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Supporting Information for Gridding India’s Population Futures for Climate Exposure

Model Inputs and State Space

The main projection is defined over state or union territory, rural-urban residence, age, sex, and educational attainment. The current paper uses 35 state and union-territory units harmonised to the 2011 Census geography. Later administrative changes are treated as harmonisation issues for the technical workflow rather than as separate projection units. This state space is also the basis for the paper’s climate-exposure argument: national totals can be decomposed into subnational control totals and population composition before being linked to gridded or hazard-specific layers.

The current India Medium Baseline is the anchor projection. Older pathway labels from previous model versions are retained only to track input histories. The paper is organised around one India Medium Baseline and named India-specific what-if experiments.

Internal Migration Input Checks

The comparison of the 2001-based legacy matrix and the recalculated 2011 Census-style matrix treats constant migration rates as a transparent baseline, not as an empirical claim that mobility patterns are stable. Census D-3 reports migrants by place of last residence, duration of residence and reason for migration; it provides the main recent-migration counts used to compare 2001 and 2011^{1,2}. Census D-12 reports recent migrants by age group and helps align the migration input with the projection's age structure³. Both sources are mapped to the same state-residence cells, same-origin/destination cells are set to zero, and rates are multiplied by their corresponding census age-sex-residence exposure populations to obtain comparable expected flows and origin out-rates. The displays in this section move from the census evidence to the model input. The first table reports directly observed D-3 migration counts. The second table shows how those counts appear once translated into the state-residence migration matrix used by the projection. The residence tables and figures show whether the update is mainly rural-to-urban or broader across residence types. The corridor figures and table show where interstate flows changed most, and the age-sex figure shows which population groups carry those changes.

Table 1: Direct Census D-3 five-year internal migration counts, 2001 and 2011. Values are millions of migrants.

Measure	2001 (m)	2011 (m)	Change (m)	Change (%)
All internal migrants (<5 years)	55.8	80.7	24.9	44.7
Interstate migrants (<5 years)	10.3	13.5	3.2	31.4
Visible to state x rural/urban model: interstate plus within-state rural/urban-change migrants	21.3	31.6	10.3	48.3
Within-state other-district migrants (<5 years)	15.5	24.1	8.6	55.7
Within-state migrants outside place of enumeration (<5 years)	45.5	67.2	21.7	47.8
Within-state migrants changing rural/urban residence (<5 years)	11.3	18.6	7.3	64.6
Within-state same-district migrants (<5 years)	30.0	43.1	13.1	43.7

The next table translates those census counts into the state-residence matrix used by the projection model, so the reader can see the input scale after harmonisation.

Table 2: Internal migration input comparison, 2001 and 2011. Expected migrants are in millions; out-rates are five-year out-migrants per 1,000 origin population.

Source	Expected 2001 (m)	Expected 2011 (m)	Change (%)	Out-rate 2001	Out-rate 2011
Model-visible state-residence matrix	22.1	31.1	41.1	21.5	25.8

The first two tables establish the scale of the update. The next display shows how the same migration evidence is distributed across rural and urban origins and destinations, because the projection uses residence as part of the demographic state space.

Rural/Urban Domestic Migration Matrix

Labels show expected migrants (M) and out-rate per 1,000

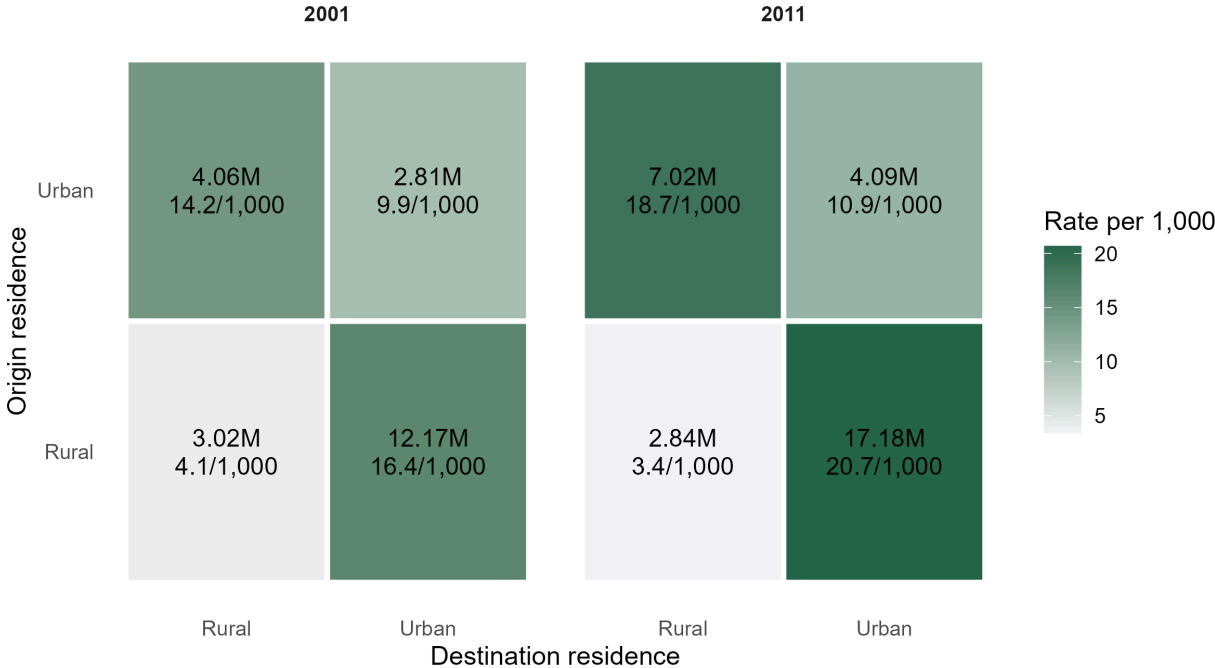


Figure 1: Rural/urban origin-destination cross-table for the 2001-based and 2011-based five-year internal migration inputs.

