An Agent-Based Model of Sex Ratios at Birth Distortions

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Abstract

The significant decline in fertility since the 1980s across Asia has been accompanied by an unprecedented and anomalous rise in the sex ratios at birth (SRB). Although the micro-level mechanisms – persistent son preference within a context of fertility decline and diffusion of sex-selective abortion technology – are known, their specific levels and trends underpinning macro-level SRB trajectories are hard to discern with existing data and approaches. We present an agent-based model (ABM) model that examines each of these. Calibrating our model to Indian data, we find that SRB distortions emerged even as son preference was declining by cohorts and over time due to the steady diffusion of sex-selective abortion practiced only at third parity at higher. Experiments with our model reveal that even relatively low levels of son preference (~30 percent wanting one son) can result in skewed SRB levels if individuals practice SSA at second or third parities.

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I. Introduction

Since the 1990s, across several parts of Asia just as the total number of births per woman has declined the proportion of male births compared to female births, usually expressed in terms of the sex ratio at birth (SRB), has steadily risen (Bongaarts 2013; Guilmoto 2009). According to available demographic estimates since the 1950s SRBs in most countries lie between 104-106 male births for every 100 female births and across different settings where fertility has declined over the past two centuries SRB levels have remained unchanged.[2] Although this unprecedented trend is by no means universal across the diverse demographic contexts present in Asia, the sizeable populations where it has been noted – China, India, South Korea, Pakistan, Vietnam, Georgia, Azerbaijan, Albania, among others – make it one of the "most notable anomalies" of contemporary demography (Guilmoto 2009, 519). While earlier literature presumed that the presence of widespread son preferences would delay the fertility transition and keep fertility rates higher than they would be in their absence (Nath and Land 1994; Amin and Marian 1987), SRBs have risen in recent decades as technology that enables couples to resort to sex-selective abortion (SSA)[3] diffuses in contexts where couples continue to desire at least one son a while seeking to minimize their total number of children. This has led demographers to speculate that SRBs may rise in other contexts where son preferences persist but safe, effective and cheap sex determination technology has yet to become available (Bongaarts 2013). Figure 1 shows United Nations estimates for total fertility rates and SRB trends from 1970 to 2010 for South Korea, China and India. Also reported are data of an example (Turkey) where a similar rise in SRB has not

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[2] The United Nations Population Division publishes a comparative global SRB time series from 1950 onward and produces SRB forecasts until 2100 (United Nations 2013). These estimates as well as other demographic studies documenting SRB trends make use of different types of data sources with varying levels of reliability: birth registration data, which is the most reliable when available; birth-history estimates from large surveys; and census data on recent births or age (Guilmoto 2009). Data quality problems for estimating SRB trends in Asia are detailed extensively elsewhere (Attané and Guilmoto 2007). Often, as a consequence of data quality issues, the WPP has revised past estimates and future forecasts on SRBs across different waves of its World Population Prospects (WPP) publication, particularly in settings where universal vital registration systems are absent such as India. Most recently, in WPP 2012 the UN revised its estimates of SRBs in India upward based on improved sample registration system estimates. According to these estimates, SRB levels peaked in the mid-2000s at 111 compared to WPP 2010 estimates in which SRBs were constant at 108 from the mid-1990s onward.

[3] Sex-selective abortion requires pre-natal sex-determination technologies as well as methods for abortion. Different technologies for pre-natal sex-determination technologies presently exist – amniocentesis, an invasive procedure that is conducted between 15 and 20 weeks of pregnancy, ultrasonography, which can determine the sex of the foetus as early as 11 weeks, and blood tests involving the analysis of the foetal DNA floating in the mother's bloodstream, which are minimally invasive procedures and can be done at home as early as 7 weeks into the pregnancy (Bongaarts 2013).

accompanied the fertility decline.

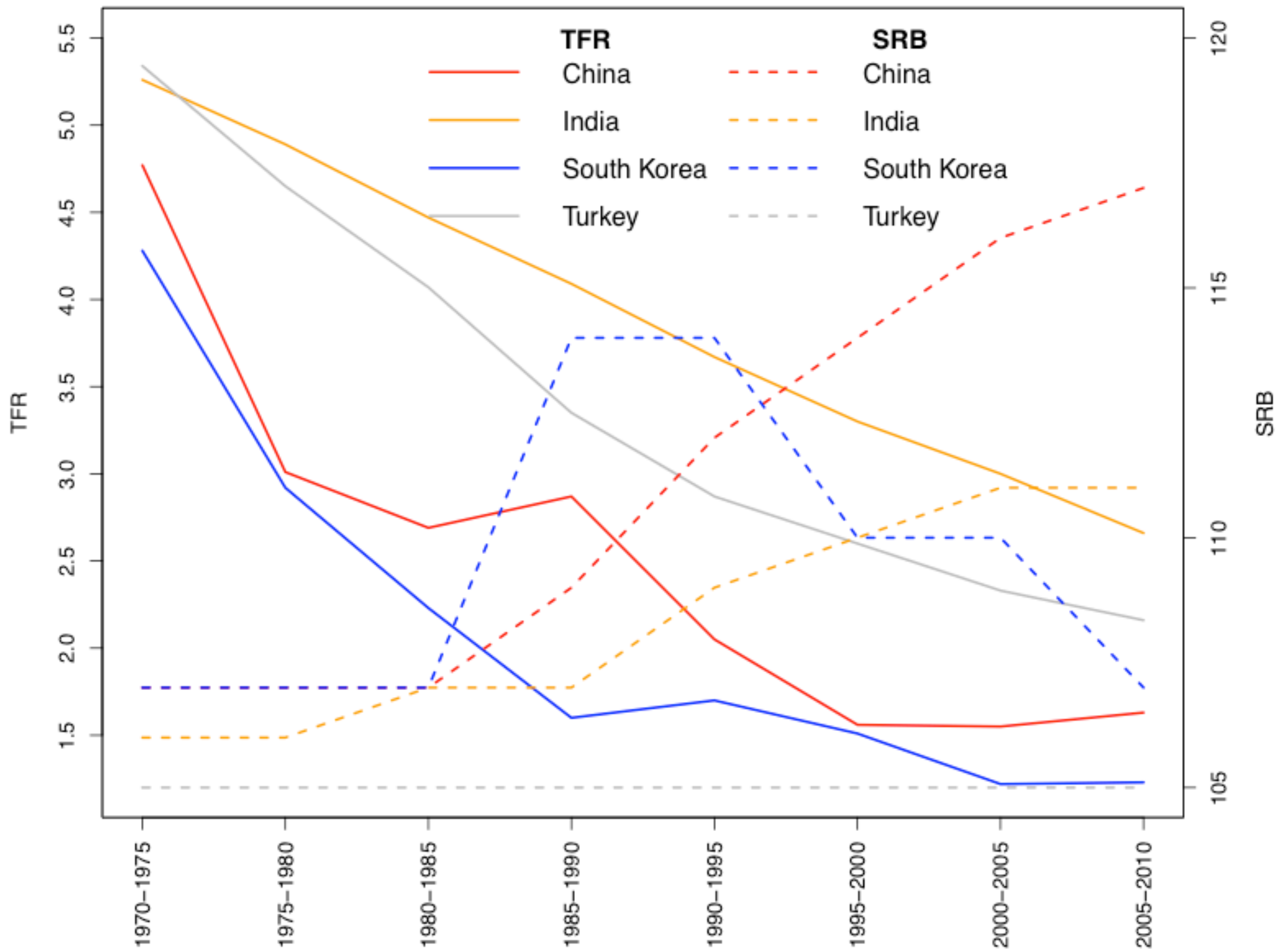

Figure 1: Total Fertility Rates (TFR) and Sex Ratio at Birth (SRB) Trends 1970 – 2010.

Source: United Nations (2013)

The causes, patterns and demographic implications of imbalanced SRBs remain the subject of much research. Extensive demographic research has paid attention to highlighting SRB levels and trends in comparative perspective across Asia and sub-regions within Asia (Duthé et al. 2012; Guilmoto 2012b; Guilmoto 2009; Attané and Guilmoto 2007; UNFPA 2007). In contrast, comparatively less attention has been paid to understanding the levels and trends of underlying son preference. The dynamics of son preference, its interactions with total family size aspirations and the availability of sex-selective abortion are important to model especially as Bongaarts notes "policymakers are hampered by an absence of methods for projecting trends in sex ratios at birth" (Bongaarts 2013, 185). Recognizing this lacuna in the literature, the focus of emerging scholarship on SRBs has been more theoretical. Guilmoto (2009) explores the micro-level fertility calculus that couples engage in that leads to skewed SRBs at the macro-level (Guilmoto 2009). Aggregating Demographic and Health Survey (DHS) data across different countries, Bongaarts (2013) posits model transition patterns of SRBs and levels of the desired sex ratio at birth (a ratio of the ideal number of sons desired to the ideal number of daughters desired) that underpin them in relation to the different stages of the fertility decline at the population-level.

