Excess under-5 female mortality across India: a spatial analysis using 2011 census data

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Summary

Background Excess female mortality causes half of the missing women (estimated deficit of women in countries with suspiciously low proportion of females in their population) today. Globally, most of these avoidable deaths of women occur during childhood in China and India. We aimed to estimate excess female under-5 mortality rate (U5MR) for India's 35 states and union territories and 640 districts.

Methods Using the summary birth history method (or Brass method), we derived district-level estimates of U5MR by sex from 2011 census data. We used data from 46 countries with no evidence of gender bias for mortality to estimate the effects and intensity of excess female mortality at district level. We used a detailed spatial and statistical analysis to highlight the correlates of excess mortality at district level.

Findings Excess female U5MR was 18·5 per 1000 livebirths (95% CI 13·1–22·6) in India 2000–2005, which corresponds to an estimated 239 000 excess deaths (169 000–293 000) per year. More than 90% of districts had excess female mortality, but the four largest states in northern India (Uttar Pradesh, Bihar, Rajasthan, and Madhya Pradesh) accounted for two-thirds of India's total number. Low economic development, gender inequity, and high fertility were the main predictors of excess female mortality. Spatial analysis confirmed the strong spatial clustering of postnatal discrimination against girls in India.

Interpretation The considerable effect of gender bias on mortality in India highlights the need for more proactive engagement with the issue of postnatal sex discrimination and a focus on the northern districts. Notably, these regions are not the same as those most affected by skewed sex ratio at birth.

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Introduction

The scientific literature on missing women (estimated deficit of women in countries with suspiciously low proportion of females in their population) has long identified China and India as the countries that account for most of the world's female deficit.[1,2] This deficit is increasingly due to prenatal sex selection through selective abortions, but the overall number of excess female deaths (postnatal discrimination) has not declined over the past 20 years and still accounted for half of new cases of missing women in 2010.[3] Most excess mortality is concentrated during the first years of life, a period during which girls actually have a biological advantage over boys in terms of mortality.[4] Furthermore, as argued in *The Lancet Global Health*, the burden of mortality tends to vary widely within countries or regions and reliable mapping of the geography of child mortality is needed.[5,6]

However, many countries, such as China and India, do not have reliable civil registration data and indirect estimates of excess female mortality are exclusively from surveys with few samples. Several studies[7,8] have provided estimates of excess female mortality and of the number of excess under-5 deaths at national level. In a country such as India that is characterised by high socioeconomic and cultural diversity, national and regional figures provide an incomplete idea of local health and gender challenges. A pioneering study[9] of under-5 mortality rates (U5MRs) in India provided various estimates by sex at district level. However, the estimated sex ratio of U5MR (used as a proxy for excess female mortality) understates the true extent of excess female mortality, since female U5MR is always substantially lower than is male U5MR, in the absence of discrimination. This estimate is also unreliable because of the size of samples available for indirect estimation. The geographical distribution of these excess mortality estimates suggests that an extreme amount of excess female mortality exists in parts of southern or eastern India where gender bias is at its lowest, whereas no excess mortality is observed in the parts of northern India where it would be expected.

In this study, we aimed to apply classic methods of indirect estimation of child mortality and sex differentials to a new set of exhaustive fertility data released by the 2011 census of India, to examine the statistical consistency of these new estimates and identify clusters of postnatal discrimination against young girls, and to

Research in context

Evidence before this study

We searched PubMed using the terms "child mortality", "mortality", "district", and "India" and identified 264 studies published between Jan 1, 1970 and Dec 31, 2017 in English. Among them, three studies calculated excess female under-5 mortality rates (U5MRs) worldwide and provided national estimates. We found one study with district-level estimates of excess female mortality in India. However, these data, which are from the 2007–08 District Level Household Survey-3, have overwhelming sample-related issues and are not consistent. The National Family Health Survey-4, done in 2015–16, is equally unable to provide subregional mortality estimates because of the scarcity of samples at district level.

Added value of this study

This study is the first to offer a reliable set of disaggregated estimates of excess female U5MR for India and of the corresponding number of annual excess deaths in 2000–05. It provides detailed mapping of specific geographical patterns of under-5 excess mortality across India's 640 districts. Our analyses show extreme diversity in excess female mortality across the country; large areas report no gender bias in child mortality, while four states in northern India account for two-thirds of all estimated excess under-5 female deaths. Additionally, our statistical analysis highlights the demographic, economic, and sociocultural determinants of inter-district variations, with high fertility, gender inequity, and low socioeconomic development emerging as major predictors of excess mortality of girls.

