Online Resource 1 — Supplementary Material

Universal but Unequal: Bayesian Small-Area Estimation of District Fertility and Infant Mortality Transitions in Rwanda, 2006–2025

Spatial Demography — supplementary material (anonymised for double-blind review)

This supplement contains the following sections:

- S1: data processing
- S2: the model and priors
- S3: computation and diagnostics
- S4: sensitivity analyses
- S5: full results tables
- S6: supplementary figures
- S7: the code package

S1 Data processing

S1.1 Recodes, districts and reference periods

The analysis uses four recodes from each RDHS round:

- the women's recode (IR: RWIR61, RWIR70, RWIR81, RWIR91);
- the birth recode (BR: RWBR61, RWBR70, RWBR81, RWBR91);
- the GPS file (GE: RWGE61, RWGE72, RWGE81, RWGE91);
- the geospatial covariate file (GC: RWGC62, RWGC72, RWGC81, RWGC91).

Fieldwork took place from 26 September 2010 to 10 March 2011 (RDHS 2010), from November 2014 to April 2015 (2014–15), from November 2019 to July 2020 with a COVID-19 interruption (2019–20), and from 5 June to 25 October 2025 (2025) (National Institute of Statistics of Rwanda et al., 2012; National Institute of Statistics of Rwanda et al., 2016; National Institute of Statistics of Rwanda et al., 2021, 2025). The weighted mean interview dates were 2010.98, 2015.05, 2020.19 and 2025.63. Subtracting 2.5 years gives reference-period midpoints of 2008.48, 2012.55, 2017.69 and 2023.13. The time covariate in the trend term is τ = (midpoint − 2015.46)/10.

Districts were taken from the survey variable (sdistr in 2010, sdistrict thereafter) and matched by name to GADM 4.1. Table S1 compares this assignment with point-in-polygon assignment of the displaced GPS coordinates; the nearest district was used for the few points falling just outside all polygons.

Table S1 District assignment of clusters

Survey	District source	Clusters	Unassigned	Agreement with GPS point-in-polygon
2010	survey variable 'sdistr'	492	0	0.996
2014–15	survey variable 'sdistrict'	492	0	0.996
2019–20	survey variable 'sdistrict'	500	0	1.000
2025	survey variable 'sdistrict'	560	0	1.000

S1.2 Fertility

For woman i with birth date b_i (CMC, v011) and interview date v_i (v008), the exposure window is months $v_i - 60$ to $v_i - 1$. Exposure in age group g (15–19, …, 45–49) is the overlap, in months, of that window with $[b_i + 12(15 + 5g), b_i + 12(20 + 5g)$

− 1], divided by 12. Births in the window (b3) were classified by the mother's age at birth. Weights are v005/10^6. The same code with a 36-month window produced the national three-year TFR in Table 2 of the main text.

S1.3 Infant mortality life table

Every child born between $v - 71$ and $v - 1$ contributes, for each month of age $m = 0, \ldots, 11$, one child-month if three conditions hold:

- the calendar month b3 + m lies in the window $[v - 60, v - 1]$;
- the child was alive at the start of month m;
- if the child died, the death occurred at age b7 ≥ m.

A death at age b7 = m is counted in that month. Child-months and deaths are pooled within the DHS age segments 0, 1–2, 3–5 and 6–11 months. The monthly hazard in segment k is $h_k = D_k/E_k$, and IMR $= 1 - \prod_k (1 - h_k)^{L_k}$ with $L = (1, 2, 3, 6)$. Nationally this reproduces the published 0–4-year IMR to within 1 per 1,000 (49.4, 31.9, 32.0, 26.5 vs. 50, 32, 33, 27). For comparison, a births-based ratio (deaths before age 12 months among births in the last 60 months) computed from the same surveys understated the published values by 3–6%.

S1.4 Design-based variances and design effects

Let district d contain strata h with n_h clusters. The replicate that deletes cluster i in stratum h sets that cluster's weight to zero and multiplies the weights of the other clusters in stratum h by $n_h/(n_h - 1)$. The JKn variance of an estimator $g(\theta)$ is

$$V = \sum_h \frac{n_h - 1}{n_h} \sum_{i \in h} \{g(\hat{\theta}_{(hi)}) - g(\hat{\theta})\}^2,$$

computed for log TFR and for the IMR. Districts with a stratum containing a single cluster were treated as one stratum (JK1). The Kish-type design effect is $\text{deff}_{dt} = V_{dt}/\{\hat{p}_{dt}(1 - \hat{p}_{dt})/n_{dt}\}$, with n_{dt} the unweighted number of births in the window. Its median over district–periods with at least five deaths was used to form effective sample sizes (1.16, 1.03, 1.20 and 1.25 by survey). We used a survey-level median because district-specific design effects are themselves very noisy with 1–26 deaths per district.

S1.5 Covariates

For each survey and covariate, the GC column closest in year to the survey year was used (Table S2). The DHS missing code −9,999 was recoded to missing. EVI was divided by 10,000 where the extract stores it as an integer. District values are means over sampled clusters. After transformation (log travel time; log of incidence + 0.001), covariates were standardised within survey round.

Table S2 GC columns used for each covariate and survey

covariate	2010	2014–15	2019–20	2025
aridity	Aridity_2010	Aridity_2015	Aridity_2020	Aridity_2020
itn_coverage	ITN_Coverage_2010	ITN_Coverage_2015	ITN_Coverage_2020	ITN_Coverage_2020
lst_c	Land_Surface_Temperature_2010	Land_Surface_Temperature_2015	Land_Surface_Temperature_2020	Land_Surface_Temperature_2020
malaria_inc	Malaria_Incidence_2010	Malaria_Incidence_2015	Malaria_Incidence_2020	Malaria_Incidence_2020
ndvi	Enhanced_Vegetation_Index_2010	Enhanced_Vegetation_Index_2015	Enhanced_Vegetation_Index_2020	Enhanced_Vegetation_Index_2020
travel_time	Travel_Times_2015	Travel_Times_2015	Travel_Times	Travel_Times

S2 Model and priors

S2.1 Scaled ICAR and BYM2

Let $Q = D - W$ be the graph Laplacian of the queen-contiguity graph (30 nodes, 69 edges, one connected component), and let Q^- be its Moore–Penrose inverse. The scaling factor is $c = \exp\{\frac{1}{30}\sum_d \log Q^-_{dd}\} = 0.366$, so that the scaled field $s^* = s/\sqrt{c}$ has a geometric-mean marginal variance of one (Riebler et al., 2016; Sørbye & Rue, 2014). In Stan, the ICAR density is implemented as $-\frac{1}{2}\sum_{i\sim j}(s_i - s_j)^2$ with a soft constraint $\sum_d s_d \sim N(0, 0.001 \cdot 30)$ (Morris et al., 2019).

S2.2 PC prior on the mixing parameter

Let $\gamma_1, \ldots, \gamma_{29}$ be the non-null eigenvalues of Q^-/c. The Kullback–Leibler divergence of the BYM2 model from the unstructured base model is

$$\mathrm{KLD}(\rho) = \tfrac{1}{2}\Big[\rho \sum_k (\gamma_k - 1) - \sum_k \log\{1 + \rho(\gamma_k - 1)\}\Big].$$

The PC prior is $\pi(\rho) = \lambda e^{-\lambda d(\rho)} \, |d'(\rho)|$ with $d(\rho) = \sqrt{2\,\mathrm{KLD}(\rho)}$ (Riebler et al., 2016). Setting Pr(ρ < 0.5) = 2/3 gives λ = −log(1/3)/d(0.5) = 0.552. Standard deviations received exponential PC priors with rate −log(0.01)/1 = 4.61, i.e. Pr(σ > 1) = 0.01 (Simpson et al., 2017).

S2.3 Fay–Herriot marginalisation

For TFR, integrating out e_{dt} gives $y_{dt} \sim N(\eta_{dt}, V_{dt} + \sigma_e^2)$. In each draw, the district–period log TFR is reconstructed as $\eta_{dt} + e_{dt}$, with $e_{dt} \sim N(w_{dt}(y_{dt} - \eta_{dt}),\, w_{dt} V_{dt})$ and $w_{dt} = \sigma_e^2/(\sigma_e^2 + V_{dt})$. This is the classical Fay–Herriot shrinkage (Fay & Herriot, 1979). For IMR, e_{dt} is sampled explicitly (non-centred).

