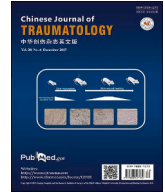




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Original Article

Associations of minimum legal drinking age law with later-life alcohol use and alcohol-attributable mortality from disease and injury: An ecological study

Jie Li^{a,f}, Peishan Ning^{b,f}, Wanhui Wang^b, David C. Schwebel^c, Li Li^b, Zhenzhen Rao^b, Peixia Cheng^d, Dan Tian^b, Guoqing Hu^{b,e,*}^a Hunan Provincial Key Laboratory of Philosophy and Social Sciences of Urban Smart Governance, Changsha, 410083, China^b Department of Epidemiology and Health Statistics, Hunan Provincial Key Laboratory of Clinical Epidemiology, Xiangya School of Public Health, Central South University, Changsha, 410013, China^c Office of Research, University of Iowa, Iowa City, IA, 52242, United States of America^d Department of Child, Adolescent and Women's Health, School of Public Health, Capital Medical University, Beijing, 100069, China^e National Clinical Research Center for Geriatric Disorders, Xiangya Hospital, Central South University, Changsha, 410008, China

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ABSTRACT

Purpose: To examine associations of minimum legal drinking age (MLDA) laws with later-life alcohol use and alcohol-attributable mortality.**Methods:** An ecological study was performed using the free-access data from the United States. Five outcome measures were considered: (1) drinking rate, (2) alcohol consumption per capita, and alcohol-attributable mortality for (3) all diseases and injuries, (4) non-injury diseases, and (5) injuries. Univariate statistical tests compared differences in 5 outcome measures during 1990–2021 across 3 types of states, classified based on different MLDA beer laws in 1970–1988. Multivariable regression examined MLDA laws' associations with 5 outcome variables, adjusting for covariates. Sensitivity analyses used MLDA classifications for wine and spirits.**Results:** Based on MLDA beer laws of 1970–1988, the 50 states and the District of Columbia were classified as Type 1 (increasing MLDA), Type 2 (fluctuating MLDA), and Type 3 (steady MLDA of 21). For all years combined, Type 1 and Type 2 states had lower and higher drinking rates (51.05% and 55.20% vs. 53.23%) and alcohol consumption per capita (463.25 and 511.57 vs. 483.92 standard drinks). Compared to Type 2 and Type 3 states, Type 1 states had the highest alcohol-attributable injury mortality for Americans aged 30 years and older (4.30 vs. 3.93 and 3.87 per 100,000). After adjusting for the included covariates, 3 types of states demonstrated differing trends in drinking rate and alcohol-attributable injury mortality but highly similar trends in the other 3 outcome measures. Sensitivity analyses generated similar findings.**Conclusions:** MLDA was associated with later-life alcohol use and alcohol-attributable mortality.© 2026 Chinese Medical Association. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Early initiation of alcohol use predicts both adult alcohol use and a wide range of adverse health outcomes during adulthood.¹ In 2021, approximately 1.81 million deaths were attributed to alcohol

use globally, accounting for 2.7% of total fatalities.² The World Health Organization recommends minimum legal drinking age (MLDA) laws to reduce harmful alcohol use by establishing a minimum age threshold for legal alcoholic beverage consumption.³ Limited evidence addresses possible relations between MLDA laws and long-term alcohol use or alcohol-related health outcomes, and associations between a high-MLDA law and short-term lower alcohol consumption^{4,5} or reduced adverse health outcomes among young adults (e.g., road traffic crashes, drink driving, and violence^{5–7}) have been reported.

Three published studies offer the most relevant evidence. First, a study in Sweden⁸ evaluated the 40-year health impact of

* Corresponding author. Department of Epidemiology and Health Statistics, Hunan Provincial Key Laboratory of Clinical Epidemiology, Xiangya School of Public Health, Central South University, Changsha, 410013, China.

E-mail address: huguoqing009@gmail.com (G. Hu).

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^f These authors contributed equally to this work.

lowering the MLDA from 21 to 16 years old in 1967. The study was limited by the fact that the lower MLDA was in place for only 8.5 months before it reverted to 21 years. A second study reported higher later-life alcohol-related mortality from liver diseases among non-college-educated participants in the United States (US) where the MLDA had been under 21 between 1967 and 1990 compared to states with an MLDA of 21 years. The MLDA in all states was amended to 21 in the 1980s.⁹ The last study, conducted in Finland, found that cohorts living in areas implementing an MLDA of 21 had lower rates of alcohol-attributable morbidity and mortality than those living in places with an MLDA of 18.¹⁰ None of these studies explored the long-term health consequences of continuous increases, or the impact of fluctuations in the MLDA over a long time period.

MLDA laws are influenced by many factors, including drinking culture, societal norms, and political willingness.³ It is likely that both the MLDA laws and pre-existing and continuing culture have joint and lasting impact on alcohol use and alcohol-attributable mortality, even when laws are changed. Enforcement of MLDA laws may also play a role in their impact on short- and long-term health outcomes.

