Global maternal mortality projections by urban/rural location and education level: a simulation-based analysis

Zachary J. Ward,[a,b,*] Rifat Atun,[b,c,d] Gary King,[e] Brenda Sequeira Dmello,[f] and Sue J. Goldie[a,b,d,g]

[a]Center for Health Decision Science, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA
[b]Department of Health Policy and Management, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA
[c]Department of Global Health and Population, Harvard T.H. Chan School of Public Health, Harvard University, Boston, MA, USA
[d]Department of Global Health and Social Medicine, Harvard Medical School, Harvard University, Boston, MA, USA
[e]Institute for Quantitative Social Sciences, Harvard University, Cambridge, MA, USA
[f]Maternal and Newborn Healthcare, Comprehensive Community Based Rehabilitation in Tanzania (CCBRT), Dar Es Salaam, Tanzania
[g]Global Health Education and Learning Incubator, Harvard University, Cambridge, MA, USA

eClinicalMedicine
2024;72: 102653
Published Online xxx
https://doi.org/10.1016/j.eclinm.2024.102653

Summary

Background Maternal mortality remains a challenge in global health, with well-known disparities across countries. However, less is known about disparities in maternal health by subgroups within countries. The aim of this study is to estimate maternal health indicators for subgroups of women within each country.

Methods In this simulation-based analysis, we used the empirically calibrated Global Maternal Health (GMatH) microsimulation model to estimate a range of maternal health indicators by subgroup (urban/rural location and level of education) for 200 countries/territories from 1990 to 2050. Education levels were defined as low (less than primary), middle (less than secondary), and high (completed secondary or higher). The model simulates the reproductive lifecycle of each woman, accounting for individual-level factors such as family planning preferences, biological factors (e.g., anemia), and history of maternal complications, and how these factors vary by subgroup. We also estimated the impact of scaling up women's education on projected maternal health outcomes compared to clinical and health system-focused interventions.

Findings We find large subgroup differences in maternal health outcomes, with an estimated global maternal mortality ratio (MMR) in 2022 of 292 (95% UI 250–341) for rural women and 100 (95% UI 84–116) for urban women, and 536 (95% UI 450–594), 143 (95% UI 117–174), and 85 (95% UI 67–108) for low, middle, and high education levels, respectively. Ensuring all women complete secondary school is associated with a large impact on the projected global MMR in 2030 (97 [95% UI 76–120]) compared to current trends (167 [95% UI 142–188]), with especially large improvements in countries such as Afghanistan, Chad, Madagascar, Niger, and Yemen.

Interpretation Substantial subgroup disparities present a challenge for global maternal health and health equity. Outcomes are especially poor for rural women with low education, highlighting the need to ensure that policy interventions adequately address barriers to care in rural areas, and the importance of investing in social determinants of health, such as women's education, in addition to health system interventions to improve maternal health for all women.

Funding John D. and Catherine T. MacArthur Foundation, 10-97002-000-INP.

Keywords: Maternal health; Global health; Simulation modelling; Health disparities; Social determinants of health

Introduction

Maternal mortality remains a large challenge in global health, and is the focus of a United Nations (UN) Sustainable Development Goal (SDG) (Target 3.1) to reduce the global maternal mortality ratio (MMR) to less than 70 maternal deaths per 100,000 live births by 2030, with no individual country exceeding 140.[1] However, progress has stalled in many countries, and on current

*Corresponding author. Center for Health Decision Science, Harvard T.H. Chan School of Public Health, 718 Huntington Ave. 2nd Floor, Boston, MA, 02115, USA.
E-mail address: zward@hsph.harvard.edu (Z.J. Ward).

Research in context

Evidence before this study

Estimates of global maternal mortality have been produced by the United Nations Maternal Mortality Estimation Inter-agency Group (UN-MMEIG) and the Global Burden of Disease Study using regression-based statistical models, based on the cross-sectional country-level association between aggregate factors and levels of maternal mortality. Recent estimates and projections of global maternal health indicators have also been produced by the Global Maternal Health (GMatH) microsimulation model using a structural model of the reproductive life courses of individual women in 200 countries and territories. We searched PubMed using the search terms "maternal mortality" and "global" on February 8, 2024, without any language or publication date restrictions, and found no other global estimates of maternal mortality. Although existing estimates provide insight into country-level disparities in maternal mortality, global estimates of within-country maternal health disparities by subgroup are lacking.

Added value of this study

Because structural models are based on a defined system of causal components and their relationships, they can offer robust predictions for complex systems and can also be used for counterfactual policy analysis. In addition, individual-level models allow for flexible aggregation of modelled outcomes, allowing subgroup-specific estimates to be made. The empirically calibrated GMatH microsimulation model accounts for heterogeneity both across and within countries, simulating each woman's level of education and urban/rural location, and accounting for individual-level family planning preferences and history of maternal complications. In this analysis we use the GMatH model to estimate a range of subgroup-specific (urban/rural location and level of education) maternal health indicators for 200 countries and territories, and assess the potential role of women's education in achieving the UN Sustainable Development Goal Target 3.1 for maternal health.

Implications of all the available evidence

We find large subgroup differences in maternal health outcomes, with an estimated global maternal mortality ratio (MMR) in 2022 of 292 for rural women vs 100 for urban women, with even larger differences by education level: 536, 143, and 85 for low, middle, and high education levels, respectively. Ensuring all women complete secondary school is associated with a large impact on the projected global MMR in 2030: 97 compared to 167 on current trends, with especially large improvements in countries such as Afghanistan, Chad, Madagascar, Niger, and Yemen. Maternal health outcomes are especially poor for rural women with low education, highlighting the need to ensure that policy interventions address barriers to care in rural areas, and the importance of investing in social determinants of health, such as women's education, in addition to health system interventions to improve maternal health for all women.

trends the SDG maternal health target is unlikely to be met.[2,3] Disparities in maternal mortality across countries are well-known,[2–4] although measurement remains challenging, with even less known about disparities in maternal health outcomes for subgroups (i.e., subnational geographic areas and demographic groups) within countries, as most estimates are country-level.[2,4]

Some studies have described disparities in maternal mortality in specific settings, such as the United States, Canada, and Zambia,[5–8] and disparities in intermediate variables such as utilization of maternal healthcare services have also been documented in sub-Saharan Africa.[9,10] However, at a global level, systematic estimates of within-country disparities in maternal mortality are lacking.

In addition, although previous analyses have focused on health system and clinical interventions that can improve maternal health,[11–13] fewer studies have explicitly examined the impact of social determinants of health, especially the role of women's education, which has been identified as a causal factor for healthcare utilization and maternal health outcomes in settings such as Peru and Uganda.[14,15] In addition to examining the impact of women's education on maternal health outcomes, understanding the impact of geography (e.g., urban/rural location) on reproductive health factors and health system access can help inform policies to improve health equity within countries.