S3 Computation and diagnostics

Each model was run with four chains of 3,000 iterations (1,500 warm-up), adapt_delta = 0.97 and a maximum tree depth of 12. No divergent transitions occurred in any model (Table S3).

Table S3 Convergence diagnostics (maximum $\hat{R}$ and minimum bulk ESS over all parameters)

model	max_rhat	min_bulk_ess	divergences	draws
tfr_M1	1.003	855	0	6000
imr_M1	1.002	1747	0	6000
tfr_M2	1.006	954	0	6000
imr_M2	1.002	1430	0	6000
tfr_M3	1.002	746	0	6000
imr_M3	1.002	1610	0	6000
tfr_M4	1.004	910	0	6000
imr_M4	1.002	1982	0	6000
tfr_M5	1.003	1403	0	6000
imr_M5	1.002	1872	0	6000

Table S4 Posterior summaries of the variance components, all models

Outcome	Model	Parameter	Posterior median (95% CrI)
TFR	M1	σ_u (district level SD)	0.107 (0.080–0.146)
TFR	M1	σ_e (district–period SD)	0.038 (0.007–0.059)
TFR	M2	σ_u (district level SD)	0.098 (0.073–0.135)
TFR	M2	σ_e (district–period SD)	0.037 (0.008–0.058)
TFR	M2	ρ_u (spatial share, level)	0.727 (0.158–0.987)
TFR	M3	σ_u (district level SD)	0.098 (0.072–0.136)
TFR	M3	σ_e (district–period SD)	0.034 (0.005–0.057)
TFR	M3	ρ_u (spatial share, level)	0.715 (0.119–0.985)
TFR	M3	σ_v (district trend SD per decade)	0.018 (0.001–0.056)
TFR	M3	ρ_v (spatial share, trend)	0.240 (0.007–0.923)
TFR	M4	σ_u (district level SD)	0.079 (0.055–0.114)
TFR	M4	σ_e (district–period SD)	0.036 (0.005–0.059)
TFR	M4	ρ_u (spatial share, level)	0.573 (0.024–0.979)
TFR	M4	σ_v (district trend SD per decade)	0.024 (0.001–0.065)
TFR	M4	ρ_v (spatial share, trend)	0.236 (0.008–0.927)
TFR	M5	σ_u (district level SD)	0.078 (0.054–0.110)
TFR	M5	σ_e (district–period SD)	0.038 (0.007–0.062)
TFR	M5	σ_v (district trend SD per decade)	0.022 (0.001–0.065)
IMR	M1	σ_u (district level SD)	0.100 (0.006–0.212)
IMR	M1	σ_e (district–period SD)	0.055 (0.003–0.171)
IMR	M2	σ_u (district level SD)	0.104 (0.009–0.214)
IMR	M2	σ_e (district–period SD)	0.052 (0.002–0.175)
IMR	M2	ρ_u (spatial share, level)	0.292 (0.010–0.951)
IMR	M3	σ_u (district level SD)	0.106 (0.008–0.213)
IMR	M3	σ_e (district–period SD)	0.051 (0.003–0.166)
IMR	M3	ρ_u (spatial share, level)	0.278 (0.009–0.941)
IMR	M3	σ_v (district trend SD per decade)	0.058 (0.002–0.204)
IMR	M3	ρ_v (spatial share, trend)	0.216 (0.007–0.926)
IMR	M4	σ_u (district level SD)	0.059 (0.003–0.168)
IMR	M4	σ_e (district–period SD)	0.048 (0.002–0.158)

Outcome	Model	Parameter	Posterior median (95% CrI)
IMR	M4	ρ_u (spatial share, level)	0.253 (0.008–0.938)
IMR	M4	σ_v (district trend SD per decade)	0.063 (0.003–0.226)
IMR	M4	ρ_v (spatial share, trend)	0.234 (0.009–0.917)
IMR	M5	σ_u (district level SD)	0.058 (0.003–0.168)
IMR	M5	σ_e (district–period SD)	0.049 (0.003–0.162)
IMR	M5	σ_v (district trend SD per decade)	0.062 (0.002–0.223)

Note: σ terms are on the log (TFR) or logit (IMR) scale. σ_v is per decade of reference-period time.

Table S5 Sensitivity of district estimates to the choice of model: agreement of district–period posterior medians with the primary model M3, and the smallest district posterior probability of decline between 2006–2010 and 2020–2025

Outcome	Model	Correlation with M3	Maximum absolute difference	Mean absolute difference	Minimum P(decline)
TFR	M1	0.999	0.10	0.02	1.000
TFR	M2	1.000	0.05	0.01	1.000
TFR	M3	–	–	–	0.999
TFR	M4	0.996	0.16	0.04	0.998
TFR	M5	0.995	0.18	0.04	0.995
IMR	M1	0.998	2.7	0.4	0.997
IMR	M2	0.999	1.5	0.2	0.998
IMR	M3	–	–	–	0.993
IMR	M4	0.933	10.8	2.8	0.966
IMR	M5	0.931	11.4	2.8	0.963

Note: Computed over the 120 district–periods. Differences are in children per woman (TFR) and deaths per 1,000 live births (IMR). The identification of the high- and low-fertility districts and the conclusion that every district declined are unchanged across models.

S4 Sensitivity analyses

Design adjustment. We refitted the M3 mortality model with a naive binomial likelihood on unweighted counts, with the design effect set to 1. District medians correlated at r = 0.998 with the primary estimates. The ratio of 95% interval widths (naive/primary) had a median of 1.02 (range 0.96–1.10). Clustering adjustment therefore matters little in these surveys, because design effects for a rare outcome with about 15 births per cluster are close to one. It would matter more for common outcomes or larger clusters.

Benchmarking. The model-based national IMR (49.3, 32.4, 32.2 and 26.4) lies within 2.3% of the published values. Ratio benchmarking would multiply all district IMRs in each period by 1.015, 0.988, 1.023 and 1.022. Rankings, exceedance of the national value and relative changes are unaffected. Benchmarked district values are stored in the imrb_* columns of T_district_estimates.csv in Online Resource 2.

Model choice. Table S5 compares the district estimates of every model with those of the primary model M3. TFR estimates are virtually identical across models (correlations ≥ 0.995). IMR estimates from M1 and M2 are also very close to M3; those from the covariate models M4 and M5 differ more (correlation 0.93), because the land-surface temperature and aridity terms redistribute a small amount of district variation. In every model, every district has a posterior probability of decline between 2006–2010 and 2020–2025 above 0.99 for TFR and above 0.96 for IMR.

Spatial autocorrelation. Moran's I of posterior medians overstates clustering, because smoothing makes neighbouring estimates similar. Table S9 therefore also reports the posterior distribution of Moran's I, computed for each draw of the latent district surface. For TFR it is 0.33–0.40 with intervals excluding zero; for IMR it is 0.05–0.07 with intervals spanning zero, so spatial clustering of infant mortality is not established.

Covariates. Covariate effects from the spatial and non-spatial models were almost identical (Table 5 of the main text). Adding covariates reduced LOO predictive performance for TFR (Table 3), so the primary estimates do not condition on them.

Precision gains. Table S6 summarises the precision of the direct and model-based estimates.

Table S6 Coefficients of variation of direct and model-based estimates (medians across districts) and counts of districts above CV thresholds

Period	Median CV direct TFR	Median CV model TFR	Median CV direct IMR	Median CV model IMR	Direct IMR CV > 0.3 (n)	Direct IMR CV > 0.5 (n)	Model IMR CV > 0.2 (n)
2006–2010	0.065	0.044	0.291	0.128	14	0	0
2010–2015	0.071	0.044	0.365	0.13	23	2	0
2015–2020	0.064	0.042	0.394	0.134	24	5	0
2020–2025	0.063	0.043	0.477	0.156	28	13	0

S5 Additional results

Table S7 District estimates for all periods: direct (SE) and model-based posterior median (95% CrI)

