US national, state and county-level trends in fertility and maternal mortality from 1980-2014

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A thesis
submitted in partial fulfillment of
the requirements for the degree of

Master of Public Health

University of Washington
2019

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Program Authorized to Offer Degree:
Global Health

University of Washington

Abstract

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Abstract

Importance Tracking subnational variability in fertility rates, quantifying inequality in maternal mortality risk, and understanding important drivers behind increases in maternal deaths is essential in guiding state- and county-level decision makers to target policies that improve reproductive and maternal health in the United States.

Objective To estimate fertility rates and maternal mortality ratios for all US counties between 1980 and 2014 and decompose changes in the number of maternal deaths due to the differences in population size, population age structure, fertility rates, and maternal mortality ratios between 1980 and 2014.

Design, Setting, and Participants Using deidentified birth records from the National Center for Health Statistics (NCHS) and population counts from the US Census Bureau, NCHS and Human Mortality Database, age-specific fertility rates were estimated with previously validated small area estimation models. Similar methods were previously used to model the maternal mortality rate which was combined with the estimated fertility rates to calculate county-level maternal mortality ratios. Das Gupta decomposition methods were used to decompose changes in the number of maternal deaths due to differences in multiple effects.

Exposures County of residence.

Main Outcomes and Measures Age-specific and total fertility rates, and age-specific, all-ages, and maternal age-standardized maternal mortality ratios (MMR).

Results The mean age at childbirth has increased in every single county in the US from 1980 to 2014 but there is still substantial variation between counties with a gap of 7.85 years between counties with the highest and lowest mean age at childbirth in 2014. US maternal mortality ratio has increased nationally from 14.76 maternal deaths per 100,000 live births (95% UI, 13.56-16.07) in 1980 to 35.3 maternal deaths per 100,000 live births (95% UI, 33.42-37.17) in 2014 and geographic inequality between counties has increased. The increasingly older fertility age distribution and increases in MMR in the 20 to 34 age group were primarily responsible for the increase in maternal deaths from 1980 to 2002 across US counties. From 2002 to 2014, increases in maternal deaths were primarily due to increases in MMR across all ages.

Conclusions and Relevance Across US counties women are having children at older ages which has partly driven the increase in the number of maternal deaths from 1980 to 2014. But the main contributor to the

large increases seen in maternal deaths since 2002 can be attributed to increases in MMR. More research is needed to understand how much of this increase in MMR throughout the US is due to improvements in identifying maternal deaths because of changes to the US standard death certificates versus actual increases in MMR. Regardless, the US MMR remains well above other high-income countries and there are large inequalities between counties.

Introduction

Fertility and maternal mortality measures make up some of the most important available indicators of development, health, and quality of health care. Fertility rates provide information about future population growth, access to family planning and reproductive health services, and are used in calculating maternal mortality ratios. Along with child mortality and life expectancy, maternal mortality is a key indicator of a community's overall health and is an important focus of many global health programs and goals including the Sustainable Development Goals (SDGs).

The United States fertility rate at the national-level is below replacement level fertility (which is the level needed to replace itself in future generations, assuming zero migration), and women are increasingly choosing to delay when they have children. The Centers for Disease Control and Prevention (CDC)[1] and the Global Burden of Disease Study 2017 (GBD)[2] have both reported state-level fertility rates that vary substantially around the national fertility estimates, but there is likely larger previously unreported variation in county fertility rates.

Compared to similar high-income countries, the United States has been shown to have poor maternal health outcomes with extensive disparities between subpopulations despite spending more on health than any other country. The GBD estimates that the maternal mortality ratio (MMR; maternal deaths per 100,000 live births) in the US has increased from 14 maternal deaths per 100,000 live births in 1990 (ranked 28th in the world) to 30 maternal deaths per 100,000 live births in 2017 (ranked 77th in the world). Within the US in 2017, GBD estimates that MMR varied from 15 (Massachusetts) to 65 (District of Columbia) maternal deaths per 100,000 births. These large disparities observed at the state-level obscure even larger differences in MMR at the county-level.

Several previous analyses have investigated county-level disparities in life expectancy[3] and cause-specific mortality[4]. Dwyer-Lindgren et al.[4] published age-specific maternal mortality rate (MMRate; maternal deaths per 100,000 females in each reproductive age group) estimates as part of a larger analysis, but the MMRate does not measure the risk of death relative to the frequency of childbirth like MMR does. Khan et al.[5] estimated county-level fertility rates but only for the 15-19 year age group. To my knowledge there have been no previously reported county-level MMR or fertility rate estimates for all reproductive age groups.

There has been increased focus in understanding what is causing the recent increase in MMR in the US and understanding why the country has so much higher MMR compared to other countries of similar development status. A previous analysis by Davis and colleagues[6] decomposed change in state-level MMR due to changes in the maternal age distribution and age-specific MMR. Conducting a similar analysis at the county-level would help in identifying critical drivers of changes in maternal mortality in the US.

The following analysis has two primary goals. First, estimate age-specific fertility rates (ASFR; number of live births per 100,000 women in each age group) and age-specific maternal mortality ratios (MMR; number of maternal deaths per 100,000 live births to women in each age group) for each county in the US from 1980 to 2014. Second, decompose changes in the number of maternal deaths at the national, state and county-level to understand the differential effects of changes in population size, population age-structure, and fertility and maternal mortality levels and age patterns.

Methods

Unit of Analysis

The following analyses were conducted at the county-level in the US. In order to create stable units of analysis, counties were combined if their boundaries changed anytime between 1980 and 2014. This reduced the number of units from 3142 counties present in 2014, to 3110 historically stable counties.

Small Area Models for Estimating ASFR, MMRate and MMR

Data

Deidentified live birth and death records were obtained from the National Center for Health Statistics (NCHS). These records captured live births and deaths occurring in the US between January 1, 1980 and December 31, 2014 to US residents. Counts of live births and deaths were tabulated by county of residence, year and age at time of event (10-14, 15-20, . . . , 45-49, 50-54). Death records were also tabulated by the registered underlying cause of death which prior to 1999 was coded to the *International Classification of Diseases, Ninth Revision (ICD-9)* and *ICD-10* for deaths occurring in 1999 or later. No live births data between 1980 and 1996 for maternal age groups 45-49 and 50-54 were used due to birth records only reporting the maternal age up to age group 45+ prior to 1997.

Female population counts by county, year and age group (10-14, . . . , 50-54) from the US Census Bureau, NCHS and the Human Mortality Database were used in this analysis. County-level covariates for levels of education, income, population density, race/ethnicity and Native American reservations were prepared using data from the US Census Bureau and NCHS.

Cause List and Garbage Code Redistribution

Maternal deaths occur as a direct consequence of pregnancy, childbirth or post-partum complications, or indirectly due to pregnancy-induced complications of pre-existing medical conditions, but do not include incidental or accidental causes of death. In order to identify maternal deaths both information about the underlying cause of death and whether or not a woman was pregnant or recently pregnant at time of death is needed. There are documented issues in collecting accurate data for both of these pieces of needed information[6].

The MMRate estimates published initially by Dwyer-Lindgren et al.[4] utilized deaths data that had been mapped from ICD codes to the GBD cause list[7]. The GBD cause list is hierarchically arranged in four levels, and the causes in each level are exhaustive and mutually exclusive. For maternal disorders it includes all deaths due to maternal hemorrhage; maternal sepsis and other maternal infections; maternal hypertensive disorders; maternal obstructed labor and uterine rupture; maternal abortion, miscarriage, and ectopic pregnancy; indirect maternal deaths; late maternal deaths; other maternal disorders and maternal deaths aggravated by HIV/AIDS. Previous research has shown that a substantial proportion of deaths are coded to nonspecific or intermediate causes of death (garbage codes)[8], so, like is done in the GBD analysis[7], these deaths are redistributed and assigned to plausible alternative underlying causes of death.

US states report whether or not a decedent was pregnant or recently pregnant differently and their methods have changed over time. The US added a pregnancy question to the standard death certificate in 2003 but there has been differential adoption of the question by individual states[9]. Prior to the revision in 2003, only 2 states included a question about whether the decedent was pregnant within 42 days of death (the current standard) while 18 other states included a pregnancy question but with a non-standard range of time (3 months, 12 months, 18 months etc.). As of early 2014, five states (California, Colorado, Massachusetts, Virginia, and West Virginia) still had not adopted the standard pregnancy question. No corrections were made in this analysis to account for the different pregnancy questions on the death certificates across state and over time.