Because migration rates are interpreted relative to the population exposed to them, the next table reports the rural and urban denominators used in the comparison.

Table 3: Rural/urban exposure population in 2001 and 2011 used in the migration-rate comparison.

Residence	Population (m)	2001	Population (m)	2011	Share (%)	2001	Share (%)	2011	Change (m)
Rural	740.6		830.8		72.2		68.9		90.2
Urban	285.3		375.5		27.8		31.1		90.3

With these denominators in view, the following figure summarises how the rural-urban origin-destination matrix changes between the 2001-based and 2011-based inputs.

Rural/Urban Migration Matrix: Change

2011 minus 2001; labels show rate per 1,000 and migrants (M)



Figure 2: Change in the rural/urban origin-destination matrix, 2011 minus 2001.

The next two figures move from residence categories to geography. They show whether the migration update is spatially diffuse or concentrated in particular origin-destination corridors.

Broad-Region Interstate Migration Matrix: Change

2011 minus 2001; labels show percentage-point and migrant-flow change

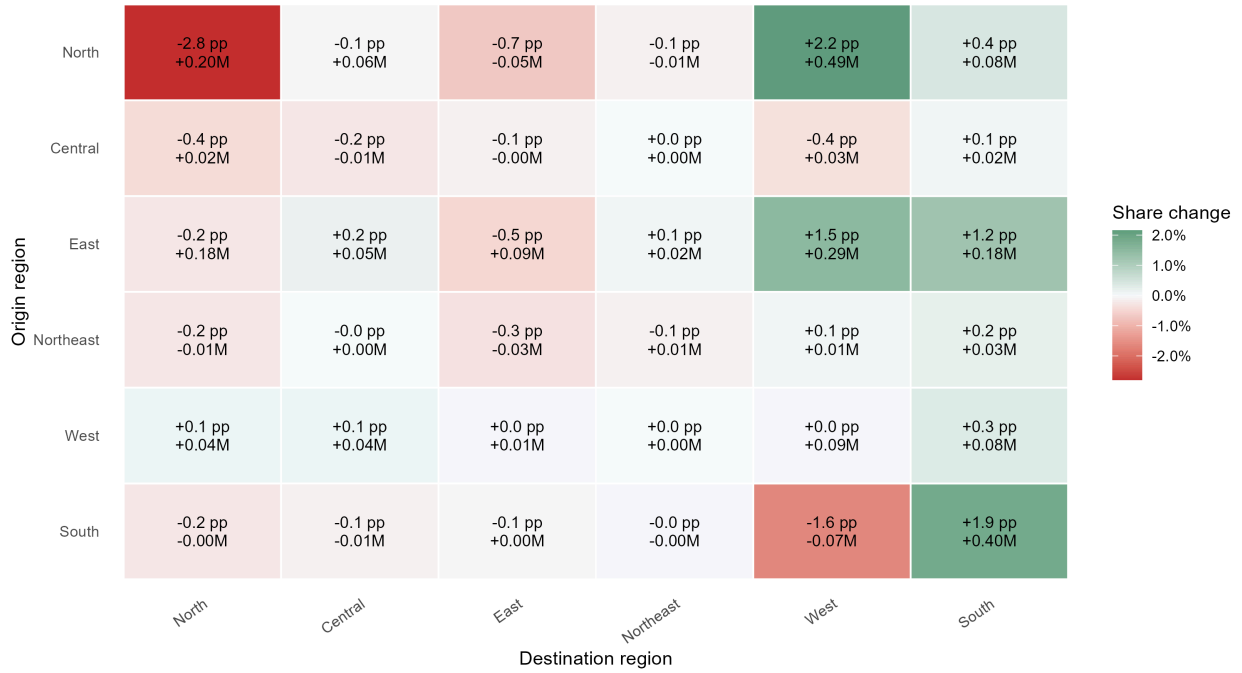


Figure 3: Change in broad-region interstate migration flows, 2011 minus 2001.

The broad-region matrix provides an overview. The circular-flow figure then shows the same update as directional interstate corridors.

Table 4: Largest interstate corridor changes in the circular-flow comparison, 2011 relative to 2001. Values are migrants in thousands; the table shows the 12 largest increases and 12 largest decreases.