Although Guilmoto's theoretical framework lucidly describes the three preconditions that cause SRB imbalances at the population level – persistent son preference, declining total family size and the spread of sex-selective abortion technology – he acknowledges that existing data preclude a "more detailed decomposition…of these distinct dimensions" in explaining observed SRB levels and trends (Guilmoto 2009, 535). Existing data and approaches make it difficult to quantify, for example, what levels and rates of change in son preference over time as well as levels of sex-selective abortion underpin observed SRB and fertility trajectories. Furthermore, limited research has sought to disentangle the impact of SSA practice on reducing fertility as distinct from a population that exclusively practices differential stopping behaviour (DSB).[4] While previous research studied the impact of DSB on slowing the fertility decline little work has quantified what impact sex-selective abortion may have in hastening fertility decline by helping couples with unmet son preferences at low parities avoid progression to higher parities. Examining counterfactual scenarios of fertility levels with and without sex-selective abortion in the presence of varying levels of son preferences and increasing access to SSA technology is challenging with existing approaches.

This paper dynamically models individual-level fertility preferences and behaviours bottom-up to examine emergent population-level SRB and total fertility patterns through the use of an agent-based computational model (ABM). Agent-based computational modelling (ABM) methods have been proposed as a valuable set of techniques to model emergent demographic phenomena through the simulation of heterogeneous individuals who follow

[4] Differential stopping behaviour (DSB) refers to fertility behaviour in which couples continue childbearing until they reach a desired number of sons by regulating their contraceptive use based on the sex composition of existing children. Several papers report the presence of DSB – manifested in higher levels of contraceptive use after bearing sons, higher levels of parity progression in daughter-only families, or high sex ratios at last birth – across different son-preferring populations (Bongaarts 2013; Retherford and Roy 2003; Clark 2000; Arnold et al. 1998; Amin and Marian 1987).

behavioural rules and adapt their behaviours in response to stimuli (Billari and Prskawetz 2003; Bonabeau 2002). In our model, individual agents have heterogeneous total parity and son preferences that we assume decline across cohorts, and practice differential stopping behaviour until technology emerges as an exogenous stimulus that diffuses steadily enabling agents to reconcile their son preferences at lower parities. In addition to a decline in son preference by cohorts, we also allow for an annual (period) decline in levels of son preference. We first fit the model with Indian mortality data derived from the UN and fertility data from three waves (1992-3, 1998-9 2005-6) of the Indian National Family Health Survey (NFHS) to find the levels and rate of son preference decline, rate of diffusion of sex-selective abortion technology, and the levels of sex-selective abortion that approximate UN estimates for SRB and fertility trajectories for India from 1980 until 2010. We extend the model until 2060 to project SRB and fertility trajectories if patterns of son preference continue to decline as observed in the NFHS data.

We find that even as son preference was gradually declining at a rate of one percent annually as data across the three waves of the NFHS indicate, the steady diffusion of SSA technology caused SRB levels to peak at 110-111 in the mid-2000s corresponding to ~3 sex-selective abortions per 100 births. Assuming that five percent of individuals with unmet son preference and access to technology practiced SSA for second parity births, half practiced SSA for third parity births and all such individuals practiced SSA by fourth and higher parity births, we estimate that SSA had a marginal impact in reducing Indian fertility levels by 1-1.5 percent starting in late 1990s. Projecting this decline in son preference forward, SRBs would fall gradually from peak levels in the mid-2000s to 108 by 2050, still remaining above normal SRBs of 104 in the period before SSA technology became available. Although the model uses data for India, it can be calibrated to any context and used to examine experimental scenarios. We then examine the impact of varying levels of son preferences and parity-specific sex-selective abortion probabilities on SRBs and fertility trends by simulating a forty-year period. These reveal that relatively low levels of son preference of around 30 percent of the population wanting one son can result in skewed SRB levels of 110-115 if individuals are willing to practice SSA at low (2^{nd} and 3^{rd}) birth parities. The impact that SSA has on reducing fertility levels varies by levels of son preferences in the population, although it is relatively marginal at 1-2.5 percent compared to a population that does not practice SSA and exclusively practices DSB.

II. Background and Theoretical Approach

1) Background

This paper contributes to a burgeoning literature that examines the reproductive preferences, behaviours, and dynamics that underlie observed SRB trajectories. This interest in the literature initially emerged from theoretical needs to understand an ostensibly unexpected trend. In recent works, this interest is motivated by policy imperatives to decipher and project the future course of SRB imbalances, given growing concern among policy makers about their negative long-run implications for marriage markets, women's status, fertility, crime and social unrest (Guilmoto 2012a; Hvistendahl 2012; Guilmoto 2010; Planning Commission of India 2012; Attané 2006; Hudson and Den Boer 2004).

From a theoretical standpoint, the steep rise in SRBs and child sex ratios across Asia and the Caucasus despite rapid modernization and development posed a severe challenge to demographic and social theory (Chung and Das Gupta 2007; Croll 2002). Why were daughters increasingly less likely to be born at an unprecedented scale in societies with norms of son preference as these societies became wealthier, had greater numbers of better educated women who joined the labour force in growing numbers and could inherit property? Within the contours of demographic transition theory the conscious reduction of marital fertility is associated with modernization, brought about by increasing returns to education, increased women's labor force participation, and opportunities for alternative old-age support outside the family. This transition to lower fertility marks a shift in the values attached to children (Kirk 1996, 364). The same modernization forces that made women educated, productive, and ensured other forms of social insurance for parents were implicitly assumed to erode the norms of son preference as well. Parents would no longer want children for extra labour, income, or social status (Croll 2002, 109) – factors that were thought to underpin son preference in pre-transitional societies. Moreover, low fertility would combine with greater industrialization and urbanization to shift families away from the extended patrilineal form, in which sons are imperative for family continuity, and towards nuclear forms with more equitable sex roles (Goode 1963). However, contrary to theoretical expectations, even as levels of fertility steadily declined in the 1990s across South Korea, China and India, skewed SRBs seemed to suggest that son preference persisted.

In the mid-1990s, SRB levels in South Korea, where pre-natal sex determination technology had diffused earlier than in China and India, peaked at 115. The SRB then started levelling off and by the late 1990s started declining (see Figure 1). By the late 2000s, SRB levels fell rapidly and by 2010 they were slightly above normal at 107. In their study of the impact of development on son preference in South Korea, Chung and Das Gupta found that societal-level modernization factors such as urbanization and educational expansion were strongly related to a secular decline in stated son preference between 1983 and 2003, as measured by a question in the Korean National Fertility and Family Health Survey that asked women if they felt it necessary to have a son (Chung and Das Gupta 2007). Chung and Das Gupta's study showed how macro-level outcomes can sometimes be misleading, as the eventual normalization in South Korean SRBs showed that son preference norms were weakening even if adverse SRB trajectories suggested otherwise. More recently, Bongaarts (2013) too found that son preference as measured by the desired sex ratio at birth calculated from the ideal fertility questions in the Demographic and Health Surveys (DHS) appeared to decline in countries across two time points for which comparable DHS data were available. The decline in the desired sex ratio is in part related to a general decline in total fertility levels that also occurred over the same period, and does not definitively indicate an eroding norm for at least one son. Nevertheless, the trend suggests that processes driving change in values about total children may also be having an impact on weakening son preferences.

Guilmoto (2009) has speculated whether South Korean SRB trajectories may be a manifestation of an "archetype transition cycle" – involving a rise, levelling off and at some stage, return to normal levels – that may eventually come about across other parts of Asia as well. The recent rise in SRBs across Asia, he argues, "resembles a diffusion process similar to that sometimes claimed to be characteristic of a fertility decline". Within this framework, he suggests that sex-determination technology can be conceptualized as "the key innovation that permits couples to resort to sex-selection in a context characterized by declining fertility and entrenched son preference" (Guilmoto 2009, 524). SRB trajectories, thus, are a complex outcome of multiple interacting forces at the micro-level with differing rates of change. For example, the 'fertility squeeze', a term proposed by Guilmoto, may be seen as resulting from a slower rate of decline in son preference norms than those about the acceptability of large families. Within this shifting fertility context, the rate of diffusion of technology then determines how many individuals facing what Guilmoto terms the 'fertility predicament' of reconciling their son preference with smaller families are actually able to do so. The specific balance of forces that cause observed trajectories however are not easily discerned from data or modelled in existing approaches. An ABM approach enables us to experiment with differing rates of change across each of these dimensions and explore their outcomes on macro-level trajectories.

