Similar Drinking, Greater Harm: Obesity, Metabolic Risk, and Rising Alcohol-Associated Liver Disease Mortality

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Abstract: Alcohol-associated liver disease (ALD) is among the fastest-growing causes of premature mortality in the United States, contributing to declining life expectancy and rising disparities in life expectancy by socioeconomic status. We show that rising ALD mortality is largely independent of changes in drinking, which have remained relatively stable or decreased for many groups. Americans are instead drinking the same or less in bodies less metabolically able to tolerate alcohol's hepatotoxic effects. Using state-level data from 1999-2023, we find that rising obesity explains approximately half of the ALD mortality increase while changes in drinking explain less than 1 percent. These findings reframe ALD as an epidemic and point towards new prevention strategies.

Alcohol-associated liver disease (ALD) mortality has risen significantly in the United States since the early 2000s.[1] In 2023 alone, more than 28,000 individuals died from ALD,[2] a disease that has over the same period become a leading indication for liver transplantation, now accounting for roughly half of all liver transplants.[3] These increases are concentrated among midlife adults without college educational attainment, and are major contributors to poor U.S. life expectancy trends as well as widening disparities in longevity.[4–9]

Despite its growing toll, the underlying drivers of rising ALD mortality remain poorly understood. Early accounts linked these trends to a broader epidemic of deaths of despair involving drug overdoses and suicides, driven by deteriorating economic and social prospects for working-class Americans since the 1970s.[5,6] However, recent work has critiqued this framework: macroeconomic conditions explain little of the rise in drug mortality once potential confounders are accounted for,[10] and the hypothesized economic forces predate the mortality increases by decades.[11] Moreover, for drug overdoses, a large literature concludes that increases are better explained by pharmaceutical industry-driven increases in opioid prescribing and the saturation of illicit drug supply with illicitly manufactured fentanyl than by changes in the macroeconomy.[12–14] Meanwhile, no alternative account has been advanced for the rise in ALD mortality.

Prior work has highlighted the role of an expanding obesogenic environment to worsening of overall midlife mortality trends,[15] but the contribution of rising obesity to increases in ALD mortality has not been quantified. There are strong biological reasons to expect that it may be playing a primary role. Obesity and related metabolic syndrome independently promote hepatic steatosis, the accumulation of excess fat in the liver that characterizes early-stage ALD, with recent studies finding that only a small proportion of hepatic steatosis is solely attributable to alcohol and that most patients also have some degree of underlying metabolic dysfunction.[16,17] Hepatic steatosis in turn primes the liver for alcohol-induced damage. Epidemiological studies consistently find that the combined risk of serious liver disease from heavy drinking and metabolic syndrome substantially exceeds the sum of their independent effects,[18–20] with no established safe level of alcohol in the presence of hepatic steatosis or metabolic risk.[21] Further, rates of obesity and metabolic syndrome have increased considerably over the same period that ALD mortality has risen,[22,23] including among people who drink.[24]

Using over two decades of state-level data on drinking, metabolic risk, and ALD mortality, we examine the extent to which changes in metabolic risk, rather than changes in drinking behavior, can explain increasing ALD mortality.

Similar Drinking, Greater Harm

Age- and sex-adjusted ALD mortality rates approximately doubled from 1999 to 2021, spiking sharply during the COVID-19 pandemic before partially receding to 69 percent above baseline by 2023 (Figure 1A). Despite this substantial increase, trends in drinking were relatively stable. Self-reported heavy drinking prevalence from the Behavioral Risk Factor Surveillance System (BRFSS) — the drinking pattern which is most closely linked with ALD risk when sustained[25] — rose by just 7.0 percent from 1999 to 2019, spiked at 15.7 percent above baseline levels amid the COVID-19 pandemic in 2020 and remained elevated through 2022, and then declined to 1.5 percent below baseline by 2023. Binge drinking prevalence, measured from 2006 onward following a change in definition for females, declined by approximately 10 percent from 2006 to

2023. These self-reported measures could understate true drinking trends if reporting propensity has declined over time. As an alternative measure, aggregate per capita alcohol consumption from state tax records compiled by the National Institute on Alcohol Abuse and Alcoholism rose by 15 percent from 1999 to 2023, a meaningful increase, albeit still considerably smaller in relative terms compared to the 69 percent increase in ALD mortality over the same period.

The overall trend masks heterogeneity by sex. ALD mortality increased substantially for both sexes, but relative increases were much larger for females — 161 percent from 1999 to the peak in 2021 compared to 77 percent over the same period for males (Figure 1B and 1C). For females, heavy drinking prevalence rose by roughly 46 percent from 1999 to its peak in 2022 before declining to 20 percent above baseline by 2023. For males, heavy drinking prevalence fell by 14 percent over the full period, and binge drinking declined similarly.

Together, these trends indicate that rising ALD mortality is unlikely to be explained by population-level changes in drinking alone — particularly for males, for whom reported drinking declined. We thus turn to changes in underlying risk as an alternative explanation.

Rising Metabolic Risk Among People Who Drink

While drinking patterns remained relatively stable, the metabolic health of people who drink deteriorated considerably. The share of heavy drinkers who were also obese increased by 117 percent from 1999 to 2023 (Figure 2A), while the share who were also diabetic or severely obese increased by 156 and 427 percent, respectively (Figure 2A and Figure S1A). These trends drove more than doublings in the combined population-level prevalences of heavy drinking with obesity, diabetes, and severe obesity — direct measures of the size of the population at highest ALD mortality risk (Figures S2A and S3A).

Like rising ALD mortality, increases in metabolic risk were sharper for females who drink heavily. Among females, the share of heavy drinkers who were also obese increased by 197 percent, compared to 88 percent for males (Figures 2B and 2C). Patterns were similar for diabetes and severe obesity (Figures 2B, 2C, S1B, S1C, S2B, S2C, S3B, and S3C). Notably, among males, these large increases in the share of heavy drinkers who were also obese, diabetic, or severely obese drove increases in the combined population-level prevalence of heavy drinking with obesity, diabetes, and severe obesity (Figures S2C and S3C), even as heavy drinking prevalence itself declined among males (Figure 1C).