Implications of all the available evidence

Our study provides a graphic illustration of the extent and distribution of postnatal sex selection in India, a discriminatory mechanism that is largely invisible without detailed statistics. It also shows that, without excess female mortality, the country would have reached the 2015 target of Millennium Development Goal 4, set at 42 deaths per 1000 births. Excess female mortality warrants more attention in policy discussions around gender bias in India because it represents a challenge for the achievement of the Sustainable Development Goals. Our research calls for the introduction of more systematic monitoring of sex differentials for child mortality through improved registration and analysis of sex differentials in mortality. More qualitative research is also essential to better elucidate the mechanisms underlying excess female mortality.

statistically analyse our estimates to identify the main regional factors associated with excess female U5MR in India.

Methods

Data sources

District-level U5MRs are not available from demographic surveys in India; therefore we used census data to indirectly estimate these U5MRs. We used the fertility series data from the census of India 2011[10] to apply the summary birth history method (or Brass method).[11,12] Fertility series data provide information for all children ever born and surviving at the time of enumeration by the age of the mother and the timing of fertility required for the application of the estimation method.

See Online for appendix

We used district-level indicators from the census, such as literacy rates, religious and social composition, household amenities, labour force participation rates, and occupations in our regression analysis. We also used other indicators that have been estimated from census data at district level in previous research, such as fertility rates[13] and sex ratio at birth.[14]

To model the "normal" (expected) relation between male and female U5MRs, we used U5MR by sex from the 2015 revision of World Population Prospects (1950–2015)[15] in 46 countries, which are official UN population estimates and projections prepared by the UN Department of Economic and Social Affairs. We chose specific countries and periods according to three criteria: countries without known prenatal or postnatal sex selection in mortality, countries with a reliable civil registration system, and periods where mortality overlaps with mortality rates in Indian districts during the 10 years before the 2011 census.

Indirect estimation of under-5 mortality

We used the Brass method to estimate U5MRs. We first calculated the mean number of children ever born and children surviving as reported by women, classified by age group. Using data on women's age at their last birth, we calculated the mean age of the age-specific fertility schedule. We then used these inputs and the coefficients from the International Union for the Scientific Study of Population estimation manual[12] to calculate U5MRs and their reference period (appendix pp 2–3).

The application of the best estimation strategy for the 2011 census data is described in the appendix (pp 4–5). Census data for some isolated districts were also identified as statistical or spatial outliers. We used four criteria to detect these outliers: small size of the mothers' sample, range of excess female mortality, unlikely sex ratio of children ever born, and strong spatial discontinuity. We removed data when two or more of these criteria were met (3·5% of districts) and re-estimated excess mortality as the spatial average of U5MR in adjacent districts. The statistical findings presented (spatial autocorrelation and regression) are strictly identical with or without these re-estimated values.

Estimation of excess mortality

We defined the excess female U5MR as the difference between observed and expected female U5MRs in India. The expected U5MR is calculated on the basis of the existing relation between male and female U5MRs observed in countries without known gender discrimination in different time periods. The expected female U5MR is calculated from a quadratic model on the relation between male U5MR (independent variable) and female U5MR (dependent variable) in 46 countries for a total of 447 time periods.

The fitted model is:

$$_5q_0^f = A \times (_5q_0^m)^2 + B \times {_5q_0^m} + C$$

where $_5q_0^f$ is female U5MR, $_5q_0^m$ is male U5MR, A=0·0006, B=0·8013, C=–0·3462, r^2 is 0·9977, and root mean squared error is 2·4401.