2) Model's Theoretical Approach

We assume norms about total family size as well as the desired number of sons change by cohort. Given existing evidence from the South Korean case that stress the significance of period effects in influencing the decline of son preference, we additionally model a period (annual) decline in son preference in our model that applies to all cohorts.

The impact of the societal transformation and macro-level structural modernization factors such as urbanization and educational expansion on demographic behaviour are captured well by using the concept of cohort (Ryder 1965). Evidence suggests changing total fertility trends in terms of children ever born as well as contraceptive use by cohorts in the developing world across diverse contexts (Pasupuleti and Pathak 2011; Cleland, Onuoha and Timæus 1994). Pooling data across three waves of the Indian National Family Health Survey (NFHS)[5], the mean number of children by five-year cohorts fell steeply from 5.12 children ever born for women born 1940-44 to 2.99 for women born 1970-74. This indicates a declining trend of an average of just under nine percent across each successive five-year cohort born from <1945 to <1975.

Mean son preference, as measured by average of the ideal number of desired sons, also fell but at a slower average decline of 3.7 percent across successive five-year cohorts from those born 1940-44 to 1970-74. A closer look at this decline in mean son preference across cohorts reveals that the decline is largely due to a decline in the proportion of women reporting a desire for more than one son (specifically declines in ideal two or three sons). When we dichotomise this variable to see how proportions desiring at least one son vary by cohort the change is less salient at just under 0.2 percent decline across successive younger birth cohorts. This suggests that the while the decline of higher son preference, that is, an ideal preference for two or three sons may be related to a wider decline in total fertility and total desired parity, the fertility decline in itself does not necessarily erode norms surrounding a desire for one son. A desire for a higher number of sons among older cohorts may also be reflective of higher mortality conditions wherein having more than one son was

[5] The National Family Health Survey is the name by which the Demographic and Health Survey (DHS) is called in India.

essential to ensure that at least one survived to adulthood. The desire for one son may then be a better indicator of the perseverance of a social norm.

Existing work by Chung and Das Gupta (2007) has found period effects to be stronger than cohort effects in understanding the decline of son preference between 1983 and 2003 as measured by the 'necessity to have a son' in their study of South Korea. The NFHS data tell a similar story. Examining proportions desiring at least one son across five common cohorts (1955-59…1975-79) across three NFHS survey waves suggests that while decline in the desire for at least one son is small, period effects are nonetheless stronger than cohort effects.[6] We assume that son preference changes by an annual period factor in our model in addition to small changes across cohorts. In the next section we describe how these measures of son preference and rates of change in son preference from the NFHS are incorporated in the ABM.

We implement the decision-making processes leading to the practice of sex-selective abortion (SSA) at the individual level by adopting a 'ready, willing and able' (RWA) behavioural approach following the formulation presented by Guilmoto (2009). Guilmoto adapts Coale's well-known RWA approach (Coale 1973; Lesthaeghe & Vanderhoeft 2001), originally used by Coale to account for the European fertility decline in the nineteenth century, to the case of SSA. The use of SSA at the individual or couple-level can be seen as the outcome of three processes – i) the Readiness of couples to practice SSA as a consequence of declining total fertility levels which decreases the utility of having a large number of offspring; ii) the Willingness of couples to be influenced by cultural norms for male offspring in their fertility behaviour; iii) the Ability to seek SSA given the availability of relatively affordable and accurate pre-natal sex determination technology and relatively liberal abortion legislation. The specific implementation in our model of the RWA approach is detailed in section III(4).

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[6] A linear regression with log son preference (dichotomized with 0 as no son preference and 1 as a desire for at least one son) as the outcome variable and two explanatory variables (cohort and survey year), pooling data on five cohorts for which data are available across all three waves of the NFHS, shows that the survey wave variable is statistically significant at $p < 0.001$ with a coefficient of -0.01. As we include the survey year as a continuous variable (years spanning 1992.5 to 2005.5), we interpret this coefficient as a 1 percent annual decline in son preference. The cohort effect is not as statistically significant, but results in-a coefficient of -0.0016.

III. Model Description

1) State Variables

The model[7] comprises individual agents who each have an identity number (*id*), age (*x*), sex (*s*), cohort (*c*), son preference (*sp*), parity preference (*pp*), children (*p*), sons (*so*), daughters (*d*), hospital (*hosp*) and abortion (*ab*). Table 1 lists agent's state variables and their values. The model is initialized as a one-sex model with 100,000 initial female agents, but then as we model male as well as female births, from the first time-step onward the model becomes two-sex. We do not model partnership formation and focus only on fertility behaviour. While partnership formation is no doubt important for fertility behaviour, modelling partnerships and households would add complexity to the model that is not necessary for its purpose.

We initialize the simulation for the year 1980 and attempt to approximate the population age structure of females of India at the time using UN data (United Nations 2013). An agent's identity number, sex, cohort, son preference and parity preference are time-constant, that is, they are assigned to the agent at birth. Cohorts are categorized by five-years (1930-34, 1935-40…). The oldest cohort comprises individual agents who are aged 50 at the beginning of the simulation and belong to the cohort 1930, as the initial year of the simulation is set at 1980. The variable 'children' (*p*) corresponds to the current parity of the female agent. Sons (*so*) refer to the number of sons she has and daughters (*da*) to the number of daughters she has. Hospital (*hosp)* is a Boolean variable that takes a True or False value depending on whether an agent has access to pre-natal sex-determination technology. Abortion (*ab*) indicates how many sex-selective abortions a female agent has over the course of her life. An agent's age, children, sons, daughters, hospital, and abortion values are time varying and are updated at each time-step in the model.

[7] The model is jointly programmed in R and Netlogo and uses the RNetLogo package (Thiele et al. 2012).

Agent's State Variables	*Variable name*	*Values*
Identity number	*id*	1 – N
Age	*x*	0 – 50 (females)
		0 – 20 (males)
Sex	*s*	1 – male
		2 – female
Cohort	*c*	5 – year
		[1930 – 34; … 2005 – 09]
Son Preference	*sp*	0, 1, 2
Parity Preference	*pp*	1 – 6
Children	*p*	0 – 10
Sons	*so*	0 – 10
Daughters	*d*	0 – 10
Hospital	*h*	1 – True; 0 - False
Abortion	*ab*	0, 1, 2, 3, 4…

Table 1: Agent's State Variables

An initial number of children (*p*) is assigned to each agent according to her age by drawing a random number from a Poisson distribution with parameter λ_p which refers to the mean number of children for a specific five-year age group (15-19, 20-24 years, etc.). Older agents have higher values of λ_p than younger ones. λ_p values are approximated such that the initial fertility levels reflect the values prevailing in India at the start of the 1980s of ~4 children per woman. Once the number of children has been imputed, the number of sons (*so*) is assigned to each agent as follows: first, a random value from a truncated normal distribution is computed, taking 0 and *p* as the lower and upper truncation points respectively, *p/2* as the mean and a standard deviation of 1. Then, the obtained value is rounded to its nearest integer. As a result, the number of sons will range between 0 and *p* (number of children) with a higher probability of being a value close to *p/2* rather than 0 or *p*. Formally,

$$so = \begin{cases} [x] & if\ x-[x] < 0.5 \\ [x]+1 & if\ x-[x] \geq 0.5 \end{cases} \quad where\ x \sim N_{0 \leq x \leq p}(\frac{p}{2},1) \qquad [1]$$

Son preference (*sp*) is assigned as follows in the model: agents have either no preference for male offspring (*sp* = 0) or a desire for one male offspring (*sp* = 1).[8] Parity preference (*pp*) indicates a desire for a specific number of children (*pp* = 0, 1, 2, 3…up to a maximum parity of 6). When the model is initialized, both son preference (*sp*) and parity preference (*pp*) are assigned to individual agents on the basis of the cohort she belongs to, with *pp* always higher than or equal to *sp*. In our first model run, we calibrate *sp* and *pp* from NFHS data on cohort-specific son preference[9] and children ever born per woman, respectively. In subsequent model runs, we experiment with different values of *sp* and *pp* to examine their effects on SRBs. As the NFHS (1992-93) has data for cohorts born between 1940-1979, we extrapolate *sp* trends for older and younger cohorts based on the linear decline of log of son preference across cohorts observed in the data. The decline in son preference across cohorts is quite small as the relatively flat slope of the line in Figure 2 suggests.