Taken together, the deterioration in metabolic health among heavy drinkers was of sufficiently large magnitude to plausibly account for the observed rise in ALD mortality, even in the absence of changes in drinking behavior. We study its role more precisely below.

ALD Mortality Concentrates Where Heavy Drinking and Obesity Coincide

Figure 3 presents a heat map of ALD mortality rates across state-years binned into deciles of obesity and heavy drinking prevalence. Mortality is highest where both exposures are elevated and lower where only one is. State-years with high obesity but low drinking, or high drinking but low obesity, have mortality rates far closer to the low-low quadrant than the high-high quadrant. This pattern is consistent with evidence from individual-level cohort studies showing that obesity and alcohol consumption interact synergistically in ALD risk[26] and suggests that the joint distribution of these risk factors, not either one alone, is an important driver of geographic and

temporal variation in ALD mortality. The pattern is similar using alternative measures of metabolic risk, diabetes prevalence and severe obesity, though not as pronounced (Figure S4).

Rising Obesity Explains Approximately Half of the Increase in ALD Mortality

To quantify the role of rising obesity in explaining ALD mortality at the population level, we estimate a Poisson regression model of state-year ALD mortality rates on heavy drinking prevalence, obesity prevalence, and their interaction, controlling for state and year fixed effects (see Materials and Methods). Coefficients from models sequentially adding each term are reported in Table S1. In the first three models, both heavy drinking and obesity prevalence are strongly and positively related to ALD mortality rates. In the full model including the interaction term, obesity prevalence and the interaction between obesity and heavy drinking prevalence are strongly and positively related to ALD mortality rates, whereas heavy drinking prevalence alone is not significantly related to ALD mortality rates. it.

Results are qualitatively similar across alternative specifications (Table S2), measures of metabolic risk (Table S3), and drinking (Table S4). Though the statistical precision and whether mortality increases load on the main metabolic risk (obesity, diabetes, or severe obesity) term or on the interaction between metabolic risk and drinking varies across specifications, they uniformly show that changes in metabolic risk and/or their interaction with drinking changes strongly predict higher ALD mortality rates whereas changes in drinking alone generally do not.

Using estimates from our preferred model (Table S1 column 4), Figure 4 reports the average marginal effects of a one percentage point increase in heavy drinking prevalence over varying levels of obesity prevalence, ranging between 1999 and 2023 obesity prevalence (19 and 33 percent, respectively). This captures how the risk landscape of drinking in the U.S. has shifted as the metabolic profile of the population changed. At 1999 obesity prevalence, a one percentage point increase in heavy drinking prevalence is related to a small and statistically imprecise increase in ALD mortality of 0.017 deaths per 100,000 (95% CI: -0.024 to 0.059). At 2023 obesity prevalence, that same increase in heavy drinking is related to 0.21 more deaths per 100,000 (95% CI: 0.031 to 0.039). This implies that rising obesity prevalence increased the average marginal effect of a 1 percentage point rise in heavy drinking prevalence over this period by 0.19 deaths per 100,000 (95% CI: -0.001, 0.389), a more than 10-fold amplification. Put differently, the same drinking behavior that carried modest population-level ALD risk in 1999 now carries greater risk — not because people drink differently, but because the metabolic context in which they drink changed considerably.

We further use our preferred model specification estimates to decompose the observed rise in ALD mortality from 1999 to 2023 into contributions from changes in heavy drinking prevalence, obesity prevalence, and their interaction (Table 1). Rising obesity prevalence alone statistically accounts for approximately 53 percent of the increase in ALD mortality over this period. Changes in heavy drinking prevalence and their interaction with obesity contribute -0.03 and -0.44 percent respectively: drinking declined modestly from 1999 to 2023 and, if anything, slightly attenuated ALD mortality growth rather than contributing to it.

Illustrative Counterfactuals Suggest Obesity as a Priority Target for ALD Prevention

To illustrate the relative importance of each factor, we use our preferred estimates to simulate the predicted reduction in ALD mortality from a hypothetical 10 percent reduction in either heavy

drinking or obesity prevalence, holding all else equal, at 2023 levels. Our estimates suggest that a 10 percent reduction in obesity prevalence could prevent approximately five times as many ALD deaths annually as an equivalent percent reduction in heavy drinking prevalence (1,517 vs. 316 deaths; Table S5). This difference reflects both the large effect of obesity in contributing to ALD and amplifying alcohol harm, as well as the considerably higher prevalence of obesity relative to heavy drinking in the U.S., meaning there is far more obesity than heavy drinking to address. Reducing both simultaneously would prevent an estimated 1,744 deaths annually — less than the simple sum of the two individual effects (1,833), because the interaction between heavy drinking and obesity means that reducing obesity prevalence also attenuates the marginal harm of heavy drinking, leaving less additional risk for reductions in drinking to eliminate.

Caveats

Several limitations warrant consideration. Our primary drinking measures rely on BRFSS self-report, though corroboration from NIAAA aggregate alcohol consumption data suggests reporting bias does not materially affect our conclusions. Our metabolic risk measures are limited to obesity and diabetes prevalence available in BRFSS, likely understating the full scope of metabolic vulnerability relevant to ALD and suggesting our estimates of the metabolic risk contribution may be a lower bound. Diabetes prevalence is additionally subject to ascertainment bias from expanded screening and evolving diagnostic thresholds, which is one reason we prefer obesity as our primary measure of metabolic risk in our regression analyses.

While state and year fixed effects control for time-invariant differences and common national trends, residual confounding remains possible. To bias our results, any confounder must be correlated with changes in obesity and obesity-drinking interactions within states, independently of changes in drinking itself. One plausible such confounder is changes in the racial and ethnic distribution of the population, as some racial and ethnic groups may be more vulnerable to ALD than others;[27] however, results are similar in models with controls for race and ethnicity distributions (Table S2). Another potential confounder, availability and quality of ALD treatment, has improved over this period as liver transplantation has become more widely accepted for ALD patients.[28] This could cause our estimates to be conservative if these increases had greater effects and thus slowed ALD mortality in areas with greater increases in obesity.