The US is unique in having diverse MLDA laws at the state level between 1970 and 1988 before all states adopted an MLDA of 21 years old in response to federal government pressure.¹¹ It is one of several countries offering publicly-accessible data on state MLDA laws, alcohol use, alcohol-attributable mortality, and key influencing factors (e.g., ethnicity, individual income, and alcohol tax), enabling us to conduct ecological research examining the lasting health impact of MLDA laws. This present study was designed, therefore, to test 2 primary research questions: (1) Are previous MLDA laws associated with later-life alcohol use and alcohol-attributable mortality? (2) If so, does the MLDA law interact with time to be associated with later-life alcohol use and alcohol-attributable mortality?

2. Methods

2.1. Study design

Because no purposive experiments or cohort study have been conducted at the individual level to assess the long-term effects of MLDA laws, we performed an ecological study to examine the research questions. This study was approved by the ethics committee of Xiangya School of Public Health, Central South University, China (NO. XYGW-2021-19).

2.2. Exposure variable

Data on state MLDA laws for purchasing and publicly consuming alcohol in 1970–1975 were retrieved from published literature,¹¹ and data for 1976–1988 were retrieved from National Highway Traffic Safety Administration reports.^{12,13} Missing data for 3 states over 3 years were imputed using media reports and the Virginia Department of Transportation Safety reports.^{14–16}

MLDA laws differed across states in the US for different types of alcohol beverage, and changed over time for some states during 1970–1988.¹² The 1984 National Minimum Drinking Age Act encouraged implementing an MLDA of 21 years old, which was fully enforced nationwide starting in 1989. Based on MLDA laws, we classified all 50 states and the District of Columbia (DC) into 3 categories:

Type 1: states with an increasing MLDA during 1970–1988;

Type 2: states with a fluctuating MLDA during 1970–1988;

Type 3: states with a steady MLDA of 21 years old during 1970–1988.

Since beer was the predominant alcoholic beverage consumed in the US from 1970 to 2021 (accounting for over 59.3% of combined per-capita alcohol consumption, [Supplementary Fig. A1](#)), our formal analysis classified states based on MLDA laws governing beer. Sensitivity analyses assessed the stability of results using state classifications by the MLDA for wine and for spirits, separately.

2.3. Outcome measures

Based on available data, we considered 5 outcome measures and selected 1999–2021 as the study window to reflect the longer-term health impact of MLDA laws (approximately an average of 10-year lagged for chronic diseases),¹⁷ thereby avoiding short-term disturbances related to early policy implementation — including transitional delays between legal enactment and effective compliance, as well as initial behavioral and market adaptation¹⁸ — while ensuring maximal covariate data availability, as some data were unavailable after 2021.

2.3.1. Drinking rate

The proportion of individuals aged 18 and older who consumed at least 1 alcoholic beverage of any sort within the past month was obtained from the Behavioral Risk Factor Surveillance System surveys,¹⁹ and age-standardized using age weights of the 2000 US standard population. Multiple imputation was employed to impute missing values for all 50 states and DC in 2000; Hawaii in 2004; New Jersey in 2019; and Florida in 2021. Imputed data represented 4.6% of all state-year observations. Convergence of the multiple imputation procedure was evaluated using trace plots, which indicated good imputation performance.

2.3.2. Alcohol consumption per capita

The average amount of alcohol consumed by a person in a calendar year was calculated as the estimated recorded gallons of ethanol for all beverages divided by the number of individuals aged 14 and older, using population estimates from the US Census Bureau. Data on per capita alcohol consumption were obtained from the Alcohol Epidemiologic Data System.²⁰ We converted the unit of alcohol consumption per capita from gallons per year to standard drinks per year based on US guidelines (0.6 fluid ounces of ethanol per standard drink).²¹

2.3.3. Alcohol-attributable mortality for all causes, injuries, and non-injury diseases

To better align the historical exposure window (1970–1988) with later-life outcomes and examine the long-term impact of MLDA laws, our analysis focused on persons aged 30 years and older in that specific calendar year. This age threshold approximates the birth cohorts exposed at aged 18–21 years during 1970–1988 (born 1949–1970) and therefore exposed to MLDA changes at the time of national changes. In 1999, the population aged ≥ 30 years (born in or before 1969) captures 21 out of 22 relevant cohorts (95.5%), and from 2000 onwards, it captures all cohorts (100.0%). Alcohol-attributable mortality data, extracted from GBD 2021 estimates based on multiple mortality data sources (e.g., vital registration and verbal autopsy) and standardized cause-of-death modeling frameworks,²² were age-standardized using 2000 US standard population weights.² GBD 2021 calculated alcohol-attributable mortality by multiplying the deaths for specific outcomes by the population attributable fraction for the risk-outcome pair for a given age, sex, location, and year.²³ This study grouped the 31 alcohol-related causes of death considered by the GBD 2021² into 2 groups — injury mortality and non-injury mortality to assess outcome heterogeneity.

2.4. Covariates

In line with data availability and previous studies,^{9,24–28} 10 state-level covariates were included: sex, age, race, ethnicity, education, individual income, unemployment rate, life expectancy, temperature, and alcohol tax.

Data on the percentage of male, population aged 20 years and younger, population aged 65 years and over, as well as life expectancy at birth were derived from GBD 2021.