District	Period	Births	Deaths	TFR direct (SE)	TFR model	IMR direct (SE)	IMR model
Bugesera	2006–2010	359	18	5.65 (0.33)	5.36 (4.95–5.82)	50.0 (8.5)	48.8 (38.4–61.3)
Bugesera	2010–2015	271	11	4.42 (0.23)	4.43 (4.12–4.78)	42.4 (14.7)	32.4 (25.3–41.2)
Bugesera	2015–2020	313	7	4.70 (0.33)	4.54 (4.18–4.94)	24.5 (10.5)	31.4 (24.2–39.7)
Bugesera	2020–2025	314	5	4.14 (0.31)	4.06 (3.70–4.45)	15.4 (8.1)	25.4 (18.6–32.8)
Burera	2006–2010	272	15	4.66 (0.30)	4.81 (4.40–5.24)	52.8 (10.3)	47.5 (36.3–60.5)
Burera	2010–2015	237	3	3.80 (0.31)	4.06 (3.67–4.42)	14.4 (10.5)	30.7 (22.9–38.4)
Burera	2015–2020	280	8	4.75 (0.22)	4.37 (4.06–4.73)	24.8 (13.7)	30.6 (23.1–39.1)
Burera	2020–2025	199	5	3.33 (0.29)	3.71 (3.33–4.09)	21.9 (10.4)	25.1 (18.0–33.3)
Gakenke	2006–2010	297	17	5.23 (0.34)	4.73 (4.35–5.16)	56.4 (18.9)	50.2 (39.6–64.4)
Gakenke	2010–2015	185	7	3.01 (0.26)	3.75 (3.36–4.08)	38.4 (14.5)	32.9 (26.0–42.0)
Gakenke	2015–2020	235	7	3.98 (0.20)	3.95 (3.69–4.23)	31.6 (11.4)	32.2 (25.2–41.0)
Gakenke	2020–2025	189	3	3.55 (0.19)	3.54 (3.29–3.82)	18.6 (9.9)	26.0 (19.2–34.7)
Gasabo	2006–2010	355	17	4.05 (0.29)	4.36 (3.97–4.77)	52.1 (10.4)	46.9 (36.2–59.3)
Gasabo	2010–2015	322	5	3.93 (0.30)	3.77 (3.45–4.15)	15.4 (6.3)	30.4 (23.1–38.0)
Gasabo	2015–2020	369	7	3.99 (0.30)	3.85 (3.52–4.22)	19.5 (8.4)	30.5 (23.0–38.3)
Gasabo	2020–2025	387	12	3.49 (0.27)	3.46 (3.15–3.82)	34.2 (12.3)	25.6 (19.2–34.4)
Gatsibo	2006–2010	334	16	5.05 (0.43)	5.15 (4.66–5.67)	45.2 (14.3)	47.6 (36.5–60.3)
Gatsibo	2010–2015	281	5	4.69 (0.27)	4.43 (4.08–4.82)	18.2 (7.4)	31.3 (23.9–39.6)
Gatsibo	2015–2020	261	9	4.39 (0.31)	4.41 (4.04–4.79)	39.4 (15.8)	32.2 (24.8–41.4)
Gatsibo	2020–2025	263	10	3.74 (0.25)	3.92 (3.58–4.28)	33.1 (12.6)	26.7 (19.7–36.2)
Gicumbi	2006–2010	282	15	4.65 (0.46)	4.74 (4.31–5.22)	52.4 (13.4)	49.9 (38.8–63.8)
Gicumbi	2010–2015	229	6	3.88 (0.27)	3.98 (3.66–4.32)	24.7 (8.6)	32.8 (25.3–42.7)
Gicumbi	2015–2020	256	15	4.29 (0.27)	4.13 (3.82–4.48)	56.6 (13.2)	33.8 (26.6–44.5)
Gicumbi	2020–2025	227	8	3.64 (0.18)	3.67 (3.41–3.95)	32.1 (12.1)	27.4 (20.7–36.9)
Gisagara	2006–2010	333	9	5.36 (0.44)	5.33 (4.86–5.85)	28.6 (9.2)	46.1 (34.5–58.3)
Gisagara	2010–2015	274	12	4.45 (0.27)	4.50 (4.14–4.88)	45.7 (17.1)	31.8 (24.7–41.2)
Gisagara	2015–2020	244	6	4.16 (0.29)	4.53 (4.12–4.92)	27.7 (15.0)	31.2 (23.6–40.3)
Gisagara	2020–2025	285	8	4.47 (0.19)	4.29 (3.99–4.60)	27.7 (13.4)	25.8 (18.9–35.1)
Huye	2006–2010	308	13	5.07 (0.33)	4.97 (4.58–5.43)	43.8 (11.5)	46.5 (35.2–58.5)
Huye	2010–2015	227	5	3.86 (0.23)	4.11 (3.78–4.44)	25.4 (10.7)	30.6 (22.7–38.7)
Huye	2015–2020	212	7	4.13 (0.27)	4.26 (3.91–4.61)	27.0 (9.7)	30.5 (22.6–39.2)
Huye	2020–2025	223	3	4.16 (0.26)	3.95 (3.63–4.29)	12.8 (7.4)	24.6 (17.5–32.9)
Kamonyi	2006–2010	270	11	4.24 (0.24)	4.38 (4.05–4.73)	39.7 (13.3)	47.3 (36.2–59.7)
Kamonyi	2010–2015	248	9	3.77 (0.23)	3.75 (3.47–4.05)	40.3 (10.1)	31.8 (24.7–40.8)
Kamonyi	2015–2020	211	5	3.79 (0.21)	3.82 (3.55–4.11)	20.6 (8.7)	31.1 (23.6–39.9)
Kamonyi	2020–2025	242	7	3.58 (0.21)	3.49 (3.23–3.79)	27.5 (18.8)	25.8 (19.0–34.2)
Karongi	2006–2010	274	12	4.58 (0.24)	4.71 (4.37–5.07)	45.5 (12.0)	47.8 (36.8–60.9)
Karongi	2010–2015	229	10	3.95 (0.39)	4.01 (3.67–4.39)	40.8 (16.8)	31.8 (24.6–40.7)
Karongi	2015–2020	263	7	4.14 (0.23)	4.11 (3.82–4.42)	23.7 (10.1)	30.9 (23.5–39.6)
Karongi	2020–2025	203	3	3.78 (0.18)	3.73 (3.48–4.01)	16.3 (8.9)	25.1 (18.3–33.2)
Kayonza	2006–2010	287	16	5.09 (0.35)	5.15 (4.71–5.63)	59.9 (18.8)	54.2 (43.1–70.9)
Kayonza	2010–2015	281	14	4.56 (0.38)	4.37 (4.02–4.80)	53.7 (15.9)	36.4 (28.9–48.3)
Kayonza	2015–2020	329	13	4.51 (0.28)	4.44 (4.11–4.82)	40.3 (10.9)	35.5 (28.0–46.9)
Kayonza	2020–2025	288	8	3.96 (0.17)	3.98 (3.71–4.25)	31.0 (10.5)	28.9 (21.2–39.9)
Kicukiro	2006–2010	331	17	3.68 (0.27)	3.75 (3.41–4.12)	51.0 (15.8)	47.7 (36.8–61.5)
Kicukiro	2010–2015	269	7	2.78 (0.29)	3.13 (2.82–3.46)	27.6 (10.0)	31.1 (23.7–39.3)
Kicukiro	2015–2020	293	12	3.15 (0.23)	3.22 (2.94–3.53)	33.1 (16.1)	30.9 (23.4–39.8)
Kicukiro	2020–2025	207	1	2.77 (0.22)	2.89 (2.62–3.18)	0.4 (0.4)	24.5 (17.2–32.4)
Kirehe	2006–2010	315	20	5.29 (0.36)	5.16 (4.73–5.62)	63.2 (19.2)	56.8 (43.7–76.6)
Kirehe	2010–2015	257	13	4.43 (0.23)	4.35 (4.04–4.68)	58.7 (14.7)	38.0 (29.4–51.9)
Kirehe	2015–2020	265	11	3.98 (0.31)	4.31 (3.91–4.71)	39.6 (11.1)	36.7 (28.0–50.5)
Kirehe	2020–2025	227	8	3.95 (0.30)	3.93 (3.58–4.33)	39.3 (12.7)	30.1 (21.6–43.2)
Muhanga	2006–2010	238	8	4.28 (0.29)	4.24 (3.90–4.64)	34.1 (16.8)	45.1 (33.3–57.3)
Muhanga	2010–2015	228	5	3.48 (0.20)	3.54 (3.26–3.83)	18.7 (8.0)	29.9 (22.0–38.2)
Muhanga	2015–2020	208	3	3.41 (0.22)	3.57 (3.28–3.87)	13.6 (7.2)	29.9 (21.9–38.1)
Muhanga	2020–2025	164	5	3.15 (0.31)	3.24 (2.93–3.58)	33.5 (17.3)	25.0 (17.8–33.9)
Musanze	2006–2010	298	26	4.86 (0.39)	4.61 (4.19–5.06)	86.5 (20.2)	55.1 (43.5–74.2)
Musanze	2010–2015	214	5	3.41 (0.25)	3.78 (3.43–4.12)	23.9 (9.0)	34.1 (26.5–44.9)
Musanze	2015–2020	295	11	3.80 (0.21)	3.89 (3.60–4.20)	39.7 (10.6)	33.7 (26.2–44.4)
Musanze	2020–2025	256	4	3.77 (0.24)	3.59 (3.30–3.92)	15.1 (9.0)	26.5 (18.9–36.2)
Ngoma	2006–2010	304	19	5.37 (0.41)	5.17 (4.72–5.67)	65.2 (15.2)	52.7 (41.2–68.8)
Ngoma	2010–2015	297	9	4.58 (0.32)	4.36 (4.01–4.76)	30.7 (10.7)	34.0 (26.4–44.0)
Ngoma	2015–2020	244	8	3.56 (0.29)	4.26 (3.84–4.66)	36.5 (12.4)	33.9 (26.2–44.5)
Ngoma	2020–2025	248	8	4.25 (0.27)	4.01 (3.69–4.38)	28.1 (15.5)	27.6 (20.5–37.3)
Ngororero	2006–2010	309	14	4.99 (0.22)	4.94 (4.60–5.29)	45.5 (14.3)	51.9 (40.3–67.3)
Ngororero	2010–2015	263	13	4.16 (0.42)	4.12 (3.76–4.52)	53.4 (19.6)	35.4 (28.1–47.5)