[8] As discussed in the previous section, a dichotomous categorization of son preference may be the most effective way to capture son preference as a social norm. Nevertheless we conduct model runs with higher order sp values (sp = 0, 1 and 2) and those results are available from the authors upon request. Here we show results from the simple case of sp = 0 (no preference for male offspring) or sp = 1 (desire for one son).

[9] Son preference, as described in the theoretical approach section, indicates the proportions of women by cohort desiring at least one son.

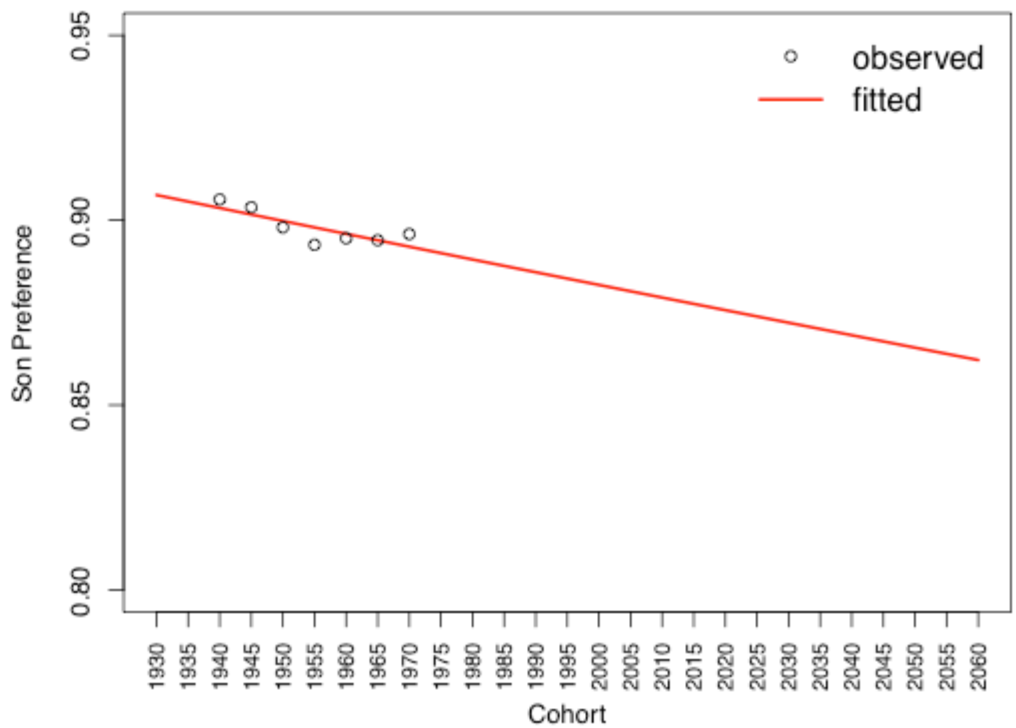

Figure 2: Son preference (proportion wanting one son) by 5-year cohorts, 1930-2060.

Source: National Family Health Survey (1992-93)

Parity preferences (*pp*) for each cohort are simulated from a Poisson distribution with cohort-specific λ_{pp_c} equal to cohort means for children ever born from the NFHS. We extrapolate the NFHS trend for older and younger cohorts by fitting a logistic function (equation 2) by maximum likelihood estimation (MLE) setting a minimum value for mean fertility at 1.8 children per woman.

$$\lambda_{pp_c} = \frac{1}{a + b^{f-k}} + 1.8 \qquad [2]$$

In equation 2, *f* is the observed values of mean children ever born for six cohorts, and *a*, *b* and *k* are parameters estimated by MLE. Figure 3 shows observed and fitted values of children ever born, clearly showing a decline in mean children ever born across successive five-year birth cohorts.

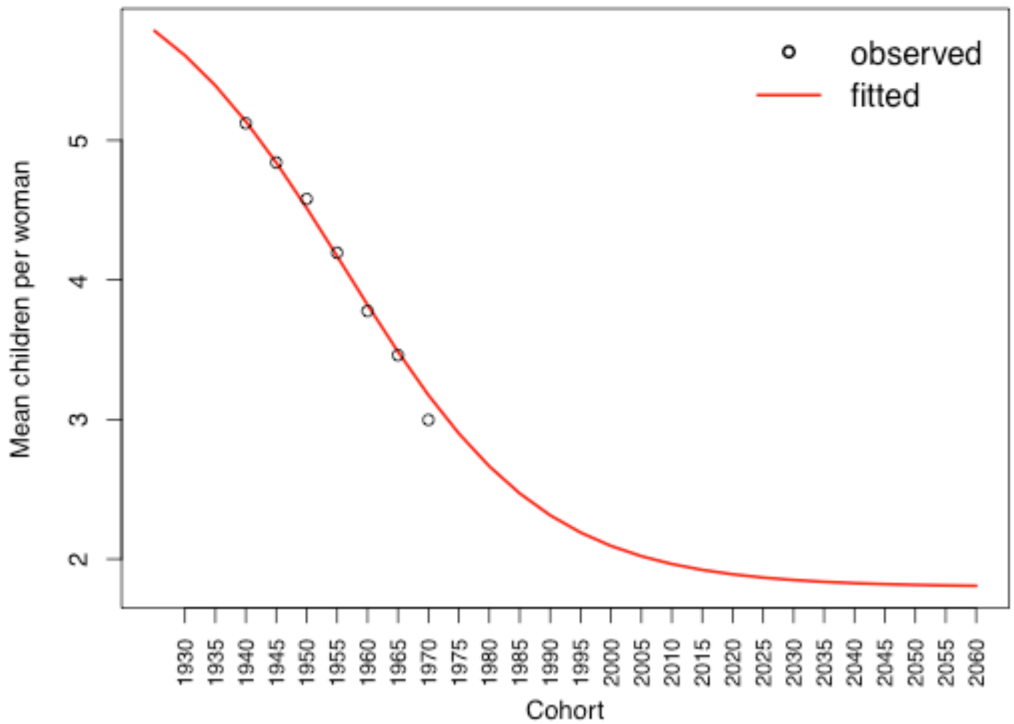

Figure 3: Mean children per woman by five-year cohort, 1930 – 2060.

Source: Pooled data from National Family Health Survey (1992-93, 98-99, 2005-06)

We intentionally approximate *pp* with observed actual childbearing behaviour (children born per woman) as *pp* drives childbearing behaviour in our model, as will be described in the next section. It attempts to capture both a preference for a certain number of children as well as the ability to implement parity control. We recognize that older cohorts may not have had a preference, per se, of moving to higher parity births, but this may have been the result of constrained access to contraception. Nevertheless, the progression to higher parities was not only a consequence of less contraceptive access and control but also a desire, for economic, demographic and cultural reasons, for larger families. Higher values of λ_{pp_c} for older cohorts than for younger cohorts reflect these cohort-based changes in the values associated with total family size and also allow for looser parity control in the reproduction procedure in the model.

Son preference declines as a function of cohort and period effects. The extent to which son preference declines by each cohort can be controlled by the parameter 'ß'. ß is a proportional change parameter, which affects how proportions with son preference change with respect to the preceding cohort. As equation [3] shows, 'ß' determines to what extent son preference remains unchanged (ß = 1), declines (ß < 1), or increases (ß > 1) across cohorts. The period decline parameter ρ is a proportional decline factor like ß, which acts on all cohorts at each time-step or tick corresponding to one year. The proportion of women having son preference in a particular cohort at a particular point in time is given by:

$$sp_{c,t} = \beta \cdot sp_{c-1} = \beta \cdot (1-\rho) \cdot sp_{c-1,t-1} \qquad [3]$$

2) Procedures

The model contains two procedures for agents: ageing and reproduction carried out at each time-step (or tick) in the model. Each tick corresponds to one year. The simulation starts in the year 1980. We first simulate 30 years (until 2010) and then project forward until 2060 to explore implications of existing trends. At each time step in the model an agent ages by one year. Since we focus on fertility, all female agents die off in our model after reaching the maximum age of reproduction set at age 50. Male agents die off at age 20. Before the age of 50 for females and 20 for males, the risk of death is determined by UN life-table five-year age-specific death rates corresponding to that year for India (United Nations 2013). By simulating male agents until age 20, we can account for child and young adult mortality for males. If a woman with a son preference had her son die in childhood, this allows her to attempt having another child.