The percentage of individuals in major racial groups, including White, Black or African American, and other races (including Asian or Pacific Islander and American Indian or Alaska Native), as well as the percentage for ethnicity (Hispanic or Latino), were aggregated from The Centers for Disease Control and Prevention's Wide-ranging Online Data for Epidemiologic Research online query system.²⁹

The percentage of high school graduates was sourced from the US Census Bureau's American Community Survey,³⁰ while personal income per capita was obtained from the US Bureau of Economic Analysis.³¹ Annual unemployment rates were calculated as the total unemployed population divided by the labor force across all counties in a state, based on the Local Area Unemployment Statistics program of the US Bureau of Labor Statistics.³² Annual average temperature data was obtained from the National Centers for Environmental Information.³³

Beer excise tax data, a proxy for alcohol taxation,³⁴ were obtained from the Alcohol Policy Information System.³⁵ For Utah (1999–2021) and DC (pre-2012), where compulsory alcohol pricing replaced specific alcohol excise taxes, estimates were obtained from the Tax Foundation.³⁶

To effectively present results, we divided each covariate into three categories based on terciles: low ($<P_{33.3}$), medium ($P_{33.3}$ to $P_{66.7}$), and high ($>P_{66.7}$).

2.5. Statistical analysis

MLDA laws between 1970 and 1988 were visualized by the state using a heat map. For all years combined, we performed Kruskal-Wallis H tests and Dunn's post-hoc pairwise comparisons to examine differences in 5 outcome measures across the 3 types of states, as categorized by MLDA laws from 1970 to 1988. Box plots were graphed to present differences in the 5 outcome measures across the 3 types of states.

We used the significance of interaction between the type of state and year based on the random state-based intercept models to examine whether the associations of MLDA laws with the 5 outcome measures changed over years. Covariates of multivariable models are specified in [Supplementary Table A1](#). Statistical models were chosen based on outcome distributions and the presence of a state-level hierarchy: linear mixed models (LMMs) for alcohol consumption per capita; negative binomial generalized LMMs for drinking rate and alcohol-attributable injury mortality; and negative binomial generalized linear models for alcohol-attributable all-cause and non-injury mortality. We fitted multivariable models separately for all 3 types of states classified by the MLDA to demonstrate inconsistent annual changes in outcome measures. Relative ratio (RR) and regression coefficient with 95% confidence intervals (CI) quantified annual changes in outcome measures from 1999 to 2021.

The goodness-of-fit of LMMs and generalized LMMs was evaluated using conditional R^2 , which denoted the variance ratio explained by both fixed and random effects. Pseudo R^2 was used for generalized linear models.

All analyses were performed using R Statistical Software (version 4.2.2). Statistical significance was based on two-tailed tests at a significance level of 0.05.

3. Results

3.1. State MLDA laws during 1970–1988

[Fig. 1](#) illustrates state MLDA laws for beer, wine, and spirits in the US between 1970 and 1988. Based on MLDA laws for beer, 14 states had increasing MLDA from 18 or 19 to 21 years old (Type 1), 25 states had fluctuating MLDA laws that first decreased and then climbed to the age of 21 years old gradually (Type 2), and the remaining 12 states consistently had a MLDA of 21 years old (Type 3) ([Fig. 1A](#)). The respective number of states in each of the 3 types were 11, 23, and 17 states when MLDA laws for wine were applied ([Figs. 1B](#)), 6 and 22, and 23, when states were categorized by the MLDA for spirits ([Fig. 1C](#)).

3.2. Later-life differences in outcome measures across the 3 types of states

For all years combined, states with an increasing MLDA (Type 1) had the lowest drinking rate (51.05%) and alcohol consumption per capita (463.25 standard drinks), while states with a fluctuating MLDA (Type 2) had the highest drinking rate (55.20%) and alcohol consumption per capita (511.57 standard drinks), $p < 0.001$ ([Fig. 2A](#) and [B](#)).

No significant group differences were detected for alcohol-attributable all-cause and non-injury mortality ($p = 0.121$ and $p = 0.276$, respectively) ([Fig. 2C](#) and [D](#)). However, there were statistically significant differences between Type 1 and Type 2 states and between Type 1 and Type 3 states in alcohol-attributable injury mortality among individuals aged 30 years and older (median mortality: 4.30 vs. 3.93 and 3.87 per 100,000 population, $p = 0.015$ and $p = 0.001$, respectively) ([Fig. 2E](#)).

3.3. Changes over time in outcome measures across the 3 types of states in later life

After adjusting for covariates, the 3 types of states classified by the MLDA for beer showed different trends in drinking rates among persons aged 18 years and older between 1999 and 2021. Compared to Type 3 states, individuals in Type 1 states demonstrated a significant increase in drinking rate during 1999–2021 (adjusted RR for interaction: 1.005, 95% CI: 1.004–1.007) ([Fig. 3A](#), [Table 1](#), and [Supplementary Table A3](#)).

Alcohol consumption per capita displayed highly similar trends across the 3 types of states among persons aged 14 years and older during 1999–2021 ($p = 0.567$ for Type 1 vs. Type 3 and $p = 0.179$ for Type 2 vs. Type 3) ([Table 2](#)), with all increasing substantially, $p < 0.001$ ([Fig. 3B](#), [Table 2](#), and [Supplementary Table A4](#)).

The 3 types of states displayed consistent trends in alcohol-attributable mortality rates for all causes combined and non-injury diseases among Americans aged 30 years and older from 1999 to 2021 ([Table 1](#)), with all increasing substantially, $p < 0.001$ and $p = 0.001$, respectively ([Fig. 3C](#) and [D](#), [Table 1](#), and [Supplementary Table A3](#)). For alcohol-attributable injury mortality, Type 2 states increased at a faster rate from 1999 to 2021 than Type 3 states (adjusted RR for interaction: 1.002, 95% CI: 1.000–1.004) ([Fig. 3E](#), [Table 1](#), and [Supplementary Table A3](#)).