	Districts (n)	Districts with excess female under-5 mortality (n)	Excess female under-5 mortality per 1000 livebirths 1996–2011 (95% CI)	Excess female under-5 deaths per year (95% CI)	Annual number of female births 1996–2011	State's share of total excess female deaths in 2000–05 (%)*	State's share of total births in 1996–2011 (%)	Relative contribution to excess female deaths (excess deaths to excess births)
Uttar Pradesh	71	71	30·5 (25·7 to 35·2)	76 782 (64 729 to 88 836)	2 522 184	32·1%	18·9%	1·69
Bihar	38	38	28·9 (24·1 to 33·6)	42 538 (35 490 to 49 586)	1 473 976	17·8%	11·2%	1·58
Rajasthan	33	33	25·4 (20·6 to 30·2)	20 963 (17 021 to 24 905)	825 023	8·8%	6·3%	1·40
Madhya Pradesh	50	50	22·1 (17·3 to 26·9)	19 302 (15 123 to 23 480)	874 209	8·1%	6·6%	1·23
Maharashtra	35	33	9·8 (5·1 to 14·6)	9850 (5063 to 14 637)	1 001 270	4·1%	7·9%	0·52
Gujarat	26	26	16·0 (11·2 to 20·7)	9331 (6534 to 12 128)	584 977	3·9%	4·6%	0·85
West Bengal	19	19	10·6 (5·8 to 15·4)	9167 (5040 to 13 293)	863 439	3·8%	6·8%	0·56
Jharkhand	24	24	17·8 (13·0 to 22·5)	7536 (5506 to 9565)	424 833	3·1%	3·3%	0·97
Odisha	30	30	13·5 (8·7 to 18·3)	5897 (3810 to 7985)	437 034	2·5%	3·3%	0·74
Andhra Pradesh	23	23	7·8 (3·0 to 12·5)	5889 (2259 to 9518)	759 357	2·5%	5·9%	0·41
Karnataka	30	28	10·2 (5·5 to 15·0)	5744 (3064 to 8424)	560 632	2·4%	4·4%	0·55
Assam	27	27	15·6 (10·8 to 20·3)	5693 (3943 to 7443)	366 123	2·4%	2·8%	0·84
Haryana	21	21	21·6 (16·8 to 26·4)	5319 (4142 to 6496)	246 385	2·2%	1·9%	1·16
Delhi	9	9	26·0 (21·2 to 30·8)	3942 (3216 to 4668)	151 658	1·6%	1·2%	1·39
Punjab	20	20	14·3 (9·5 to 19·1)	3234 (2152 to 4316)	226 270	1·4%	1·8%	0·75
Chhattisgarh	18	16	5·9 (1·1 to 10·7)	1736 (324 to 3149)	295 444	0·7%	2·3%	0·32
Uttarakhand	13	13	16·4 (11·7 to 21·2)	1735 (1230 to 2239)	105 562	0·7%	0·8%	0·87
Jammu and Kashmir	22	19	10·2 (5·4 to 15·0)	1436 (761 to 2111)	141 397	0·6%	1·1%	0·54
Meghalaya	7	7	21·5 (16·7 to 26·3)	942 (732 to 1152)	43 909	0·4%	0·3%	1·21
Tamil Nadu	32	26	9·0 (4·2 to 13·8)	825 (385 to 1264)	585 356	0·3%	4·6%	0·07
Tripura	4	4	15·0 (10·3 to 19·8)	545 (372 to 718)	36 233	0·2%	0·3%	0·81
Nagaland	11	10	20·6 (15·8 to 25·4)	490 (377 to 604)	23 834	0·2%	0·2%	1·11
Kerala	14	8	1·4 (–3·4 to 6·1)	358 (–902 to 1617)	263 320	0·1%	2·2%	0·07
Arunachal Pradesh	16	12	16·4 (11·6 to 21·2)	297 (211 to 384)	18 154	0·1%	0·1%	0·91
Manipur	9	8	8·9 (4·1 to 13·7)	260 (120 to 401)	29 362	0·1%	0·2%	0·46
Mizoram	8	5	7·9 (3·1 to 12·7)	98 (39 to 158)	12 481	<0·1%	0·1%	0·42
Chandigarh	1	1	6·9 (2·1 to 11·6)	58 (18 to 99)	8524	<0·1%	0·1%	0·36
Goa	2	2	1·8 (–3·0 to 6·6)	25 (–42 to 91)	10 857	<0·1%	0·1%	0·12
Dadra and Nagar Haveli	1	1	4·7 (–0·1 to 9·5)	17 (0 to 35)	3630	<0·1%	<0·1%	0·25
Sikkim	4	3	2·7 (–2·1 to 7·5)	16 (–12 to 43)	5782	<0·1%	<0·1%	0·14
Lakshadweep	1	0	3·3 (–1·5 to 8·1)	2 (–1 to 5)	588	<0·1%	<0·1%	0·18
Daman and Diu	2	0	0·5 (–4·3 to 5·3)	1 (–8 to 9)	1790	<0·1%	<0·1%	0·03
Andaman and Nicobar Islands	3	0	7·6 (2·8 to 12·4)	–44 (–16 to –72)	3211	<0·1%	<0·1%	–0·73
Himachal Pradesh	12	8	3·5 (–1·3 to 8·3)	–264 (97 to –624)	59 268	–0·1%	0·5%	–0·23
Puducherry	4	1	11·3 (6·6 to 16·1)	–402 (–232 to –572)	10 372	–0·2%	0·1%	–2·04
India	640	596	18·5 (13·1 to 22·6)	239 317 (169 138 to 292 991)	12 976 445	100%	100%	1·00

*Calculated from the previous column.