District	Period	Births	Deaths	TFR direct (SE)	TFR model	IMR direct (SE)	IMR model
Ngororero	2015–2020	271	13	4.57 (0.29)	4.25 (3.94–4.64)	54.6 (20.5)	35.2 (27.8–47.3)
Ngororero	2020–2025	198	6	3.50 (0.16)	3.65 (3.39–3.91)	38.4 (20.0)	28.6 (21.5–39.8)
Nyabihu	2006–2010	335	22	5.46 (0.35)	5.10 (4.67–5.59)	64.7 (10.4)	52.4 (41.8–67.8)
Nyabihu	2010–2015	251	6	3.98 (0.35)	4.18 (3.79–4.59)	23.6 (9.6)	33.6 (26.1–43.6)
Nyabihu	2015–2020	292	12	4.23 (0.35)	4.25 (3.86–4.66)	41.5 (14.0)	34.0 (26.7–45.0)
Nyabihu	2020–2025	216	9	3.59 (0.27)	3.77 (3.40–4.14)	39.1 (13.4)	27.8 (20.9–37.8)
Nyagatare	2006–2010	357	13	5.58 (0.33)	5.46 (5.04–5.93)	32.5 (5.9)	44.1 (32.5–56.1)
Nyagatare	2010–2015	271	6	4.49 (0.29)	4.55 (4.19–4.94)	23.8 (10.1)	29.7 (22.0–38.3)
Nyagatare	2015–2020	313	8	4.68 (0.36)	4.65 (4.26–5.06)	25.7 (7.1)	30.1 (22.0–38.6)
Nyagatare	2020–2025	325	9	4.25 (0.23)	4.20 (3.88–4.54)	26.9 (7.4)	25.0 (18.0–34.1)
Nyamagabe	2006–2010	285	18	5.26 (0.23)	5.04 (4.68–5.43)	62.0 (14.3)	50.9 (40.3–66.0)
Nyamagabe	2010–2015	233	7	3.89 (0.29)	4.09 (3.73–4.44)	28.4 (8.5)	33.1 (25.6–43.3)
Nyamagabe	2015–2020	241	11	4.02 (0.35)	4.16 (3.78–4.54)	50.9 (20.0)	33.5 (26.3–44.7)
Nyamagabe	2020–2025	195	7	3.28 (0.26)	3.68 (3.31–4.02)	35.4 (12.4)	27.3 (20.3–37.3)
Nyamasheke	2006–2010	300	11	4.98 (0.25)	5.28 (4.87–5.67)	38.6 (15.1)	42.4 (29.9–54.9)
Nyamasheke	2010–2015	334	2	4.95 (0.31)	4.64 (4.31–5.06)	3.7 (3.3)	27.1 (18.9–34.9)
Nyamasheke	2015–2020	304	5	4.90 (0.23)	4.74 (4.42–5.09)	15.5 (7.0)	27.8 (19.2–36.1)
Nyamasheke	2020–2025	266	7	4.19 (0.26)	4.22 (3.88–4.57)	22.4 (10.6)	23.0 (15.4–31.8)
Nyanza	2006–2010	267	12	5.36 (0.28)	5.17 (4.78–5.59)	45.9 (16.0)	49.8 (38.4–64.1)
Nyanza	2010–2015	249	10	4.35 (0.37)	4.29 (3.94–4.69)	35.3 (12.8)	33.2 (26.2–43.0)
Nyanza	2015–2020	252	15	4.23 (0.27)	4.32 (3.98–4.68)	57.5 (20.7)	33.8 (26.5–44.8)
Nyanza	2020–2025	188	5	3.59 (0.33)	3.85 (3.48–4.23)	29.2 (13.2)	27.3 (20.3–37.4)
Nyarugenge	2006–2010	315	8	3.44 (0.25)	3.88 (3.50–4.25)	29.1 (11.5)	45.3 (34.0–56.5)
Nyarugenge	2010–2015	329	9	3.56 (0.29)	3.39 (3.09–3.75)	28.0 (8.1)	30.6 (23.2–38.7)
Nyarugenge	2015–2020	286	9	3.61 (0.28)	3.46 (3.16–3.82)	30.6 (17.8)	31.0 (23.4–39.4)
Nyarugenge	2020–2025	189	7	2.71 (0.33)	3.08 (2.76–3.44)	37.4 (11.1)	25.9 (18.8–35.0)
Nyaruguru	2006–2010	330	20	5.79 (0.33)	5.70 (5.26–6.17)	59.5 (13.9)	50.2 (39.5–65.0)
Nyaruguru	2010–2015	269	7	4.75 (0.30)	4.78 (4.40–5.17)	31.0 (10.8)	32.7 (25.1–42.4)
Nyaruguru	2015–2020	257	7	4.97 (0.35)	4.90 (4.50–5.33)	29.6 (11.7)	32.3 (24.8–41.9)
Nyaruguru	2020–2025	210	7	4.54 (0.29)	4.44 (4.08–4.82)	36.7 (13.7)	26.7 (19.6–36.1)
Rubavu	2006–2010	309	17	5.56 (0.25)	5.55 (5.18–5.96)	54.7 (9.1)	51.2 (39.8–66.7)
Rubavu	2010–2015	316	11	4.88 (0.24)	4.71 (4.40–5.06)	35.0 (10.2)	33.7 (26.3–43.6)
Rubavu	2015–2020	329	14	4.81 (0.30)	4.72 (4.38–5.10)	39.6 (11.4)	33.4 (26.1–44.1)
Rubavu	2020–2025	324	9	4.01 (0.20)	4.14 (3.83–4.46)	26.9 (12.9)	27.1 (19.9–36.6)
Ruhango	2006–2010	245	7	4.47 (0.24)	4.60 (4.25–4.96)	28.5 (8.4)	46.7 (35.4–58.5)
Ruhango	2010–2015	225	11	3.93 (0.21)	3.92 (3.64–4.21)	49.1 (14.0)	31.9 (24.5–41.5)
Ruhango	2015–2020	239	8	4.05 (0.22)	4.01 (3.73–4.32)	29.9 (14.7)	31.2 (23.9–39.7)
Ruhango	2020–2025	201	4	3.63 (0.23)	3.61 (3.34–3.91)	16.1 (8.9)	25.4 (18.4–33.5)
Rulindo	2006–2010	240	11	3.68 (0.20)	4.06 (3.73–4.38)	48.1 (10.3)	48.2 (37.0–60.8)
Rulindo	2010–2015	232	7	3.90 (0.29)	3.62 (3.34–3.97)	34.9 (9.9)	31.9 (24.6–40.8)
Rulindo	2015–2020	216	4	3.70 (0.23)	3.67 (3.39–3.98)	17.9 (10.3)	31.3 (23.7–39.9)
Rulindo	2020–2025	196	7	3.46 (0.26)	3.34 (3.06–3.68)	34.7 (14.6)	26.1 (19.3–34.8)
Rusizi	2006–2010	318	18	5.25 (0.51)	5.57 (4.99–6.13)	56.5 (16.1)	49.3 (37.9–63.1)
Rusizi	2010–2015	302	13	4.66 (0.39)	4.74 (4.30–5.20)	39.8 (16.8)	32.3 (25.0–41.6)
Rusizi	2015–2020	301	7	4.78 (0.39)	4.85 (4.41–5.30)	23.2 (11.0)	31.1 (23.5–40.0)
Rusizi	2020–2025	304	5	4.72 (0.23)	4.52 (4.18–4.88)	18.7 (10.8)	25.1 (18.0–33.4)
Rutsiro	2006–2010	332	12	5.56 (0.32)	5.36 (4.94–5.84)	35.1 (10.9)	47.4 (35.8–60.1)
Rutsiro	2010–2015	283	12	5.09 (0.78)	4.47 (4.04–4.95)	47.6 (14.6)	32.2 (24.7–41.9)
Rutsiro	2015–2020	313	8	4.63 (0.30)	4.51 (4.15–4.91)	26.5 (9.5)	31.0 (23.3–39.3)
Rutsiro	2020–2025	221	1	3.62 (0.24)	3.92 (3.56–4.30)	5.4 (5.4)	24.8 (17.5–33.0)
Rwamagana	2006–2010	296	14	4.71 (0.26)	4.71 (4.36–5.07)	48.1 (15.9)	48.9 (38.3–62.1)
Rwamagana	2010–2015	277	8	4.28 (0.28)	4.03 (3.73–4.39)	30.1 (12.6)	32.5 (25.4–41.2)
Rwamagana	2015–2020	229	7	3.56 (0.20)	3.92 (3.59–4.23)	28.6 (10.3)	32.6 (24.9–41.9)
Rwamagana	2020–2025	259	10	3.88 (0.22)	3.70 (3.42–4.02)	40.6 (12.4)	27.3 (20.7–36.8)