Small Area Model

Bayesian spatially explicit mixed-effects regression models were estimated for age-specific MMRate and fertility rates. These models have previously been used to estimate all-cause and cause-specific county-level mortality rates[4]. The model used to estimate age-specific MMRate as described by Dwyer-Lindgren et al.[4] was specified as:

$$D_{j,t,a} \sim \text{Poisson}(m_{j,t,a} \cdot P_{j,t,a})$$

$$\log(m_{j,t,a}) = \beta_0 + \boldsymbol{\beta_1} \cdot \boldsymbol{X}_{j,t} + \gamma_{1,t,a} + \gamma_{2,j} + (\gamma_{3,j} \cdot t + \gamma_{4,j,t}) + (\gamma_{5,j} \cdot a + \gamma_{6,j,a})$$

$D_{j,t,a}$, $m_{j,t,a}$, and $P_{j,t,a}$ are the number of maternal deaths, the underlying MMRate and the population in each county (j), year (t) and age group (a). β_0 is the global intercept, $\boldsymbol{\beta_1}$ is the fixed effect coefficients and $\boldsymbol{X}_{j,t}$ is a vector of covariates for each county and year. $\gamma_{1,t,a}$ is an age-group and year level random intercept that describes the global age-time pattern and $\gamma_{2,j}$ is a county-level random intercept that accounts for spatial effects that persist across ages and over time. $\gamma_{3,j}$ is a county-level random slope on year that allows for county-specific linear deviations from the global time pattern and $\gamma_{5,j}$ is a county-level random slope on age that allows for county-specific linear deviations from the global age pattern. Unlike the model used to estimate ASFR described next, this model also includes $\gamma_{4,j,t}$, a county- and year-level random intercept, and $\gamma_{6,j,a}$, a county- and age-level random intercept. These additional random intercepts allow for additional non-linear deviations away from the global age-time pattern. By pooling strength over ages for the county- and year-level random intercept and over time for the county- and age-level random intercept, these models absorb more variation in smaller counties compared to the model used for ASFR.

The model used in this analysis to estimate age-specific fertility rates was specified as:

$$B_{j,t,a} \sim \text{Poisson}(f_{j,t,a} \cdot P_{j,t,a})$$

$$\log(f_{j,t,a}) = \beta_0 + \boldsymbol{\beta_1} \cdot \boldsymbol{X}_{j,t} + \gamma_{1,t,a} + \gamma_{2,j} + \gamma_{3,j} \cdot t + \gamma_{5,j} \cdot a + \gamma_{7,j,t,a}$$

Here $B_{j,t,a}$ is the number of births and $f_{j,t,a}$ is the ASFR in each county, year and age group. The county- and year-level random intercept ($\gamma_{4,j,t}$), and county- and year-level ($\gamma_{6,j,a}$) random intercepts are replaced by a county-, age- and year-level random intercept ($\gamma_{7,j,t,a}$) leading to less pooling of strength across dimensions. The three-way interactions between county, age and year allow for larger non-linear deviations away from the global age-time pattern which is beneficial for an outcome that occurs more frequently and has substantial variation in county-age-time patterns.

$\gamma_{1,t,a}$, $\gamma_{2,j}$, $\gamma_{3,j}$, and $\gamma_{5,j}$ were assumed to follow conditional autoregressive distributions that smooth across age and time, and across counties. Independent mean zero normal distributions were specified for $\gamma_{4,j,t}$, $\gamma_{6,j,a}$, and $\gamma_{7,j,t,a}$.

For both models seven covariates were included: the proportion of the population above age 25 that has graduated from high school, proportion of the population that is Hispanic, proportion of the population that is black, proportion of the population that is a race other than white or black, proportion of county land area that is in a Native American reservation, the median household income, and the population density.

1000 draws of $m_{j,t,a}$ and $f_{j,t,a}$ were taken from their respective posterior distributions. Rates for aggregate age-groups (age 10-19 ASFR, etc.), and state and national rates were calculated from the population weighted average of the county, year and age specific rates. $f_{j,t,a}$ was used to calculate summary measures of the distribution of age-specific fertility rates, these indicators depend on the assumption that a hypothetical cohort of women would experience at each age the age-specific fertility rates in year t and live through the entire reproductive age span (age 10-54 years). The total fertility rate (TFR) represents the the average number of children a woman in this hypothetical cohort would have and the mean age at childbearing represents the mean maternal age in the hypothetical cohort (calculated as the mean of the midpoint of each five year age group weighted by the age-specific fertility rates).

Draws of $m_{j,t,a}$ and $f_{j,t,a}$ were combined by county, year and age to calculate the age-specific maternal mortality ratios, $MMR_{j,t,a}$. MMR for aggregate age groups (age 10-54 $MMR_{j,t,a}$), and state and national MMR were calculated from the live births weighted average of $MMR_{j,t,a}$. Live births estimates ($f_{j,t,a} \cdot P_{j,t,a}$) were used rather than live births data for aggregation.

The standard used to calculate maternal-age standardized $MMR_{j,t,a}$ was produced by calculating the proportional distribution of live births by mother's age in each year in each state between 1997 and 2014, and then taking the average distribution across all state-years. Only years after 1997 were used due to birth records only reporting maternal age up to 45+.

Decomposition of Change Over Time in the Number of Maternal Deaths

Direct standardization is often used when comparing overall mortality rates across populations in order to remove the effect of differential population age-structures. This method recalculates overall mortality rates using a particular standard age-structure. Das Gupta decompositions[10] use standardization to decompose the difference between populations into the additive contributions of differences in two or more factors. In this analysis I decomposed the change over time in the number of maternal deaths for a given location into the change due to differences in population size, population age-structure, ASFR, and MMR. The number of maternal deaths can be calculated as:

$$D_{l,t,a} = P_{l,t} \cdot c_{l,t,a} \cdot f_{l,a,t} \cdot MMR_{l,a,t}$$

where $D_{l,t,a}$, $f_{l,a,t}$, and $MMR_{l,a,t}$ are the number of maternal deaths, ASFR, and MMR in each location (l), year (t), and age group (a). $P_{l,t}$ is the total population in each location-year, and $c_{l,t,a}$ is the proportion of the population in each age group in each location-year.

Consider the decomposition of change in number of maternal deaths between time point 1 and 2 as an example. The number of maternal deaths standardized to remove the effects of changes in population size, structure and fertility for a given location at time point 1 and time point 2 can be calculated as:

$$D_{1,P,c,f\ Standardized} = Q \cdot MMR_1$$

$$D_{2,P,c,f\ Standardized} = Q \cdot MMR_2$$

where Q is a function of P_1, P_2, c_1, c_2, f_1 and f_2 as described in detail by Das Gupta[10].

$$Q = \frac{P_1 c_1 f_1 + P_2 c_2 f_2}{4} + \frac{P_1 c_1 f_2 + P_1 c_2 f_1 + P_2 c_1 f_1 + P_2 c_2 f_1 + P_2 c_1 f_2 + P_1 c_2 f_2}{12}$$

The effect of the difference in MMR between time point 1 and 2 on the change in number of maternal deaths can then be calculated as the difference between these two standardized maternal death counts.

$$effect_{MMR} = D_{2,P,c,f\ Standardized} - D_{1,P,c,f\ Standardized}$$

This effect can be similarly calculated for the effect of the change in the total population, the population age-structure and the age-specific fertility rate.

The total change in the number of maternal deaths between time 1 and 2 is equal to the sum of each effect.

$$D_2 - D_1 = effect_P + effect_c + effect_f + effect_{MMR}$$

The percent change in the number of maternal deaths is calculate by dividing by the number of deaths at time 1.

$$\frac{D_2 - D_1}{D_1} = \frac{effect_P}{D_1} + \frac{effect_c}{D_1} + \frac{effect_f}{D_1} + \frac{effect_{MMR}}{D_1}$$

The decomposition of the change in the number of maternal deaths was done for each five year age group for each county, state and at the national-level between 1980-2014, 1980-2002 and 2002-2014. The 1980-2002 and 2002-2014 ranges were selected because of the extremely different trends in US national-level MMR between these two time periods. Since each effect is in terms of number of maternal deaths, the effects can also be added to calculate the effect of aggregate-age groups. For ease of interpretation in the decomposition figures and maps, the effects were aggregated into three age groups, 10-19, 20-34 and 35-54 years.

Results

Variation in Fertility Patterns

Fertility trends and patterns vary considerably across US counties both in level and age-pattern. The TFR at the national-level in the US has slightly increased from 1.816 live births (95% UI, 1.814-1.818) in 1980 to 1.867 (95% UI, 1.866-1.869) in 2014, but reached an intermediate peak in 2007 at a TFR of 2.13 (95% UI, 2.128-2.132). In 2014 at the county level, TFR ranged from a high of 4.14 live births (95% UI, 3.67-4.64) in Benson County, North Dakota compared to a low of 0.87 (95% UI, 0.74-1.03) in Echols County, Georgia county. 46.6% of counties (22.2% statistically significant) had a TFR above replacement level (assumed to be around 2.05 in the US), this is the TFR level such that a population replaces itself between generations assuming no migration. The states with over 80% of its counties over replacement level fertility in 2014 includes North Dakota (94%), Nebraska (90%), Utah (90%), South Dakota (89%), and Kansas (87%) (Figure 1).