Fig. 1. State minimum legal drinking age by type of alcoholic beverage in the United States, 1970–1988.

The minimum legal drinking age varied across 50 states and the District of Columbia (from 18 to 21 years old) in the United States during 1970–1987; starting in 1988, it became 21 years old for all 50 states and the District of Columbia.

Type 1: states with an increasing minimum legal drinking age; Type 2: states with a fluctuating minimum legal drinking age; Type 3: states with a steady minimum legal drinking age. AL: Alabama; AK: Alaska; AZ: Arizona; AR: Arkansas; CA: California; CO: Colorado; CT: Connecticut; DE: Delaware; FL: Florida; GA: Georgia; HI: Hawaii; ID: Idaho; IL: Illinois; IN: Indiana; IA: Iowa; KS: Kansas; KY: Kentucky; LA: Louisiana; ME: Maine; MD: Maryland; MA: Massachusetts; MI: Michigan; MN: Minnesota; MS: Mississippi; MO: Missouri; MT: Montana; NE: Nebraska; NV: Nevada; NH: New Hampshire; NJ: New Jersey; NM: New Mexico; NY: New York; NC: North Carolina; ND: North Dakota; OH: Ohio; OK: Oklahoma; OR: Oregon; PA: Pennsylvania; RI: Rhode Island; SC: South Carolina; SD: South Dakota; TN: Tennessee; TX: Texas; UT: Utah; VT: Vermont; VA: Virginia; WA: Washington; WV: West Virginia; WI: Wisconsin; WY: Wyoming; DC: District of Columbia

3.4. Sensitivity analyses

For all years combined, results for both drinking rate and alcohol consumption per capita were generally similar across the 3 types of states categorized by MLDA laws for beer, wine, and spirits, although a few differences emerged in pairwise comparisons (Supplementary Table A2). In contrast, distinct results were observed for alcohol-attributable mortality (all-cause, non-injury diseases, and injuries) when states were classified according to MLDA laws for beer, wine, and spirits (Supplementary Table A2).

Multivariate analysis confirmed generally similar findings for drinking rate and alcohol-attributable mortality (all-cause, non-injury, and injury) under the state classifications by MLDA laws for beer, wine, and spirits (Table 1 and Supplementary Table A3). For alcohol consumption per capita, both Type 1 and Type 2 states showed faster increases than Type 3 states under the state classifications based on MLDA laws for spirits (Table 2 and Supplementary Table A4).

4. Discussion

4.1. Principal findings

Unlike previous research examining the long-term impact of one-time changes in MLDA law on alcohol use and health outcomes,^{8–10,37} this research considers the enduring later-life impact of MLDA laws on individuals who lived through MLDA law changes years earlier, with a particular focus on the long-term consequences of continuous increases or fluctuations in the MLDA. We hypothesized that early-life legislation could have a lifelong impact on drinking behavior, even if the laws were amended years ago during individuals' youth. We yielded 2 primary findings. First, MLDA laws in 1970–1988 were associated with alcohol use and alcohol-attributable mortality in 1999–2021. Specifically, states with an increasing MLDA (Type 1) exhibited the lowest drinking rate and alcohol consumption per capita, while states with a fluctuating MLDA (Type 2) had the highest. Notably, Type 1 states had higher