Note: Births and deaths are unweighted counts; direct and model-based values are weighted. Direct IMR is the life-table estimate per 1,000.

Table S8 District TFR and IMR (per 1,000) in 2020–2025 and change since 2006–2010, all 30 districts, primary model M3, ordered by TFR (full version of Table 4 in the main text)

District	Province	TFR 2020–2025	P(TFR > national)	ΔTFR since 2006–2010	IMR 2020–2025	P(IMR > national)	ΔIMR since 2006–2010
Kicukiro	Kigali	2.89 (2.62–3.18)	0.00	−0.86 (−1.23 to −0.50)	24.5 (17.2–32.4)	0.31	−22.9 (−37.9 to −12.1)
Nyarugenge	Kigali	3.08 (2.76–3.44)	0.00	−0.80 (−1.18 to −0.36)	25.9 (18.8–35.0)	0.44	−19.5 (−30.8 to −4.7)
Muhanga	South	3.24 (2.93–3.58)	0.00	−0.99 (−1.44 to −0.60)	25.0 (17.8–33.9)	0.36	−19.9 (−32.2 to −7.0)
Rulindo	North	3.34 (3.06–3.68)	0.01	−0.72 (−1.07 to −0.26)	26.1 (19.3–34.8)	0.47	−21.9 (−35.6 to −9.5)
Gasabo	Kigali	3.46 (3.15–3.82)	0.04	−0.90 (−1.31 to −0.44)	25.6 (19.2–34.4)	0.42	−21.1 (−34.1 to −8.2)
Kamonyi	South	3.49 (3.23–3.79)	0.03	−0.90 (−1.27 to −0.48)	25.8 (19.0–34.2)	0.43	−21.4 (−34.7 to −8.8)
Gakenke	North	3.54 (3.29–3.82)	0.05	−1.18 (−1.64 to −0.78)	26.0 (19.2–34.7)	0.46	−23.9 (−38.7 to −12.7)

District	Province	TFR 2020–2025	P(TFR > national)	ΔTFR since 2006–2010	IMR 2020–2025	P(IMR > national)	ΔIMR since 2006–2010
Musanze	North	3.59 (3.30–3.92)	0.13	−1.02 (−1.47 to −0.57)	26.5 (18.9–36.2)	0.51	−28.1 (−49.2 to −16.1)
Ruhango	South	3.61 (3.34–3.91)	0.14	−0.99 (−1.39 to −0.56)	25.4 (18.4–33.5)	0.39	−21.1 (−33.7 to −8.8)
Ngororero	West	3.65 (3.39–3.91)	0.18	−1.28 (−1.70 to −0.92)	28.6 (21.5–39.8)	0.71	−23.4 (−37.3 to −9.3)
Gicumbi	North	3.67 (3.41–3.95)	0.25	−1.07 (−1.55 to −0.61)	27.4 (20.7–36.9)	0.61	−22.5 (−35.4 to −8.9)
Nyamagabe	South	3.68 (3.31–4.02)	0.30	−1.36 (−1.85 to −0.94)	27.3 (20.3–37.3)	0.59	−23.7 (−38.5 to −10.4)
Rwamagana	East	3.70 (3.42–4.02)	0.32	−1.01 (−1.40 to −0.58)	27.3 (20.7–36.8)	0.59	−21.7 (−34.8 to −7.8)
Burera	North	3.71 (3.33–4.09)	0.39	−1.10 (−1.57 to −0.63)	25.1 (18.0–33.3)	0.35	−22.2 (−36.2 to −10.6)
Karongi	West	3.73 (3.48–4.01)	0.38	−0.98 (−1.36 to −0.57)	25.1 (18.3–33.2)	0.36	−22.4 (−36.0 to −11.6)
Nyabihu	West	3.77 (3.40–4.14)	0.50	−1.32 (−1.88 to −0.88)	27.8 (20.9–37.8)	0.64	−24.5 (−39.3 to −11.8)
Nyanza	South	3.85 (3.48–4.23)	0.68	−1.30 (−1.82 to −0.88)	27.3 (20.3–37.4)	0.59	−22.6 (−35.8 to −8.9)
Gatsibo	East	3.92 (3.58–4.28)	0.79	−1.22 (−1.76 to −0.73)	26.7 (19.7–36.2)	0.52	−21.0 (−33.2 to −7.4)
Rutsiro	West	3.92 (3.56–4.30)	0.79	−1.43 (−2.01 to −0.99)	24.8 (17.5–33.0)	0.34	−22.2 (−36.4 to −10.6)
Kirehe	East	3.93 (3.58–4.33)	0.81	−1.22 (−1.74 to −0.75)	30.1 (21.6–43.2)	0.78	−26.5 (−44.5 to −12.1)
Huye	South	3.95 (3.63–4.29)	0.85	−1.04 (−1.47 to −0.56)	24.6 (17.5–32.9)	0.32	−21.6 (−34.9 to −9.9)
Kayonza	East	3.98 (3.71–4.25)	0.94	−1.17 (−1.66 to −0.71)	28.9 (21.2–39.9)	0.72	−25.4 (−41.0 to −12.1)
Ngoma	East	4.01 (3.69–4.38)	0.92	−1.15 (−1.65 to −0.66)	27.6 (20.5–37.3)	0.61	−24.9 (−41.1 to −12.3)
Bugesera	East	4.06 (3.70–4.45)	0.95	−1.29 (−1.83 to −0.83)	25.4 (18.6–32.8)	0.38	−23.2 (−37.2 to −12.5)
Rubavu	West	4.14 (3.83–4.46)	0.99	−1.40 (−1.90 to −0.97)	27.1 (19.9–36.6)	0.57	−24.0 (−40.1 to −10.9)
Nyagatare	East	4.20 (3.88–4.54)	1.00	−1.25 (−1.77 to −0.78)	25.0 (18.0–34.1)	0.36	−19.1 (−31.1 to −5.3)
Nyamasheke	West	4.22 (3.88–4.57)	0.99	−1.06 (−1.50 to −0.55)	23.0 (15.4–31.8)	0.21	−19.1 (−31.9 to −7.3)
Gisagara	South	4.29 (3.99–4.60)	1.00	−1.06 (−1.58 to −0.52)	25.8 (18.9–35.1)	0.44	−20.3 (−32.5 to −5.6)
Nyaruguru	South	4.44 (4.08–4.82)	1.00	−1.26 (−1.76 to −0.75)	26.7 (19.6–36.1)	0.53	−23.4 (−38.6 to −10.9)
Rusizi	West	4.52 (4.18–4.88)	1.00	−1.06 (−1.59 to −0.43)	25.1 (18.0–33.4)	0.36	−23.7 (−39.1 to −12.2)

Note: Posterior medians with 95% credible intervals. P(· > national) is the posterior probability that the district exceeds the national value for 2020–2025.