Between 1980 and 2014 99.2% of counties had statistically significant declines in adolescent fertility (the age-specific fertility rate for females age 10–19). In 2014 adolescent fertility rates ranged from 1.8 live births per 1,000 females ages 10-19 (95% UI, 1.3-2.5) in Pitkin County, Colorado to 37.8 (95% UI, 33.5-42.9) in Geary County, Kansas. Adolescent fertility rates were highest in counties in Texas, New Mexico, along the lower half of the Mississippi, Georgia, Kentucky, Montana, North Dakota and South Dakota (Figure 2). Counties with the lowest adolescent fertility rates were located in the Northeast, along with parts of the Midwest, Colorado, California and Washington (Figure 2). The difference between the 1st and 99th percentile among counties declined from 53 live births per 1,000 females ages 10-19 in 1980 to 27.4 in 2014.

The mean age at childbearing has increased nationally from 26.01 years of age (95% UI, 26-26.01) in 1980 to 28.96 years of age (95% UI, 28.96-28.97) in 2014. Every county had a statistically significant increase in the mean age at childbearing between 1980 and 2014. Substantial variation in the mean age at childbearing exists in 2014 with the highest age in San Francisco County, California at 33.06 years of age (95% UI, 32.91-33.21) and the lowest age in Lake County, Tennessee at 25.21 years of age (95% UI, 24.64-25.83). Counties with low mean age at childbearing were present throughout the South although there were a few counties in these states that have a higher mean age at childbearing (Figure 3). Counties in California, Colorado, Washington, New Jersey, New York, Connecticut and Massachusetts had the highest mean age at childbearing.

Trends and Inequalities in MMR

The maternal mortality ratio for ages 10-54 (all-ages MMR) slightly increased between 1980 and 2002 in the US from 14.8 maternal deaths per 100,000 live births (95% UI, 13.6-16.1) to 15.9 (95% UI, 14.8-17), but since 2002 has increased to 35.3 (95% UI, 33.4-37.2) in 2014. This national value hides substantial variation observed across counties in the US with extremely high MMR in counties along the Mississippi River, the Southern Belt and some counties in Montana, Texas and North Carolina (Figure 4A). Counties with the lowest MMR were seen along the Westcoast, New England, the Upper Midwest, along with parts of Alaska, Colorado, Virginia and other states.

94.4% of all counties experienced a statistically significant increase between 1980 and 2014, and especially large increases in MMR were seen in counties in the mountain states (Figure 4B). Between 1980 and 2002 there were actually statistically significant declines in MMR in 119 counties, mainly located in Massachusetts, North Carolina, Rhode Island and Virginia (Supplemental Figure 2), but still 40.8% of counties experienced a statistically significant increase in MMR during this period. In contrast all but 7 counties had a statistically significant increase between 2002 and 2014.

The difference between the 1st and 99th percentile counties, a measure of absolute geographic inequality, has increased from 31.4 maternal deaths per 100,000 live births in 1980 to 79.2 in 2014. The state with the largest gap between its highest and lowest county MMRs in 2014 was Georgia, where Chattahoochee County had a MMR of 20.2 maternal deaths per 100,000 live births (95% UI, 11.6-32.7) while Hancock County had a MMR of 176.5 (95% UI, 103.5-280.5) (Figure 6).

There was also large variation in age-specific MMR for five-year age groups from 10-54 years (Supplemental figures 3-11) but most age groups had similar spatial patterns to those observed in all-ages MMR. At the national-level between 1980 and 2002 MMR between ages 30 and 44 decreased but from 2002 to 2014 rebounded to previous levels observed in 1980. Consistent with other studies, the highest maternal mortality risk is observed in the oldest age groups and there is also higher MMR for females age 10-14.

Maternal-age standardized MMR decreased between 1980 and 2002 at the national-level in the US from 26.5 maternal deaths per 100,000 live births (95% UI, 23.8-29.8) to 15.9 (95% UI, 14.8-17.1) but similar to all-ages MMR has increased since 2002 to 30.9 (95% UI, 29.3-32.6) in 2014. After adjusting for differences in fertility between counties, the spatial patterns in 2014 remain very similar to all-ages and age-specific MMR (Figure 5A).

Increases in maternal age-standardized MMR between 1980 and 2014 were still observed in Montana, Idaho, Wyoming and Utah but there were also significant decreases in Virginia, North Carolina, Tennessee and Alabama (Figure 5B). Between 1980 and 2002 most counties had a decline in maternal age-standardized MMR (95.9%; statistically significant in 71% of counties). Between 2002 and 2014 all counties experienced an increase in maternal age-standardized MMR (statistically significant in 99.8%).

Drivers of the Change in the Number of Maternal Deaths in US Counties

Between 1980 and 2014 the number of maternal deaths in the US increased by 165.1%. This varied at the state and county level with all states experiencing anywhere from a 21.9% to 510.3% increase in maternal deaths (Figure 7) while 33.4% of counties experienced an increase above the national increase in maternal deaths (Figure 8). Nationally, increases in fertility rates observed in the 35 to 54 age group contributed to a 80% (95% UI, 71-91) increase in the number of maternal deaths between 1980 and 2014 while an increase in MMR in the 20 to 34 age group contributed to another 51% (95% UI, 38-64) increase in maternal deaths. Fertility rate increases among 35-54 year olds was also the biggest contributor in 36 states and 71.6% of counties, while increases in MMR for 20 to 34 year olds was the largest contributor to changes in the number of maternal deaths in 13 states and 25.1% of counties.

Changes in fertility rates in the 35 to 54 age group contributed to increasing the number of maternal deaths in almost every county in the US with especially high contributions in parts of Utah, Texas, Georgia, Florida, the Mid Atlantic (Figure 9). Fertility declines in the 20 to 34 age group in counties in the Mountain States dampened the increase in maternal deaths observed in those counties.

Increases in MMR in the 20 to 34 age group helped increase maternal deaths in counties in the Mountain States, along with some counties in the South. MMR changes in the 35 to 54 age group had less impact on changes in maternal deaths. The effect helped increase maternal deaths in the Mountain States but helped reduce the number of maternal deaths in counties along the Eastern US and parts of Colorado and California.

Discussion

This analysis utilized previously published small area estimation methods to produce the first US county-level estimates of both age-specific fertility rates and maternal mortality ratios. I found large differences between counties, and corresponding state- and national-level estimates; identification of this variation is important for future program and policy planning.

In this analysis I made age-specific fertility estimates for females between the age of 10 and 54. Most fertility estimates are only produced for females age 15-49[1], but there is a non-trivial fertility rate in the 10-14 and 50-54 age groups and it is especially important to measure for ensuring accurate maternal mortality estimates since maternal mortality risk is elevated at the tails of the reproductive age span. The GBD estimates fertility for women 10-54 but uses a simple linear regression of the log of the ratio of 10-14 ASFR and 15-19 ASFR to estimate 10-14 ASFR, and for estimating 50-54 ASFR they use a constant ratio across all locations and all years between 45-49 ASFR and 50-54 ASFR[2]. The US has births data disaggregated for females age

10-14 and 50-54 (from 1997 onwards) which allows direct estimation of ASFR in these age groups within the statistical model which produces more accurate US national- and state-level 10-14 and 50-54 ASFR estimates.

Estimation of ASFR for women between ages 10 and 19 enables tracking of progress of the SDG indicator for goal 3, target 3.7. A previous study[5] estimated US county-level fertility rates in females age 15-19 but did not estimate fertility rates in females age 10-14 which are still above zero in the US (2,769 births to females age 10-14 in 2014, 10,169 in 1980). I found that age-specific fertility rates for females 10-14 decreased from 1.13 live births per 100,000 females in age group 10 to 14 (95% UI, 1.1-1.15) in 1980 to 0.27 (95% UI, 0.26-0.28) in 2014 in the US as a whole, and for adolescents (10-19) decreased from 28.67 live births per 100,000 females in age group 10 to 19 (95% UI, 28.6-28.74) to 12.16 (95% UI, 12.12-12.21) Even though the US as a whole has made significant progress in reducing adolescent fertility rates, 55 counties are still above the national adolescent fertility rate in 1980.

A limitation of this study is that US births data were only available up to age 45+ from 1980 to 1996. Due to this constraint our final model only utilized data from 1997 onwards for ages 45-49 and 50-54. This means that estimates for these age groups prior to 1997 are dependent on the observed trends from other age groups and after 1997. If the relationship between fertility rates up to age 45 and fertility rates above age 45 changes significantly between the two time periods then our estimated fertility rates in these age groups will be biased. During model development, I compared the estimate of aggregate ASFR in the 45-54 age group to the aggregated data for the corresponding age group in order to validate ASFR estimates for 45-49 and 50-54 age groups.