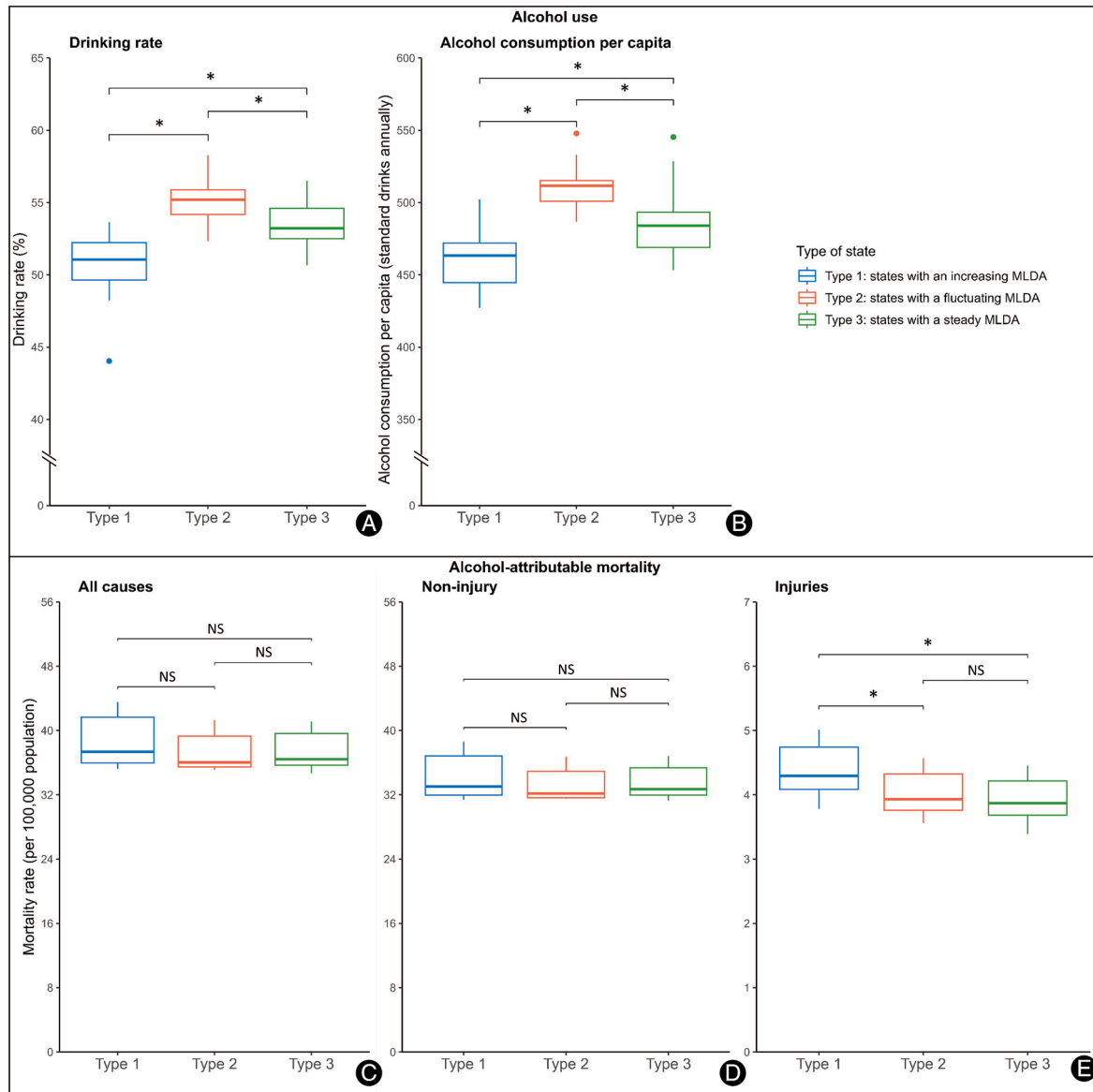


Fig. 2. Alcohol use measures and alcohol-attributable mortality from 1999 to 2021 across 3 types of states.

MLDA: minimum legal drinking age; NS: not significant.

*: $p < 0.05$.

alcohol-attributable injury mortality rates than Type 2 and Type 3 states (those with a constant MLDA of 21 years old) for individuals aged 30 and older. Second, the differences across the 3 types of states generally persisted in parallel during 1999–2021 for alcohol consumption per capita and alcohol-attributable mortality rates for all causes combined and for non-injury diseases, but changed for drinking rate and alcohol-attributable injury mortality.

4.2. Comparison with other studies

The first primary finding supports our hypothesis. Observed differences across the 3 types of states in the 5 health outcome measures likely reflect long-term, state-level variation in alcohol policy environments shaped by historic MLDA trajectories, which may, in turn, influence population drinking behaviors, social norms, and drinking culture. These population-level features provide a plausible contextual pathway through which historic

MLDA changes may be associated with later differences in alcohol-related health outcomes across states.

Specifically, a lower legal drinking age during 1970–1988 would likely have increased alcohol availability and consumption for 18–21-year-olds at the state level. This may be associated with earlier drinking initiation in populations exposed to these policy environments, a situation linked in previous research to a higher likelihood of excessive drinking and alcohol dependence in adulthood.^{1,5–7} Higher levels of excessive drinking and alcohol dependence among adults, in turn, shape drinking culture and habits in the population, including offspring drinking behaviors through household-level exposure; previous research reports that adolescents from households with adult drinkers had higher drinking rates and consumption than those from non-drinking households.³⁸

States with lower or fluctuating MLDA laws experienced higher drinking rates and consumption levels. Conversely, states where