***Table 1:* Contribution of Indian states to total excess female under-5 deaths, circa 2003**

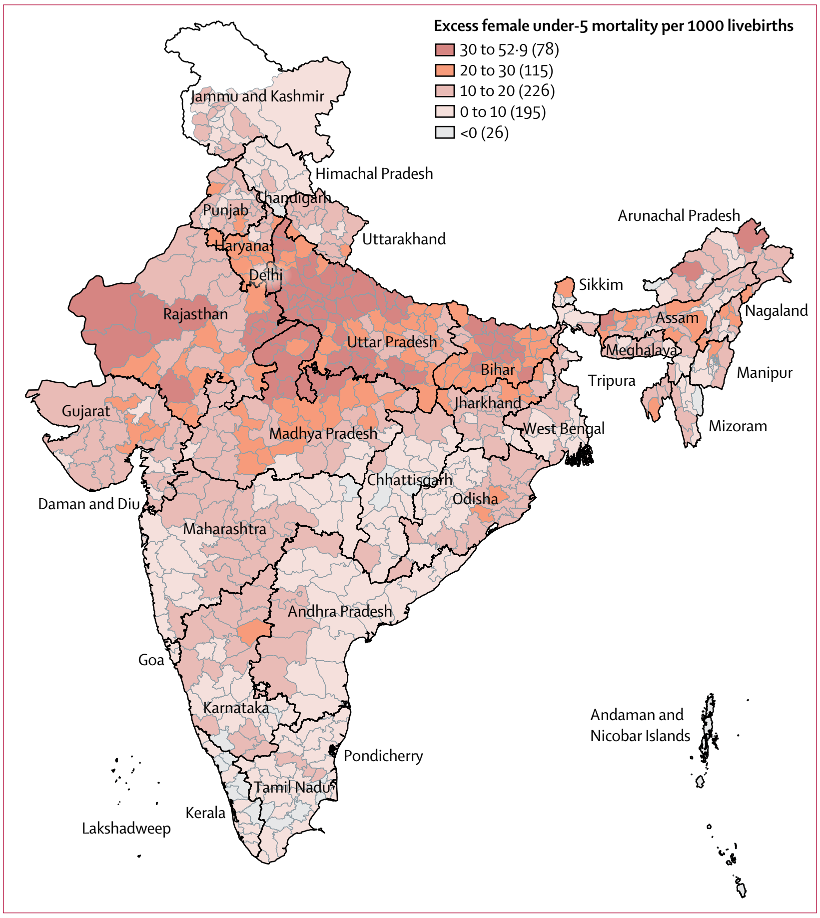

Figure 1: **Excess female under-5 mortality (per 1000 livebirths) in Indian districts, circa 2003**
Data in brackets are the number of districts per band.

We subtracted the expected female U5MR from the observed female U5MR to calculate the excess female U5MR nationally and for India's districts and states. This procedure corresponds to the descriptive method of excess mortality estimation.[3,7,8]

Estimation of the absolute number of excess under-5 female deaths

To calculate the number of excess female under-5 deaths in each district, we applied excess mortality rates to the mean size of annual birth cohorts during the 14 years before the 2011 census. The size of birth cohorts was computed by back projection of the population below 15 years enumerated in 2011 with a survival ratio (appendix p 6). The survival ratio is taken from the South Asian life tables corresponding to the district-level U5MRs.[16]

Statistical and geostatistical analysis

We did multiple linear regression analysis with district-level excess female mortality rate as the outcome variable. In line with the published literature[17,18] on determinants of sex discrimination, we tested a large set of contextual variables available at district level, including development and economic indicators (amount of work participation, percentage of households with household industry, literacy, urbanisation, access to safe drinking water, and housing quality), social indicators (proportion of population by religion and proportion of Scheduled Castes and Scheduled Tribes), and sex indicators (sex differences for literacy and work participation, and birth masculinity measured by the sex ratio at birth [2004–11]).

We also tested the amount of spatial autocorrelation (Moran's *I*) by using a queen proximity matrix in which each district's estimate is compared with that of its immediate neighbours. In addition to the standard regression model, we used spatially autoregressive models to account for the high amount of spatial autocorrelation among residuals. After separate testing, we retained the spatial error model because it performs better than the alternative spatial lag model. This spatial regression model corresponds to the presence of unobserved factors in the residual error term that are spatially autocorrelated.[19] The general form of the model is given in the formulas:

$$EFM = X\beta + u;$$
$$u = \lambda W u + \varepsilon$$

where EFM is the excess female under-5 mortality rate, X is a vector of independent variables and β is the corresponding parameters to be estimated, u is the spatially autocorrelated residual of the multilinear model, W is the contiguity matrix (1 for adjacent districts, 0 otherwise), λ is the parameter of the spatially autoregressive factor u, and ε is the error term.[20] A system of two simultaneous equations can be derived and solved by the maximum likelihood method to estimate coefficients β and λ.

Role of the funding source

This study is based on publicly available data and is not funded. Both CZG and NS had full access to all data in the study and had final responsibility for the decision to submit for publication.

Results

The average level of excess female under-5 mortality was 18·5 per 1000 livebirths (95% CI 13·1–22·6) in 2000–05. 178 100 (2%) of 13·0 million girls born during the study period died because of sex discrimination, which means that 22% of the overall mortality burden of young girls in India is attributable to gender bias. This excess mortality translates into an average of 239 000 (95% CI 169 000–293 000) excess deaths of girls aged 0–4 years per year, or 2·4 million per decade.

Our most notable finding is the regional distribution of excess mortality rates of females younger than 5 years. Our results show that 29 of 35 states were affected by a significant amount of excess mortality (table 1). All states and union territories include at least one district with excess female mortality—except the Andaman and Nicobar Islands (figure 1).

