male-biased sex ratios and very high fertility rates.

## ***4.2 Consequences of Biased Sex Ratios for Population Age Structure***

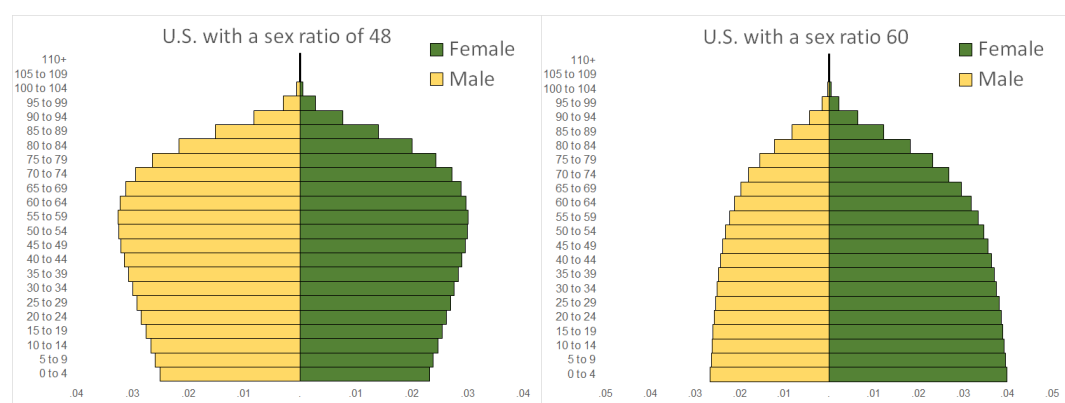
In the following section, we explore the consequences for the age structure of the population given the scenarios outlined above. In human societies, children and infants are provided resources and care by adults (to a large extent their parents), and in contemporary high-income societies, elderly individuals also provide substantial support. The importance of lifecycle transfers to the age structure of a population has been widely recognized in anthropology, economics, and evolutionary biology, where it forms the basis of life course theory (Kaplan, 1994; Lancaster et al., 2000; Lee & Mason, 2011).

The high population growth rates illustrated in Table 1 produce a high share of young dependents in the population in the long term, which we illustrate in Figure 1. The calculations are based on the same fertility and mortality schedules as in Table 1. The stable age structure of a population under a given  $r$  and  $l_x$  is given by Equation 4 (Euler-Lotka equation, in discrete form for 5 year age groups, see Slogett (2015), where  $l_x$  is the remaining life years at age  $x$ , and the numerator is the share of life years at time  $x$ , divided by the denominator, which is the sum of all life years in the population up to age  $\omega$ . From the stable population equations, we can calculate the age distribution and show population pyramids by sex for our different scenarios. Using the age structure calculated from Equation 4, we also show various measures of demographic dependency.<sup>7</sup>

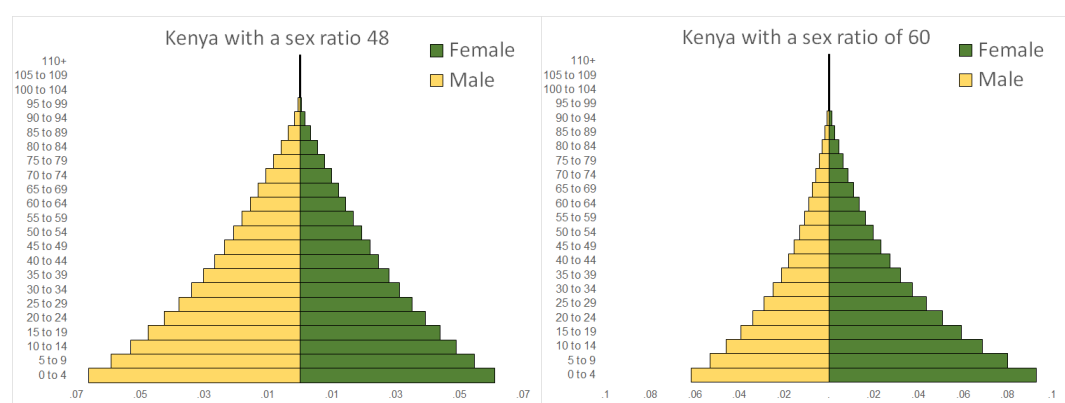
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<sup>7</sup> We present three different measures. We calculated traditional dependency ratios for our population  $((a_{0-14} + a_{65+}) / a_{15-64})$ . We also approximated how much of an adult working age individual's life (age 20–64) is spent on childcare in our stable population scenarios by summing the total share of life years in the 0–19 population and assuming that each life year of a child needs a third of an adult's life-year for education, child rearing, procreation, etc. The exact input a child needs will of course vary according to culture and context, and the value of  $\frac{1}{3}$  is only for illustration. We then divided the sum of time needed to take care of the young population by the available time in the adult population to obtain a rough estimate of how much of all productive (and leisure) time of the population aged 20–64  $(a_{0-19} \times \frac{1}{3} / a_{20-64})$  must be spent on rearing the subsequent generations. We make the second calculations both for men and women and the denominator, and for only women in the denominator.