Our contemporaneous exposure measures likely do not fully capture the long biological lag between drinking, metabolic dysfunction, and ALD mortality, though our conclusions are unchanged in specifications incorporating 3-to-5-year lags (Table S2). Our analysis is ecological and we cannot directly observe whether individuals dying from ALD are those with both risk factors present; however, individual-level cohort evidence supporting a synergistic obesity-alcohol interaction in ALD risk provides important complementary support for our population-level findings.[21,26] BRFSS was redesigned in 2011, creating measurement error in our exposure variables; however, results are similar using only post-2011 data (Table S2). Finally, ALD mortality spiked during the COVID-19 pandemic,[1] potentially reflecting pandemic-related increases in drinking, disruptions to healthcare access, and interactions between COVID-19 and liver disease;[29] still, conclusions are also similar if we end our analysis in 2019 (Table S2).

Reframing the ALD Epidemic and Its Solutions

ALD has emerged as one of the fastest-growing causes of premature mortality in the United States, contributing to the broader deterioration in American life expectancy that has been attributed to deaths of despair.[5,6] Our findings show that for ALD, this framing is incomplete. Americans do not appear to be drinking substantially more than they were two decades ago — rather, they are drinking in bodies that are less able to tolerate alcohol's hepatotoxic effects. This reframing points towards a potentially tractable set of solutions.

The rise of effective metabolic therapies creates a unique opportunity to address the ALD epidemic through a channel that has been largely overlooked. GLP-1 receptor agonists have demonstrated substantial efficacy in reducing obesity and metabolic dysfunction,[30,31] and emerging evidence suggests that they may additionally reduce alcohol consumption and craving directly.[32,33] If confirmed, these therapies could prove doubly valuable for ALD prevention, addressing both vulnerability and exposure simultaneously.

Interventions targeting drinking remain important and are in fact even more valuable today than two decades ago from an ALD prevention perspective, particularly for females for whom drinking is also rising. Because drinking now occurs in a higher-harm metabolic environment, any reduction in drinking carries a larger marginal benefit for ALD prevention. Yet the treatment landscape for alcohol use disorder has seen little innovation in recent decades, with no new pharmaceutical treatments having been approved since 2006 (Vivitrol), underscoring the urgent need for accelerating research into novel therapeutic approaches like GLP-1s and others yet to be discovered. Policies that effectively reduce alcohol use, such as higher taxes,[34,35] have also seen little movement over the past two decades and might warrant greater attention.

More broadly, modern obesogenic environments and the dramatic rise in population metabolic dysfunction may be amplifying harm from a wide range of behavioral and environmental exposures that contribute to America's poor health trajectory. Obesity and metabolic disease have reached historically high levels in the U.S. and continue to rise across much of the world.[36] Beyond ALD, elevated COVID-19 mortality rates in countries with higher obesity prevalence also offers yet another stark example of how such metabolic vulnerability can amplify the mortality consequences of various exposures at the population level.[23,37] Whether similar dynamics are shaping mortality trends from other behavioral or environmental exposures, and how to best address them, represents an important frontier for further research.

Materials and Methods

Data

ALD mortality data are from the National Vital Statistics System (NVSS), maintained by the National Center for Health Statistics (NCHS), covering 1999 to 2023. We identify ALD deaths using ICD-10 codes K70.0-K70.9 (alcoholic liver disease) as the underlying cause of death. All mortality rates are among adults ages 18+ and age- and sex-adjusted to the U.S. 2000 standard population using direct standardization with approximately five-year age groups and top-coding at 80+ (18-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 64-69, 70-74, 75-79, and 80+). State population data, used for constructing rates and standardization, are from the Surveillance, Epidemiology, and End Results (SEER) program, which provides intercensal population estimates by age, sex, and state over our study period.

Drinking and metabolic risk prevalence measures are from the Behavioral Risk Factor Surveillance System (BRFSS), an annual state-level telephone survey of U.S. adults conducted by the Centers for Disease Control and Prevention. We construct consistent measures of heavy drinking, defined as more than 14 drinks per week for men and more than 7 drinks per week for women, and obesity, defined as body mass index of 30 or above derived from self-reported height and weight, from 1999 to 2023, harmonizing variable definitions across survey years to account for changes in question wording and response categories. Other measures are described in the supplementary appendix. BRFSS underwent a significant methodological redesign in 2011, transitioning from landline to cellphone-based sampling. We demonstrate robustness of our results to this change in the Supplementary Appendix. Prevalence estimates are age- and sex-adjusted to the U.S. 2000 standard population using the same age groups noted above and use survey weights. As a validation of self-reported drinking trends, we also use state-level per capita alcohol consumption data compiled by the National Institute on Alcohol Abuse and Alcoholism (NIAAA) from state tax and shipment records, which are not subject to self-report bias.

Statistical Analysis

We quantify the contribution of changes in drinking, metabolic risk, and their interaction to rising ALD mortality using a Poisson regression model with state and year fixed effects. The model includes heavy drinking prevalence, obesity prevalence, and their interaction as key regressors, capturing both the direct effects of obesity on ALD mortality and its effects on amplifying heavy drinking-related harm. State and year fixed effects control for time-invariant differences across states and common national shocks, and effects are thus identified from within-state changes in drinking, metabolic risk, and their co-movements. Regressions are weighted by state adult population, and standard errors are clustered at the state level. The full regression model specification is provided in the Supplementary Appendix.

We use heavy drinking prevalence and obesity as our primary proxies for alcohol exposure and metabolic risk in our regression models. ALD risk rises sharply with regular and sustained heavy consumption, making heavy drinking the most clinically relevant exposure measure.[25] Obesity is consistently recorded over time and, because it is derived from self-reported height and weight, is unlikely to be influenced by changes in healthcare access or evolving diagnostic practices.

We translate model estimates into average marginal effects[38–40] to quantify how the mortality consequences of a given level of drinking have changed as obesity prevalence has risen. We first evaluate the average marginal effect of a one percentage point increase in heavy drinking prevalence at 1999 and 2023 average obesity prevalence levels, capturing the shift in the population-level harm profile of drinking over this period. We then use average marginal effects to decompose the observed rise in ALD mortality from 1999 to 2023 into contributions from changes in heavy drinking prevalence, changes in obesity prevalence, and their interaction using counterfactual predictions that hold each factor at its 1999 level in turn. Lastly, we use average marginal effects to estimate the predicted reduction in ALD mortality from a hypothetical 10 percent reduction in either heavy drinking or obesity prevalence at 2023 levels. These estimates assume proportional reductions in prevalence across the population, including among heavy drinkers specifically, and should be interpreted as illustrative of the relative importance of each risk factor rather than precise predictions about any particular intervention.