In this analysis, we use an empirically calibrated microsimulation model of global maternal health[3] to estimate a range of maternal health indicators by subgroup (urban/rural location and level of education) for 200 countries and territories and assess the potential role of women's education in achieving the SDG Target 3.1 for maternal health.

Methods

Model overview

We developed the Global Maternal Health (GMatH) microsimulation model (previously described)[3] to simulate the reproductive histories of individual women in 200 countries and territories between 1990 and 2050, using the best demographic, epidemiologic, and clinical data, including over 4.6 million individual-level Demographic and Health Survey (DHS)[16] respondents. The model accounts for heterogeneity both across and within countries, simulating women's level of education and urban/rural location, and accounting for individual-level family planning preferences and history of maternal complications. Monthly probabilities of conception are based on maternal age, breastfeeding status, and contraceptive use. Pregnant women may experience ectopic pregnancy or miscarriage, and risks of induced abortion are modeled for unintended pregnancies.

Complications during pregnancy and childbirth are based on individual-level risk factors, with incidence and case fatality rates impacted by health system factors, such as appropriate referral and transport to facilities, availability of clinical interventions, and quality of care. In addition to death from pregnancy-related complications (i.e., direct maternal deaths), women also face risks of indirect maternal deaths (e.g., deaths due to medical causes such as pre-existing conditions aggravated by pregnancy), as well as mortality from other causes.

Variations in factors such as health system quality and accessibility both across and within countries were accounted for by country- and subgroup-specific model parameters. We used Bayesian hierarchical models for all parameters in the GMatH model to synthesize available data, allowing us to make estimates for countries with no data and regularize the available empirical data. Model documentation and technical details for all parameters are available online (www.gmath-model.org). See Section 1 in the Supplementary Appendix for a figure of the GMatH conceptual model.

We calibrated the model to empirical data for a range of fertility, process, and mortality indicators related to maternal health, reserving a test set of indicators to assess the predictive accuracy of the model, and found that it performs well, with coverage probabilities (i.e., proportion of times the empirical point estimate was contained within the model 95% UI) of 96.0% for maternal mortality indicators and a mean error of 2.6 deaths (SE 8.9) for total maternal deaths (Section 2 in the Supplementary Appendix).[3]

Subgroup trends

Individual women in each country are assigned an urban/rural location (based on trends from the UN Urbanization Projections[17]), and conditional on their location are assigned one of three levels of education: low (less than primary), middle (less than secondary), and high (completed secondary or higher), based on data from the United Nations Educational, Scientific and Cultural Organization (UNESCO)[18] and DHS, resulting in six mutually exclusive demographic subgroups (Section 3 in the Supplementary Appendix).

Subgroup-specific parameters

Using our structural model, we leveraged information from multiple sources along the reproductive pathway to estimate outcomes that are unobserved, or observed with less certainty. This approach also allowed us to make estimates for subgroups, using a consistent model structure to predict the impact of empirical differences in model parameters by subgroup on maternal health outcomes. Although we do not have subgroup-specific estimates used to calibrate the model (e.g., MMR by subgroup), we do have subgroup-specific parameters that yield model predictions consistent with overall empirical data.

Model parameters that vary by subgroup include family planning and health system parameters, whereas we assumed that biological and clinical variables do not vary subgroup, except for anemia and elective c-section (see Table 1). Obstetric complications are impacted by risk factors such as age, anemia status, and delivery site, so are indirectly influenced by subgroups which impact these risk factors. Similarly, the availability of clinical interventions, quality of care, and underreporting of maternal deaths are indirectly influenced by subgroups as these are conditional on facility location, which is directly influenced by subgroup.

When calibrating the model, we had empirical data to inform the prior probability distributions (priors) for some subgroup parameters, while for others we used the same priors for all subgroups but enforced constraints (e.g., weakly monotonic parameter values by education level) when empirical data were unavailable but we wanted to account for subgroup trends (see Table 1). We briefly describe subgroup-specific parameters below and provide details in the appendix (see Section 3).

Anemia

Anemia is a risk factor for maternal mortality compounding risks related to unsafe abortion, hemorrhage, sepsis, and risk of developing pre-eclampsia/eclampsia.[19,20] The main causes of anemia are poor nutrition, infectious diseases (e.g., malaria), and untreated hemoglobin disorders.[21] Estimates of anemia prevalence among pregnant women were available from the World Health Organization (WHO) Global Health Observatory (GHO) database[22] (country-level) and DHS by subgroup (i.e., urban/rural location and level of education).

Family planning parameters

At the beginning of the model, women are initialized with a number of living children born before the analytic timeframe begins, based on subgroup-specific DHS data. Each woman who enters the model over time is also assigned an age of sexual debut, to simulate the beginning of her reproductive life-cycle, based on subgroup-specific DHS data.

Each woman has certain fertility preferences, operationalized by her stated ideal family size (based on subgroup-specific DHS data). Women who have met (or exceeded) their desired number of children are considered to be ‘limiting’ their family size (i.e., they do not want to ever become pregnant again), while women who

	Subgroup-specific parameters	Subgroup-specific priors based on empirical data	Data source
Demographics			
Countries/territories			UN World Population Prospects 2022
Population size projections, Urbanization projections			UN World Population Prospects 2022; UN World Urbanization Prospects 2018
Lifetables			UN World Population Prospects 2022
Proportion of deaths due to injury			Global Burden of Disease 2019
Education projections	X	X	DHS, UNESCO
Migration	X	X	Subgroup-specific weights estimated via raking
Biological parameters			
Natural fecundity/fertility			Medical literature
Sex ratio—primary			Medical literature
Twinning rates			Medical literature
Miscarriage			Medical literature
Ectopic pregnancy			Medical literature
Stillbirths (antepartum)			Medical literature
Month of delivery			Medical literature
Lactational amenorrhea			Medical literature
Menopause			Medical literature
Anemia (hemoglobin distribution)	X	X	DHS, WHO GHO database
Family planning parameters			
Age of sexual debut	X	X	DHS
Number of living children	X	X	DHS
Desired number of children	X	X	DHS
Unmet need	X	X	DHS
Contraception method mix	X	X	DHS
Contraception failure rates	X	[Constraint]	DHS, medical literature
Method duration of use	X	X	DHS
Abortion: incidence and proportion of medical abortions	X	[Constraint]	Medical literature
Sex ratio—secondary	X		UN World Population Prospects 2022
Breastfeeding	X		UNICEF
Health system parameters			
Antenatal care	X	X	DHS data, Medical literature
Starting delivery site	X	X	DHS, WHO GHO database, medical literature
Recognition and referral	X	[Constraint]	Medical literature
Transportation	X	[Constraint]	Medical literature
Referral facility	X		Medical literature
Quality of care			Prior probabilities set by income group
Maternal death under-reporting			Medical literature
Obstetric complications			
Preeclampsia/eclampsia			Medical literature
Obstructed labour			Medical literature
Postpartum hemorrhage			Medical literature
Sepsis			Medical literature
Other direct			Medical literature, WHO Mortality Database
Late maternal deaths			Medical literature, WHO Mortality Database
Indirect maternal deaths			WHO Mortality Database
Clinical interventions			
Elective c-section	X	X	DHS, UNICEF
Active management of the third stage of labor			Medical literature
Partograph			Medical literature
Clean delivery			Medical literature
Ectopic pregnancy management			Medical literature
Hypertension management			Medical literature