The extent of excess female mortality greatly varies among states, ranging from 0 per 1000 livebirths to 30 per 1000 livebirths. Table 1 ranks the states by declining contribution to the overall number of excess under-5 deaths of girls. The mean amount of excess female under-5 mortality exceeds 20 per 1000 livebirths in eight out of 35 states and union Territories: Uttar Pradesh, Bihar, Rajasthan, Madhya Pradesh, Haryana, Delhi, Meghalaya, and Nagaland (table 1). Except for two states in the northeast, all these states are in northern India. Uttar Pradesh, which is India's most populated state, has the highest number of sex differentials in mortality (30·5 per 1000 livebirths; table 2). By contrast, the other large states of Maharashtra, West Bengal, and Tamil Nadu have excess female mortality that is well below the national average (table 1).

Figure 1 shows district-level variation in excess female mortality plotted on the 2011 administrative map of India. District estimates with prediction intervals are given in the appendix (pp 8–30). The highest rates of excess female mortality in childhood were in northern India. The map highlights a large cluster of almost 60 adjacent districts in Madhya Pradesh, Uttar Pradesh, and Rajasthan where excess female mortality exceeds 30 per 1000 livebirths. These are rural, agricultural districts, characterised by high population density. Furthermore, there is a hot spot of extreme gender bias in western Rajasthan and another cluster in northern Bihar comprising 15 adjacent districts. In 24 of these districts, excess mortality exceeds 40 per 1000 livebirths and amounts to 30–50% of overall female U5MR (appendix pp 8–30). By contrast, almost no excess female mortality was reported in most of southern India and in several inland regions with a strong tribal population. In 215 districts, excess female mortality was not significantly different from five deaths or fewer per 1000 livebirths, while it is not different from zero in 92 of them (appendix pp 9–30).

Another notable finding of this map is the strong regional patterning of excess mortality of girls, which cuts across state boundaries (state-level variations account only for 63% of the overall variance of excess female mortality [data not shown]). Moran's indicator of spatial autoregression (Moran's *I*) is as high as 0·70 for the 640 districts studied (data not shown).

Figure 2 shows the overall effect of excess mortality among girls at district level and gives an estimation of the absolute number of excess under-5 deaths. This map differs from figure 1 because of variations in the number of births, a value that is affected by the overall size of the districts and their respective birth rates. Together, Bihar, Madhya Pradesh, Rajasthan, and Uttar Pradesh account for two-thirds (66·7%) of all excess deaths of girls younger than 5 years in India (table 1).

Table 2 shows the variables used in our regression analysis for the 640 districts. We sequentially introduced social (model 1), development (model 2), and sex (model 3) variables to four ordinary least squares models (table 3). Regression coefficients were standardised to facilitate comparison. The synthetic model (model 4) accounted for two-thirds of the variations seen across India (r^2 0·675; table 3). Since the regression residuals of this model remained strongly spatially autocorrelated, we used a spatial error model (model 5) to correct for any remaining spatial bias (r^2 0·749; table 3).

	Mean (SD; minimum–maximum)
Excess female under-5 mortality rate (per 1000 livebirths)	15·9 (11·3; 0·00–52·80)
Hindu (proportion of population)	0·74 (0·27; 0·01–0·99)
Muslim (proportion of population)	0·13 (0·17; 0·00–0·99)
Christian (proportion of population)	0·07 (0·20; 0·00–0·98)
Sikh (proportion of population)	0·02 (0·11; 0·00–0·93)
Scheduled Caste (proportion of population)	0·15 (0·09; 0·00–0·50)
Scheduled Tribe (proportion of population)	0·18 (0·27; 0·00–0·99)
Literacy (proportion of population aged 7 years and older)	0·72 (0·10; 0·36–0·98)
Work participation (proportion of population aged 7 years and older)	0·41 (0·07; 0·26–0·67)
Agricultural labourers (proportion of total workers)	0·21 (0·14; 0·00–0·61)
Household workers (proportion of total workers)	0·03 (0·02; 0·00–0·22)
Cultivators (proportion of total workers)	0·32 (0·17; 0·00–0·81)
People with disabilities (proportion of population)	0·02 (0·01; 0·00–0·05)
Urban areas (proportion of population)	0·26 (0·21; 0·00–1·00)
Dilapidated housing (proportion of houses)	0·05 (0·03; 0·00–0·18)
Houses with no latrine (proportion of houses)	0·54 (0·26; 0·01–0·94)
Houses with no electricity (proportion of houses)	0·34 (0·28; 0·00–0·98)
Fertility 2011 (children per woman)	2·80 (0·90; 1·20–5·80)
Aged ≥60 years (proportion of population)	0·08 (0·02; 0·02–0·18)
Sex ratio for literacy rate (male to female)	128·8 (15·4; 89·40–191·10)
Sex ratio for labour force participation rate (male to female)	246·3 (132·1; 86·20–886·70)
Sex ratio at birth in 2004–11 (male to female)	108·0 (4·8; 94·20–127·50)