Robustness checks examining alternative regression specifications and measures of drinking and metabolic risk are reported in the Supplementary Appendix.

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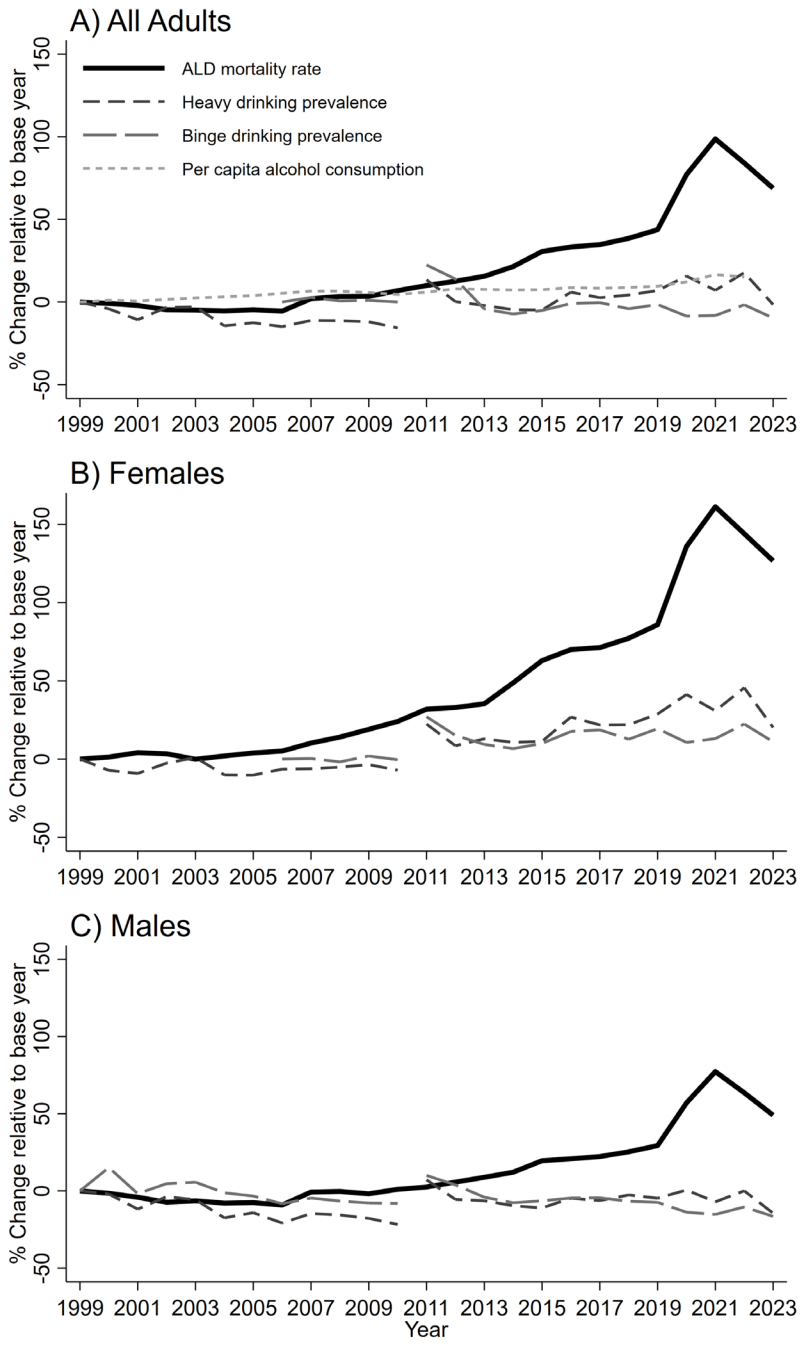


Fig. 1. ALD mortality rises sharply without proportional increases in drinking. ALD mortality, heavy drinking prevalence, binge drinking prevalence (males), and per capita alcohol consumption indexed to 1999; binge drinking (all adults and females) indexed to 2006 following a change in the female-specific definition from 5+ to 4+ drinks per occasion. ALD mortality rates from the National Center for Health Statistics (NCHS). Heavy drinking defined as >14 drinks/week for men and >7 drinks/week for women; binge drinking as 5+ drinks per occasion for men and 4+ for women. ALD mortality and prevalence measures are age- and sex-adjusted to the U.S. 2000 standard population. BRFSS series shown in two segments reflecting a 2011 switch from landline to cellphone-based sampling that introduced a level shift in measured prevalence unrelated to actual changes in drinking behavior. Per capita alcohol consumption from the National Institute on Alcohol Abuse and Alcoholism (NIAAA), compiled from state tax records, shown for all adults only. Panels B and C show sex-specific trends, age-adjusted to the U.S. 2000 standard population; NIAAA consumption data not available by sex.