(Table 1 continues on next page)

	Subgroup-specific parameters	Subgroup-specific priors based on empirical data	Data source
(Continued from previous page)			
Assisted delivery			Medical literature
Hemorrhage management			Medical literature
Antibiotics			Medical literature

UNESCO, United Nations Educational, Scientific and Cultural Organization; DHS, Demographic and Health Survey; WHO, World Health Organization; GHO, Global Health Observatory; UNICEF, United Nations Children's Fund, [Constraint] indicates that the same prior probability distributions were used for all subgroups but that logical constraints (e.g., weakly monotonic values) were enforced for subgroup parameters when calibrating the model.

Table 1: **Summary of model inputs and subgroup-specific parameters.**

have not yet met their desired number of children are considered to be 'spacing' births (i.e., they wish to become pregnant again at some point, either soon or at a later time). This modelling approach accounts for women's preferences of family size and timing of births, which influences the demand and patterns of contraceptive use (e.g., method type, duration of use, etc.). Age-specific probabilities of conception (i.e., natural fecundity) are modified by contraceptive use and breastfeeding status, which may vary by subgroup.

Unmet need for family planning is defined as "women who do not want to become pregnant but are not using contraception",[23] and is modelled based on subgroup-specific DHS data. For women whose need for family planning is met, we model the subgroup- and age-specific mix of contraceptive methods, based on DHS data. Women may switch between methods for reasons such as side-effects or method failure (i.e., becoming pregnant given typical method use). Contraceptive failure rates vary by socioeconomic status, with the poorest and youngest women at highest risk of experiencing unintended pregnancy.[24,25] We set the same priors for each subgroup within a country, but constrained the calibrated failure rates to be non-decreasing by increasing education level to account for this socioeconomic gradient. Duration of method use and reason for discontinuation are simulated for women who are 'spacing', based on subgroup-specific DHS data.

Women who experience an unwanted pregnancy face the risk of induced abortion, which may be 'safe' (e.g., medical abortion with misoprostol) or 'unsafe' (e.g., traditional methods). Safe abortion requires access to quality medical services, which is typically higher in urban areas, while unsafe abortion may be performed by a nonmedical person (including the woman herself) under unhygienic conditions, or a health worker outside of the prescribed facilities.[26] Due to lack of data we set the same priors for all subgroups within a country, but allowed these parameters to vary by subgroup, and enforced non-decreasing probabilities of medical ('safe') abortion by increasing level of education to account for differences in access to care. The risk of induced abortion is also affected by the secondary sex ratio (i.e., ratio of males to females at birth), which may vary by subgroup as it can be driven by socioeconomic-related factors such as son preference and availability of technology for prenatal sex determination.[27,28]

Health system parameters

During pregnancy, we model the number of antenatal care (ANC) visits each woman attends (based on subgroup-specific DHS data), which we assume can improve anemia status and recognition of pregnancy-related complications.[29] At the time of birth women may begin delivery either at home or in a facility (based on DHS data), which is defined by the level of emergency obstetric care available.[30]

In the event of a delivery complication, the complication must first be recognized and referred for appropriate management (i.e., the 'first delay').[31] A systematic review found that socioeconomic factors, women's autonomy, and knowledge of obstetric danger signs were major factors that contributed to delays in seeking appropriate care.[32] Although we do not have empirical data on recognition/referral by subgroup, to account for socioeconomic factors and women's knowledge, which do vary by subgroups, we constrained these parameters to be non-decreasing by increasing education level when calibrating the model.

Once a complication has been referred, the woman needs timely transportation to a facility. A systematic review identified that availability of transportation infrastructure, distance from the health facility, and lack of finance for transportation were factors that impacted this 'second delay'.[32] We therefore assumed that women with higher education are more likely to have the resources to obtain transport, and that women in urban areas have shorter distances to travel.

In addition to arranging transportation, a target referral facility must also be selected. When referral networks are well-established, women can be taken to a facility that provides the appropriate level of care. However, sometimes women are taken to multiple places in an attempt to find a facility capable of treating them,[33–35] and wealthier women may bypass facilities to seek care in higher-level facilities located farther away.[36] We therefore allowed the referral facility parameters to vary by subgroup.

Elective c-section

The use of caesarean section (c-section) has increased substantially in recent decades, driven by major increases in non-medically indicated procedures in middle- and high-income countries,[37] and with large differences between the poorest and richest women within countries, with many women delivering by elective c-section in private medical facilities.[38] We assume that women who undergo elective c-section are no longer at risk for pre-eclampsia/eclampsia, obstructed labour, or postpartum hemorrhage, but face increased risks of postpartum infection (sepsis),[39] with no change in the risk of other direct complications. We obtained data on c-section rates by country from the United Nations Children's Fund (UNICEF)[40] and subgroup-specific DHS data.

Policy interventions

Using the calibrated model, we estimated the impact of clinical and health system-focused interventions, with scale-up defined by minimum coverage targets informed by the mean level of high-income countries in 2022 (previously described).[11] Specifically, we modelled the following integrated strategies of policy interventions: family planning (contraception, medical abortion), community-based interventions and linkages to care (antenatal care, skilled birth attendants for home births, improved referral and transportation to health facilities), facility-based interventions and linkages to care (increased facility births, availability of clinical services, and improved linkages to care), a facility-based intervention that also improves the quality of care, and a comprehensive strategy (all policy interventions). See Section 4 in the Supplementary Appendix for details.

In addition to these clinical and health system-focused interventions, we simulated two counterfactual scenarios to estimate the impact of scaling up women's education such that all women achieve at least 1) middle (i.e., completed primary, less than secondary), or 2) high (i.e., completed secondary or higher) levels of education. These scenarios were modelled by ensuring that all women in the population achieved (at least) the specified level of education by 2030. In these scenarios, the counterfactual assumption is that women with low educational attainment in the baseline scenario (i.e., on current trends) would instead behave like women with higher education within their own context (e.g., similar fertility preferences, care-seeking behavior, etc.), thus accounting for potential cultural differences across countries and by urban/rural settings within countries.