Direction	Corridor	2001 (000s)	2011 (000s)	Change (000s)	Change (%)
Increase	UP -> MH	503	691	187	37.2
Increase	UP -> GJ	144	321	177	123.0
Increase	BR -> GJ	67	160	93	140.0
Increase	AD -> KA	141	233	92	64.8
Increase	UP -> UT	143	227	84	58.5
Increase	RJ -> GJ	103	187	84	80.8
Increase	BR -> UP	136	207	70	51.6
Increase	KL -> TN	45	104	59	130.8
Increase	BR -> MH	142	199	57	40.4
Increase	UP -> DL	448	504	56	12.5
Increase	UP -> RJ	96	152	56	58.4
Increase	BR -> HR	107	156	49	45.5
Decrease	DL -> UP	89	0	-89	-100.0
Decrease	DL -> HR	75	0	-75	-100.0
Decrease	CT -> MH	107	54	-54	-50.0
Decrease	CT -> UP	63	26	-37	-58.1
Decrease	Other -> BR	40	6	-33	-83.9
Decrease	DL -> MH	25	0	-25	-100.0
Decrease	AD -> MH	128	104	-24	-19.1
Decrease	CT -> MP	56	34	-22	-38.8
Decrease	JH -> WB	99	78	-21	-21.1
Decrease	JH -> UP	54	33	-20	-37.6
Decrease	KL -> MH	62	42	-19	-31.4
Decrease	CT -> HR	26	7	-19	-72.4

The final migration-rate figure asks whether these changes are concentrated in particular age-sex groups, which matters because migration can reshape the age structure of destination populations.

Change in Domestic Out-Migration Rates, 2001 to 2011

2011 rate minus 2001 rate, per 1,000 origin population

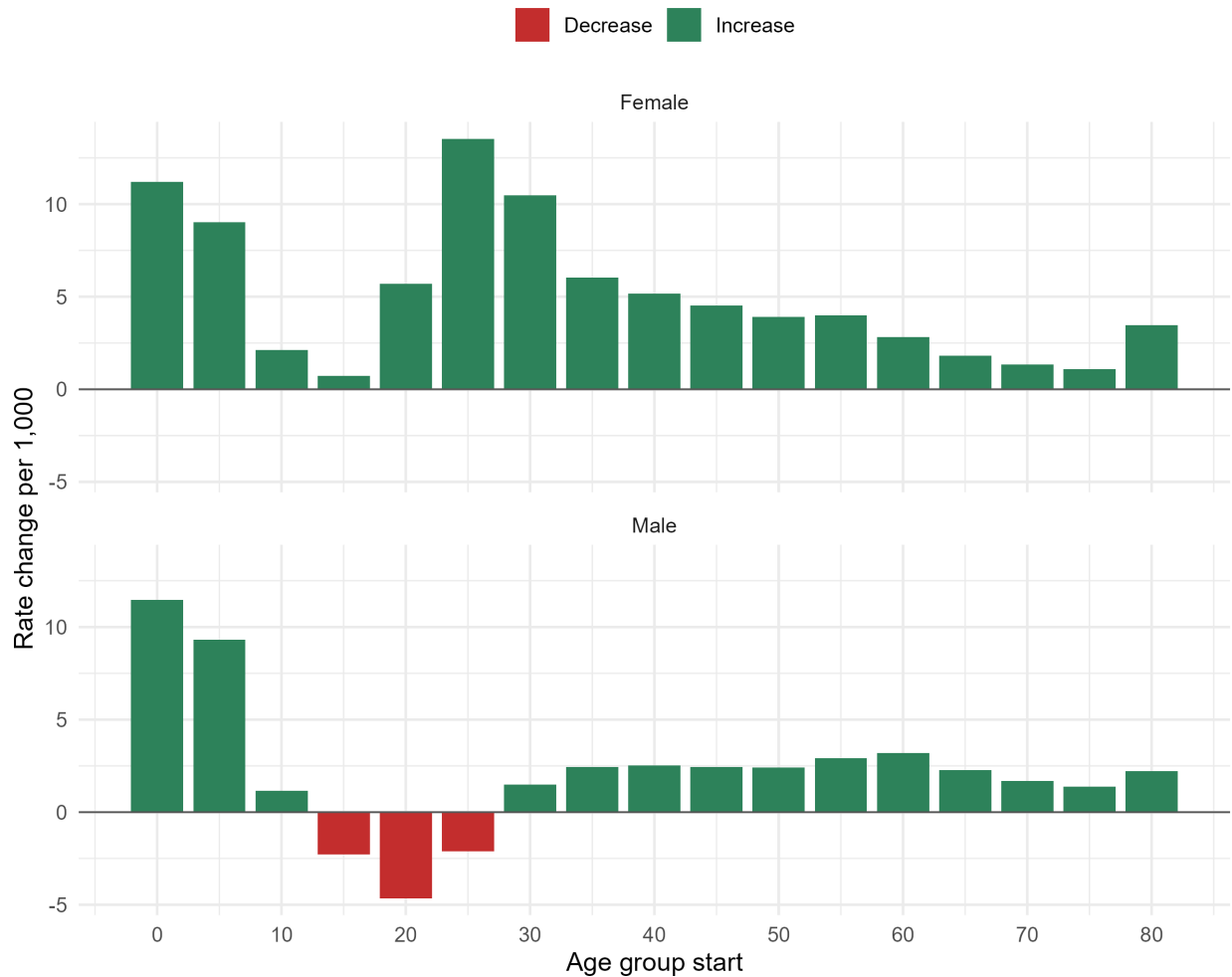


Figure 5: Age-sex change in domestic out-migration rates, 2011 minus 2001.

Education-Specific Migration Calibration

The education-specific migration experiment splits the 2011 state-residence migration matrix into six education categories. The method preserves each original origin-destination-age-sex total while redistributing flows across education. Origin education composition supplies the prior split, and Census 2011 D-04 recent-migrant education profiles calibrate broad education shares by destination state, destination residence, previous residence, age, and sex⁴. D-04 does not provide a full origin-state by destination-state by education matrix, so the result is a calibrated mechanism experiment.