Figure 1 : Population Pyramids at Equilibrium for Fertility Rates of the U.S. (2017) and Kenya (2014). Two different scenarios under two different sex ratios.



	Dependency ratio (population -14 and above 65 divided by population aged 15-64)	Ratio of available labor of primary age adults (age 20-64) spent on childcare	Ratio of available labor of primary age women (age 20-64) spent on childcare
U.S. 48	0.70	0.12	0.26
U.S. 60	0.66	0.19	0.27



	Dependency ratio (population -14 and above 65 divided by population aged 15-64)	Ratio of available labor of primary age adults (age 20- 64) spent on childcare	Ratio of available labor of primary age women (age 20-64) spent on childcare
Kenya 48	0.66	0.16	0.27
Kenya 60	0.85	0.38	0.63

*Note.* The figure uses the same values and assumptions as in Table 1. It shows the eventual equilibrium age structure if fertility and mortality rates remain constant indefinitely.

Equation 4:

$$a_x = \frac{l_x e^{r(x+2,5)}}{\sum_0^{\omega} l_x e^{r(x+2,5)}}$$

It is clear from Figure 1 that very high population growth rates (as seen in Table 1) cause a very young age structure. In the U.S., current fertility rates and sex ratios imply a shrinking population (from natural growth) with an old age structure, while similar fertility rates with a 60% female-biased sex ratio would instead result in a growing population with a younger age structure. Across the different populations shown in Figure 1, it is clear that female-biased sex ratios result in higher population growth, a higher share of women (naturally), and more resources that will have to be spent on supporting and rearing the young. For the U.S., with moderate/low fertility, the impact of age structure on different dependency ratios (see Figure 1) is relatively small and may even be beneficial. With Kenyan fertility levels, on the other hand, the high population growth and corresponding young populations with a highly biased female sex ratio would have consequences for the ability of adult members of society to adequately support the younger generations.

## 5. Discussion

### 5.1 Will Sex Selection Become Widespread in High-income Countries?

It should be noted that many people still express disapproval of non-medical parental sex selection, even with novel methods such as flow cytometry (Ethics Committee of the American Society for Reproductive Medicine, 2015). In a general population survey in the U.S. in 2006, only 18% of individuals aged 18–45 said they were positive, and 22% were undecided, if they had the option to use a cost-free, risk-free, non-invasive method to choose the gender of their child (Dahl et al., 2006). While most parents express a preference for a “balanced” family (i.e., at least one child of each sex), parents with one son are keener to do so than those with one daughter (Miranda et al., 2018).

On the contrary, we may have reasons to believe that the use of sex selection technologies will become more prevalent in the near future. According to a 2017 survey, 77% of fertility clinics in the U.S. that offer PGD also offer sex selection for non-medical reasons, which represents a substantial increase from 2006, when only 42% of clinics that offered PGD offered non-medical sex-selection (Capelouto et al., 2018). Flow cytometry in combination with insemination is more affordable and less risky than PGD (which requires IVF) and less likely to be seen as morally objectionable, as it does not involve the discarding of fertilized eggs, meaning that access to this technology is likely to increase the use of sex selection in the general population.