Table S9 Global Moran's I with row-standardised queen weights: permutation tests (9,999 permutations) for direct estimates and posterior medians, and the posterior distribution of Moran's I of the latent district surface (model M3)

Period	TFR direct	TFR posterior median	TFR posterior I (95% CrI)	IMR direct	IMR posterior median	IMR posterior I (95% CrI)
2006–2010	0.440 (0.0003)	0.463 (0.0002)	0.40 (0.27–0.51)	0.203 (0.0221)	0.255 (0.0122)	0.07 (−0.18 to 0.37)
2010–2015	0.335 (0.0018)	0.431 (0.0005)	0.37 (0.23–0.48)	0.068 (0.1794)	0.231 (0.0143)	0.07 (−0.19 to 0.38)
2015–2020	0.154 (0.0610)	0.385 (0.0004)	0.33 (0.16–0.46)	−0.074 (0.6121)	0.190 (0.0348)	0.05 (−0.20 to 0.37)
2020–2025	0.293 (0.0048)	0.437 (0.0001)	0.37 (0.22–0.50)	−0.130 (0.7957)	0.194 (0.0337)	0.05 (−0.20 to 0.38)

Note: Permutation p-values in parentheses. The posterior I is computed for each of the 6,000 posterior draws of the district surface; its expected value under no spatial autocorrelation is $-1/29 \approx -0.03$. Moran's I of posterior medians is inflated by smoothing, which makes neighbouring estimates similar; the posterior I is the appropriate Bayesian summary.

Table S10 Between-district dispersion by period (posterior median and 95% CrI)

Outcome	Period	Between-district SD	Coefficient of variation
TFR	2006–2010	0.544 (0.465–0.629)	0.111 (0.095–0.128)
TFR	2010–2015	0.448 (0.384–0.521)	0.109 (0.093–0.126)
TFR	2015–2020	0.447 (0.381–0.514)	0.106 (0.091–0.122)
TFR	2020–2025	0.409 (0.350–0.471)	0.108 (0.092–0.125)
IMR	2006–2010	6.597 (2.494–10.879)	0.134 (0.051–0.219)

Outcome	Period	Between-district SD	Coefficient of variation
IMR	2010–2015	4.163 (1.284–7.319)	0.128 (0.040–0.219)
IMR	2015–2020	4.065 (1.207–7.151)	0.126 (0.037–0.217)
IMR	2020–2025	3.688 (1.382–6.421)	0.139 (0.052–0.237)

Table S11 σ- and β-convergence, 2006–2010 to 2020–2025

Outcome	P(CV fell, 2006–2010 to 2020–2025)	β-convergence slope (95% CrI)
TFR	0.63	−0.35 (−0.53 to −0.21)
IMR	0.37	−0.74 (−1.42 to −0.41)

Note: The β-convergence slope is from a draw-wise regression of the absolute change on the initial level. Because the initial level is estimated with error, the slope is biased towards negative values (regression to the mean) and should be interpreted together with the CV.

Table S12 Across-district association between TFR and IMR

Period	Correlation TFR–IMR across districts (95% CrI)	P(r > 0)
2006–2010	0.10 (−0.25 to 0.43)	0.71
2010–2015	0.07 (−0.26 to 0.39)	0.67
2015–2020	0.03 (−0.30 to 0.36)	0.58
2020–2025	0.02 (−0.32 to 0.36)	0.55

Table S13 Posterior ranks in 2020–2025 (1 = lowest), median and 95% CrI

District	TFR rank (95% CrI)	IMR rank (95% CrI)
Kicukiro	1 (1–3)	10 (1–27)
Nyarugenge	2 (1–5)	14 (1–29)
Muhanga	3 (1–9)	11 (1–29)
Rulindo	4 (2–12)	15 (2–29)
Gasabo	6 (3–16)	14 (2–29)
Kamonyi	7 (3–16)	14 (1–29)
Gakenke	8 (4–17)	15 (2–29)
Musanze	9 (4–19)	17 (1–30)
Ruhango	10 (4–19)	13 (1–29)
Ngororero	11 (5–19)	23 (4–30)
Gicumbi	12 (5–20)	20 (3–30)
Nyamagabe	12 (4–22)	19 (2–30)
Rwamagana	13 (5–22)	19 (3–30)
Burera	13 (4–23)	11 (1–29)
Karongi	14 (6–22)	12 (1–28)
Nyabihu	15 (5–24)	21 (3–30)
Nyanza	18 (7–26)	19 (2–30)
Gatsibo	19 (9–27)	17 (2–30)
Rutsiro	19 (9–27)	11 (1–28)
Kirehe	20 (9–27)	26 (4–30)
Huye	20 (11–27)	10 (1–28)
Kayonza	21 (13–27)	23 (4–30)
Ngoma	22 (12–28)	20 (2–30)
Bugesera	23 (13–29)	12 (1–28)
Rubavu	25 (17–29)	18 (2–30)
Nyagatare	26 (19–30)	12 (1–29)
Nyamasheke	26 (19–30)	6 (1–27)
Gisagara	27 (21–30)	14 (1–29)
Nyaruguru	29 (23–30)	17 (2–30)
Rusizi	30 (25–30)	12 (1–28)

S6 Supplementary figures

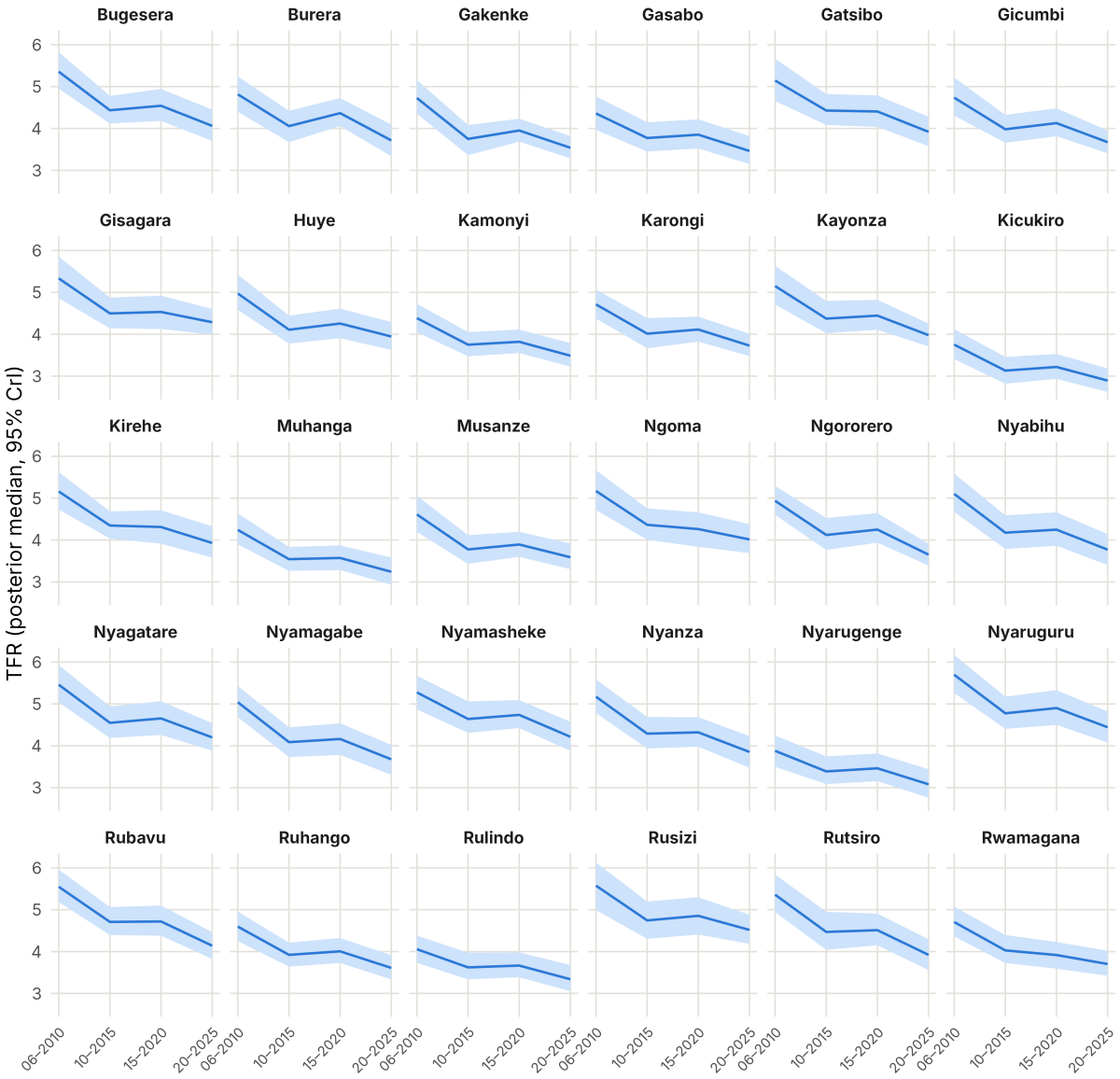


Fig. S1 District TFR trajectories, posterior median and 95% CrI (model M3)