The displays in this section show why the education-specific migration experiment matters for the projection results. The national urban-share table reports the resulting change in urbanisation, while

the main article shows the corresponding state-level pattern. The fertility table confirms that the experiment mainly changes redistribution rather than fertility. The final table and figure decompose the additional urban population into natural increase, domestic migration, reclassification and residual accounting terms.

The main article reports an education-specific migration scenario family: the education-neutral baseline, education-specific migration, accelerated education expansion combined with education-specific migration, and slow education expansion combined with education-specific migration. The accelerated education case moves cohorts somewhat faster into upper-secondary and higher attainment. The slow education case holds progress back substantially; among women aged 25-29 in 2051, upper-secondary-or-higher attainment is about 52 per cent in the slow case compared with about 87 per cent in the baseline and about 90 per cent in the accelerated case. Because fertility among upper-secondary and higher education groups has already converged substantially, accelerated education has a limited additional fertility effect, while slow education raises population size by keeping more women in higher-fertility attainment groups for longer.

Table 5: National urban-share change from 2011 to 2101 under the education-specific migration scenario family.

Scenario	Urban 2011 (%)	Urban 2101 (%)	Change (pp)	Urban 2101 (m)	Total 2101 (m)
Accelerated education + edu-specific migration	31.1	65.0	33.9	1,109.4	1,706.4
Baseline: education-neutral	31.1	47.9	16.8	818.5	1,708.2
Education-specific migration	31.1	63.8	32.6	1,091.3	1,711.1
Slow education + edu-specific migration	31.1	50.3	19.1	931.9	1,853.2

The fertility table checks whether the urban-share differences are accompanied by major fertility changes, or whether the result is primarily redistribution.

Table 6: Total fertility rate in selected five-year periods, 2011-2016, 2051-2056 and 2096-2101, under the education-specific migration scenario family.

Scenario	2011-2016	2051-2056	2096-2101
Accelerated education + edu-specific migration	2.33	1.79	1.73
Baseline: education-neutral	2.33	1.81	1.77
Education-specific migration	2.33	1.79	1.73
Slow education + edu-specific migration	2.36	1.92	1.88

The next table separates the cumulative additional urban population from 2011 to 2101 into demographic components. It is not a period-by-period table; the following figure shows the same component logic for each five-year projection period.

Table 7: Cumulative component difference over 2011-2101 in the education-specific migration experiment relative to the education-neutral baseline. Values are totals over the projection period, not five-year period changes.

Residence	Natural increase (m)	Net domestic migration (m)	Reclassification (m)	Residual (m)	Stock change (m)
Rural	-22.6	-231.7	-15.0	-0.7	-269.9
Urban	25.7	231.7	15.0	0.5	272.8

The accompanying figure shows the same component logic period by period, making the timing of the urbanisation effect visible.

Urban population change by component
 Five-year periods; domestic migration is net urban domestic migration