Statistics

We ran the model 1000 times for each scenario (i.e., baseline or intervention strategy), in each iteration sampling a parameter set, thus accounting for both first-order (individual-level) and second-order (parameter) uncertainty around all outcomes. We report the mean and 95% uncertainty intervals (UI), calculated as the 2.5 and 97.5 percentiles of the simulation results. We estimated a range of subgroup-specific maternal indicators, including the total fertility rate (TFR), maternal mortality ratio (MMR, an indicator of obstetric risk), and lifetime risk of maternal death (LTR, an indicator sensitive to both levels of fertility and obstetric risk) from 1990 to 2050. More information on subgroup parameter differences for intermediate factors (e.g., anemia) is available online (www.gmath-model.org).

Ethics

Ethical approval was not required for this modelling study as it was based on publicly available data.

Role of the funding source

The funder of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Subgroup disparities

Table 2 reports estimated subgroup-specific TFR, MMR, and LTR in 2022 by country income groups, and reveals large differences in these indicators globally by rural vs urban location (e.g., MMR of 292 [95% UI 250–341] for rural women vs 100 [95% UI 84–116] for urban women) and education level (e.g., MMR of 536 [95% UI 450–594] for low education, 143 [95% UI 117–174] for middle education, 85 [95% UI 67–108] for high education levels). These differences diminish by increasing country income groups, but with disparities by education level persisting by urban/rural location and larger educational disparities in rural settings. Urban/rural disparities decrease by educational level and by country income group (e.g., low vs high income). Fig. 1 shows LTR by subgroup and geographic area, with the largest absolute disparities in Africa, but large relative disparities also present in Asia, Latin American and the Caribbean, and Oceania. Group and country-specific results are available in the Supplementary Appendix (Section 5) and in a public online repository (https://doi.org/10.7910/DVN/I2EFAL).

Education interventions

Globally, improving women's education was associated with a substantial reduction in the projected MMR in 2030 (Fig. 2). Ensuring all women achieve a middle level of education (i.e., complete primary, less than secondary) was associated with a global MMR of 139 (95% UI 118–159), which was of similar magnitude to a family planning strategy (149 [95% UI 128–169]), or a community-based strategy that improves ANC coverage,

Income group	Overall					Rural			Urban		
	Rural	Urban	Low education	Middle education	High education	Low education	Middle education	High education	Low education	Middle education	High education
Total Fertility Rate (TFR)											
Global	2.90 (2.52–3.40)	2.35 (2.13–2.63)	4.06 (3.46–4.43)	2.54 (2.18–2.99)	2.31 (1.98–2.65)	4.38 (3.75–4.85)	2.55 (1.94–3.43)	2.57 (1.74–3.47)	3.06 (2.46–3.64)	2.53 (2.09–3.06)	2.20 (1.80–2.59)
Low	4.66 (4.39–4.94)	4.08 (3.66–4.38)	5.34 (5.08–5.69)	4.37 (3.85–4.85)	2.87 (2.26–3.46)	5.52 (5.14–5.86)	4.06 (3.42–4.64)	2.54 (1.83–3.31)	4.45 (3.92–5.15)	4.76 (4.17–5.31)	3.04 (2.26–3.82)
Lower middle	2.89 (2.32–3.66)	2.67 (2.13–3.34)	3.38 (2.46–4.13)	2.68 (2.21–3.51)	2.87 (2.20–3.58)	3.55 (2.59–4.41)	2.67 (1.76–3.96)	3.08 (1.75–4.45)	2.72 (1.72–3.59)	2.71 (2.13–3.69)	2.70 (1.86–3.83)
Upper middle	1.51 (1.07–1.97)	2.04 (1.54–2.46)	2.22 (1.46–3.01)	1.94 (1.36–2.62)	1.90 (1.44–2.33)	2.53 (1.58–3.30)	1.18 (0.60–1.69)	1.76 (1.24–2.44)	2.05 (1.31–3.04)	2.18 (1.37–3.24)	1.94 (1.41–2.54)
High	2.16 (1.65–2.85)	1.85 (1.52–2.24)	2.92 (2.12–3.89)	2.02 (1.56–2.54)	1.87 (1.57–2.28)	2.71 (1.65–4.11)	2.69 (2.22–3.23)	2.04 (1.48–2.87)	2.95 (2.09–4.05)	1.88 (1.39–2.48)	1.83 (1.35–2.31)
Maternal Mortality Ratio (MMR)											
Global	292 (250–341)	100 (84–116)	536 (450–594)	143 (117–174)	85 (67–108)	596 (494–657)	200 (147–274)	91 (59–132)	261 (184–338)	100 (75–130)	83 (62–109)
Low	602 (502–676)	250 (197–302)	671 (545–755)	323 (269–398)	214 (149–304)	728 (577–825)	411 (319–506)	183 (105–296)	327 (230–442)	231 (172–302)	228 (151–335)
Lower middle	199 (157–251)	144 (102–181)	412 (309–483)	145 (104–211)	122 (86–171)	431 (334–503)	159 (99–266)	108 (59–185)	314 (172–470)	129 (85–178)	139 (90–201)
Upper middle	79 (52–168)	37 (23–64)	182 (101–273)	45 (22–121)	36 (24–57)	312 (170–474)	66 (28–206)	47 (26–77)	87 (33–173)	39 (17–92)	34 (19–59)
High	20 (12–31)	17 (12–22)	49 (12–106)	21 (12–33)	15 (11–21)	97 (7–271)	24 (9–43)	17 (8–27)	42 (9–110)	21 (11–34)	15 (10–21)
Lifetime Risk of Maternal Death (LTR)											
Global	0.83 (0.74–0.91)	0.23 (0.19–0.26)	2.13 (1.65–2.47)	0.36 (0.28–0.45)	0.19 (0.15–0.24)	2.56 (1.97–3.01)	0.49 (0.36–0.68)	0.22 (0.15–0.30)	0.76 (0.52–1.03)	0.24 (0.19–0.32)	0.18 (0.14–0.23)
Low	2.88 (2.38–3.25)	1.04 (0.79–1.30)	3.58 (3.01–4.07)	1.43 (1.14–1.79)	0.65 (0.40–1.04)	4.03 (3.29–4.64)	1.70 (1.27–2.18)	0.53 (0.24–0.91)	1.44 (0.97–2.02)	1.11 (0.74–1.54)	0.70 (0.41–1.17)
Lower middle	0.57 (0.47–0.67)	0.37 (0.29–0.45)	1.34 (0.88–1.72)	0.39 (0.28–0.52)	0.34 (0.25–0.43)	1.46 (0.89–1.90)	0.42 (0.26–0.62)	0.31 (0.17–0.45)	0.83 (0.39–1.29)	0.34 (0.23–0.48)	0.36 (0.25–0.47)
Upper middle	0.11 (0.08–0.23)	0.08 (0.05–0.14)	0.35 (0.17–0.55)	0.08 (0.04–0.21)	0.07 (0.04–0.11)	0.72 (0.35–1.09)	0.08 (0.03–0.27)	0.08 (0.04–0.13)	0.15 (0.05–0.30)	0.08 (0.04–0.20)	0.07 (0.04–0.11)
High	0.04 (0.02–0.06)	0.03 (0.02–0.04)	0.12 (0.03–0.29)	0.04 (0.02–0.07)	0.03 (0.02–0.04)	0.25 (0.01–0.84)	0.06 (0.02–0.11)	0.03 (0.01–0.05)	0.10 (0.02–0.30)	0.04 (0.02–0.07)	0.03 (0.02–0.04)

Estimates shown are mean (95% uncertainty interval). Low Education = Less than primary, Middle Education = Less than secondary, High Education = Completed secondary or higher.