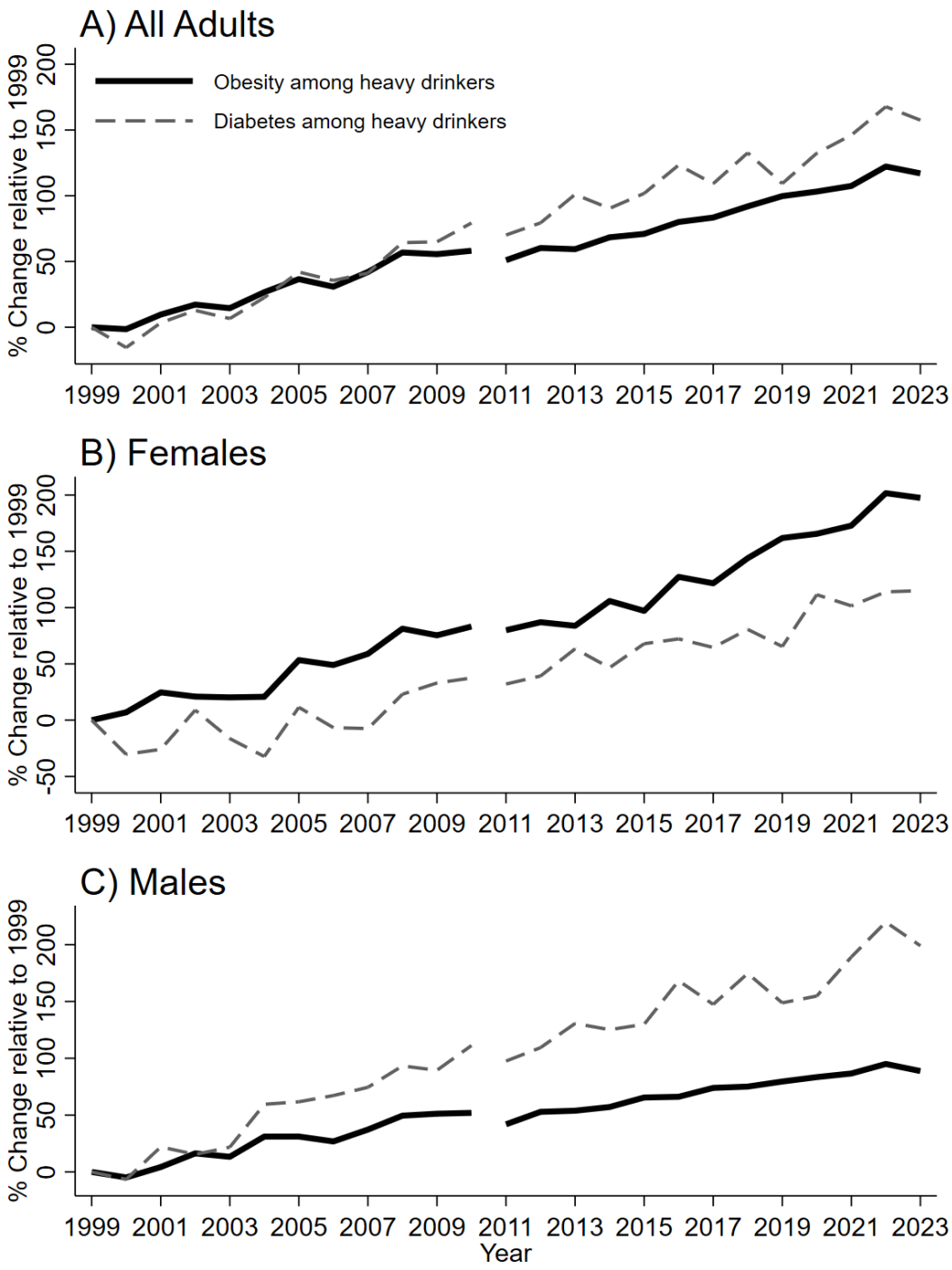


Fig. 2. The metabolic health of people who drink heavily has deteriorated sharply since 1999. Share of heavy drinkers who are also obese or have diabetes, computed from Behavioral Risk Factor Surveillance System (BRFSS) microdata using survey weights. Heavy drinking defined as >14 drinks/week for men and >7 drinks/week for women. Obesity defined as BMI ≥30; diabetes based on self-reported diagnosis. BRFSS series shown in two segments reflecting a 2011 switch from landline to cellphone-based sampling that introduced a level shift in measured prevalence unrelated to actual changes in drinking or metabolic health. Panels B and C show sex-specific trends.

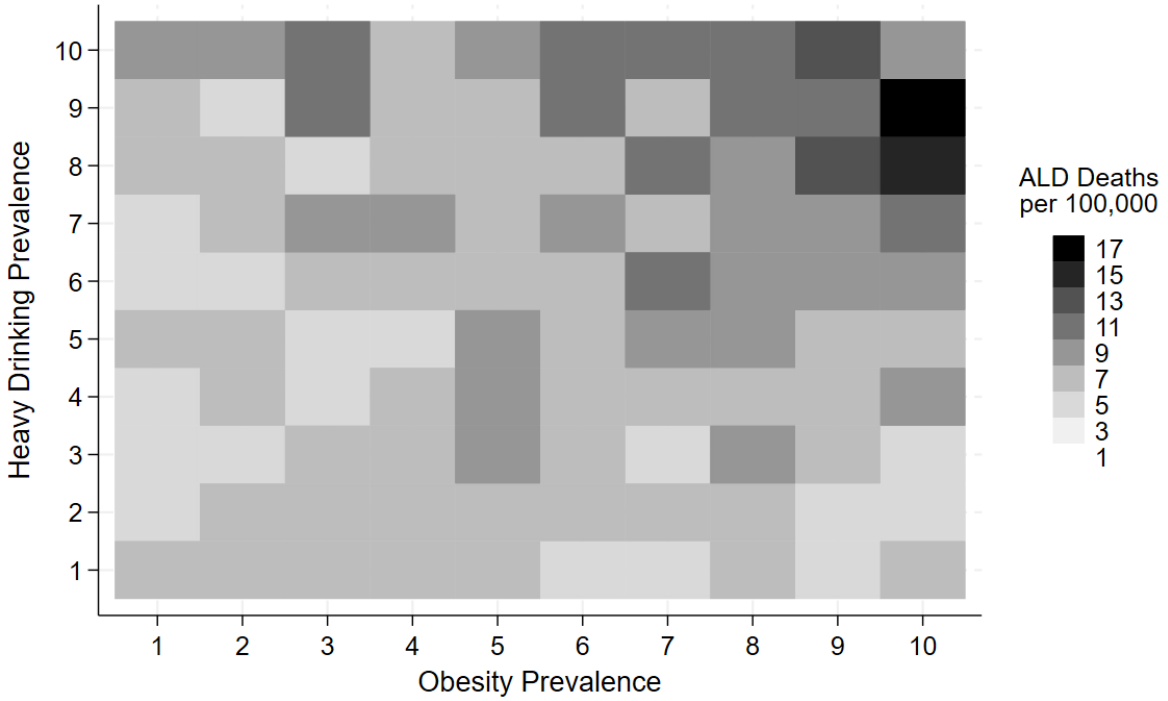


Fig. 3. ALD mortality concentrates where heavy drinking and obesity coincide. ALD mortality rates for state-year observations binned into deciles of obesity and heavy drinking prevalence, 1999 to 2023. ALD mortality rates from the National Center for Health Statistics (NCHS), age- and sex-adjusted to the U.S. 2000 standard population. Heavy drinking and obesity prevalence from the Behavioral Risk Factor Surveillance System (BRFSS), age- and sex-adjusted to the U.S. 2000 standard population.