The reproduction procedure models conception and birth. The risk of childbirth $h(x,p)$ for each agent is determined by her age (x) and her current parity (p). The age- and parity-specific hazard rates used in the model are Nelson-Aalen cumulative hazards estimated from a multistate model based on the NFHS estimated until parity 6 by which the vast majority of women in the survey complete childbearing (Datta and Satten 2001). As shown in equation [4], for parities 6 and higher, the parity transition rates have been modelled assuming an exponential decrease with respect to the risk of childbirth at parity 5, in such a way that $h(x,6) = h(x,5)^{1.5}, h(x,7) = h(x,5)^2$ and so on.

$$h(x,p)_{p\geq 6} = h(x,5)^{1+\frac{p-5}{2}} \qquad [4]$$

The sex of the birth is determined at the point of conception by a natural probability of 0.51 for male births and 0.49 for female births, which corresponds to an SRB of 104. We model sex-differential birth stopping behaviour and as our model moves in time, we also model the opportunity for female agents to have sex-selective abortions in case they have not met their desired son preference within the constraints of their parity preference. Details of how both these behaviours are modelled in our agents are described in the next sections.

3) Differential Stopping Behaviour (DSB)

Although the parity transition rates we obtain from the NFHS are not sex-specific, we model differential stopping behaviour (DSB) through each female agent's son preferences (*sp*) and parity preferences (*pp*). DSB in son-preferring societies is reflected in higher risk of parity progression and lower probability of using contraception for those without sons compared to those with sons. In the model, female agents having unmet son preferences are less likely to practice contraception and are more likely to move to higher parities.

$$if\left(sp_i < so_i\right) \Rightarrow h(x,p) = \gamma \cdot h(x,p) \qquad [5]$$

As [5] shows, if the current number of sons (*so*) of female agent *i* is less than her son preference (*sp*), her age and parity-specific risk of childbirth $h(x,p)$ is increased by a factor of γ where $\gamma > 1$. If $\gamma = 1.3$, this implies that a woman with unmet son preference experiences a fertility risk that is thirty percent higher than the standard age- and parity-specific hazard $h(x,p)$ that normally determines her parity transitions in the model. γ may be conceptualised as a son preference intensity parameter.

When female agents realise their son preference and their parity preferences, their birth risk is adjusted down by a factor of α where $\alpha < 1$, indicating a reduced risk from the standard parity transition schedule $h(x,p)$.

$$if\{(sp_i \geq so_i)\,\&\,(p_i \geq pp_i)\} \Rightarrow h(x,p) = \alpha \cdot h(x,p) \qquad [6]$$

For female agents with no son preference ($sp = 0$) the first condition in [6] is always met. Their birth risk is hence only reduced when they have met their desired parity. Until then they are subject to the standard age and parity transition risks $h(x,p)$.

4) Modelling Sex-Selective Abortion (SSA)

Using the 'Ready Willing and Able' approach, agents practice SSA when – i) they are 'ready' to consider sex-selection as a consequence of declining total family size desires at the individual-level. This is captured by declining parity preferences *pp* by cohorts in our model; ii) they are 'willing' to use technology because of they consider it important to bear male offspring (*sp* in our model); iii) they are 'able' to practice sex-selection due to the availability of pre-natal sex determination technology that allows them to determine the sex of the foetus safely, effectively and affordably and abort unwanted pregnancies. We model the spread of technology as an exogenous shock that emerges at a particular point in time and at first slowly then steadily diffuses as a function of time (*t*) before levelling off when almost all agents have access to it. We use the logistic diffusion model, widely used to describe the diffusion of new technologies, to model an agent's 'ability' or in other words their access to medical facilities where they may obtain SSA (Geroski 2000).

$$Ability = \frac{\exp(\upsilon \times (t - \phi))}{1 + \exp(\upsilon \times (t - \phi))} \qquad [7]$$

In eq. [7] 'Ability' simulates the proportion of agents at a particular time-step gaining access to pre-natal sex-determination technology, υ determines the slope or rate of increase, ϕ the inflection point, and t the time-step in the simulation (e.g t = 0, 1, 2…30 for a 30-year simulation covering a period of 1980 - 2010) of the logistic diffusion curve (Figure 4).

Field evidence indicates that pre-natal sex determination technologies became available in India in the mid-1980s but started spreading over the course of the 1990s and had spread widely by the late 1990s and early 2000s (Patel 2007; Arnold, Kishor and Roy 2002). To approximate this technological diffusion timeline we set $\upsilon = 0.6$ and $\phi = 14$. At the initialization of the model no agent has access to technology (*hosp* = False), but as 'Ability' gets recalculated at each time-step, a random number for each agent is redrawn, which when less than 'Ability' sets *hosp* = True for that agent.

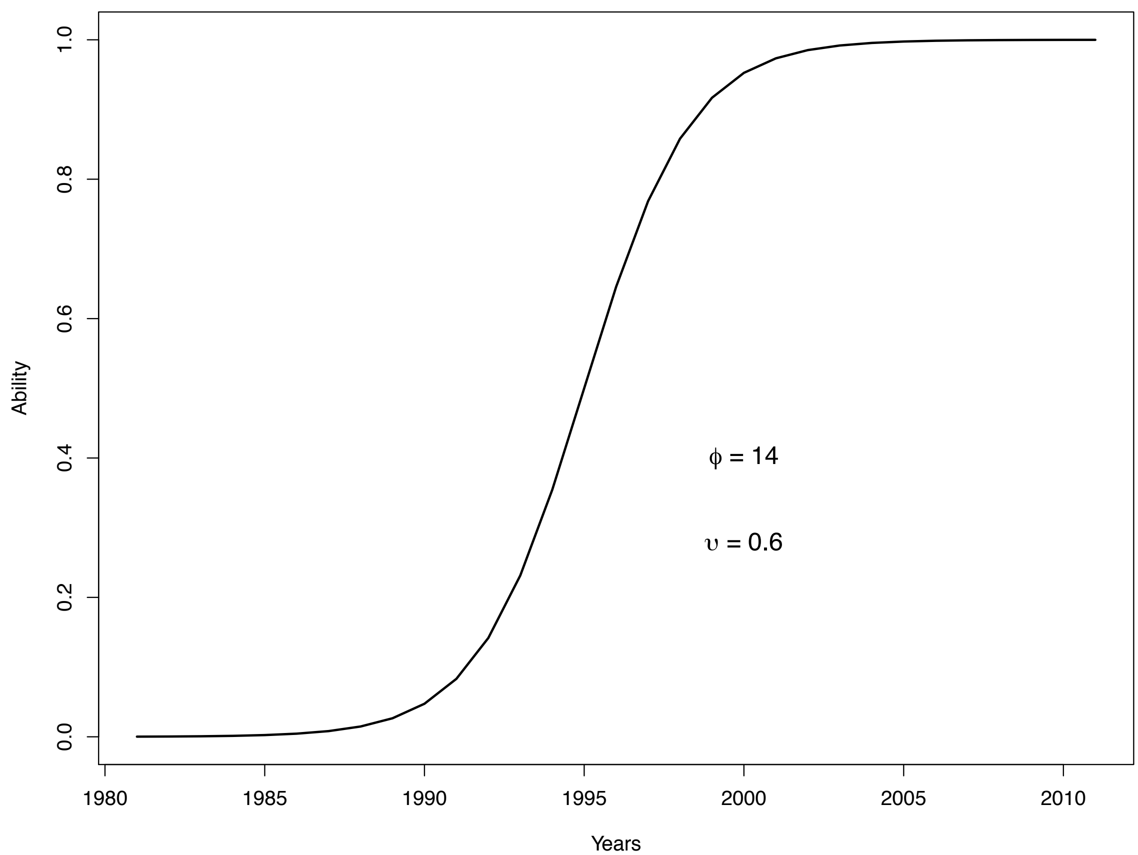

Figure 4: Logistic functional form determining diffusion of technology enabling sex-selective abortion

Agents are only able to sex-selectively abort female foetuses if their son preference is unmet ($sp_i < so_i$) and can do so if technology is available to them (*hosp* = True). The probability to abort (*abprob)* is as parity-specific, which can be interpreted at the population-level as how many agents with unmet son preferences and access to technology choose to use it at a particular parity. SRBs rose in India when fertility levels were still relatively high at levels over 2.5 (Guilmoto 2009) and SRBs disaggregated by parity showed that SRB levels at first and second parity births were normal but became skewed at third parity and higher (Arnold, Kishor and Roy 2002). This suggests that individuals were not likely to practice sex-selective abortion for their first or even second birth, but largely from the transition from second to third birth, that is, at third parity and higher. The extent of the 'fertility squeeze' in the Indian case is clearly different from the Chinese case where the one child policy encourages individuals with unmet son preferences to abort at lower parities (Li, Yi and

Zhang 2011). Table 3 lists the relevant parameters that control the three factors – son preference, fertility decline and SSA availability – in the model.