Table 2: **Subgroup comparisons of selected maternal health indicators by country income group in 2022.**

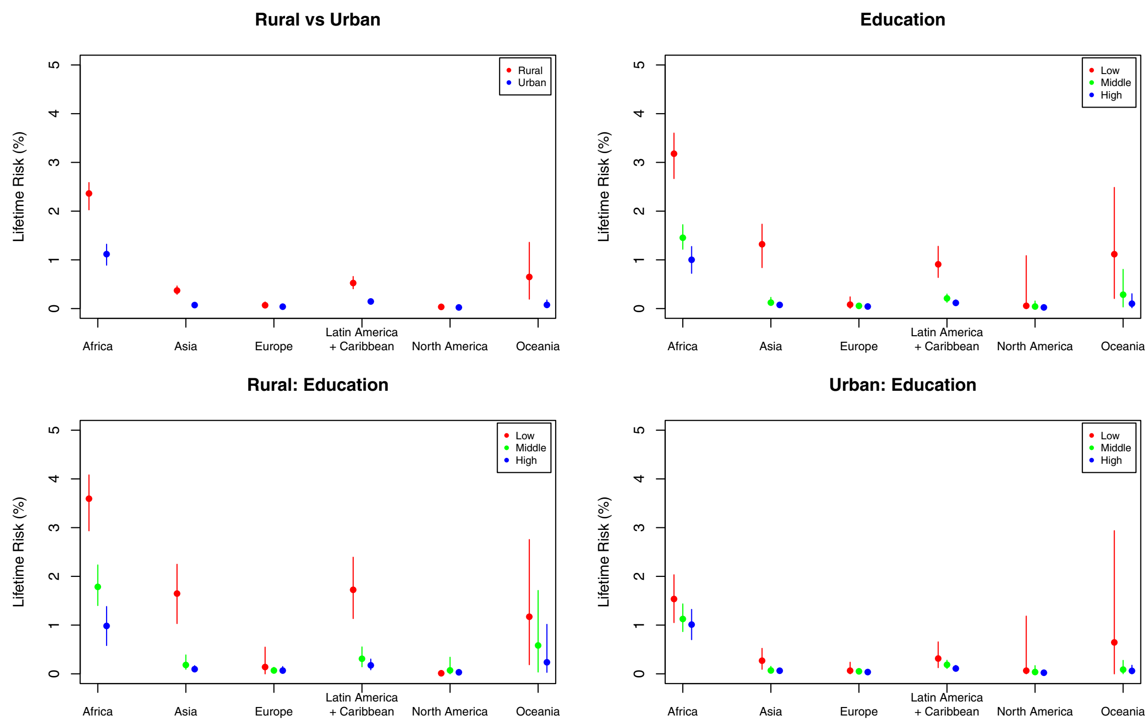

Fig. 1: Lifetime risk of maternal death (%) in 2022 by area and subgroup. Points indicate means. Vertical lines indicate 95% uncertainty intervals.

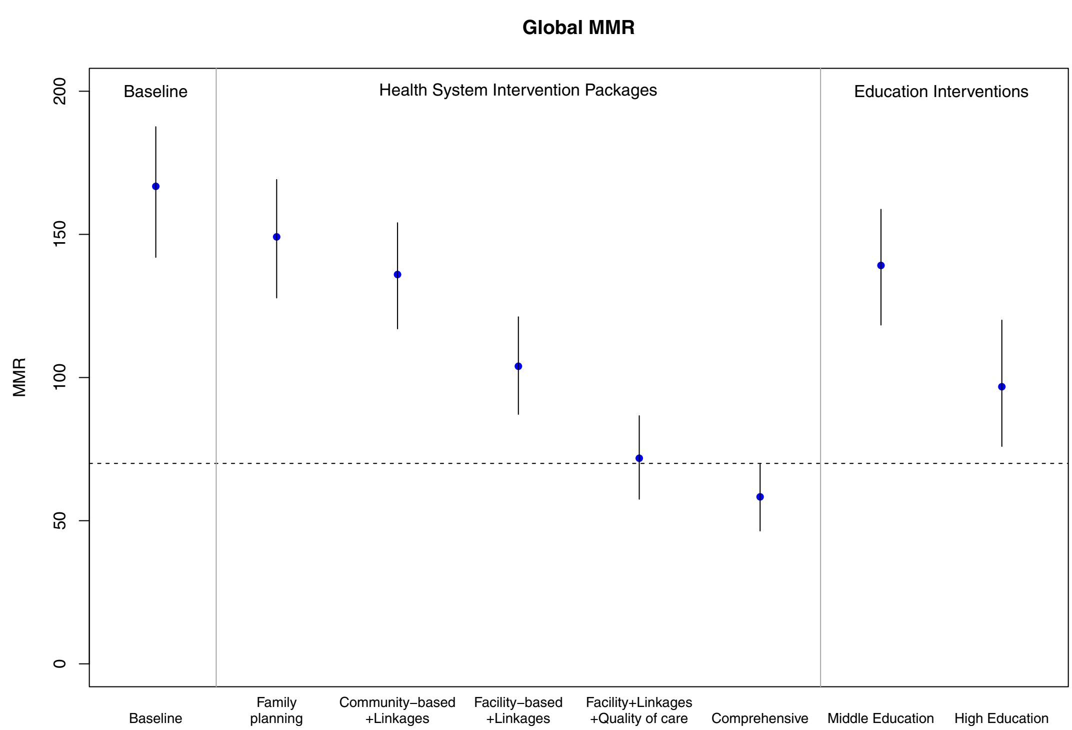

Fig. 2: Projected Global MMR in 2030 by policy intervention. Points indicate means. Vertical lines indicate 95% uncertainty intervals. The dashed horizontal line indicates the Sustainable Development Goal of a global maternal mortality ratio (MMR) of 70 by 2030.

skilled birth attendants for home births, and linkages to care (MMR of 136 [95% UI 117–154]). Ensuring all women complete secondary school was associated with an MMR of 97 (95% UI 76–120), which was of a similar magnitude to a strategy that increases facility births, availability of clinical services, and linkages to care (MMR of 104 [95% UI 87–121]).