Similar to national total fertility rates from 1980-2014 I found that most counties have remained just below or above replacement level fertility but there is still significant variation in total fertility rates. The GBD found that 59 countries have a TFR of over 3 in 2017 (41 in Sub-Saharan Africa), in this study I found 47 counties had a TFR over 3 in 2014. Increased understanding of the drivers of higher TFR in these counties is needed to understand whether it is related to lack of access to contraceptives, lower female education levels or other reasons.

The age-specific fertility estimates revealed not only large differences in the fertility level but also the age pattern. The mean age at childbearing increased in every single county in the US from 1980 to 2014 but there are still large differences between counties in 2014, with a gap between the highest and lowest county of 7.85 years. The patterns in Figure 3 suggest that urban counties tend to have a higher mean age at childbearing. I used the urban and rural county classifications produced by the United States Department of Agriculture and found that the mean age at childbirth was 1.62 years higher in urban counties compared to rural counties in the US in 2013 (Supplemental figure 1). The overall increase in the mean age at childbearing indicates that more women are delaying when they choose to have children possibly due to better access to reproductive health services, employment opportunities and increased education levels.

Recent studies have highlighted worrying increases and high levels of maternal mortality in the United States and some specific states[6]. This analysis identified similar trends at the national- and state-level but importantly revealed large inequalities in maternal mortality ratios between counties with some counties significantly worse off than the already high national MMR levels. SDG goal 3.1 is to reduce MMR to below 70 maternal deaths per 100,000 live births by 2030. Even though the US is still well below this goal at the national-level I found there are 173 counties with MMR higher than 70 maternal deaths per 100,000 maternal deaths.

As shown in this study, fertility patterns in the US have changed extensively over time, vary substantially across counties and have a significant effect on changes in MMR. In order to better compare over time and across counties I standardized MMR for differences in maternal-age. A standard distribution of age of mother at childbirth was used in order to remove the differences in fertility level and age pattern, and the population size and age structure of women of reproductive age. After standardizing for the maternal age distribution, I found even larger disparities between the counties with the highest and lowest MMR. The counties with high maternal-age standardized MMR typically have a younger fertility age pattern which should mean that women in those counties are giving birth at ages that in general have lower maternal mortality risk but these results suggest that other factors in these counties are contributing to make their MMR higher than counties with older fertility age patterns.

Understanding in what combination the older maternal age distribution, increased maternal mortality risk and changes in female population size and structure are driving the increase in the number of maternal deaths in the US is helpful for guiding future policy decisions. In this analysis I found that increased fertility rates among 35 to 54 year old women and increases in MMR in the 20 to 34 age group are the two factors most attributable for the increase in maternal deaths observed in the US between 1980 and 2014 but that increases in MMR were predominantly responsible for increases in maternal deaths since 2002 (Supplemental Figures 17-19). Davis and colleagues[6] decomposed all-ages MMR into changes in the maternal age distribution and age-specific MMR at the state-level. Consistent with results found in this analysis, they concluded that the increase in MMR observed over the past decade was mainly attributable to increases in MMR. Importantly they also highlight the difficulty in assessing whether the increase in MMR is real or due to changes to the pregnancy question on death certificates during the previous decade.

As has been previously documented[9], the most difficult issue in analyzing US MMR is the inconsistency over time and within the US in death certificate standards for reporting whether or not the decedent was pregnant at time of death or within a certain time frame. The maternal deaths data used in this analysis were corrected for garbage code causes of death but no corrections were made for the differential identification of decedents as recently pregnant at death. This source of error is most likely to bias MMR estimates prior to 2003 and more significantly in states that delayed switching to the updated standard death certificate, so careful interpretation of time trends is needed. The source of error is less likely to affect more recent estimates of MMR given that as of 2014, all but five states had adapted the standard death certificate pregnancy question with a 42-day timeframe.

MacDorman and colleagues[9] compiled a list of the date each state switched to the national standard death certificate as of 2014, whether the state included a pregnancy question in their unrevised death certificate and if so, what the timeframe was used. In future analyses it may be possible to use this information to try to correct for these inconsistencies prior to modeling or include additional variables in the model itself. Continued work is needed to standardize and improve maternal death reporting and identification in order to more accurately measure trends in maternal mortality within the US.

This study has additional limitations not already mentioned. A strength of the small area estimation models used to estimate ASFR and the MMRate is that they smooth across locations, time and age groups which is beneficial when analyzing rates in small populations due to statistical noise. This can also be a limitation because it is possible to over smooth real fluctuations in the underlying modeled rate. The births data, population and covariates used in this analysis are all subject to error but uncertainty from these inputs as well as uncertainty in the corrections applied to maternal deaths data for garbage codes and other issues were not propagated to the ASFR and MMR estimates.

Due to separately modeling ASFR and the MMRate their is no constraint in the model that MMR should be between 0 and 1. This is problematic in counties with extremely high MMR compared to the rest of the US where some counties are estimated to have an MMR greater than 100,000 maternal deaths per 100,000 live births in the 45-49 and 50-54 age group as can be seen in Supplmental Figures 10 and 11. This issue is also present in GBD2017 results, for example the MMR for Mississippi in 2017 for the 50 to 54 age group is above 200,000 deaths per 100,000 live births. One potential source of this issue is that the standard denominator for MMR is live births but should possibly include all pregnancies: livebirths, stillbirths, miscarriages, and abortions. Future work should compare results from directly modeling MMR with a logit link, and including all pregnancies in the denominator for MMR.

Conclusions

Across US counties women are having children at older ages which has partly driven the increase in the number of maternal deaths from 1980 to 2014. But the main contributor to the large increases seen in maternal deaths since 2002 can be attributed to increases in MMR. More research is needed to understand how much of this increase in MMR throughout the US is due to improvements in identifying maternal deaths because of changes to the US standard death certificates versus actual increases in MMR. Regardless, the US

MMR remains well above other high-income countries and there are large inequalities between counties.

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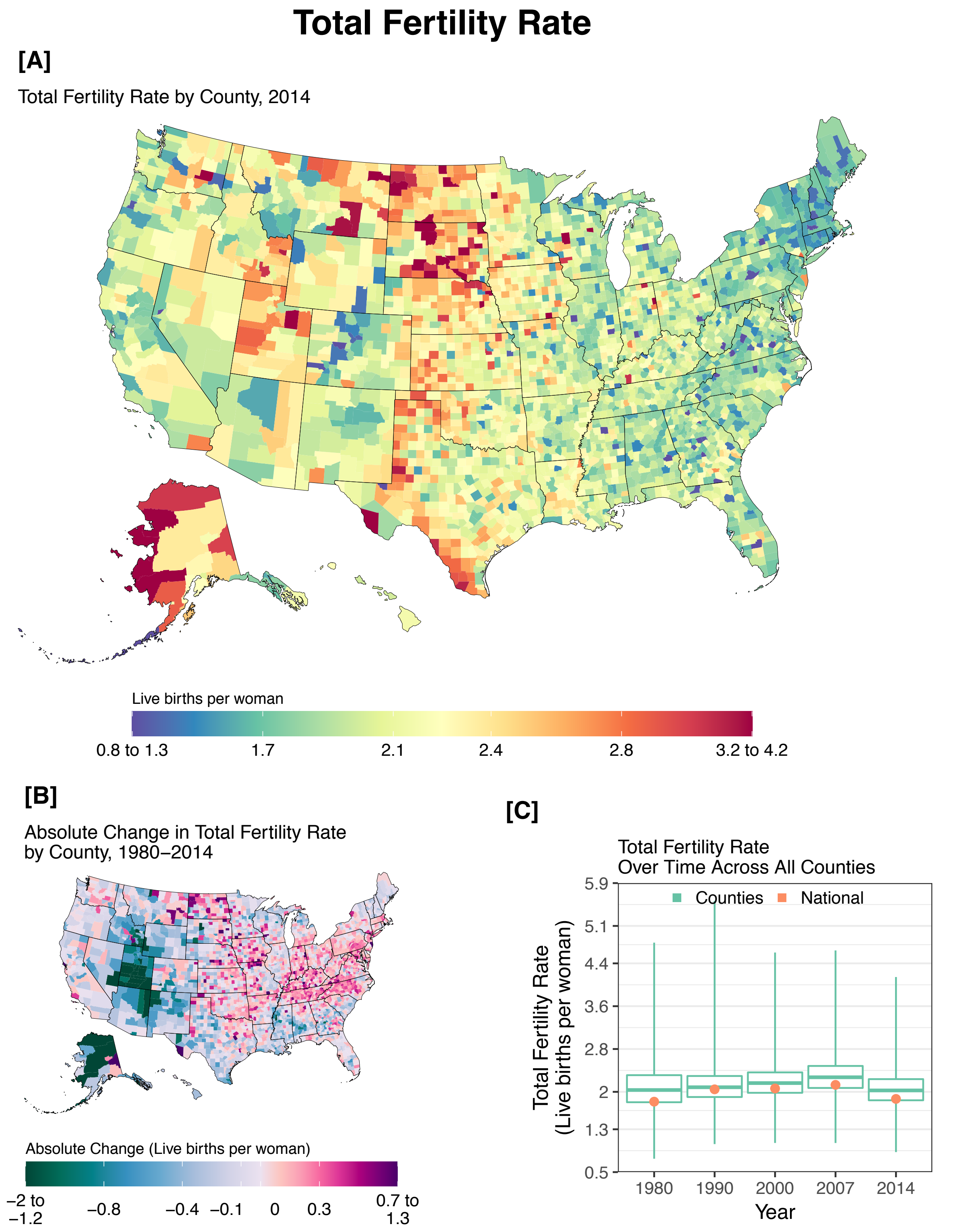