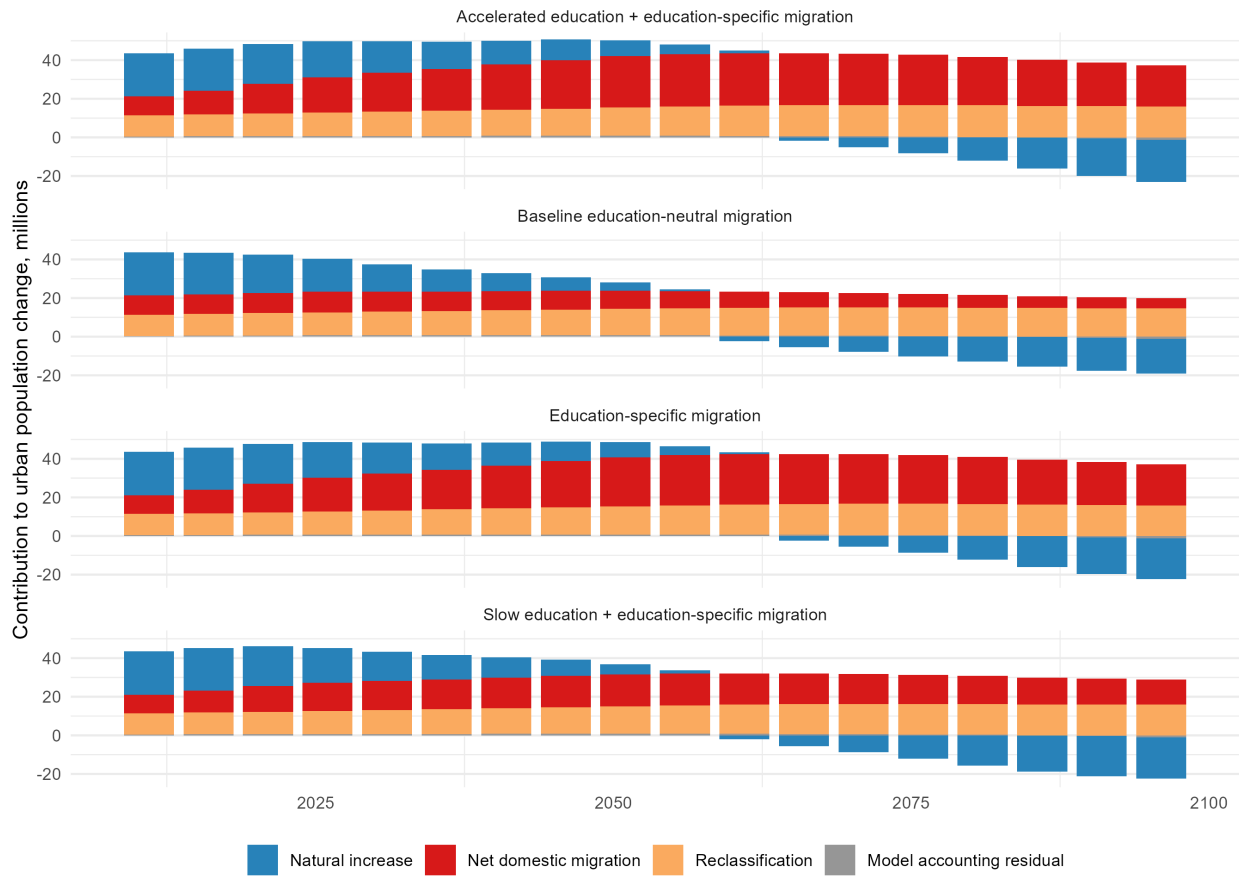


Figure 6: Five-year urban population change from 2011 to 2101 decomposed into natural increase, net domestic migration, reclassification, and accounting residual.

Fertility Patterns

The fertility patterns support the main-text claim that education and residence remain important demographic dimensions. Fertility among more educated urban women is already low, while younger cohorts are becoming more educated. This combination makes the future fertility floor depend on both behaviour within groups and compositional change across groups. The figures therefore show, in sequence, the national fertility path relative to other sources, fertility differences by education and residence, and the changing education composition of women in reproductive ages.

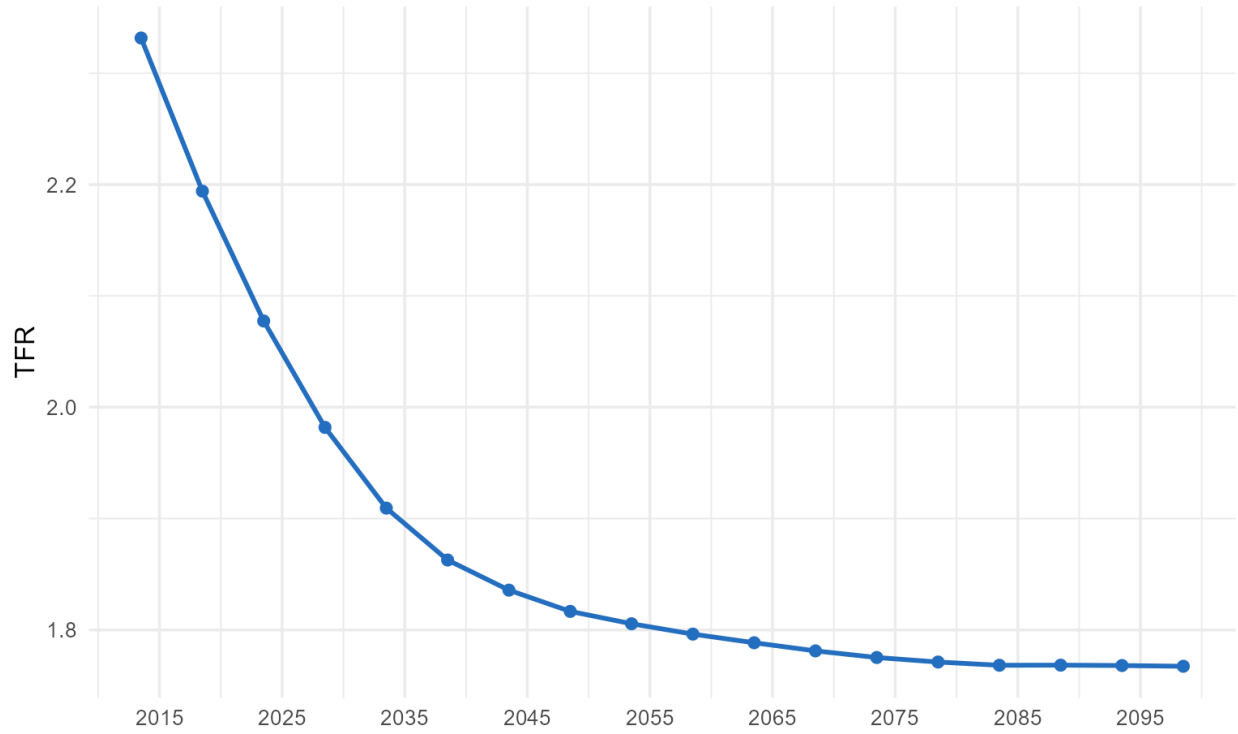


Figure 7: Total fertility rate for India by several sources over the projection period.

After comparing the national fertility path with other sources, the next figure shows the education and residence differences that make composition important for the projection.