Fig. 3 shows the country-specific reduction in (cumulative) projected maternal deaths between 2030 and 2050 associated with an intervention that ensures all women complete secondary education. The impact ranges from close to 0% to over 70%, highlighting large disparities in women's education globally and the impacts on health outcomes. In particular, in countries such as Afghanistan, Chad, and Yemen improving women's education is associated with large improvements in maternal mortality compared to current trends, suggesting that comprehensive interventions to improve women's education could potentially yield large benefits in addition to health system strengthening interventions. In contrast, in some countries with a high burden of maternal deaths, such as India and Nigeria, most women are already projected to complete secondary school on current trends.

Discussion

We provide the first estimates, to our knowledge, of within-country subgroup disparities for global maternal health outcomes, and estimate the potential impact of scaling up women's education. We find large disparities both across and within countries, with the largest disparities by education level; however, large differences still exist by urban/rural status. This highlights the importance of ensuring targeted efforts are made in rural areas to improve maternal health equity.

Strengthening health systems and improving clinical care will be critical to improve global maternal health.[11] Our analysis also shows that improving women's education is associated with reductions in maternal mortality, with universal secondary education for women associated with a substantial reduction in the global MMR, on a par with modeled interventions that increase facility births, availability of clinical services, and linkages to care. However, the wide disparities that exist in women's education globally means that the gains expected from improvements in education would be greater in selected countries. For example, increasing women's education in countries such as Afghanistan, Chad, Madagascar, Niger, and Yemen was associated with large reductions in maternal mortality. In contrast, in countries such as Nigeria and India, where women's education is projected to reach high levels on current trends, the incremental benefits are smaller, highlighting the importance of health system interventions in these countries, both of which have large numbers of maternal deaths.

Indeed, a strong health system with high quality emergency obstetrical care is necessary in all settings to address women's reproductive health needs. Along with

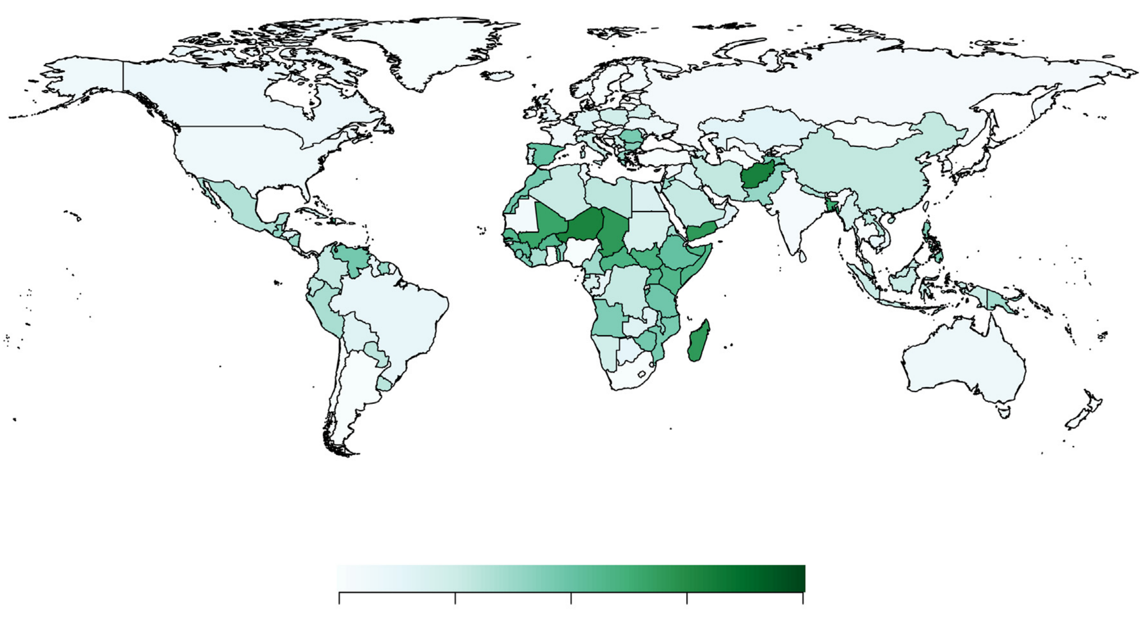

Fig. 3: Projected reduction in maternal deaths 2030–2050 (%) associated with universal female secondary education by country. Projected percentage reduction in cumulative maternal deaths between 2030 and 2050 associated with ensuring all women complete secondary education, compared to current trends.

improving women's education, health system strengthening interventions will therefore also be needed to respond to the behavioral results of increased women's education (e.g., higher levels of facility use, contraception demand), that lie on the causal pathway between education and maternal health outcomes.

Women's education impacts multiple maternal health factors, and can address these factors across the continuum of pregnancy and childbirth. For example, education increases women's earning power,[41] which improves access to transport and medical facilities. In addition to influencing women's fertility preferences and behaviors, education can also improve health-seeking behavior, as schools can help women acquire skills including decision-making, problem-solving, and communication, and has been empirically demonstrated to improve maternal healthcare utilization and outcomes.[14,15] The intersectionality, gender, and rights-based lenses linked to education highlight the importance of going beyond exclusively biomedical approaches when addressing causes of maternal mortality.[42]

Recognizing that education is a powerful vehicle for sustainable development across many domains, Goal 4 of the SDGs aims to "ensure that all girls and boys complete free, equitable and quality primary and secondary education", and "eliminate gender disparities in education and ensure equal access to all levels of education".[43] Encouragingly, we find that progress towards this goal would also yield improvements for the maternal health SDG Target 3.1. However, efforts will be needed to ensure sustainable growth in these education projections, as the current trends are based on sustained efforts over long periods of time.

Although improving women's education would yield benefits in maternal health (among numerous other benefits), there remain obstacles to be addressed in various contexts. For example, lack of financial resources may prevent families from sending daughters to school, and cultural factors such as gender bias and social norms means that in some contexts educating girls has a lower value than educating boys.[44] Girls may also be expected to help with household responsibilities that prevent school attendance.[45] Although barriers to women's education persist, real progress has been made and evidence exists for interventions that work, such as making schools more affordable (addressing both direct and indirect costs), building schools closer to girls' homes and employing flexible schedules to reduce travel time and accommodate competing responsibilities, and community mobilization interventions, among others.[45,46] Pregnancy during adolescence has also been identified as both a cause and effect of school dropout,[47–49] highlighting the interdependence of family planning and health system factors with broader social determinants of maternal health.