Figure 1: **Total Fertility Rate (TFR).** The average number of children a woman would have if they experienced the age-specific fertility rates observed in a given year throughout their life. A, TFR in 2014. B, Relative percent change in TFR between 1980 and 2014. In panels A, and B, the color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale. C, TFR in 1980, 1990, 2000, 2007, and 2014. The bottom border, middle line, and top border of the boxes indicate the 25th, 50th, and 75th percentiles, respectively, across all counties; whiskers, the full range across counties; and circles, the national-level rate.

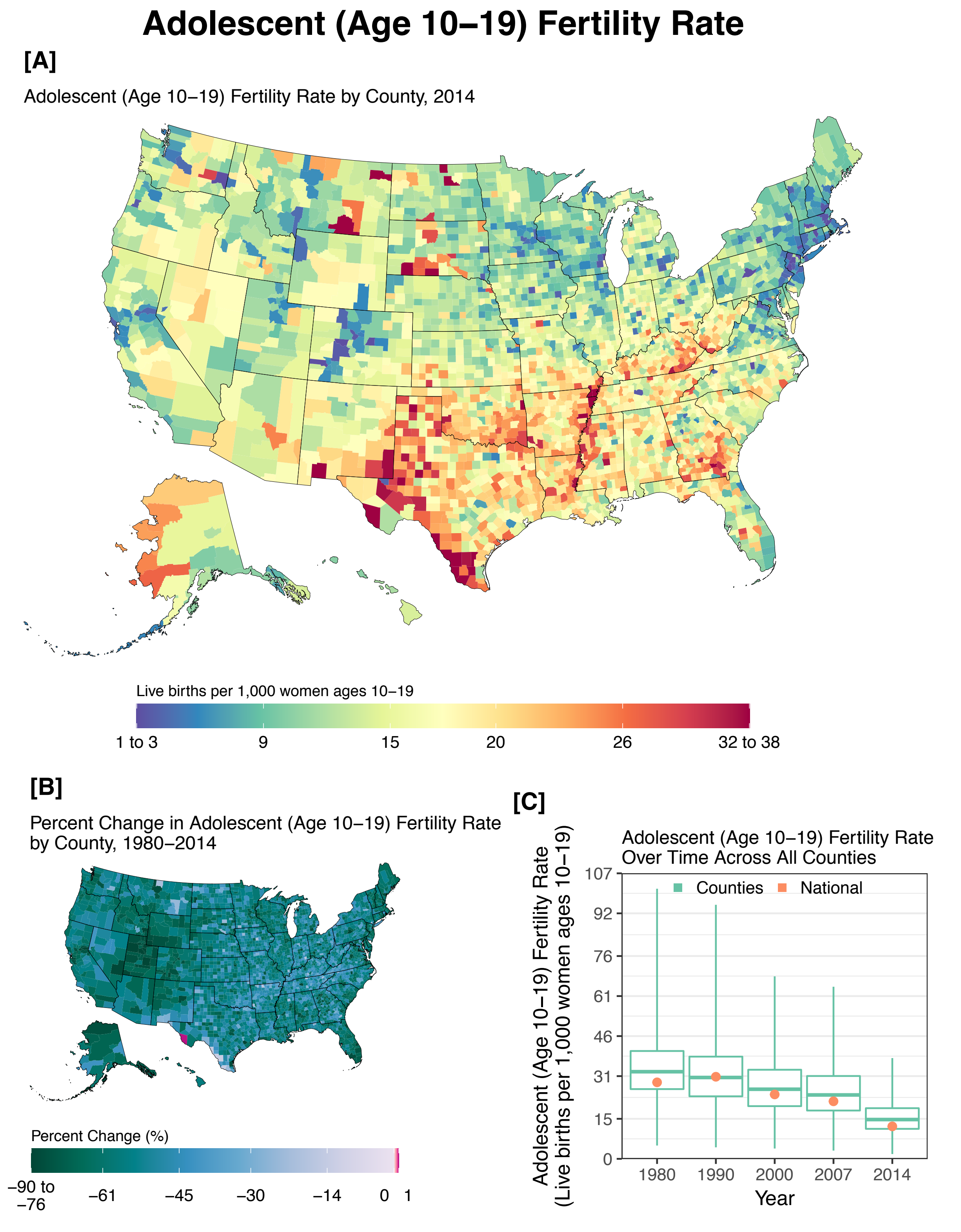

Figure 2: **Adolescent (Age 10-19) Fertility Rate.** The annual number of births to females between age 10 and 19 per 1,000 females in the age group. A, Adolescent fertility rate in 2014. B, Relative percent change in the adolescent fertility rate between 1980 and 2014. In panels A, and B, the color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale. C, Adolescent fertility rate in 1980, 1990, 2000, 2007, and 2014. The bottom border, middle line, and top border of the boxes indicate the 25th, 50th, and 75th percentiles, respectively, across all counties; whiskers, the full range across counties; and circles, the national-level rate.

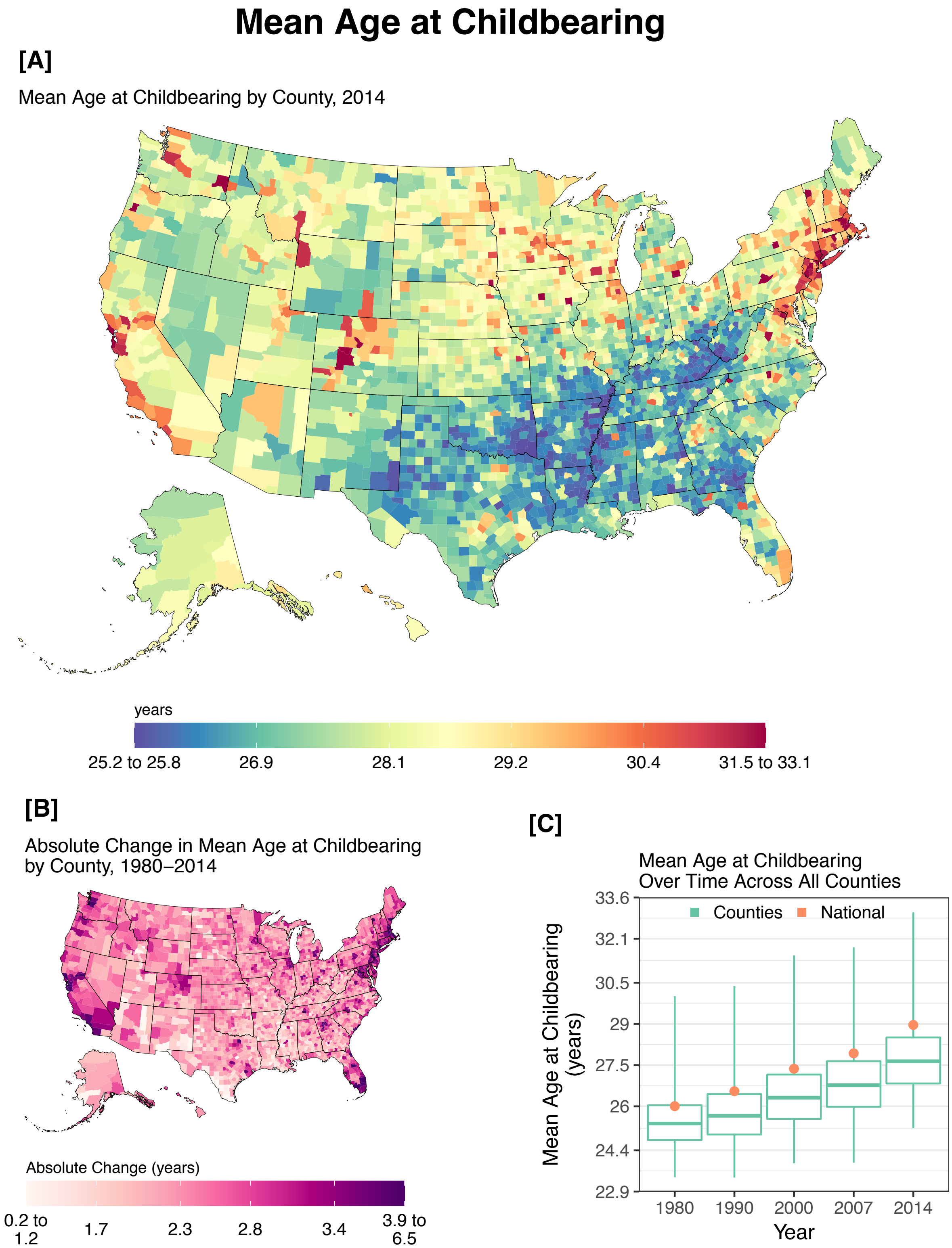

Figure 3: **Mean Age at Childbearing.** The mean age of mothers when giving birth if they experienced the age-specific fertility rates observed in a given year throughout their life. A, Mean age at childbearing in 2014. B, Relative percent change in mean age at childbearing between 1980 and 2014. In panels A, and B, the color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale. C, Mean age at childbearing in 1980, 1990, 2000, 2007, and 2014. The bottom border, middle line, and top border of the boxes indicate the 25th, 50th, and 75th percentiles, respectively, across all counties; whiskers, the full range across counties; and circles, the national-level rate.