All data are from the 2011 census except excess mortality (calculated by the authors), fertility in 1994–2011,[12] and sex ratio at birth in 1994–2011.[11]

Table 2: **Outcome and explanatory variables across 640 Indian districts in 2011**

The analysis of the regression results highlight some of the main correlates of excess female under-5 mortality in India. Contrary to variations of skewed birth masculinity, the social composition of the population (model 1) had a negligible role in variations of excess female under-5 mortality (r^2 0·059; table 3). The apparent link with the underprivileged Dalit (Scheduled Castes) population disappears in the synthetic model (model 4; table 3). However, when other variables are introduced in the regression, the analysis shows the mitigating effect of specific compositional variables: female under-5 mortality is significantly decreased among Muslim and tribal (Scheduled Tribes) populations (table 3). These correlations are consistent with previous findings showing that preference of a son tends to be more pronounced among specific religious groups, such as Hindus.[21]

Development variables (model 2) have a strong and mostly beneficial effect on excess mortality, an effect

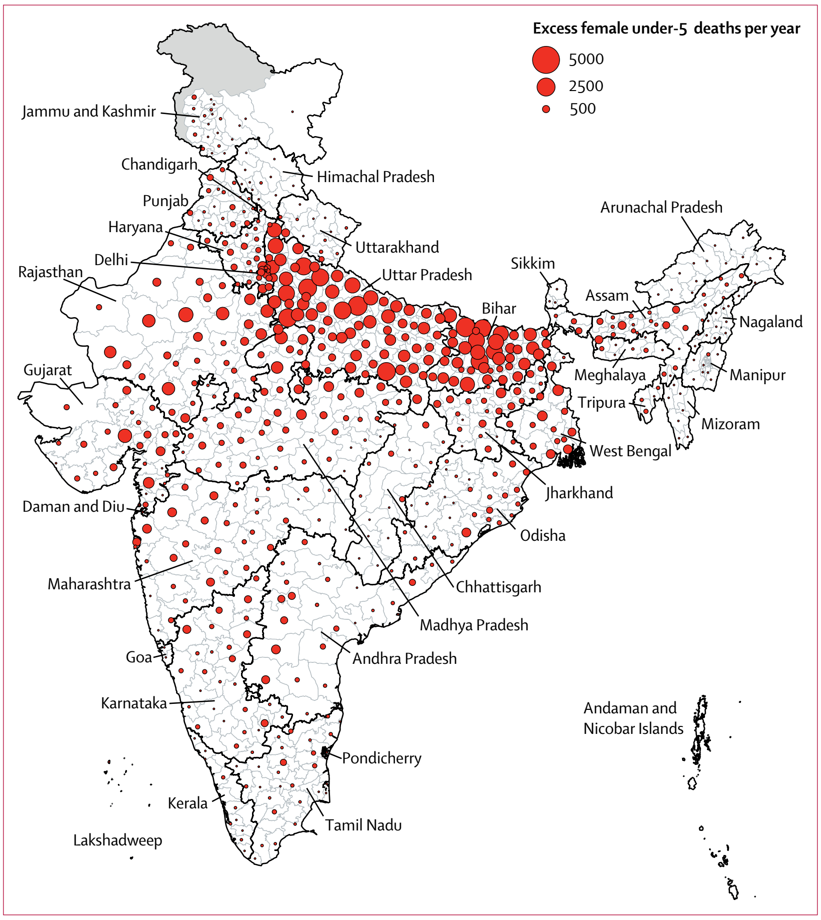

Figure 2: **Number of annual excess female under-5 deaths in Indian districts, circa 2003**

that is still strong when socioeconomic and spatial factors are added to the model (models 4 and 5; table 3). Access to electricity and employment outside agriculture and household work significantly reduce postnatal excess mortality. High fertility is the strongest predictor of postnatal discrimination against girls, suggesting that excess deaths of girls is partly a consequence of unwanted childbearing and ensuing neglect of female children (table 3). All sex variables (model 3) are positively correlated with excess mortality, which means that relatively high female literacy and work participation significantly reduce the risk of excess under-5 mortality (table 3).

The spatial error model (model 5) reduces the strength of most ordinary least squares coefficients, several of them becoming non-significant once regional patterning is factored in (table 3). This model also confirms the presence of a strong unobserved spatial factor (λ 0·592; table 3). This factor might relate to the effect of local cultural and institutional standards (such as the strength of patriarchy and traditional gender inequity), features that are not captured by usual census variables. Data limitations prevented us from testing the significance of other variables, such as birth parity, patrilineal kinship, or income levels.