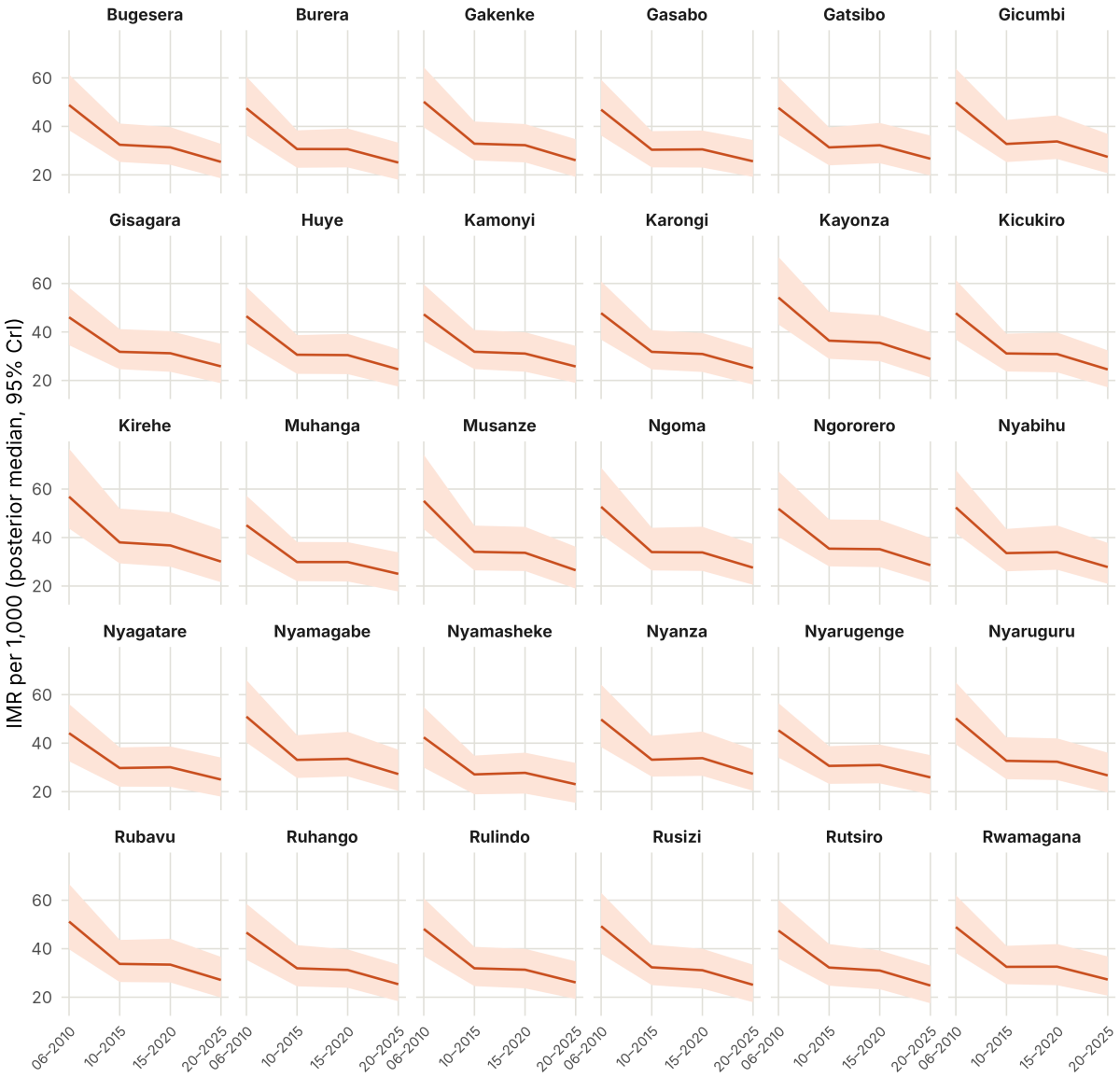


Fig. S2 District IMR trajectories, posterior median and 95% CrI (model M3)

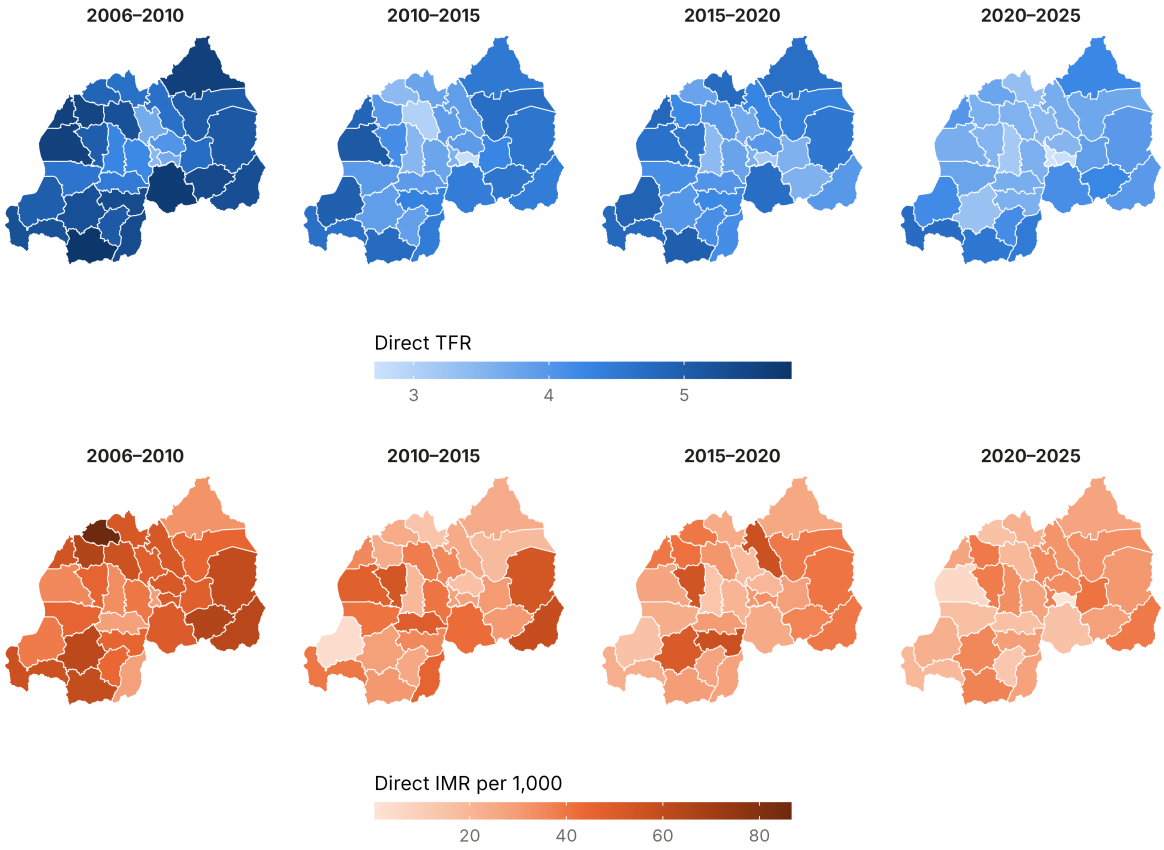


Fig. S3 Direct survey-weighted estimates of TFR and IMR (unsmoothed)