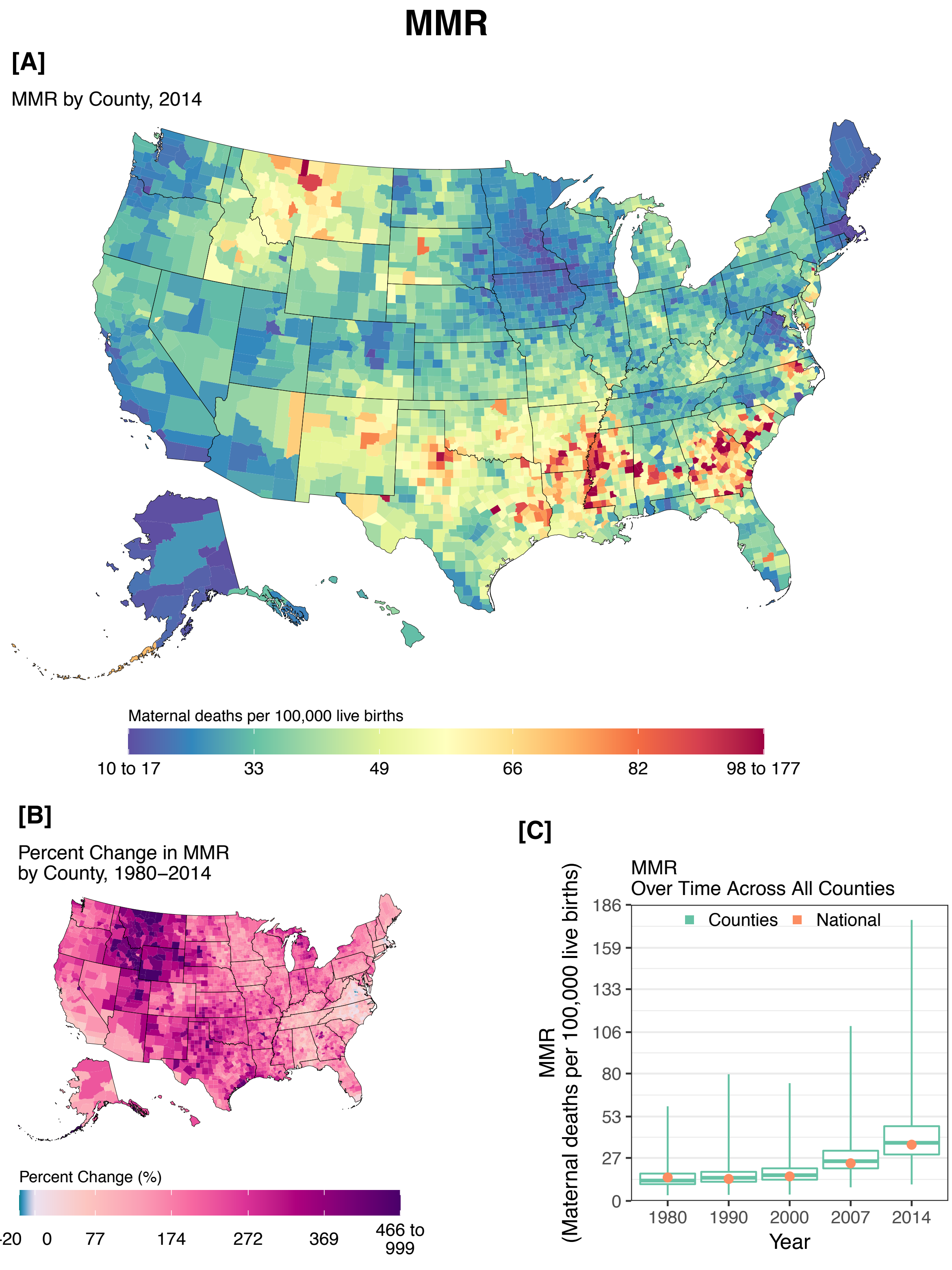

Figure 4: **Maternal Mortality Ratio (MMR)** The annual number of maternal deaths per 100,000 live births to women between age 10 and 54. A, MMR in 2014. B, Relative percent change in MMR between 1980 and 2014. In panels A, and B, the color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale. C, MMR in 1980, 1990, 2000, 2007, and 2014. The bottom border, middle line, and top border of the boxes indicate the 25th, 50th, and 75th percentiles, respectively, across all counties; whiskers, the full range across counties; and circles, the national-level rate.

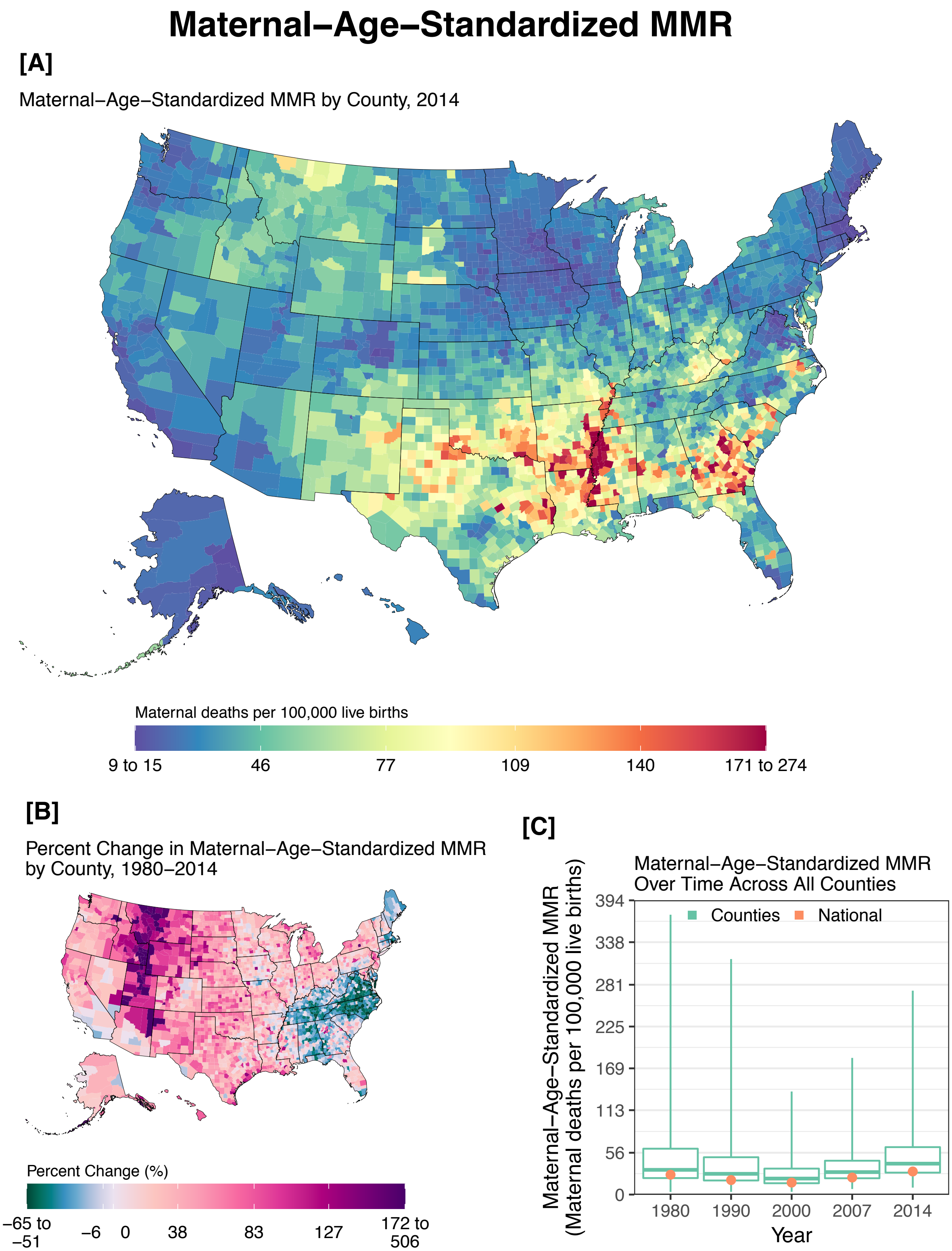

Figure 5: **Maternal-Age-Standardized Maternal Mortality Ratio (MMR)** The annual number of maternal deaths per 100,000 live births to women between age 10 and 54 standardized using a standard distribution of maternal-age-specific live births as weights. A, Maternal-Age-Standardized MMR in 2014. B, Relative percent change in Maternal-Age-Standardized MMR between 1980 and 2014. In panels A, and B, the color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale. C, Maternal-Age-Standardized MMR in 1980, 1990, 2000, 2007, and 2014. The bottom border, middle line, and top border of the boxes indicate the 25th, 50th, and 75th percentiles, respectively, across all counties; whiskers, the full range across counties; and circles, the national-level rate.