Discussion

Our study provides reliable estimates of excess under-5 female mortality after birth across all districts in India. In more than 10% of northern Indian districts, excess under-5 mortality exceeded 30 per 1000 livebirths, showing that geography is a key factor in infant and child death among girls. This estimated excess rate is similar to the rate of 21·8 per 1000 livebirths computed for India[8] by using the fixed mortality ratio derived by Hill and Upchurch.[22] Our annual estimate of excess female under-5 deaths lies midway between the lower figure of 216 300, interpolated from estimates for 1990 and 2012 by Alkema and colleagues,[7] and the higher figure of 329 900, derived by Bongaarts and Guilmoto.[3] Although the lower estimate is based on demographic sample surveys, the higher estimate is derived from UN population figures.[15] Our estimates are derived from a different source, the exhaustive census records on mothers' fertility. Other studies[23,24] on excess mortality in India do not provide annual estimates of excess female under-5 deaths.

The skewed sex ratio for children is one of the most spatially clustered dimensions of India's demography.[25] National and regional figures conceal extreme local variability in the burden of sex discrimination faced by Indian women in their early life, confirming the need for a geographical approach to the analysis of child mortality differentials based on disaggregated estimates.[5] Our statistical and mapping analyses also show the close association between excess female under-5 mortality and socioeconomic variables at district level, such as relative underdevelopment and reliance on agricultural and household work, but also the decreased prevalence of gender bias among the Muslim and tribal populations. Excess mortality is also associated with indicators of gender bias, although prenatal sex selection is seen in different regions of India than postnatal discrimination is.[26] Notably, high fertility was the strongest predictor of excess mortality. Gender bias, underdevelopment indicators, and high fertility also explain the geographical clustering of excess female deaths in parts of northern India where son preference and large families go together. By contrast, the more rapid fertility decline in western India—where the need for a male offspring prevails—has been accompanied by the earliest observations of prenatal sex selection and a skewed sex ratio at birth since the 1990s. This transition from postnatal to prenatal sex selection across districts mirrors the overall observation for India in 1970–2010, in which the effect of missing female births on the overall female deficit is growing.[3] The country can be divided into three parts: northern regions with pronounced excess mortality among girls, western regions characterised by elevated birth masculinity similar to those reported in China, and

	Model 1: social composition*		Model 2: development*		Model 3: sex*		Model 4: all*		Model 5: spatial regression†	
	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value
Hindu	0·110	0·365	..	..	..	..	−0·050	0·514	−0·080	0·376
Muslim	0·130	0·124	..	..	..	..	−0·181‡	0·001	−0·179‡	0·007
Christian	0·036	0·692	..	..	..	..	−0·008	0·894	−0·025	0·717
Sikh	−0·051	0·447	..	..	..	..	−0·097§	0·031	−0·065	0·250
Scheduled Caste	0·234‡	<0·0001	..	..	..	..	0·048	0·197	0·039	0·336
Scheduled Tribe	0·025	0·707	..	..	..	..	−0·164‡	0·002	−0·051	0·365
Literacy	..	..	−0·047	0·291	..	..	0·032	0·540	0·003	0·963
Work participation	..	..	−0·366‡	<0·0001	..	..	−0·142‡	0·002	−0·187‡	<0·0001
Agricultural labourer	..	..	0·090§	0·029	..	..	0·114‡	0·003	0·118‡	0·009
Household work	..	..	0·095‡	0·002	..	..	0·079‡	0·003	0·064§	0·010
Cultivators	..	..	0·308‡	<0·0001	..	..	0·234‡	<0·0001	0·153‡	0·002
Disability	..	..	−0·011	0·710	..	..	−0·015	0·570	<0·001	0·989
Urbanisation	..	..	0·238‡	<0·0001	..	..	0·124‡	0·003	0·147‡	0·001
Dilapidated housing	..	..	−0·066	0·075	..	..	−0·035	0·310	0·027	0·466
No latrine	..	..	0·070	0·120	..	..	−0·093	0·054	−0·030	0·609
No electricity	..	..	0·098	0·056	..	..	0·213‡	<0·0001	0·231‡	<0·0001
Fertility 2011	..	..	0·436‡	<0·0001	..	..	0·366‡	<0·0001	0·253‡	<0·0001
Age ≥60 years	..	..	0·077	0·059	..	..	−0·099§	0·016	−0·065	0·141
Sex ratio for literacy rate	..	..	..	..	0·535‡	<0·0001	0·200‡	<0·0001	0·223‡	<0·0001
Sex ratio for participation rate	..	..	..	..	0·317‡	<0·0001	0·157‡	<0·0001	0·061	0·147
Sex ratio at birth in 2004–11	..	..	..	..	0·141‡	<0·0001	0·223‡	<0·0001	0·221‡	<0·0001
Spatial autocorrelation (λ)	..	..	..	..	..	..	..	..	0·592‡	<0·0001
Constant	6·82‡	0·179	11·0‡	0·084	−77·4‡	<0·0001	−70·4‡	<0·0001	−64·5‡	<0·0001
r^2	0·059	..	0·556	..	0·358	..	0·675	..	0·749	..
Log likelihood	..	..	..	..	..	..	..	..	−2043·0	..
Observations	640	..	640	..	640	..	640	..	640	..