Technologies associated with reproduction, including ART but also contraceptives of various kinds, have been highly controversial when introduced, and some remain so. However, we have

consistently seen that attitudes toward different reproduction technologies have improved steadily over time. For example, IVF was once considered a highly divisive procedure. In the spring of 1972, the British magazine *Nova* ran a cover story suggesting that “test-tube babies” were “the biggest threat since the atom bomb” (Eschner, 2017; Henig, 2003). We can reasonably expect that at least part of current aversions to sex selection is due to a similar “yuck effect,” which tends to dissipate as the use of the technology in question becomes normalized. Indeed, van Balen (2006) has described the technological trend toward more accessible, less invasive means of choosing the sex of a child as “nearly inevitable,” and that any governmental countermeasures are likely to be largely ineffectual. We think it is plausible that the eventual prevalence of sex selection will be based primarily on the preferences among parents, rather than any technological barriers.

Some objections to sex selection concern some of the techniques used for this purpose. For example, those who object to abortions naturally also find their use as a means of sex selection objectionable. This “pro-life” stance sometimes also includes objections to IVF, especially when it involves the destruction of embryos. This makes the use of PGD for the purposes of sex selection an unattractive option. However, the use of flow cytometry does not involve killing a fetus or destroying an embryo and may therefore find less opposition among “pro-life” campaigners than other forms of sex-selection.

In sum, we argue that the combination of a latent and increasing daughter preference, new technology that facilitates sex selection (including flow cytometry), and increasing acceptance of ART in general suggest that sex selection is likely to become more prevalent in high-income countries over the coming decades.

## ***5.2 Is Sex Selection a Self-reinforcing Practice?***

In the study of cultural evolution, it has been noted that certain phenomena are self-reinforcing and increase in prevalence over time, while others are not. By contrast, other practices are self-limiting, in the sense that they produce outcomes that make them less prevalent or attractive. The phenomenon of sex selection may not only affect population growth directly (as demonstrated in section 4) but also have intergenerational consequences over multiple generations. For most practices, it can be observed that children are more likely to resemble and copy the behavior of their parents than that of unrelated members of society. If this also applies to norms and fertility practices, this will affect how prevalent the preference is in the next generation, as those parents who have fertility preferences that promote population growth will have more children, and those children will (often) share their parents’ preferences (Kolk et al., 2014).

A practice can be self-reinforcing at both an individual and a group level (Murphy & Wang, 2001). For example, if individuals with a certain trait (e.g., a preference for having many children) have more children, and those children in turn also have that trait, the preference for having many children will increase in prevalence over time. Likewise, a group (e.g., a religious group or an ethnicity) where membership is inherited across generations will also increase in relative prevalence if its members have more children on average. In both cases, the practice

will become more common in the population over time. In the context of this study, we argue that the practice of using sex selection technologies to select female children in high-income countries could become a self-reinforcing process, both at a population and a sub-population level, in ways that the practice of selecting male children in some countries has not.

As shown above, populations with female-biased sex ratios have higher rates of population growth. As a population grows, the norms and practices of that population become more prevalent, all other things being equal. By contrast, selecting male children reduces population growth, and thus over time reduces the global impact of the norms of male-biased populations. Parents with an unusually strong preference for daughters may therefore decide to use sex selection, and then their daughters (and possibly sons) will themselves be more likely to sex-select than their peers.

This mechanism may be reinforced if social learning of practices and norms is itself sexually biased (Bandura & Walters, 1977).<sup>8</sup> In other words, daughters may be more influenced in their reproductive choices by their mothers than by their fathers (Murphy, 1999). This means that women who more strongly prefer daughters are more likely to have offspring that will inherit this daughter preference. Moreover, since women on average have a stronger preference for daughters than men, in each generation daughter preferences (and selection for daughters) may become more common as women become a larger share of the population. This will be particularly true for the increasing share of women who choose to have children without a male co-parent, either as single mothers or in same-sex couples. If these groups both have more daughters than the average individual in a society, and their children share their preferences for sex selection, both the share of women raising children without men and the practice of sex selection may increase accordingly.