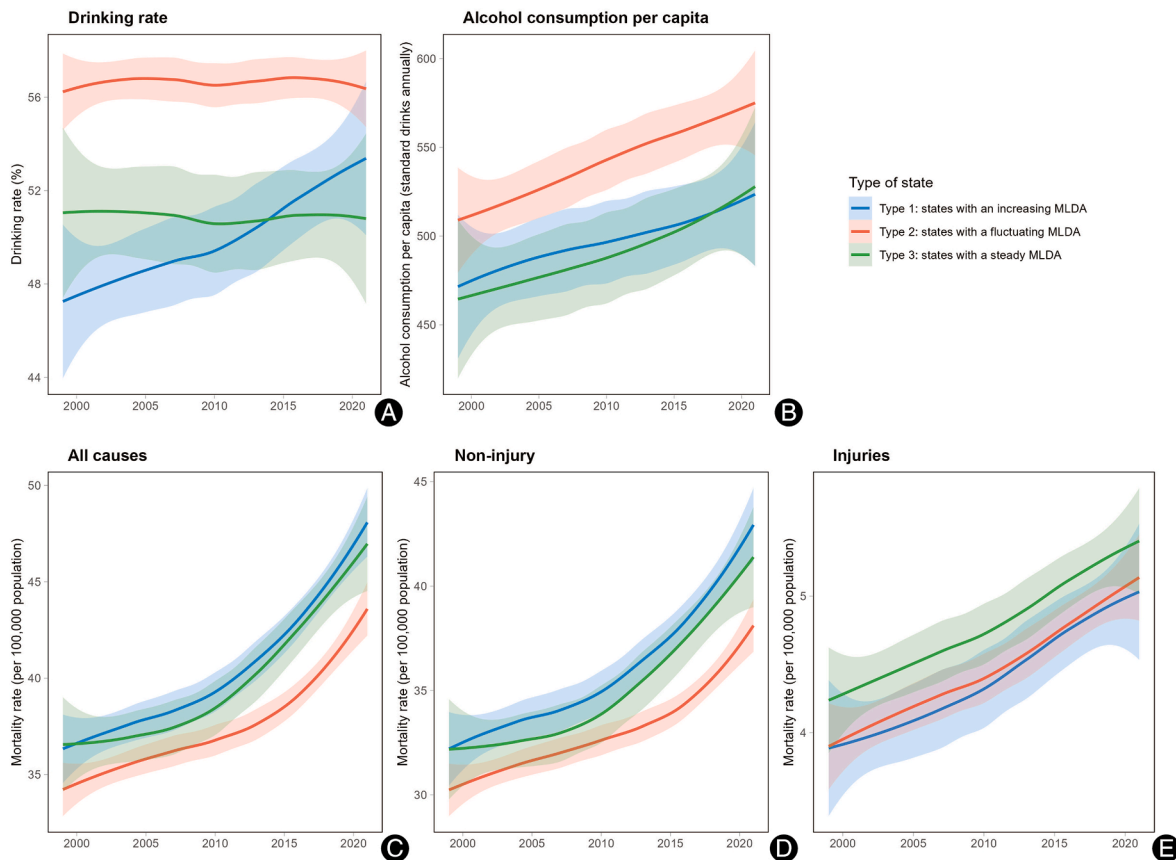


Fig. 3. Changes in alcohol use measures and alcohol-attributable mortality from 1999 to 2021 across 3 types of states.

For the null models with drinking rate, alcohol consumption per capita, and alcohol-attributable injury mortality as outcome variables, the intraclass correlation coefficients (ICCs) at the state level were 0.027, 0.930, and 0.038 ($p < 0.05$), respectively, indicating significant variability between states. In contrast, the ICCs for the null models with alcohol-attributable all-cause and non-injury mortality as outcome variables were all below 0.005, suggesting negligible state-level variation. Accordingly, to account for the hierarchical structure, multivariable negative binomial generalized linear mixed models were fitted for drinking rate and alcohol-attributable injury mortality, while multivariable linear mixed models were fitted for alcohol consumption per capita. For alcohol-attributable all-cause and non-injury mortality, multivariable negative binomial generalized linear models were fitted, as the ICCs indicated the need for multilevel models.

Statistical tests indicated low multicollinearity among all predictors across all statistical models, according to the widely used criterion of an adjusted generalized standard error inflation factor < 3.2 .

The shaded area for each line represents the estimated 95% confidence intervals from statistical models.

MLDA: minimum legal drinking age.

the MLDA consistently increased from 1970 to 1988 demonstrated stronger legislation, enforcement, and educational efforts, along with more restrictive alcohol policy environments,³⁹ possibly reducing adolescent access to alcohol. Research evidence suggests that MLDA laws restricting alcohol use to older ages help lower alcohol consumption among adolescents.⁴⁰ Notably, fluctuations in MLDA might cause conflicting drinking norms and culture according to social norm theory,⁴¹ which is harmful for preventing illegal underage drinking and subsequent alcohol consumption patterns.

The higher alcohol-attributable injury mortality rates in states with consistently increasing MLDA compared to states with stable or fluctuating MLDA states may not solely be attributed to MLDA itself. Other factors, such as MLDA enforcement, socioeconomic development, the implementation of additional alcohol control policies, and broader alcohol-related culture norms in the states^{42,43} could also play a role. Another possible explanation is that although states with rising MLDA raised the age at which individuals could purchase or consume alcohol, individuals were still affected by the previously lower MLDA laws. The lack of significant differences in alcohol-attributable mortality rates between fluctuating and stable MLDA states may support this

explanation, indicating that temporarily lowering the MLDA did not immediately eliminate the influence of previously high MLDA laws on alcohol-attributable mortality rates.

Beyond the descriptive later-life differences summarized above, our primary conclusions are based on differences in longitudinal trends in outcome measures across the 3 MLDA types during 1999–2021. Consistent differences in alcohol consumption per capita and alcohol-attributable all-cause and non-injury mortality rates during 1999–2021 across the 3 types of states might be due to the enduring influence of MLDA law on drinking behaviors, culture, and social norms. In states with increasing MLDA, drinking rate increased at a faster pace than in states with steady MLDA. States with fluctuating MLDA experienced a faster growth in alcohol-attributable injury mortality than those with steady MLDA; however, this contrast was not observed under MLDA for spirits, suggesting that stronger long-term associations may emerge when policy signals target the dominant source of alcohol exposure.⁴

In states with an increasing MLDA, early leniency in MLDA law may have led to weaker enforcement and diminished the policy's ability to suppress risky drinking behaviors among adolescents and young adults. Although these states eventually raised their

Table 1
Associations of 1970–1988 MLDA laws with drinking rates and alcohol-attributable mortality in the United States from 1999 to 2021.