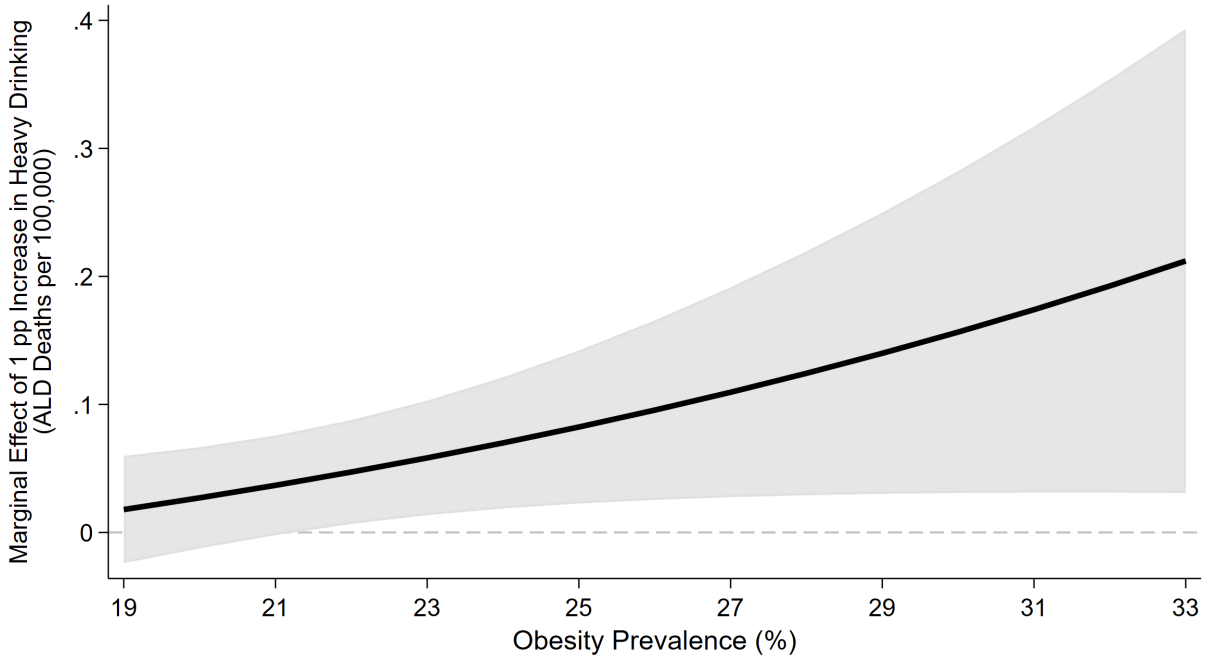


Fig. 4. Higher obesity prevalence amplifies the effect of heavy drinking prevalence on population ALD mortality rates. The average marginal effect of a 1 percentage point increase in heavy drinking prevalence is evaluated at different levels of obesity prevalence, ranging from the prevalence in 1999 (19 percent) to 2023 (33 percent). These average marginal effects are derived from a Poisson model of ALD death rates on heavy drinking prevalence, obesity prevalence, their interaction, and state and year fixed effects from 1999 to 2023 (Equation 1). Effects are shown as the solid black line and 95% confidence intervals are shaded in grey.

Tab. 1. Changes in obesity prevalence explain over half of the increase in ALD mortality rates from 1999 to 2023. Each row presents a counterfactual scenario: (1) the predicted change in ALD deaths per 100,000 based on changes in heavy drinking prevalence from 1999 to 2023 (holding obesity prevalence fixed at 1999 levels); (2) the predicted change based on changes in obesity prevalence (holding heavy drinking prevalence fixed); and (3) the predicted change based on both changes interacting with one another. The first column shows average marginal effects based on Equation 1 and 95% confidence intervals in brackets. 95% confidence intervals are derived from the delta method. The second column shows the percent of the average change in ALD death rates (shown in the bottom row) that each scenario explains.

	Average marginal effect	% Explained
Effect of change in drinking (holding obesity fixed)	-0.0014 [-0.0053, 0.0024]	-0.03
Effect of change in obesity (holding drinking fixed)	2.1721 [1.5872, 2.7570]	53.01
Interaction between changes in drinking and obesity	-0.0182 [-0.0364, 0.0001]	-0.44
Change in ALD death rate, 1999 to 2023	4.25	

Supplementary Materials for

Same Drinking, Greater Harm: Obesity, Metabolic Risk, and Rising Alcohol-Associated Liver Disease Mortality

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Figs. S1 to S4
Tables S1 to S5

Materials and Methods Supplement

Additional Details About the Behavioral Risk Factor Surveillance System (BRFSS)

This section presents additional details about the BRFSS measures on drinking and metabolic risk. Heavy drinking was defined in the main manuscript text. Binge drinking prevalence was defined as ≥ 5 drinks on a single occasion for men (beginning in 1999) and ≥ 4 drinks on a single occasion for females (beginning in 2006). Because of the change in definition for females in 2006, binge drink prevalence is generally presented from 2006-, except for males for whom the variable was consistently defined from 1999-. Obesity and severe obesity were defined using self-reported height and weight, converted to body mass index (kg/m^2). Individuals with self-reported height of greater than 84 inches (7 feet) or weight of greater than 500 pounds were excluded consistent with prior research. Though, results were not sensitive to this choice. Obesity was defined as a body mass index (BMI) of greater than 30 and severe obesity was defined as a BMI of greater than 40. Diabetes prevalence was defined using affirmative responses to a question of whether respondents had ever been told that they have diabetes.

The module collecting information on drinking was optional for states in 2000, resulting in only 12 of 51 states reporting drinking data in that year. Data for states that did report in 2000 are included in all analyses; results are not sensitive to excluding 2000 entirely. A small number of states also did not report any data to BRFSS in certain years: Hawaii in 2004, New Jersey in 2019, Florida in 2021, and Kentucky and Pennsylvania in 2023. These states are included in all other years; results are not sensitive to their exclusion.