The cultural evolutionary logic above suggests that even if only a small minority of a population is positively disposed to sex selection, mechanisms exist through which this practice could become increasingly commonplace in each subsequent generation. If the self-reinforcing dynamic of this process proves to be correct, we should expect that populations with a female-biased ratio will be increasingly common in high-income countries. However, it is possible to raise some objections to arguments against an increasing prevalence of sex selection, which we explore in the following section.

### ***5.3 Will there be Counteracting Mechanisms to Sex Selection?***

When assuming higher population growth among populations with female-biased sex ratios, we have used demographic calculations in which the availability of male partners is completely independent of the fertility rates of women in the population. This is common in demographic analysis, but such cases typically do not foresee very biased sex ratios. Similarly, in section 5.2, we highlighted a mechanism by which the female sex ratio would continue to increase. Both assumptions that (a) the sex ratio will not affect the age-specific fertility rates for a female

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<sup>8</sup> It has been noted that this sexual bias may explain how female infanticide can become an entrenched practice, even when it leads to fewer children and lower population growth (Strimling, Elrath & Richerson, unpublished).

in a population and (b) a cultural evolutionary mechanism will steadily increase the preference for female sex selection are almost certainly unrealistic for scenarios that deviate significantly from a balanced sex ratio. Indeed, at some level of bias in the sex ratio, it is reasonable to expect that other societal mechanisms may counteract these trends. Below, we discuss such possibilities, beginning with social mechanisms and concluding with arguments from evolutionary biology on why sex ratios tend to be balanced by natural selection across the animal kingdom.

A first counterargument is that while the biological/technological constraints of sex selection may be relaxed with the help of ART, as long as most childbearing takes place in different-sex partnerships, a deficit of males will constrain childrearing, availability of fathers, and eventual fertility rates. Traditional demographic models (including ours) assume that women are largely unconstrained by the availability of male partners for their fertility choices. This may be reasonable for sex ratios close to 50–50, but it becomes increasingly implausible with very unbalanced sex ratios, even if ART removes the biological necessity of males for female childbearing. We find it plausible that a male deficit would eventually make very unbalanced sex ratios unlikely, though we note that it does not apply to single mothers or to female same-sex relationships. Indeed, as we have noted, the same cultural processes that increase the female sex ratio may also increase the share of women that choose to procreate and rear children without men.

A second mechanism that may counteract a very large share of women in a population is how societies need to adjust the ways in which they provide resources for children. As we show in section 4.3, very rapid population growth leads to unbalanced dependency ratios between the young and adults. Similarly, if an increasing share of women choose to raise daughters by themselves, it seems likely that a single woman raising a child alone would settle for, on average, fewer children than what a couple would. Similarly, in a female same-sex relationship, the desired number of children per woman is very likely to be lower than that in a different-sex relationship; this is clear from the demography of same-sex parenthood shown by Kolk and Andersson (2020).

A third objection is that people may find a very unbalanced sex ratio “unnatural” or “disagreeable.” More recently, feminist scholars have also objected to this practice. For example, Arianne Shahvisi (2018) argues that sex selection for the purposes of “family balancing” entrenches heteronormative stereotypes and misuses the moral mandate of reproductive autonomy. Elsewhere, Strange and Chadwick (2010) contend that prohibitive legislation against non-medical sex selection is justified because sex selection promotes restrictive conceptions of sex, gender, and family. Ultimately, if societies find an unbalanced sex ratio undesirable, they may adjust social policies to make such outcomes less likely. It is also plausible that parental preferences themselves may become increasingly less daughter-biased if we see a very biased female sex ratio. The preferences we see in high-income countries for a moderate daughter preference, may look quite different if the sex ratio is strongly biased towards females.



In animal populations, sex ratios are nearly close to 50–50. The evolutionary biological logic according to which offspring of the sex that is temporarily underrepresented will have greater reproductive success is known as Fisher’s principle (Hamilton, 1967). However, this logic is not relevant to the opportunity to procreate in our scenario, since ART reduces the correlation between reproductive success and the sex ratio for women. Nevertheless, the self-balancing mechanisms related to childrearing described in our first and second objections can be seen as analogous scenarios through which a sex ratio would be stabilized at an equilibrium, thereby stopping a process that would otherwise gradually increase the share of women.