Standardised β coefficients were used. *Ordinary least squares analysis model was used. †Spatial error model was used. ‡1% significance level. §5% significance level.

***Table 3:* Ordinary least squares and spatial regression results for excess female under-5 mortality rate in India, circa 2003**

the rest of India, where the effect of gender bias on mortality appears to be moderate or negligible.

When seeking an explanation for the concentration of postnatal discrimination against girls in northern India, it is noteworthy that this geographical distribution across India is not consistent with the map of skewed birth masculinity.[14,27] The most skewed sex ratios at birth are in western India, from Punjab and Haryana to Gujarat and Maharashtra. We found that, except for Haryana, none of these states has severe excess female under-5 mortality. By contrast, the sex ratio at birth in the cluster of high female mortality in northern India (Bihar and Uttar Pradesh) is not particularly skewed; the statistical correlation between prenatal and postnatal discrimination against girls at district level is surprisingly weak (r^2 0·07). Therefore, sex-selective abortions and excess female mortality in childhood might stem from the same bias against female children, but they are not observed in the same regions.

Areas in north central India—where excess female under-5 deaths are concentrated—are characterised by high population density and fertility. They form the BIMARU states identified in 1980s by Ashish Bose[28] as being the least developed part of India. Elsewhere in India, the number of excess female deaths is often negligible. In 289 districts, the estimates are not significantly different from fewer than 100 female deaths per year (appendix pp 9–30).

Our method has two limitations. First, census data remain fragile and indirect methods might be affected by inaccuracy in reporting of age and other reporting errors in ways that are difficult to assess. Second, our estimates refer to a period centred on 2003, and with the rapid reduction in under-5 mortality, the present magnitude of female deaths in India is probably lower nowadays than was reported in this study. Nevertheless, we believe our analysis provides the only reliable and consistent disaggregated figures of excess under-5 mortality. It is otherwise unfeasible to estimate regional variations in excess female mortality from sources such as death registration statistics or the most recent health surveys—the Annual Health Survey in 2011–13, the fourth District-Level Household Survey in 2012–13, and the National Family Health Survey in 2015–16. Estimates for the current decade will be available only in 10 years when district-level data from the future 2021 census are published. New estimates for India state that under-5 mortality for boys is 40 per 1000 livebirths, compared with 53 per 1000 livebirths for girls (Sample Registration System 2011–15).[29] These national estimates correspond to an excess female rate of 14·2 per 1000 livebirths in 2015—a decline of 23% when compared with our estimate for 2000–05. However, this latest estimate of excess female under-5 mortality in India remains one of the highest in the world[7,8] and its unique geography is unlikely to have changed in view of its firm rooting in local family and gender traditions.

Notably, if excess female mortality had completely disappeared by 2015, under-5 mortality in India would have dropped below 40 per 1000 livebirths. Without excess female mortality, India would have reached the 2015 target of Millennium Development Goal 4 set at 42 deaths per 1000 births.[30] Our findings, therefore, have important implications for contextual interventions. Excess mortality among girls is primarily associated with the combination of low social development and gender bias. It is heavily concentrated in north central India, extending from Rajasthan to Bihar. As shown by the regional estimates of excess deaths of girls, any intervention to reduce discrimination against girls in terms of food and health-care allocation should, therefore, target priority regions of Bihar and Uttar Pradesh where poverty, low social development, and patriarchal institutions persist and investment in girls is scarce. We also show that excess mortality is specifically associated with high fertility. This finding suggests that the sustained fertility decline currently observed in northern India is likely to lead to a reduction in postnatal discrimination. However, unless son preference diminishes, reduced fertility might cause a rise in gender-biased sex selection, as was observed in the late 1990s in western India. This situation reinforces the need to directly address gender discrimination and to encourage social and economic development for the benefit of Indian women.

Compared with prenatal sex selection, excess female mortality is rarely studied for two main reasons. First, the mechanisms of gender discrimination are complex and multilayered, ranging from deliberate neglect in health-seeking behaviour to invisible routine bias in food allocation. Second, the data that are necessary for statistical evidence—age-specific mortality rates by sex—are rarely available in developing countries. As a result, research and interventions to combat postnatal discrimination against girls are scarce, despite their importance in a country like India. Excess female mortality warrants more attention in policy discussions around gender bias in India, which tend to focus on prenatal sex selection. Our research calls for the introduction of more systematic monitoring of sex differentials in child mortality. This monitoring, based primarily on increased collection and sharing of death registration data, should help to provide a strong basis for benchmarking progress towards greater gender equality. More qualitative research is also required to better document the unfair distribution of resources and discriminatory treatment of boys and girls in intra-household health-care and food allocation, which is at the core of excess female mortality.

Contributors
CZG and NS developed the idea for this work, did the research, and analysed the data with JKB. All authors wrote this manuscript.

Declaration of interests
We declare no competing interests.

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