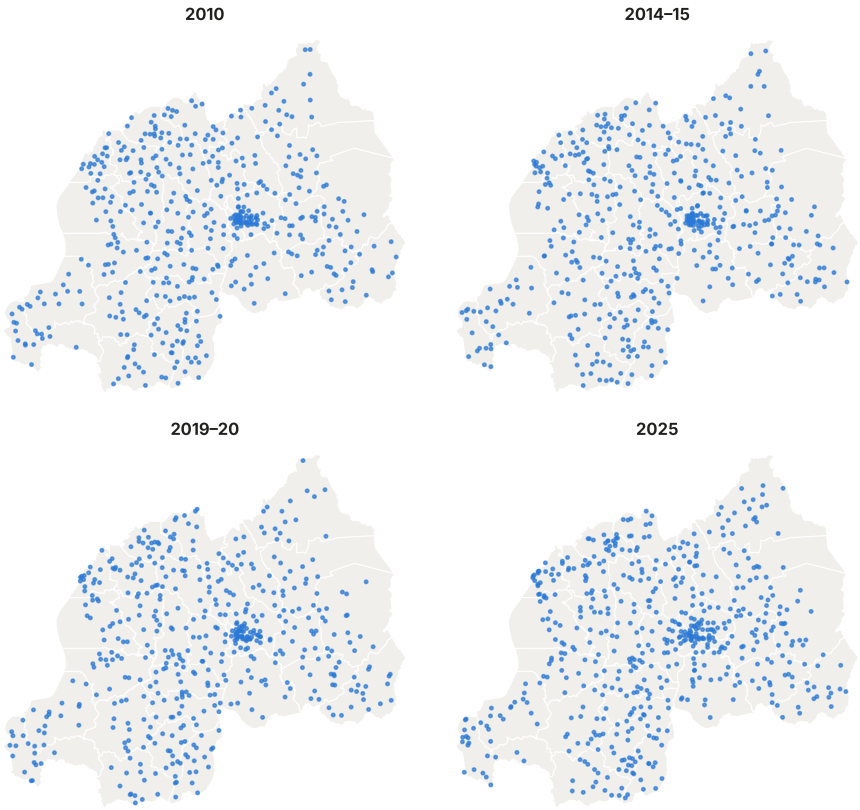


Fig. S4 Displaced DHS cluster locations by survey

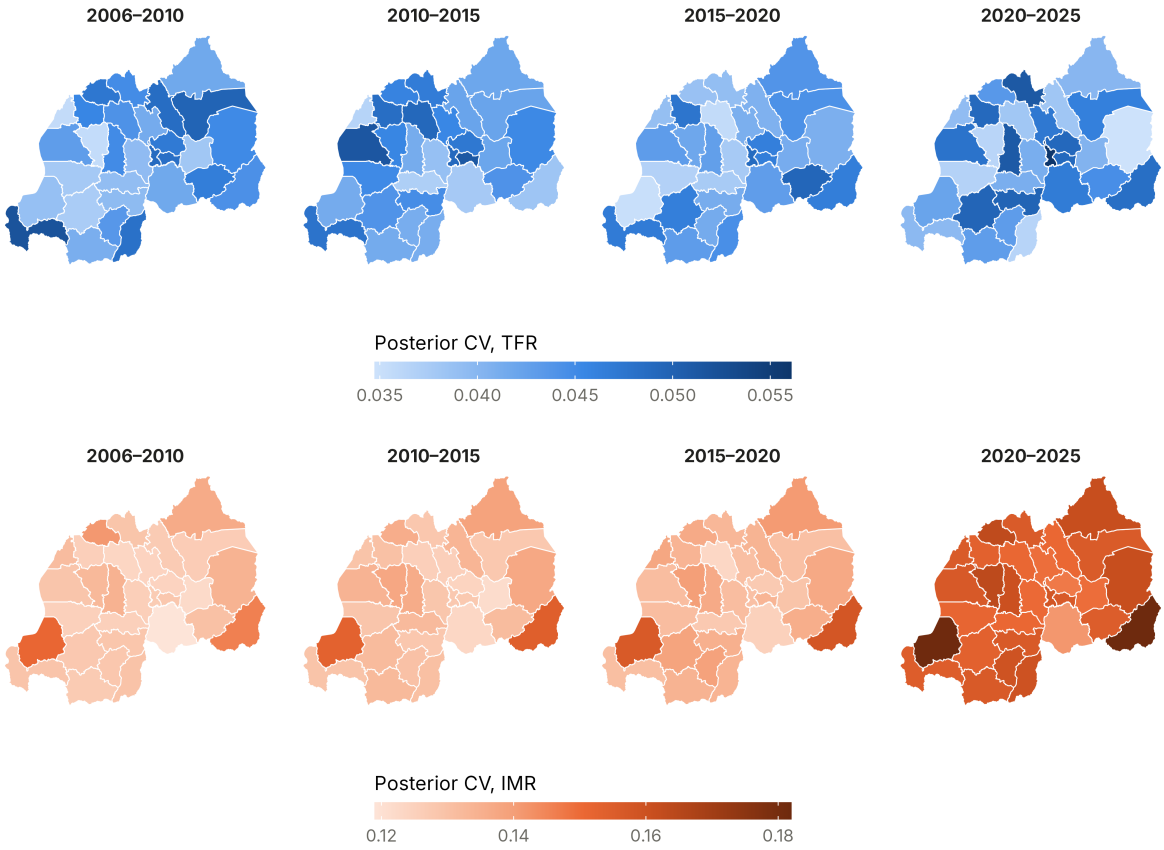


Fig. S5 Posterior coefficients of variation of district TFR and IMR

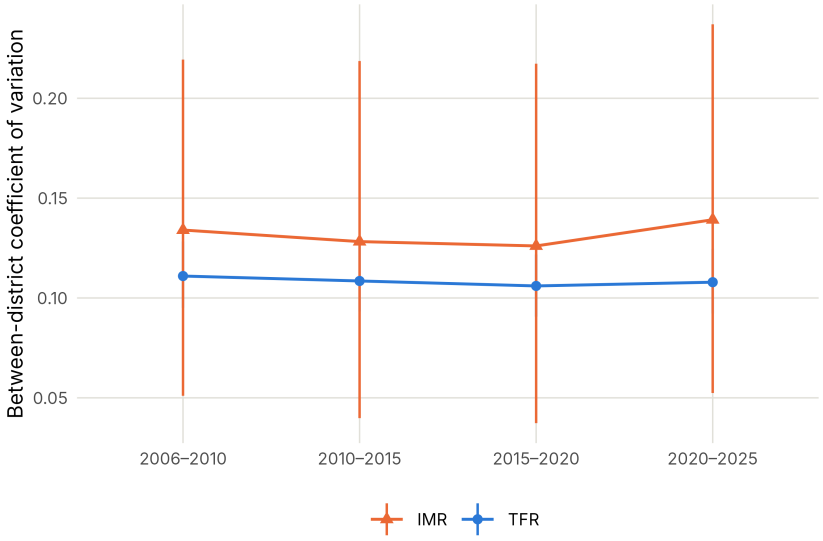


Fig. S6 Between-district coefficient of variation of TFR and IMR, posterior median and 95% CrI



Fig. S7 Study area: districts (GADM 4.1) and provinces

S7 Code and data (Online Resource 2)

Online Resource 2 is a ZIP archive containing the analysis script, the Stan program, a README and the Outputs1 folder (data, tables and figures). Setting DATA_ROOT at the top of rwanda_district_sae_pipeline.R to the folder holding the four unzipped DHS downloads and gadm41_RWA_2.json reproduces every table and figure in Outputs1. The script requires R ≥ 4.1 with haven, dplyr, tidyr, readr, sf, spdep, rstan (≥ 2.26, with a C++ toolchain), loo, ggplot2, patchwork, scales and MASS. A full run takes 30–60 minutes on a laptop, and an interrupted run can be resumed from the saved fits. DHS microdata, GPS and covariate files are not redistributed and must be obtained from the DHS Program.

Path	Content
rwanda_district_sae_pipeline.R	Complete pipeline: file discovery, district assignment, TFR and life-table IMR with JKn variances, covariates, Stan models M1–M5 and S1, PSIS-LOO, posterior summaries, figures
model/sae_spacetime.stan	Stan program (Fay–Herriot and effective-sample-size binomial likelihoods; BYM2 level and trend; PC priors)
Outputs1/data/district_period_panel.csv	120 district–period direct estimates, variances, design effects and covariates
Outputs1/tables/*.csv	All tables of the paper and this supplement
Outputs1/figures/*.png	All figures

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