Outcome variable/independent variable	RR and 95% CI		
	By MLDA for beer	By MLDA for wine	By MLDA for spirits
Y₁: Drinking rate, %			
Type of state (Ref. = Type 3)			
Type 1	0.924 (0.806, 1.059)	0.927 (0.811, 1.059)	1.009 (0.858, 1.187)
Type 2	1.089 (0.964, 1.230)	1.098 (0.984, 1.224)	1.072 (0.964, 1.191)
Year	0.998 (0.995, 0.999)*	0.998 (0.996, 1.000)*	1.000 (0.998, 1.002)
Year × Type 1 (Ref. = Type 3)	1.005 (1.004, 1.007)*	1.005 (1.003, 1.006)*	1.002 (1.000, 1.004)*
Year × Type 2 (Ref. = Type 3)	1.001 (0.999, 1.002)	1.000 (0.999, 1.001)	1.000 (0.998, 1.001)
Y₂: Alcohol-attributable all-cause mortality			
Type of state (Ref. = Type 3)			
Type 1	1.008 (0.962, 1.057)	1.030 (0.980, 1.083)	0.905 (0.857, 0.955)*
Type 2	0.962 (0.922, 1.004)	0.981 (0.944, 1.020)	0.928 (0.895, 0.962)*
Year	1.008 (1.004, 1.012)*	1.009 (1.006, 1.013)*	1.008 (1.004, 1.011)*
Year × Type 1 (Ref. = Type 3)	1.001 (0.998, 1.005)	1.000 (0.996, 1.003)	1.001 (0.997, 1.005)
Year × Type 2 (Ref. = Type 3)	0.999 (0.996, 1.002)	0.997 (0.994, 1.000)	0.999 (0.996, 1.001)
Y₃: Alcohol-attributable non-injury mortality			
Type of state (Ref. = Type 3)			
Type 1	1.022 (0.974, 1.074)	1.044 (0.992, 1.100)	0.916 (0.866, 0.970)*
Type 2	0.975 (0.934, 1.019)	0.995 (0.956, 1.035)	0.933 (0.899, 0.969)*
Year	1.006 (1.002, 1.010)*	1.007 (1.004, 1.011)*	1.006 (1.002, 1.009)*
Year × Type 1 (Ref. = Type 3)	1.001 (0.998, 1.005)	1.000 (0.997, 1.004)	1.001 (0.997, 1.006)
Year × Type 2 (Ref. = Type 3)	0.998 (0.995, 1.001)	0.997 (0.994, 1.000)	0.998 (0.996, 1.001)
Y₄: Alcohol-attributable injury mortality			
Type of state (Ref. = Type 3)			
Type 1	0.770 (0.499, 1.190)	0.771 (0.502, 1.184)	0.564 (0.374, 0.851)*
Type 2	0.915 (0.622, 1.347)	0.925 (0.651, 1.313)	0.938 (0.719, 1.223)
Year	1.008 (1.005, 1.011)*	1.010 (1.007, 1.013)*	1.010 (1.007, 1.012)*
Year × Type 1 (Ref. = Type 3)	1.001 (0.999, 1.003)	0.998 (0.995, 1.000)*	0.998 (0.995, 1.000)
Year × Type 2 (Ref. = Type 3)	1.002 (1.000, 1.004)*	1.001 (0.999, 1.002)	1.000 (0.998, 1.002)

Type 1 denotes states with an increasing minimum legal drinking age between 1970 and 1988, Type 2 denotes states with a fluctuating minimum legal drinking age over that time period, and Type 3 denotes states with a steady minimum legal drinking age between 1970 and 1988.

Covariates for four multivariable regression models are specified in [Supplementary Table A1](#).

Ref: reference; MLDA: minimum legal drinking age; RR: relative risk; CI: confidence interval.

Table 2
Associations of state MLDA from 1970 to 1988 with alcohol consumption per capita in the United States from 1999 to 2021.

Independent variable	Regression coefficient for annual change in alcohol consumption per capita		
	By MLDA for beer	By MLDA for wine	By MLDA for spirits
Type of state (Ref. = Type 3)			
Type 1	26.526 (45.966)	53.501 (46.037)	3.380 (50.983)
Type 2	54.796 (40.136)	65.536 (35.833)	35.217 (32.122)
Year	2.153 (0.385)*	1.918 (0.374)*	1.380 (0.346)*
Year × Type 1 (Ref. = Type 3)	−0.292 (0.303)	−0.108 (0.310)	1.139 (0.356)*
Year × Type 2 (Ref. = Type 3)	−0.079 (0.275)	0.328 (0.248)	0.804 (0.232)*

Notes: Type 1 denotes states with an increasing minimum legal drinking age between 1970 and 1988, Type 2 denotes states with a fluctuating minimum legal drinking age over that time period, and Type 3 denotes states with a steady minimum legal drinking age between 1970 and 1988.

Regression coefficients (*b*) were estimated from multivariable models using the state MLDA separately for beer, wine, and spirits, and the numbers in parentheses are the standard errors of the regression coefficients.

Regression coefficients (*b*) with asterisks are statistically significant.

Covariates for multivariable regression models are shown in [Supplementary Table A1](#).

MLDA: minimum legal drinking age.