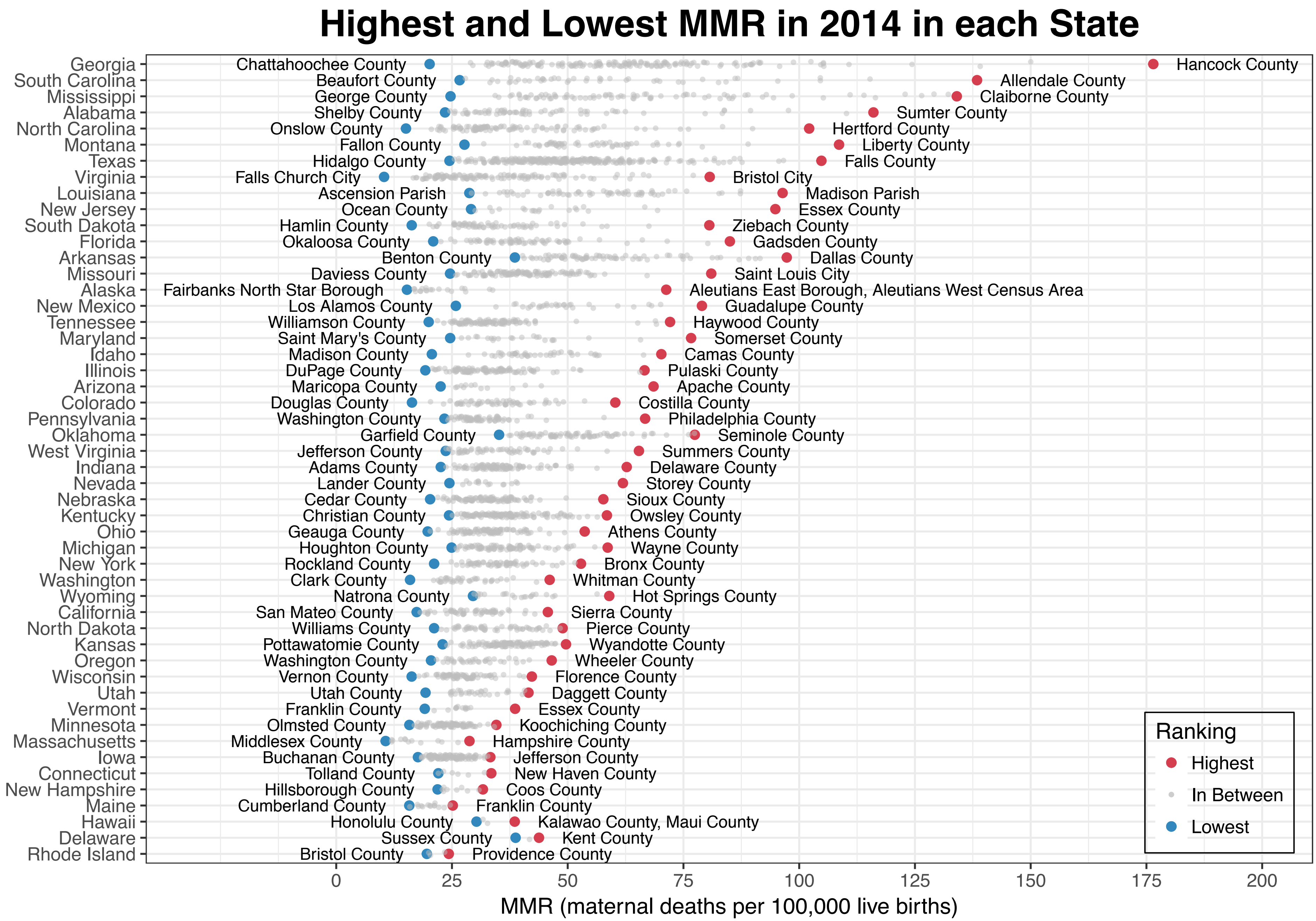

Figure 6: **Inequality in MMR levels within each State** Counties with the lowest MMR within each state are plotted in blue and labeled while counties with the highest MMR within each state are plotted in red and labeled. All other counties within each state are plotted in gray. States are ordered by the magnitude of difference between the county with the lowest and highest MMR.

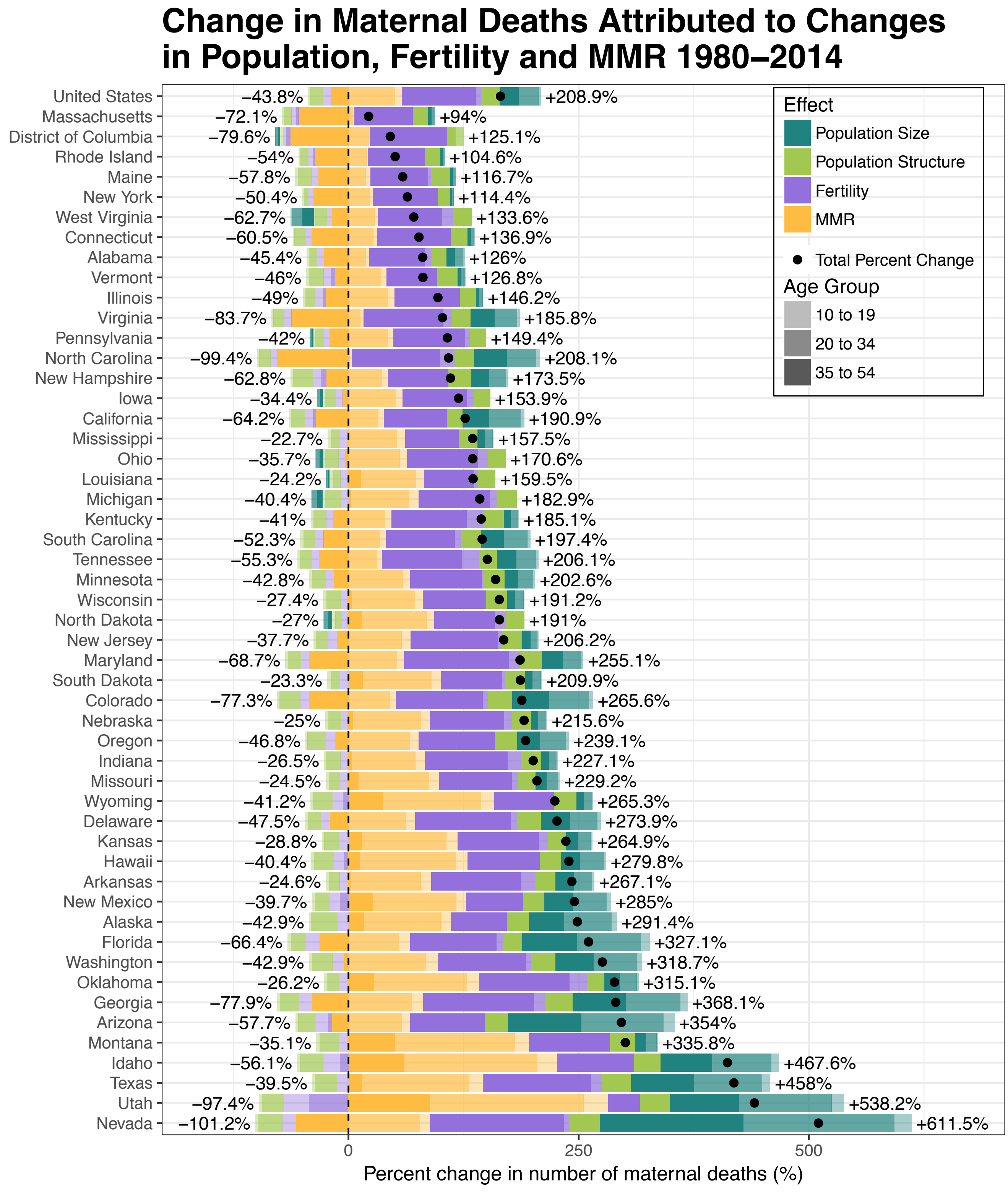

Figure 7: **National and State Level Decomposition of the Change in Number of Maternal Deaths between 1980 and 2014** Percent change in number of maternal deaths due to changes in population size, population age-structure, fertility and MMR by age group. States are ordered by the total percent change in number of maternal deaths over the time period.