Taken together, the arguments above suggest that the potential cultural mechanisms that would increase the share of women in the population are more likely to have a moderate rather than substantial effect on the future equilibrium sex ratio, even if daughter preference becomes increasingly widespread, since counteracting mechanisms may limit the prevalence of sex selection for daughters. Based on the arguments above, we find it plausible that female-biased sex ratios will eventually reach equilibrium and that this equilibrium will not be particularly extreme. However, we do not know at which point this equilibrium will be reached.

## **6. Conclusions**

The desire to select the sex of one’s children is ancient in origin. In recent decades, selective abortions have mostly been used in low- and middle-income settings, and overwhelmingly to select male children. More recently, modern technology has made sex selection an inexpensive and non-invasive possibility that is less fraught with moral and medical concerns than abortion. We have argued that current trends suggest that this technology will become more accepted and more widely used over time in high-income countries, where parents now seem to prefer female children over male children. Whether this turns out to be true is uncertain, but will depend on social trends and norms, the development of which is difficult to predict. Significantly, however, it would appear that governments can do little to restrict the use of flow cytometry, as doing so would involve legally unlikely infringements on bodily autonomy. We have also argued that if sex selection technology were to become routinely used to select female children, this practice may have a self-reinforcing dynamic, potentially leading to a consistent and durable bias in the sex ratio. In section 4, we described how such a sex ratio may affect population growth and the age structure, concluding that such effects are substantial and could help reach replacement rate fertility in high-income countries, while it would lead to rapid growth in countries with higher fertility.

The argument presented here is by its very nature speculative and based on the kind of uncertainty always associated with forecasting trends, but we argue that it also presents a plausible scenario. Our demographic calculations are not based on the empirical scenarios we consider most likely; rather, they aim to illustrate that the process will, over many generations, lead to substantial effects on demographic outcomes. While we do not foresee such demographic impacts to be substantial in the short term, over a longer time horizon their ramifications may be larger. If uptake of sex selection technology is small or moderate (which is plausible), the demographic effect may still be substantive. If used at lower frequencies, the dynamic effects that counteract a linear impact between sex ratios and population growth will

also be less important, and a more linear relationship between more females and higher fertility will be observed. Ultimately, the aim of this article has not been to argue in favor or against the use of this technology, but to highlight its social impact over the long term. As our analysis makes clear, the consequences for population growth and social dynamics may be considerable over longer timescales.

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**Table S1**

*Consequences of Varying Assumptions of Fertility Rates, Sex Ratios, and Mortality for Population Growth Rate (upper panel) and Population Change over 50 years (lower panel)*

Growth rate (r)

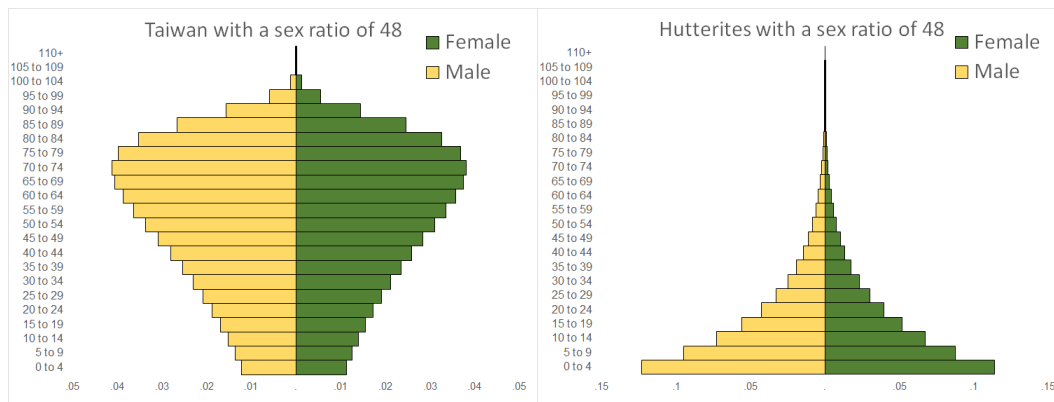
	fertility schedule			
	Taiwan (2014)	U.S. (2017)	Kenya (2014)	Hutterite (1920s)
Number of female births over 100 total births				
30	-0.035	-0.022	0.005	0.037
48	-0.022	-0.007	0.022	0.052
70	-0.008	0.007	0.035	0.065
90	0.001	0.016	0.044	0.073
100	0.005	0.020	0.048	0.076