Category	*Parameters*	*Description*
Son preference	β	Rate of change of son preference by cohort
	ρ	Rate of change of son preference by time
	γ	Son preference intensity
Fertility decline	α	Parity-control
	pp	Cohort-specific parity preference distribution
Sex-selective parity control	*abprob*	Probability of sex-selective abortion by parity
	Ability: ϕ *Ability:* υ	Onset of technology availability Rate of technology diffusion

Table 2: Agent-based Model Parameters

IV. Results

We present results from simulations that address four questions: 1) What are the levels and intensity of son preference and SSA rates that underpin observed SRB and fertility trajectories in India from 1980 to 2010 according to our model? 2) What might future trajectories looks like given observed patterns of change? 3) What are the minimum levels of son preferences and abortion rates in a context of fertility decline and technological diffusion that produce skewed SRBs? 4) How does the presence of sex-selective abortion probabilities impact fertility levels?

To answer the first question, we calibrate the model with cohort-specific son preferences and parity preferences from three waves of NFHS data and shown in Figure 2 and Figure 3 respectively. We estimate period decline factor in son preference derived from exploiting the differences in cohort-specific son preference levels across three different survey waves.[10] The average annual decline in son preference (ρ) for all cohorts estimated from the NFHS is 1 percent. Figure 5 shows SRB and fertility trajectories averaged over six simulation runs with 100,000 initial agents each with the following parameters values: $\gamma = 1.3$, $\alpha = 0.6$, $\upsilon = 0.6$, $\phi = 14$, $\rho = 0.01$, *abprop* = 0 for first, 0.005 for second parities, 0.5 for third parity and 1 for fourth parity and higher. These values for *abprob* specify that five percent of those with unmet son preferences will have a sex-selective abortion as they transition from first to second parity births (that is, at their second parity) if they have access to technology, half of those with unmet son preferences will have a sex-selective abortion as they transition from second to third birth (that is, at their third parity) if they are able to, and all those who are able to will intervene at fourth parity (transition from third to fourth birth) and higher. Assuming the same rates of decline in son preferences and fertility as seen in the NFHS, we project SRB and fertility levels forward until 2060 (shown with the dotted line). Figure 5 also shows a counterfactual scenario that addresses what fertility and SRB levels might have been in the absence of sex-selective abortion with agents practicing differential stopping behaviour only. In this case all parameters are held the same as before except *abprob*, which is set at 0 for all parities.

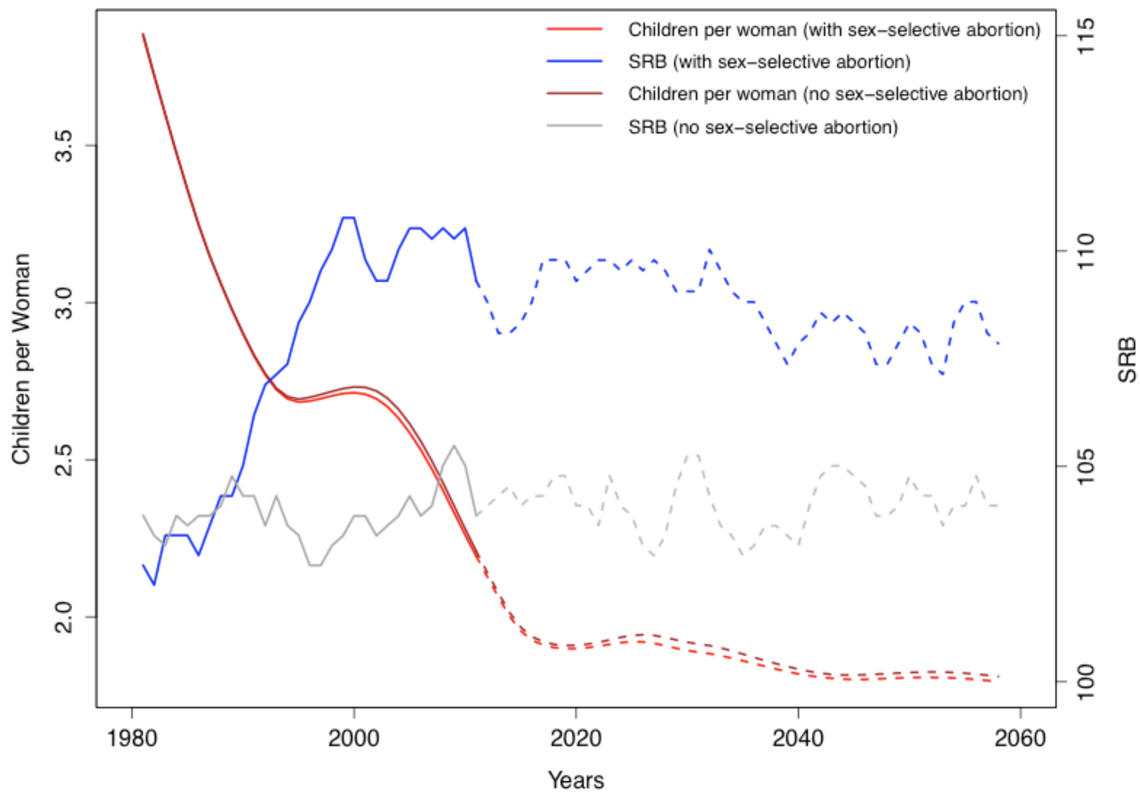

Figure 5: Simulated fertility and sex ratio at birth trajectories, 3-year moving averages. 1980 - 2010 (solid line) 2011-2060 (dotted line).

The solid blue line shows how SRB levels remain relatively stable around 104 until the early 1990s and start rising steadily in the late 1990s, reaching their peak levels of 111 around 2005. These levels and trends approximate UN SRB trends for India (Figure 1). For births between 2000-2006 in NFHS 2005-06, the SRB was 109 and sample registration system estimates indicated SRB levels to be 112 for 2004-06 (Guilmoto 2009). Our model clearly shows how even as son preference is gradually declining by one percent annually after 1980, the steady diffusion of pre-natal sex-determination technology among agents predominantly willing to practice sex-selection abortion at third parity and higher can result in skewed SRB levels over 110. As has been noted by scholars of SRB trends, in contrast to the Chinese case where policy forced a sharp fertility decline, Indian SRB levels rose to levels of 110 at fertility levels well above replacement levels at over 2.5 children per woman. Peak SRBs of 111 in the simulation correspond to around 3-3.5 sex-selection abortions per 100 births. By the early 2000s our model assumes that the diffusion of technology is complete, and as the proportions gaining access to technology level off, SRB levels stabilize and then start registering a decline in the late 2000s.

From 2010 onward, assuming a continuation of the rate of son preference decline and abortion probabilities same as before, SRB levels are projected to slightly reduce and stabilize at levels of 109 until 2030, and hover around 108 until 2050. This entails a decline in sex-selection abortion rates of 3.5sex-selection abortion per 100 births at peak levels of 111-112 to levels of 2.5 by 2030, falling further to levels between 2.2-2.3 by 2060.

In the counterfactual scenario, where we assume that agents did not have access to sex-selection abortion, the grey line in Figure 5 illustrates that SRB levels remain stable at 104-105 throughout the 80-year simulation.

Although our model is specified to converge to fertility levels of 1.8 children per woman (see equation 2, figure 3), fertility levels decline steadily until 2020 (Figure 5, solid red line) after which the rate of decline slows down (Figure 5, dotted red line). Fertility levels appear to stabilize at levels of 1.80-1.81 children per woman by the mid 2040s. Interestingly, the differences in fertility levels in the presence versus the absence of sex-selective abortion (brown line, Figure 5) are not particularly big indicating that the use of sex-selective abortion likely contributed marginally at just over 1-1.5 percent in hastening the fertility decline starting in the 2000s in India. Agents largely make use of SSA at third parity and higher, which likely explains why fertility levels between the two scenarios do not diverge to a great extent. These differences in the fertility trajectories first appear around the early 2000s and continue moving forward until the 2050s. From 2020 onward, the differences remain slightly over 1 percent, stabilizing at levels of 1.82 in the counterfactual no SSA scenario compared to 1.80 with SSA.

In our next set of results we experiment with varying son preference levels in the context of different parity-specific abortion probabilities to examine their impact on SRB trends over a forty-year simulation.