Using our individual-level structural model of maternal health which allows for flexible aggregation of model outcomes, we leverage information on observed subgroup differences in intermediate factors to estimate differences in maternal health outcomes. Although we do not have subgroup-specific estimates of these outcomes, we do have subgroup-specific parameters that yield model predictions consistent with empirical data for women overall.[3] This approach could be generalized to other topics where only marginal (overall) outcomes are observed, but subgroup-specific information on intermediate factors are available. Although empirical data are often lacking, and there is typically wide uncertainty around estimates that are available, our modelling approach can be used to examine trends in maternal health indicators by subgroup and the potential impact of policies to improve health equity.

However, there are limitations to our approach. In particular, empirical data on subgroup-specific maternal health outcomes would help to refine the precision of our estimates. However, given the scarcity of maternal mortality data and measurement difficulties even for country-level estimates, we do not anticipate that these will be widely available in the near future, although wherever available they may improve the precision of the model estimates for specific settings.

For example, among 21 countries studied in sub-Saharan Africa, Tanzania was the only country where the neonatal mortality rate was significantly higher in urban areas than rural areas,[50] an example of the 'urban disadvantage' found in some cities. Although our findings provide important insights based on available subgroup data across countries, local factors that are exceptions to these trends highlight the importance of further developing this work with local partners to better contextualize the model to specific settings.

Although we allow many of the model parameters to vary by subgroup, we did not have sufficient data to allow competing mortality (i.e., background lifetables), proportion of deaths due to injury, risk of antepartum stillbirths, menopause, or risk of indirect maternal deaths to vary by subgroup, although these factors may vary within countries. Our estimates of the magnitude of subgroup disparities are therefore likely conservative, as there may be subgroup variation in other factors which we did not capture in the model. Similarly, we did not consider other benefits of improved women's education, such as infant and child health outcomes or economic productivity, so our estimates of the benefits of improved women's education with respect to maternal health are also likely conservative.

We find that in addition to the large disparities in global maternal health that exist across countries, there are substantial within-country subgroup disparities in maternal health outcomes which present a large challenge for population health and health equity. Outcomes are especially poor for rural women with low education, highlighting the need to ensure that policy interventions adequately address barriers to care in rural areas, and the importance of investments to address social determinants of health, such as women's education, in addition to health system interventions to improve maternal health outcomes for all women.

Contributors
ZJW acquired the data, performed the analyses, and developed the model based on a conceptual framework developed by SJG. ZJW and SJG accessed and verified the data. All authors designed the study, interpreted the results, and contributed to the writing of the report. All authors had access to the data and the final responsibility to submit for publication.

Data sharing statement
Simulation results are available in a public data repository: https://doi.org/10.7910/DVN/I2EFAL.

Declaration of interests
We declare no competing interests.

Acknowledgements
ZJW and SJG received support from the John D. and Catherine T. MacArthur Foundation (Grant No. 10-97002-000-INP). The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Appendix A. Supplementary data
Supplementary data related to this article can be found at https://doi.org/10.1016/j.eclinm.2024.102653.

References

1 EPMM working group. *Strategies toward ending preventable maternal mortality (EPMM)*. Geneva: World Health Organization; 2015.
2 *Trends in maternal mortality 2000 to 2020: estimates by WHO, UNICEF, UNFPA, World bank group and UNDESA/population division*. Geneva: World Health Organization; 2023. Available from: https://www.who.int/publications/i/item/9789240068759.
3 Ward ZJ, Atun R, King G, Sequeira Dmello B, Goldie SJ. Simulation-based estimates and projections of global, regional and country-level maternal mortality by cause, 1990-2050. *Nat Med*. 2023;29(5):1253–1261.
4 Global Burden of Disease Collaborative Network. *Global burden of disease study 2019 (GBD 2019) results*. Seattle, United States: Institute for Health Metrics and Evaluation (IHME); 2020. Available from: http://ghdx.healthdata.org/gbd-results-tool.
5 Fleszar LG, Bryant AS, Johnson CO, et al. Trends in state-level maternal mortality by racial and ethnic group in the United States. *JAMA*. 2023;330(1):52–61.
6 Harrington KA, Cameron NA, Culler K, Grobman WA, Khan SS. Rural-urban disparities in adverse maternal outcomes in the United States, 2016-2019. *Am J Public Health*. 2023;113(2):224–227.
7 Ray JG, Park AL, Dzakpasu S, et al. Prevalence of severe maternal morbidity and factors associated with maternal mortality in ontario, Canada. *JAMA Netw Open*. 2018;1(7):e184571.
8 Banda R, Fylkesnes K, Sandøy IF. Rural-urban differentials in pregnancy-related mortality in Zambia: estimates using data collected in a census. *Popul Health Metr*. 2015;13:32.
9 Yaya S, Bishwajit G, Shah V. Wealth, education and urban–rural inequality and maternal healthcare service usage in Malawi. *BMJ Glob Health*. 2016;1:e000085.
10 Samuel O, Zewotir T, North D. Decomposing the urban-rural inequalities in the utilisation of maternal health care services: evidence from 27 selected countries in Sub-Saharan Africa. *Reprod Health*. 2021;18(1):216.
11 Ward ZJ, Atun R, King G, Sequeira Dmello B, Goldie SJ. A simulation-based comparative effectiveness analysis of policies to improve global maternal health outcomes. *Nat Med*. 2023;29(5):1262–1272.
12 Goldie SJ, Sweet S, Carvalho N, Natchu UC, Hu D. Alternative strategies to reduce maternal mortality in India: a cost-effectiveness analysis. *PLoS Med*. 2010;7:e1000264.
13 Jamison DT, Alwan A, Mock CN, et al. Universal health coverage and intersectoral action for health: key messages from disease control priorities, 3rd edition. *Lancet*. 2018;391:1108–1120.
14 Weitzman A. The effects of women's education on maternal health: evidence from Peru. *Soc Sci Med*. 2017;180:1–9.
15 Amwonya D, Kigosa N, Kizza J. Female education and maternal health care utilization: evidence from Uganda. *Reprod Health*. 2022;19(1):142.
16 ICF. Demographic and health surveys (various) [Datasets]. Funded by USAID. Rockville, Maryland: ICF [Distributor]. Available from: https://dhsprogram.com/.
17 United Nations, Department of Economic and Social Affairs, Population Division. *World urbanization prospects: the 2018 revision*. Online Edition; 2018. Available from: https://population.un.org/wup/Download/.
18 UNESCO Institute for Statistics (UIS). Share of population by educational attainment, population 25 years and older. February 2019 release. Available from: http://uis.unesco.org/sites/default/files/datacentre/Educational_attainment_-_Niveau_d'%C3%A9ducation_atteint.xlsx.
19 Brabin BJ, Hakimi M, Pelletier D. An analysis of anemia and pregnancy-related maternal mortality. *J Nutr*. 2001;131(2S-2):604S–614S.
20 Bilano VL, Ota E, Ganchimeg T, Mori R, Souza JP. Risk factors of pre-eclampsia/eclampsia and its adverse outcomes in low- and middle-income countries: a WHO secondary analysis. *PLoS One*. 2014;9(3):e91198.
21 Rahman MM, Abe SK, Rahman MS, et al. Maternal anemia and risk of adverse birth and health outcomes in low- and middle-income countries: systematic review and meta-analysis. *Am J Clin Nutr*. 2016;103(2):495–504.
22 World Health Organization. Prevalence of anaemia in pregnant women - estimates by country. Global Health Observatory. Available from: https://apps.who.int/gho/data/view.main.ANAEMIAWOMENPWv?lang=en.
23 Demographic and health survey documentation. Unmet need. Available from: http://dhsprogram.com/topics/Unmet-Need.cfm.
24 Bradley SEK, Polis CB, Bankole A, Croft T. Global contraceptive failure rates: who is most at risk? *Stud Fam Plann*. 2019;50(1):3–24.
25 Moreau C, Trussell J, Rodriguez G, Bajos N, Bouyer J. Contraceptive failure rates in France: results from a population-based survey. *Hum Reprod*. 2007;22(9):2422–2427.
26 WHO. Unsafe abortion. *Global and regional estimates of incidence of unsafe abortion and associated mortality in 2008*. 6th ed. Geneva: World Health Organization; 2011.
27 Chao F, Gerland P, Cook AR, Alkema L. Systematic assessment of the sex ratio at birth for all countries and estimation of national imbalances and regional reference levels. *Proc Natl Acad Sci U S A*. 2019;116(19):9303–9311.
28 Chao F, Gerland P, Cook AR, Alkema L. Global estimation and scenario-based projections of sex ratio at birth and missing female births using a Bayesian hierarchical time series mixture model. *Ann Appl Stat*. 2021;15(3):1499–1528.
29 World Health Organization. *WHO recommendations on antenatal care for a positive pregnancy experience*; 2016. Available from: http://apps.who.int/iris/bitstream/10665/250796/1/9789241549912-eng.pdf.
30 World Health Organization, UNFPA, UNICEF, AMDD. *Monitoring emergency obstetric care: a handbook*. Geneva: World Health Organization; 2009. Available from: http://whqlibdoc.who.int/publications/2009/9789241547734_eng.pdf.
31 Thaddeus S, Maine D. Too far to walk: maternal mortality in context. *Soc Sci Med*. 1994;38(8):1091–1110.
32 Geleto A, Chojenta C, Musa A, Loxton D. Barriers to access and utilization of emergency obstetric care at health facilities in sub-Saharan Africa: a systematic review of literature. *Syst Rev*. 2018;7(1):183.
33 Echoka E, Makokha A, Dubourg D, Kombe Y, Nyandieka L, Byskov J. Barriers to emergency obstetric care services: accounts of survivors of life threatening obstetric complications in Malindi District, Kenya. *Pan Afr Med J*. 2014;17 Suppl 1(Suppl 1):4.
34 Chaturvedi S, Randive B, Diwan V, De Costa A. Quality of obstetric referral services in India's JSY cash transfer programme for institutional births: a study from Madhya Pradesh province. *PLoS One*. 2014;9(5):e96773.
35 Raj SS, Manthri S, Sahoo PK. Emergency referral transport for maternal complication: lessons from the community based