Effect over 50 years (ratio to original population)

	fertility schedule			
	Taiwan (2014)	U.S. (2017)	Kenya (2014)	Hutterite (1920s)
Number of female births over 100 total births				
30	0.17	0.32	1.28	6.28
48	0.34	0.72	2.92	12.90
70	0.66	1.41	5.61	22.85
90	1.04	2.19	8.62	33.30
100	1.25	2.63	10.31	38.97
TFR	1.16	1.76	3.90	10.31
mean age of childbearing	31.08	29.39	28.13	31.20

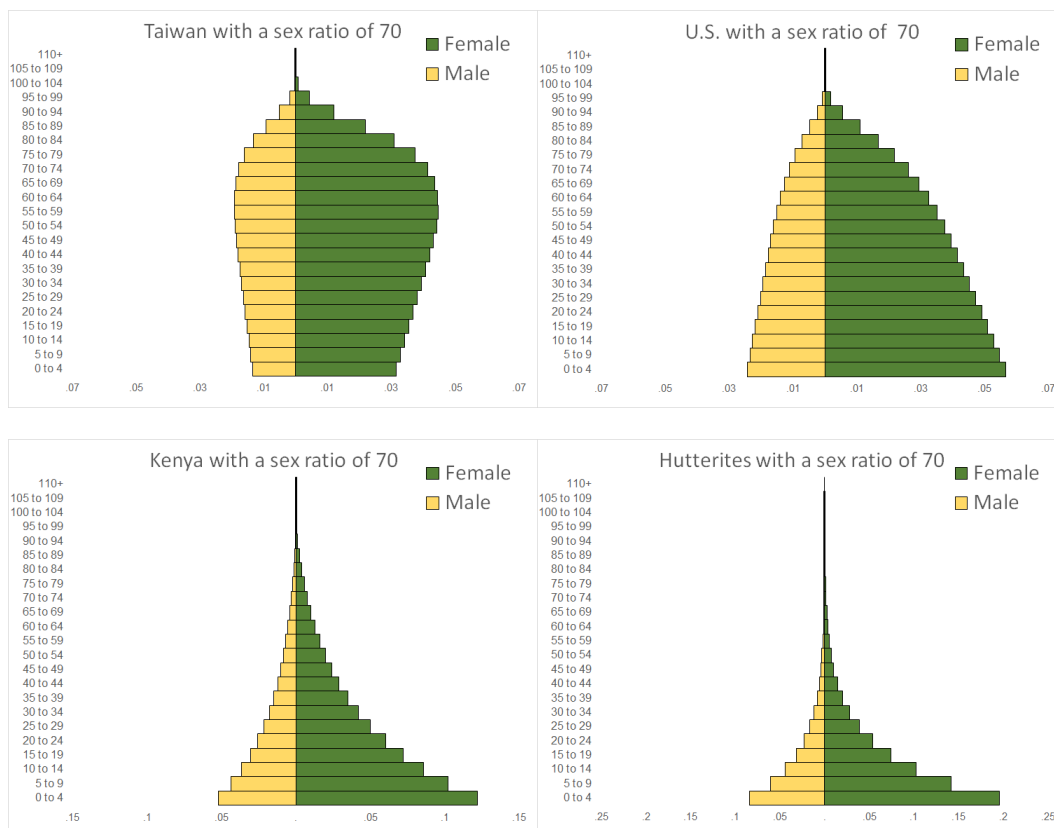
**Figure S1**

Population Pyramids at Equilibrium for Fertility Rates of Taiwan (2017) and the Hutterites (1920) with a sex ratio of 48



**Figure S2**

Population Pyramids at Equilibrium for Fertility Rates of Taiwan (2014), U.S (2017), Kenya (2014) and the Hutterites (1920s) with a sex ratio 70





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