BRFSS underwent a significant methodological redesign in 2011, transitioning from landline to cellphone-based sampling; we demonstrate robustness of our results to this change in the Supplementary Appendix. For this reason, in all time-series figures we present pre-2011 and post-2011 time-series separately. We also implement a robustness check to our regressions (below) which stratify the full period, to ensure that our results are not influenced by this.

Statistical Analysis

We quantify the contribution of changes in drinking, changes in metabolic risk, and their interaction to rising ALD mortality using a Poisson regression model of the form:

$$E[Y_{st}] = Exp(\beta_1 D_{st} + \beta_2 MR_{st} + \beta_{12} D_{st} \times MR_{st} + \alpha_s + \tau_t). \quad (1)$$

Here, Y_{st} denotes state-year age- and sex-adjusted ALD mortality rates, D_{st} represents heavy drinking prevalence, MR_{st} denotes metabolic risk prevalence, and $D_{st} \times MR_{st}$ interacts drinking and metabolic risk to capture the hypothesis that alcohol is more harmful in populations with higher underlying metabolic risk. α_s and τ_t are state and year fixed effects, which control for time-invariant differences across states and common national shocks respectively. Effects are thus identified from within-state changes in drinking, metabolic risk, and their co-movements.

We use heavy drinking prevalence and obesity as our primary proxies for alcohol exposure and metabolic risk. ALD risk rises sharply with regular and high levels consumption, making heavy drinking the most clinically relevant exposure measure. Obesity is consistently recorded over

time and, because it is derived from self-reported height and weight, is unlikely to be influenced by changes in healthcare access or evolving diagnostic practices like diabetes. It is also more common than severe obesity and prior work shows that it is related to faster progression of ALD and increased ALD mortality risk among people who drink.

We use Poisson regression models both to account for the non-negative and skewed distribution of mortality rates and to allow for non-linear interactions between drinking and metabolic risk. Effects are presented in terms of average marginal effects. Regressions are weighted by population and standard errors are clustered at the state-level.

We also present robustness to the following alternative specifications that: (i) controls for the % non-Hispanic Black, Hispanic, and % non-Hispanic Other in each state-year; (ii) use 3- and 5-year lags of heavy drinking and obesity prevalence rather than contemporaneous prevalences; (iii) restrict the data to 2011 to 2023 (after the BRFSS redesign); (iv) restrict the data to the pre-COVID-19 pandemic period from 1999 to 2019; (v) that use alternative measures for metabolic risk (diabetes and severe obesity prevalence), interacted with heavy drinking prevalence; and (vi) that use alternative measures for drinking (binge drinking prevalence and alcohol consumption per capita from the National Institute on Alcohol Abuse and Alcoholism). Results from these alternative robustness specifications are reported below.

Decomposition and Counterfactual Methods

We use average marginal effects to decompose changes in ALD mortality rates from 1999 to 2023 into three components: changes in heavy drinking prevalence alone (i.e., holding obesity prevalence fixed at 1999 levels), changes in obesity prevalence alone (i.e., holding heavy drinking prevalence fixed), and the interaction between simultaneous changes in both measures. This entails recoding each of the state-year observations in the data to have the drinking prevalence/obesity prevalence observed in 1999 and 2023, taking the difference between these predictions, and averaging over the differences in the population. Standard errors, used to construct confidence intervals, are constructed using the delta method. The same method was used for alternative measures of drinking and obesity prevalence.

We used a similar approach to estimate counterfactual reductions in deaths due to interventions that reduce obesity and heavy drinking prevalence by 10%. Specifically, we predict ALD mortality rates at observed levels and then under the counterfactual that obesity and/or heavy drinking prevalence were 10% lower than that for every state-year in the data, and we then sum over the difference within a single year (2023).