maternal deaths audits in Unnao district, Uttar Pradesh, India. *Int J Health Policy Manag*. 2015;4(2):99–106.
36 Sabde Y, De Costa A, Diwan V. A spatial analysis to study access to emergency obstetric transport services under the public private "Janani Express Yojana" program in two districts of Madhya Pradesh, India. *Reprod Health*. 2014;11:57.
37 Boerma T, Ronsmans C, Melesse DY, et al. Global epidemiology of use of and disparities in caesarean sections. *Lancet*. 2018;392(10155):1341–1348.
38 Ronsmans C, Holtz S, Stanton C. Socioeconomic differentials in caesarean rates in developing countries: a retrospective analysis. *Lancet*. 2006;368(9546):1516–1523.
39 Buddeberg BS, Aveling W. Puerperal sepsis in the 21st century: progress, new challenges and the situation worldwide. *Postgrad Med J*. 2015;91(1080):572–578.
40 UNICEF. Maternal and newborn health coverage database. Available from: https://data.unicef.org/topic/maternal-health/delivery-care/; 2020.
41 Psacharopoulos G, Patrinos HA. Returns to investment in education: a further update. *Education Economics*. 2004;12(2):111–134.
42 Souza JP, Day LT, Rezende-Gomes AC, et al. A global analysis of the determinants of maternal health and transitions in maternal mortality. *Lancet Glob Health*. 2024;12(2):e306–e316.
43 UNDP. Goal 4: quality education. Available from: https://www.undp.org/sustainable-development-goals/quality-education.
44 Hillman AL, Jenkner E. *Educating children in poor countries*. International Monetary Fund; 2004. Economic Issues No. 33. Available from: https://www.imf.org/external/pubs/ft/issues/issues33/.
45 Lloyd CB, Young J. *New lessons: the power of educating adolescent girls – a girls count report on adolescent girls*. New York Population Council; 2009. Available from: https://knowledgecommons.popcouncil.org/departments_sbsr-pgy/1168/.
46 Sperling GB, Winthrop R. *What works in girls' education: evidence for the world's best investment*. Brookings Institution Press; 2016. Available from: https://www.brookings.edu/books/what-works-in-girls-education-evidence-for-the-worlds-best-investment/.
47 Cruz E, Cozman FG, Souza W, Takiuti A. The impact of teenage pregnancy on school dropout in Brazil: a Bayesian network approach. *BMC Public Health*. 2021;21(1):1850.
48 Sobngwi-Tambekou JL, Tsague-Agnoux M, Fezeu LK, Ndonko F. Teenage childbearing and school dropout in a sample of 18,791 single mothers in Cameroon. *Reprod Health*. 2022;19(1):10.
49 Stoner MCD, Rucinski KB, Edwards JK, et al. The relationship between school dropout and pregnancy among adolescent girls and young women in South Africa: a HPTN 068 analysis. *Health Educ Behav*. 2019;46(4):559–568.
50 Norris M, Klabbers G, Pembe AB, et al. A growing disadvantage of being born in an urban area? Analysing urban-rural disparities in neonatal mortality in 21 Africa countries with a focus on Tanzania. *BMJ Glob Health*. 2022;7:e007544.