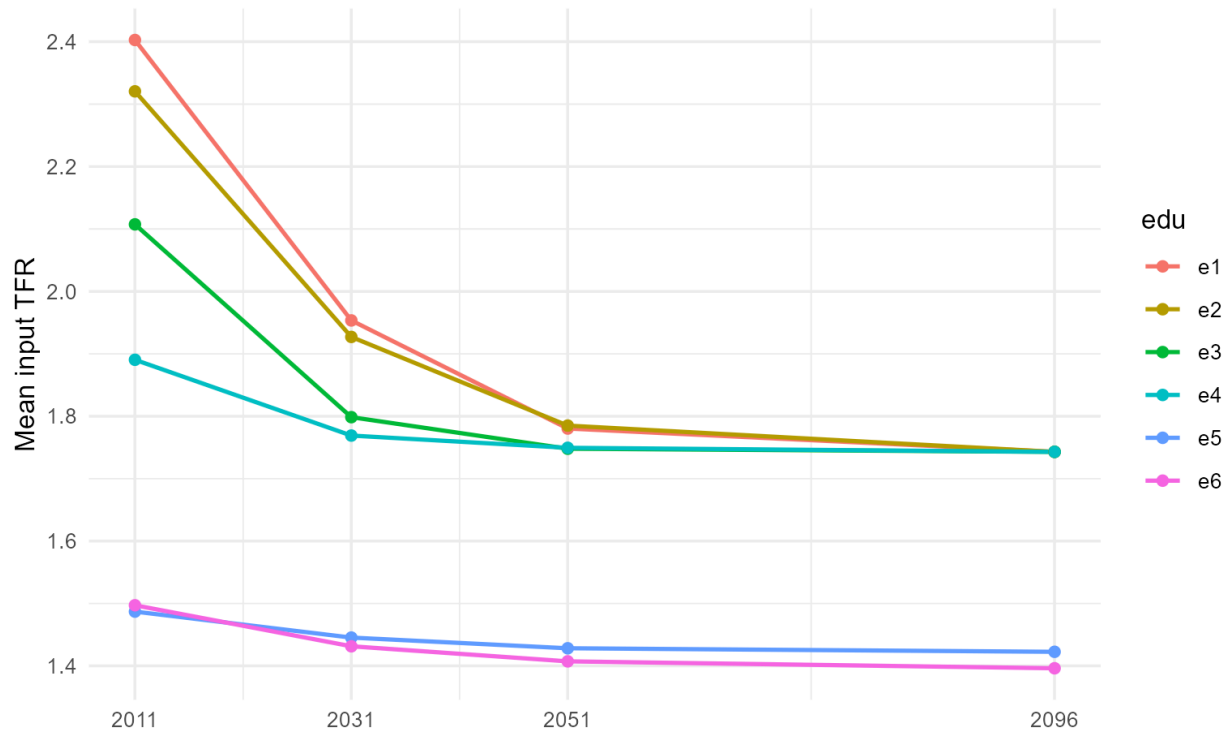


Figure 8: Total fertility rate by education for India and its urban and rural areas in selected projection periods.

The final figure links those fertility differences to the changing education composition of women in reproductive ages over the projection period.

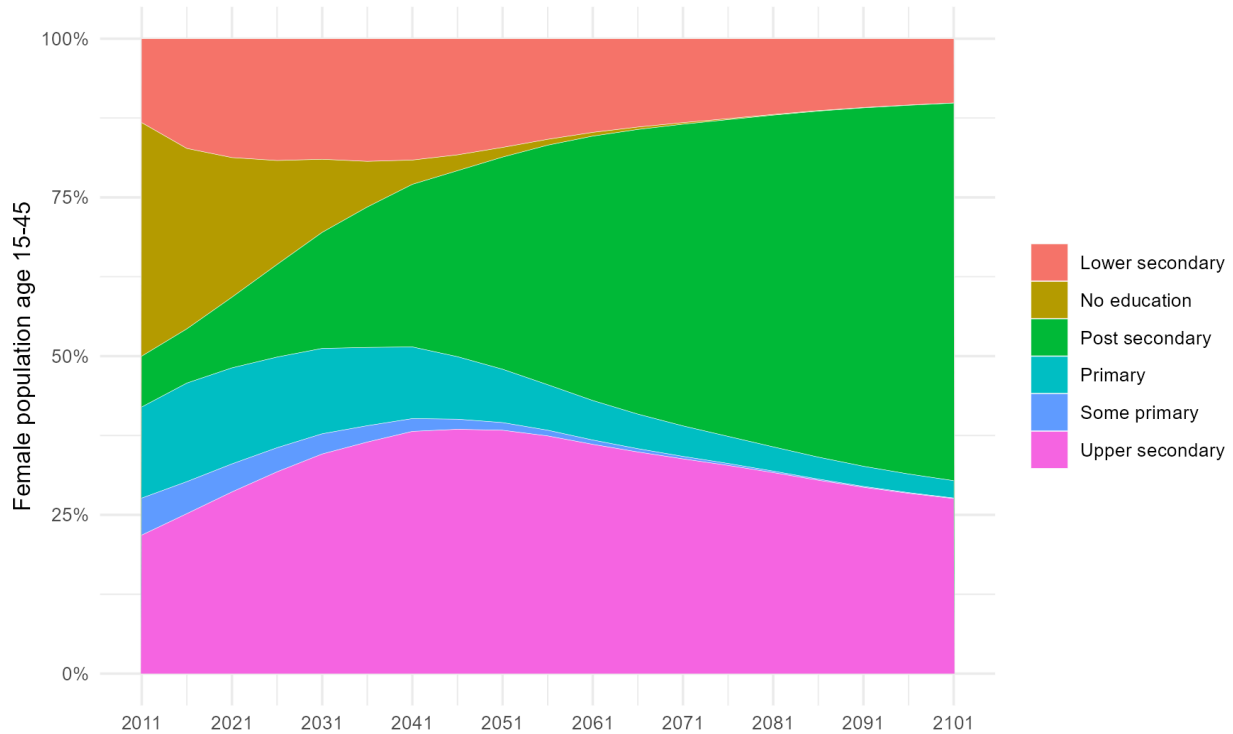


Figure 9: Female education composition in the India projection workflow from 2011 to 2101.