Figure 6 reports results from different experiments when different proportions of agents have son preference averaged over six simulation runs, each of forty years with 100,000 initial agents with the following parameters values: $\gamma = 1.3$, $\alpha = 0.6$, $\upsilon = 0.6$, $\phi = 14$, with a decline in parity preferences *(pp)* from 4 to 1.5. In these experiments, however, we hold son preferences constant across cohorts (no decline scenario, $\beta = 1$) and over time, and specify three sex-selective abortion scenarios – in Figure 6 (a), we specify that 100 percent of those with unmet son preference and technology access practice SSA for third parity births and higher. In 6(b), we assume that half practice sex-selective abortion for second parity births, and for third parity births and higher all those with unmet son preference and access to technology practice SSA. In 6(c), we assume that all agents intervene early with abortion probabilities set at 100 percent for parity two and higher. Figure 7 shows the levels of SSA (reported as the number of sex-selective abortions per 100 births) that correspond to different SRB levels, pooling data from all simulations with different son preference levels.

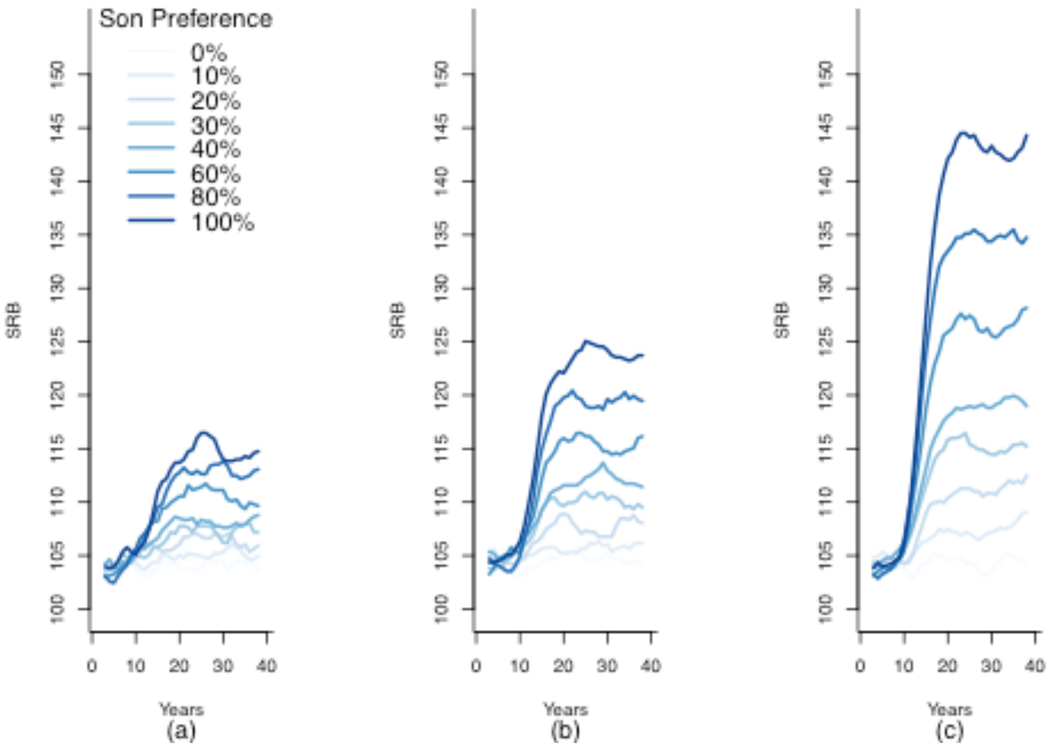

Figure 6 (a, b, c): Simulated sex ratio at birth trajectories, 5-year moving averages, over 40 years with varying son preference distributions and varying abortion probabilities. In (a) 100 percent of those with unmet son preference and technology access practice SSA at third parity births and higher; (b) 50 percent of those with unmet son preference and technology access practice SSA at second parity births and 100 percent for third parity and higher; (c) 100 percent practice SSA at second parity births and higher.

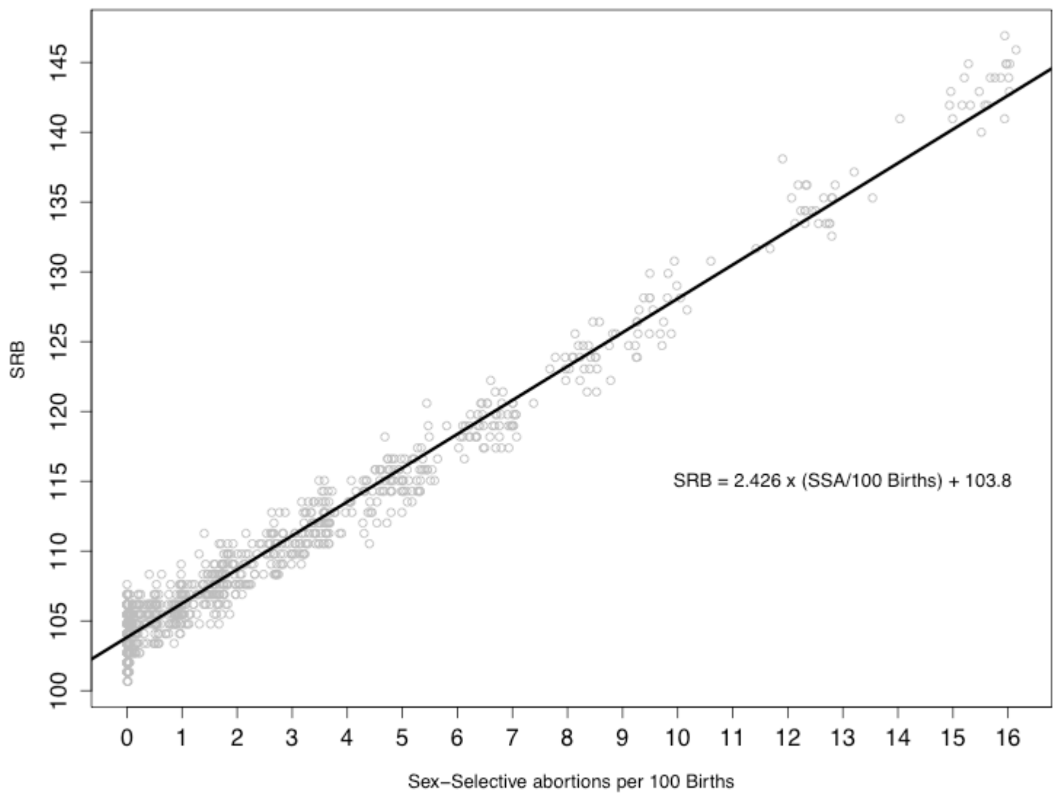

Figure 7: Sex-selective abortion rates (SSA per 100 births) and their corresponding sex ratio at birth levels. Data pooled across all simulation experiments with varying son preferences and abortion probabilities.

Figure 6 illustrates how SRB trajectories in each scenario start out at normal levels of 104-105 but sharply diverge from these levels as an interaction of the levels of son preferences and the parity at which able agents are ready to practice SSA. It is clear that the parity at which able agents intervene strongly matters – even relatively low levels of son preference can result in significantly skewed SRBs when able agents are ready to practice SSA at low parities. At mean son preference levels of 0.30 with 30 percent of individuals wanting one son, assuming all willing and individuals practice SSA only for third parity births and higher SRB levels rise to maximum levels of 108 when technology diffusion peaks, stabilizing then at levels of 107 (Figure 6(a)) corresponding to 1-1.5 sex-selective abortion per 100 births (see Figure 7). The same levels of son preference assuming half willing and able agents practice SSA for second parity births and all do by third and higher parity births, SRB levels stabilize at 110 (Figure 6(b)) corresponding to 2.5-2.8 sex-selective abortions per 100 births (Figure 7). In the most severe scenario, assuming all willing and able individuals practice SSA from second birth parity and higher SRB levels stabilize at 115 (4-5 sex-selective abortion per 100 births). At this intensity of SSA, SRB levels reach 145 when 100 percent of the population has son preference, levels that have seldom been recorded in national-level population statistics. Looking at Figure 7, SRB levels of 145 correspond to around 15 sex-selective abortions per 100 births. The slope of the line fitted to the data in Figure 7 indicates that each sex-selective abortion per 100 births increases the SRB on average by 2.4.