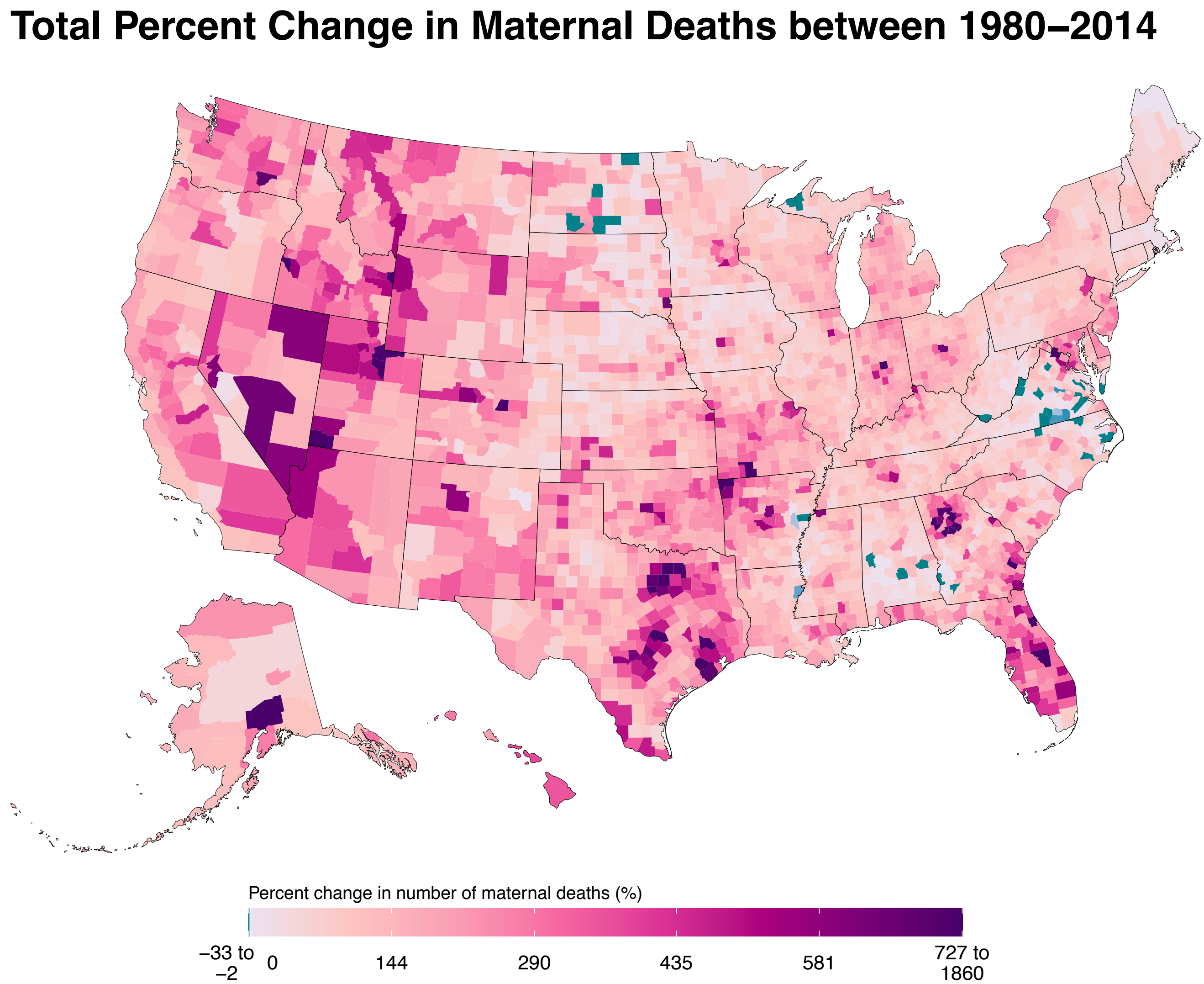

Figure 8: **Total Percent Change in Number of Maternal Deaths between 1980 and 2014** The color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale.

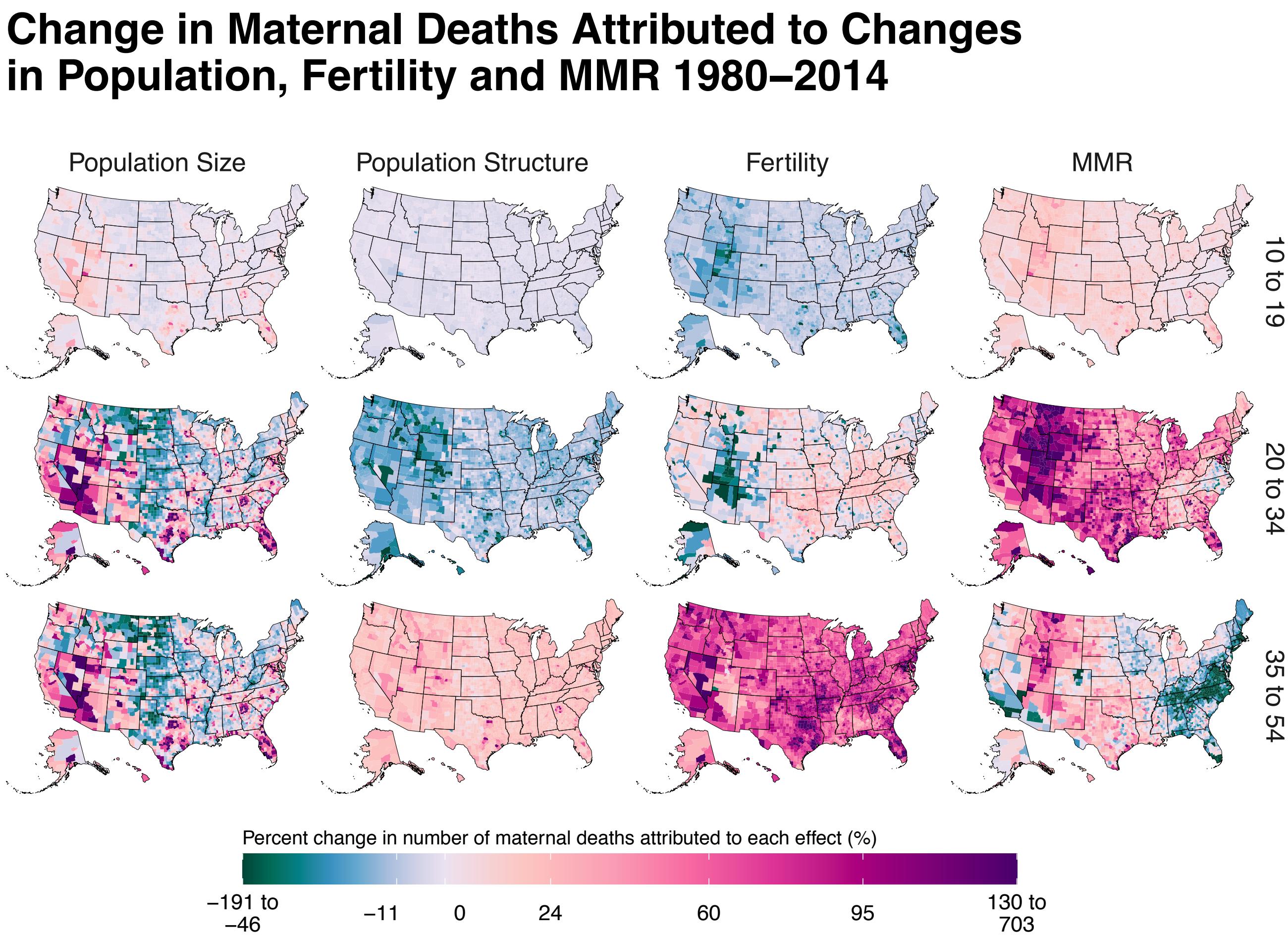

Figure 9: **County Level Decomposition of the Change in Number of Maternal Deaths between 1980 and 2014** Percent change in number of maternal deaths due to changes in population size, population age-structure, fertility and MMR changes by age group. The color scale is truncated at approximately the first and 99th percentiles as indicated by the range given in the color scale.