Gridded Urban Exposure Experiment

Climate-impact studies usually require population on grids or within hazard footprints. To test whether the India state-space projection can improve this step, we implemented a controlled gridding experiment that preserves an observed baseline urban-population surface and changes only the geographic control totals used to allocate future urban growth. The experiment starts from GHS-POP 2010, masks the surface to urban and semi-dense settlement classes in GHS-SMOD, calibrates each state’s baseline grid cells to the projection’s 2011 state urban total, and then allocates projected urban growth using the Gao and O’Neill SSP2 2100 urban-land fraction grid as a common weighting surface⁵⁻⁷. It does not create a new urban-land forecast.

The displays in this section separate two gridding choices. The first table reports what changes when projected urban growth is constrained by state demographic totals rather than one national total; the corresponding spatial pattern is shown in the main article. The next table repeats that national-versus-state comparison under alternative urban-land forms. The final table changes the urban-land form while holding the population projection fixed, showing how settlement pattern assumptions affect exposure placement after the demographic control problem has been separated.

The experiment compares two growth-allocation rules. Both start from the same calibrated 2011 GHSL urban-population baseline and use the same Gao and O’Neill SSP2 2100 urban-land fractions as growth weights. In the national-growth rule, India’s projected urban increase from 2011 to 2101 is allocated across eligible grid cells in proportion to each cell’s urban-land weight. In the state-growth rule, projected urban growth is first split into state and union-territory totals from the demographic projection, and each area’s growth is then allocated only within that area using the same weights. The two outputs therefore differ only in the demographic control totals used before gridding: one national total versus state-specific totals.

The gridding workflow clips the grids to India, intersects cells with harmonised state/UT boundaries, calibrates the baseline to state urban totals, applies the two allocation rules and produces the comparison grid used in the main article. Formal allocation details and code will be made available with the archived analysis files.

Table 8: Summary of the GHSL-baseline national-growth versus state-growth gridding experiment from the 2011 baseline to the 2101 final population.

Measure	Value
Urban population, base period	377.1 million
Urban population, end period	1,091.3 million
Projected urban increase	714.2 million
Urban population reallocated by state controls	202.9 million
Reallocated share of projected increase	28.4%

The summary table gives the total amount of population reallocated by state controls. The main article shows where that reallocation appears across grid cells.

This experiment is scientifically useful because it is a controlled counterfactual rather than an unconstrained map comparison. The national-growth and state-growth grids use the same calibrated GHSL baseline, the same urban-land growth weights, the same time points, the same India boundary, and the same national urban-growth total. The only intended difference is the demographic geography imposed before gridding future growth. In the education-specific migration scenario, this changes the placement of about 203 million people, or 28 per cent of projected urban population growth. The result is directly relevant for climate-exposure applications: sea-level-rise, heat, flood, air-quality, and health-impact studies can use the same hazard layer but obtain different exposed populations depending on whether gridding begins from a national urban total or from subnational state-residence trajectories.

The national-growth versus state-growth comparison can also be repeated under alternative Gao and O’Neill urban-land forms. This is not the main-text comparison, where SSP2 is used as the middle-of-the-road weighting surface, but it shows that the demographic-control result is not unique to one urban-expansion pattern. Holding the projected population and baseline surface fixed, replacing national controls with state controls reallocates about 180 million people under SSP1, 203 million under SSP2, 194 million under SSP3 and 220 million under SSP5. The range reflects the fact that compact, fragmented and expansive urban-land surfaces place future growth weights in different grid cells before the demographic control totals are applied.

Table 9: National-growth versus state-growth reallocation by 2101 under alternative Gao/O’Neill urban-land forms. Each row compares national and state demographic controls while holding the baseline, projected urban growth and urban-land weighting surface fixed.

Urban form	Reallocated people	Share of growth
SSP1 compact/sustainable	180 million	25.1%
SSP2 middle-of-road	203 million	28.4%
SSP3 fragmented/regional	194 million	27.1%
SSP5 rapid/expansive	220 million	30.8%

SSP Urban-Land Form Sensitivity

The main gridding experiment holds the urban-land surface fixed and changes the demographic control totals. We also test the complementary sensitivity: holding the demographic projection fixed while changing the type of future urban land expansion. In this experiment, the GHSL-calibrated 2011 baseline, the education-specific migration population projection, and the projected state urban-growth totals are identical in all runs. The only changing input is the Gao and O’Neill 2100 urban-land fraction surface used as the within-state growth-weighting layer⁷.

We use SSP2 as the reference because it is the middle-of-the-road urban-land pathway. We then replace the SSP2 weighting surface with SSP1, SSP3 and SSP5 surfaces while keeping population unchanged. This is therefore not an SSP population scenario comparison. It is an urban-form sensitivity test: compact or sustainability-oriented land patterns, fragmented or regionally uneven land patterns, and rapid or expansive land patterns are applied to the same projected urban population.

The two urban-expansion exercises therefore answer different questions. The national-versus-state exercise asks how much spatial allocation changes when the demographic control total is moved from India as a whole to state-specific urban growth, conditional on a chosen urban-land form. The SSP urban-form exercise asks how much spatial allocation changes when the demographic

controls are held fixed but the future urban-land weighting surface changes. The values should not be added together as a single reallocation total, because each exercise compares a different pair of counterfactual grids.