These experiments let us examine different son preference levels and SSA behaviours that result in SRB levels and trends. When assessing which underlying behaviours best describe different real-world contexts, it is important to bear in mind that the parity at which individuals choose to practice SSA is a consequence of how 'squeezed' they feel with regard to the total number of children they are ready to have whilst being able to realize their son preferences. In the Chinese case, this squeeze is strongly experienced by individuals as a result of a policy that restricts total number of children resulting in significantly higher SRBs of 120 (mainland areas 2004 estimates) in contrast to the Indian case where SRB levels were around 110 in the absence of a policy mandated squeeze. This suggests that individuals are more likely to practice SSA for second or even first birth parities in China compared to India where observed SRB levels are compatible with SSA delayed to higher parities.[11] How much then does the practice of sex-selective abortion hasten the fertility decline? By enabling individuals who might otherwise have practiced differential stopping behaviour to abort unwanted pregnancies, sex-selective abortion likely has an impact on reducing fertility levels faster than they might be in the absence of such technology. Figure 8 reports results from simulation experiments described before looking at the impact of different levels of son preferences (Table 3) and SSA behaviours on fertility levels. The y-axis reports the average value of children per woman reached in the last five-years of the simulation (time-steps 36-

[11] These national-level estimates mask significantly regional variations in both China and India. The 1% survey estimates from 2004 for Chinese regions reveal steep imbalances for Jiangxi (137), Anhui (132) and Hunan (127). Similarly for India the northwest where son preferences has been often noted to be significantly stronger than the rest of the country SRB levels in Punjab (123.8, 2004 Sample Registration System estimates), Delhi (118, 2007 Civil Registration Estimates), Haryana (120.9, 2005 Civil Registration System estimates) were higher than national levels (estimates from Guilmoto 2009). Long-run time-series are not as readily available for states and sub-regions. Nevertheless when SRB and fertility levels are known, the model can help gauge underlying son preferences and SSA behaviour.

40). The points refer to the actual averages from six simulation runs and the lines are linear regression lines fitted to the data.

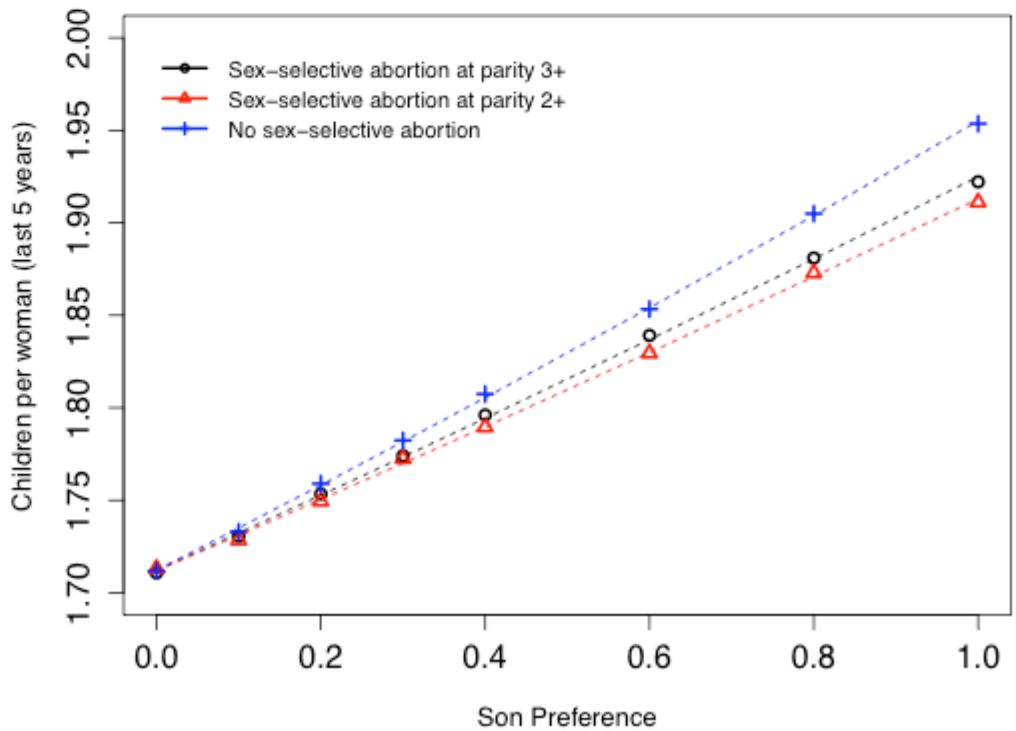

Figure 8: Fertility levels (children per woman) reached in last five-years of simulation across varying mean son preferences and abortion probabilities.

Figure 8 shows that even in the presence of SSA, son preferences keep fertility levels higher than what they would be in their absence. The practice of SSA does not guarantee a male conception; it acts by reducing the probability of carrying an unwanted female pregnancy to term. While the practice of SSA does reduce fertility levels (~1-2.5 percent at mean son preference levels > 0.50) compared to the differential stopping behaviour only scenario, this effect is marginal even when individuals are willing to practice SSA at low parities for their second birth. With no son preference in the population, fertility levels fall to around 1.71 children per woman. The slope of the blue line regressing fertility on son preference levels in the absence of sex-selective abortion indicates that there is a 13 percent difference in fertility levels between populations with a mean son preference of 0 versus that with son preference = 1, that is, 100 percent of the population desire a son. At son preference of less than 0.4 the differences between the three scenarios – no sex-selective abortion, only differential stopping behaviour (blue line), assuming all those who are willing and able resort to SSA at third parity births and higher (black line), all those willing and able resort to SSA at parity two and higher (red line) – is not particularly large. As son preferences become more widespread in the population, fertility levels in the no sex-selective abortion scenario diverge from both SSA scenarios (parity 3+ and parity 2+) with the greatest deviations from SSA as expected at parity 2 and higher scenario. At 100 percent son preference, fertility levels fall to 1.953 with only differential stopping behaviour and no SSA. Assuming individuals practice SSA at parity 3 and higher, fertility falls to 1.922, or 1.6 percent lower than in the absence of SSA. Assuming individuals practice SSA at parity 2 and higher, fertility falls by an additional 0.6 percentage points marginally lower to 1.911, a difference of 2.2 percent from the no SSA scenario.

V. Discussion

What will be the future course of SRB trajectories? What will be the impact of the rapid diffusion of pre-natal sex determination technology and abortion access in populations where son preference exist and people seek to restrict their total family size? When will SRB levels, which appear to show an incipient decline in some contexts (Das Gupta, Chung and Li 2009), become normal? While each geographical context has its own set of underlying factors that will determine the course of future trajectories, the ABM presented here provides a valuable computational tool that will enable researchers to test the implications of unique sets of micro-level forces – individual fertility preferences, behaviours, and technology use – to explain both current macro-level trends as well as project future ones.

By calibrating the model for the Indian case, we find that declining son preference and the practice of sex-selective abortion predominantly for third parity births and higher plausibly underpin observed SRB and fertility trajectories in India. In Guilmoto's transition paradigm, India is currently in the phase where SRBs have stopped rising and are levelling-off. Projecting these behaviours forward, we find that while fertility and SRBs will both continue to decline, SRB decline will be much more gradual. To be able to witness the SRB turnaround as South Korea did in the 1990s, son preferences will need to decline significantly faster than they appear to have in the past three decades. Decomposing the levels of professed son preference across two time points, Chung and Das Gupta found the remarkable decline of son preference in South Korea to be driven only partially by population compositional change, that is, the greater presence of a more urban, educated individuals, and largely by wider changes in norms, which they argue came about as an outcome of a societal-level modernization that happened when the country had reached high levels of development. Although India remains quite far from comparable levels of development, a number of changes to complement broader societal-level modernization forces might potentially impact the future directions of SRB trajectories in India and other contexts such as China, Vietnam, Pakistan, and the Caucasus countries.

These changes might include better enforcement of existing laws that ban the use of pre-natal sex determination technology, which would reduce the likelihood of practicing SSA. Although some have suggested that such laws kept child sex ratios and SRBs from worsening (Nandi and Deolalikar 2011), demographers have been largely skeptical of the impact of such legislations on curbing the practice of SSA. Others have expressed concern that strengthening punitive methods may adversely affect access to safe and liberal abortion for all women and require active state intervention and monitoring that may encroach on rights to privacy in reproductive decision-making (Patel 2007; Zilberberg 2007). Pre-natal sex-determination technologies continue to become more accurate at earlier stages of the pregnancy, with new procedures such as the analysis of fetal DNA that are minimally invasive and can be carried out at home. Bongaarts notes that "technologies are rapidly evolving and become more accessible and affordable even to the poorest couple" (Bongaarts 2013, 201). The rapid proliferation and ease of access will only make the use of such technologies harder to monitor, and raises the distinct possibility that in settings where son preferences exist and technology has yet not completely diffused, the practice of SSA may still rise. Directly tackling son preference offers a more long-term solution to demographic sex imbalance. Integrating social awareness campaigns that promote gender equality and challenge son preference norms within wider family planning policies and initiatives, financial incentives and support systems for parents whose son preferences is rooted in economic reasons, and others to encourage investment in daughters' education and health provide ways to accelerate the erosion of the social norm (Das Gupta et al. 2003).

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