MLDA to 21, the lack of long-term and persistent laws may have hindered the development of a sustained culture of responsible drinking, resulting in a more pronounced increase in adult drinking rates.⁴⁴ There may also have been some impact of counter-culture; young people, frustrated by the increased legal age for alcohol consumption and recognizing weak enforcement of the policy, may have formed irresponsible and heavier lifelong drinking habits compared to their counterparts in other states.

In contrast, long-term strict age restriction laws in stable states may have cultivated a stable and comparatively strong anti-drinking culture. Similarly, temporary fluctuations in MLDA laws within certain states might have negatively affected the formation of a protective drinking culture. Policy instability might reinforce a lenient drinking culture, particularly during periods of lowered

MLDA.³⁷ These unhealthy behaviors could persist as an adolescent grows older.⁴⁵ Further, when MLDA was raised again in fluctuating states, insufficient enforcement and public adherence, along with cultural habits, may have failed to fully reverse the accumulated behavioral patterns and risks.⁴⁶

4.3. Policy implications

Our findings have 2 important implications for the US and other global settings with broadly similar policy, cultural, and social environments. First, they reveal the possibility of lasting effects of fluctuating MLDA laws and highlight the importance of establishing and maintaining consistent MLDA laws, ideally at age 21. Governmental and non-governmental public health agencies

might consider measures to mitigate the later-life adverse effects of MLDA laws that were changed many years ago. Strict enforcement of existing policies, along with complementary efforts such as zero-tolerance laws for drinking and driving, driver's license revocation, off-premise sale restrictions, and advertising limitations,^{47,48} should be implemented to reduce the adverse health effects of alcohol consumption.

Second, although the present study is based on a US-specific historical context, its findings are consistent with previous studies,⁴⁻⁷ suggesting that a higher MLDA (e.g., 21 years old) is associated with lower levels of alcohol-related harm. According to the Global Status Report on Alcohol and Health,³ 11 World Health Organization member states lack an MLDA law, and 134 and 133 countries have MLDA laws below 21 years old for beer/wine and spirits, respectively (with the lowest in Burkina Faso, at 13 years old). Aligned with the broader base of evidence, an MLDA of 21 years may serve as a useful policy benchmark for countries without an MLDA or with lower thresholds. In countries where cultural pressure hinders legislative progress, efforts to raise the MLDA to the best practice standard while transforming societal drinking norms and reducing alcohol access for vulnerable adolescents should be considered.

The study was limited by data availability and the quality of relevant data, including outcome measures and covariates. For example, data on legal enforcement of MLDA laws by the state is not publicly available, and there is evidence both that violations of MLDA laws are common⁴⁸ and that enforcement plays a critical role in their effectiveness.⁴⁹

Although our models included multiple available state-level covariates to mitigate confounding, residual confounding from unmeasured factors cannot be fully excluded. Other alcohol control policies, such as restrictions on off-premise sale and advertising, which may also affect harmful alcohol use across the lifespan,⁵⁰ are also likely influences of our outcome measures.

Alcohol-attributable mortality estimates were derived from the Global Burden of Diseases, Injuries, and Risk Factors Study 2021 modeling framework. Although source data are comprehensive and reliable, especially from high-income countries with substantial public health infrastructure like the US,²² the data may be subject to uncertainty inherent to its model-based estimation. Additionally, while the Behavioral Risk Factor Surveillance System survey is nationally representative of the US adult population,¹⁹ it is prone to self-report bias and coverage gaps for those without phone access and may not reflect situations in other countries.

Further, our classification of states by MLDA laws may influence the study findings, as variations within Type 1 and Type 2 states prevent a precise quantification of the later-life health impact of MLDA laws changes. Our analytic strategies were logically reasonable and selected to ensure each group had a sufficient sample size for analysis. Finally, as an ecological study, the observed associations are subject to the risk of ecological fallacy and should be interpreted as population-level associations rather than as evidence of individual-level causal relationships.

Study results suggest MLDA laws are associated with alcohol use and alcohol-attributed mortality in later life, even when the laws were amended many years ago. These findings, which should be interpreted as population-level associations and are subject to data and design limitations, highlight the importance of considering both the short-term and long-term impacts of MLDA policy change, particularly for jurisdictions that implemented changes decades ago. Efforts to enact new legislation – and enforce existing policies – are critical to remedying the harmful impacts of historic changes. Future research incorporating individual-level data and policy implementation measures may further clarify the mechanisms linking historical MLDA changes to later-life outcomes.

CRediT authorship contribution statement

Jie Li: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Peishan Ning:** Writing – original draft, Validation, Project administration, Funding acquisition. **Wanhui Wang:** Investigation. **David C. Schwebel:** Writing – review & editing. **Li Li:** Writing – review & editing. **Zhenzhen Rao:** Software. **Peixia Cheng:** Visualization. **Dan Tian:** Data curation. **Guoqing Hu:** Writing – review & editing, Methodology, Conceptualization.

Ethical statement

This ecological study was approved by the ethics committee of Xiangya School of Public Health, Central South University, China (NO. XYGW-2021-19).

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Declaration of competing interest

The authors declare no conflict interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cjtee.2026.01.007>.

Data availability

The integrative dataset of this study is available on the Dryad repository (<http://datadryad.org/share/CrFXdkDatob6wXfSbodxNWOAueDWgBb66Zh1Wpe6AHg>). The codes supporting this study's findings are available from the corresponding author upon reasonable request.

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