Table 10: Same-population sensitivity to Gao/O’Neill SSP urban-land form by 2101. Each row compares an alternative SSP surface with SSP2 while holding the GHSL-calibrated baseline and projected state urban-growth totals fixed.

Urban form	Reference	Reallocated people	Share of growth
SSP1	SSP2	169.9 million	23.8%
SSP3	SSP2	123.2 million	17.3%
SSP5	SSP2	137.6 million	19.3%

The magnitude is large enough to matter for exposure analysis. Relative to SSP2, the alternative urban-land forms reallocate about 170 million people under SSP1, 123 million under SSP3 and 138 million under SSP5, equivalent to 24 per cent, 17 per cent and 19 per cent of projected urban population growth, respectively. These values are smaller than, but comparable to, the 203 million people reallocated when replacing a national demographic control with state-specific demographic controls in the main gridding experiment. The implication is that gridded exposure estimates should document both choices: the demographic control totals used to place people and the urban-land surface used to represent settlement form.

The two gridding experiments have four limitations. First, they allocate urban population using Gao and O’Neill urban-land fractions, so they do not distinguish residential density, built-up intensity, or within-city socioeconomic gradients. Second, they use published SSP urban-land surfaces rather than a new India-specific urban land model. Third, they test state-level demographic controls, not a complete settlement-level decomposition of existing-city growth, peri-urban expansion, and in-situ reclassification. Fourth, the SSP urban-form sensitivity should be interpreted as a controlled exposure-layer experiment, not as a claim that India will follow one specific global SSP land pathway. These limitations define the next step: combine the state-space projection with settlement boundaries, census-town/reclassification data, and gridded built-up or population-density products so that the same demographic scenario can be allocated separately to existing cities, expanding peripheries, and newly urbanising settlements.

Extensions Beyond the Present Analysis

International Migration

International migration should be treated as a separate extension because it answers a different question from internal migration. Internal migration redistributes India's population across states and rural-urban places, which is the mechanism most relevant to the gridded exposure experiments in the main article. International migration removes or adds people to the national state space and may affect the education composition of young adults, remittances, and exposure to destination-country policy shocks. For the present analysis, the projected contribution is small relative to fertility, mortality, education, domestic migration and rural-urban reclassification. Census D-03 reports 5.49 million migrants whose last residence was outside India, equal to 1.2% of all migrants. Among migrants with duration of residence below five years, the corresponding count is 0.69 million, or 0.85% of recent migrants. The released Census migration tables also do not provide a defensible state-residence-age-sex-education schedule for international flows. The Census table structure confirms this limitation: D-03 includes last-residence categories for outside India, but does not provide the education-specific schedule needed for this model, while D-04 contains age-sex-education profiles only by broad last-residence categories rather than by country of last residence or subnational origin²⁴. Until such schedules can be prepared and validated, the India Medium Baseline should retain a zero or near-zero net international migration assumption and focus the redistribution analysis on internal migration.

Sex Ratio at Birth

Sex ratio at birth is already present in the projection machinery because total births are allocated by sex before newborn cohorts are advanced. A future submission-ready SRB module should expose the implied assumptions, validate sex-specific births in the saved outputs, and define scenarios for rapid normalization, slow normalization, and persistence in selected states.

Climate-Linked Mobility Corridors

The migration matrix can support future climate-linked mobility scenarios by applying shocks to established or emerging corridors rather than assuming random redistribution. This would allow sea-level, heat, drought, or flood exposure to be translated into corridor-specific internal mobility pathways.

References

Bibliography

1. Office of the Registrar General & Census Commissioner, India. Population Census 2001. Table D-03: Migrants by Place of Last Residence, Duration of Residence and Reason for Migration (All), India - 2001. <https://censusindia.gov.in/nada/index.php/catalog/19463> (2001).
2. Office of the Registrar General & Census Commissioner, India. Population Census 2011. Table D-03: Migrants by Place of Last Residence, Duration of Residence and Reasons for Migration, India - 2011. <https://www.censusindia.gov.in/nada/index.php/catalog/10840> (2011).
3. Office of the Registrar General & Census Commissioner, India. Population Census 2011. Table D-12: Migrants by Place of Last Residence with Duration of Residence as 0-9 Years and by Age Group, India and States/UTs - 2011. <https://censusindia.gov.in/nada/index.php/catalog/11271> (2011).
4. Office of the Registrar General & Census Commissioner, India. Population Census 2011. Table D-04: Migrants by Place of Last Residence, Age, Sex, Educational Level and Duration of Residence, India - 2011. https://censusindia.gov.in/nada/index.php/catalog/study/PC11_D04-00 (2011).
5. Schiavina, M. *et al.* GHS-POP R2023A - GHS Population Grid Multitemporal (1975-2030). https://human-settlement.emergency.copernicus.eu/ghs_pop2023.php (2023) doi:10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE.
6. Schiavina, M., Melchiorri, M. & Pesaresi, M. GHS-SMOD R2023A - GHS Settlement Layers, Application of the Degree of Urbanisation Methodology to GHS-POP R2023A and GHS-BUILT-S R2023A, Multitemporal (1975-2030). https://human-settlement.emergency.copernicus.eu/ghs_smod2023.php (2023) doi:10.2905/A0DF7A6F-49DE-46EA-9BDE-563437A6E2BA.
7. Gao, J. & O'Neill, B. C. Mapping Global Urban Land for the 21st Century with Data-Driven Simulations and Shared Socioeconomic Pathways. *Nature Communications* **11**, 2302 (2020).