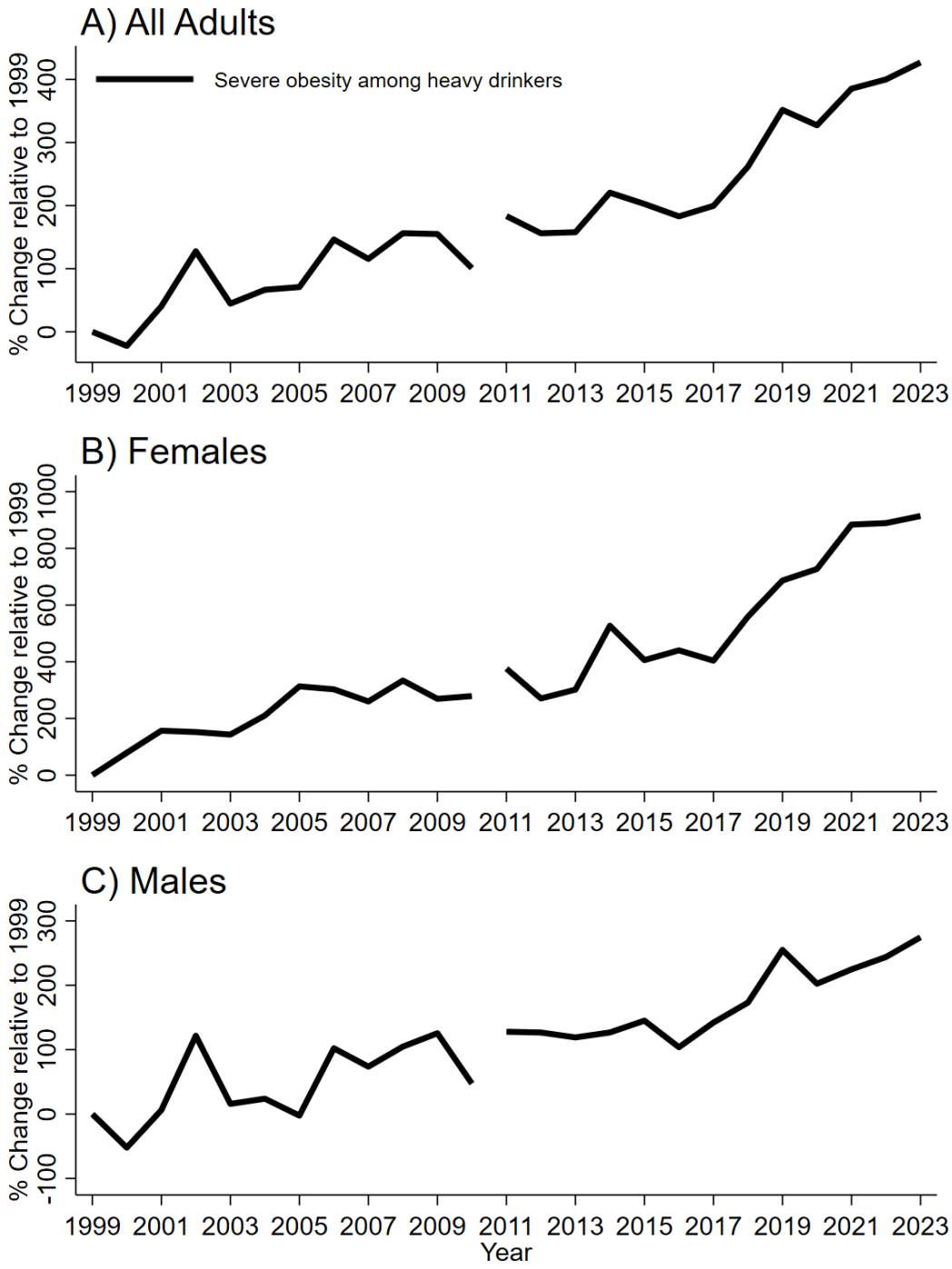


Fig. S1. Trends in severe obesity prevalence among people who report drinking heavily.
Notes: Changes are indexed relative to 1999. Data are from the Behavioral Risk Factor Surveillance System (BRFSS). The series are shown in two segments reflecting a switch from landline to cellphone-based sampling in 2011.

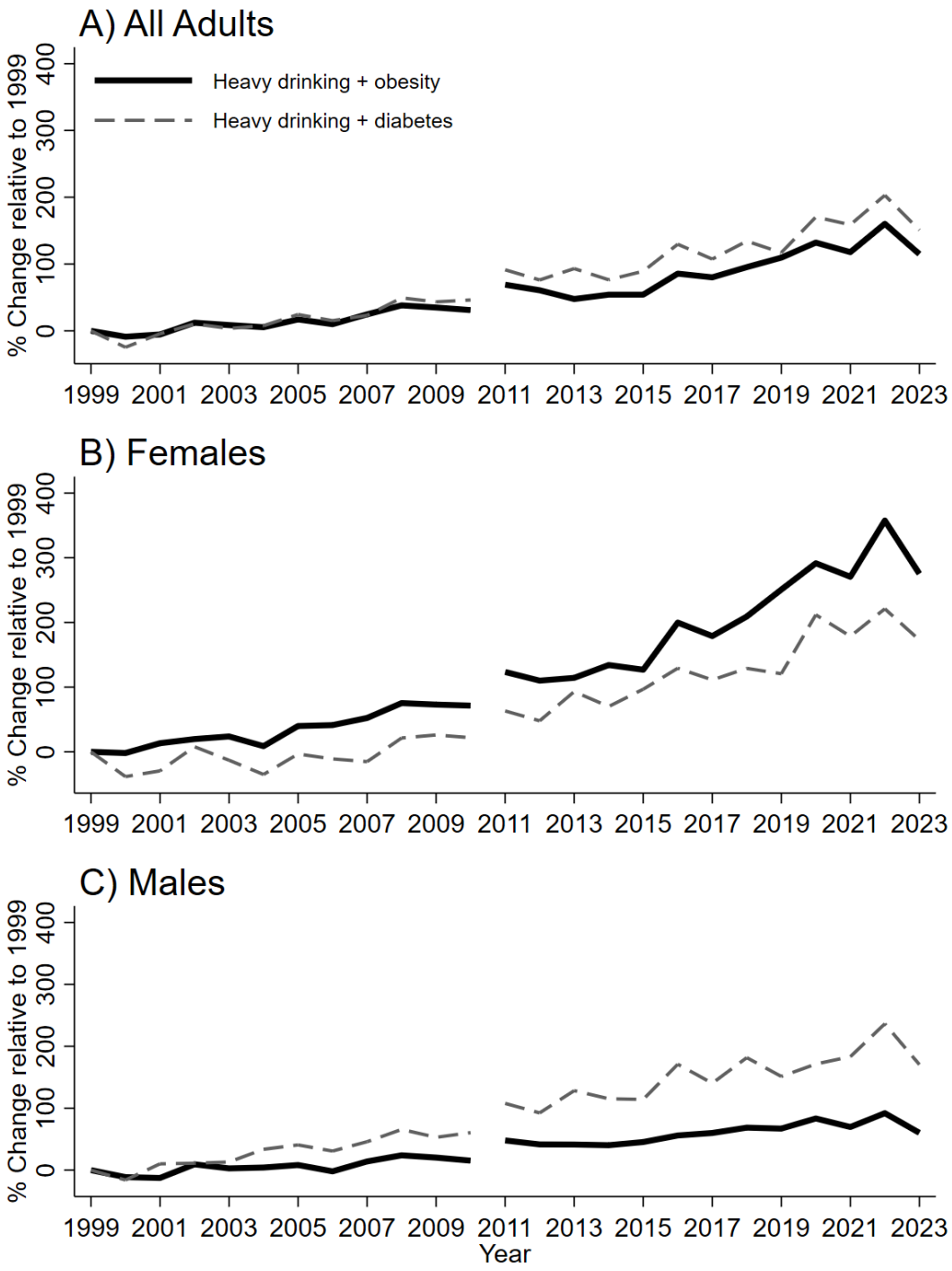


Fig. S2. Trends in combined heavy drinking and obesity/diabetes prevalence. *Notes:* Changes are indexed relative to 1999. Data are from the Behavioral Risk Factor Surveillance System (BRFSS) and age- and sex-adjusted to the U.S. 2000 standard population (Panel A). Panels B and C present trends age-adjusted trends stratified by sex. The series are shown in two segments reflecting a switch from landline to cellphone-based sampling in 2011.

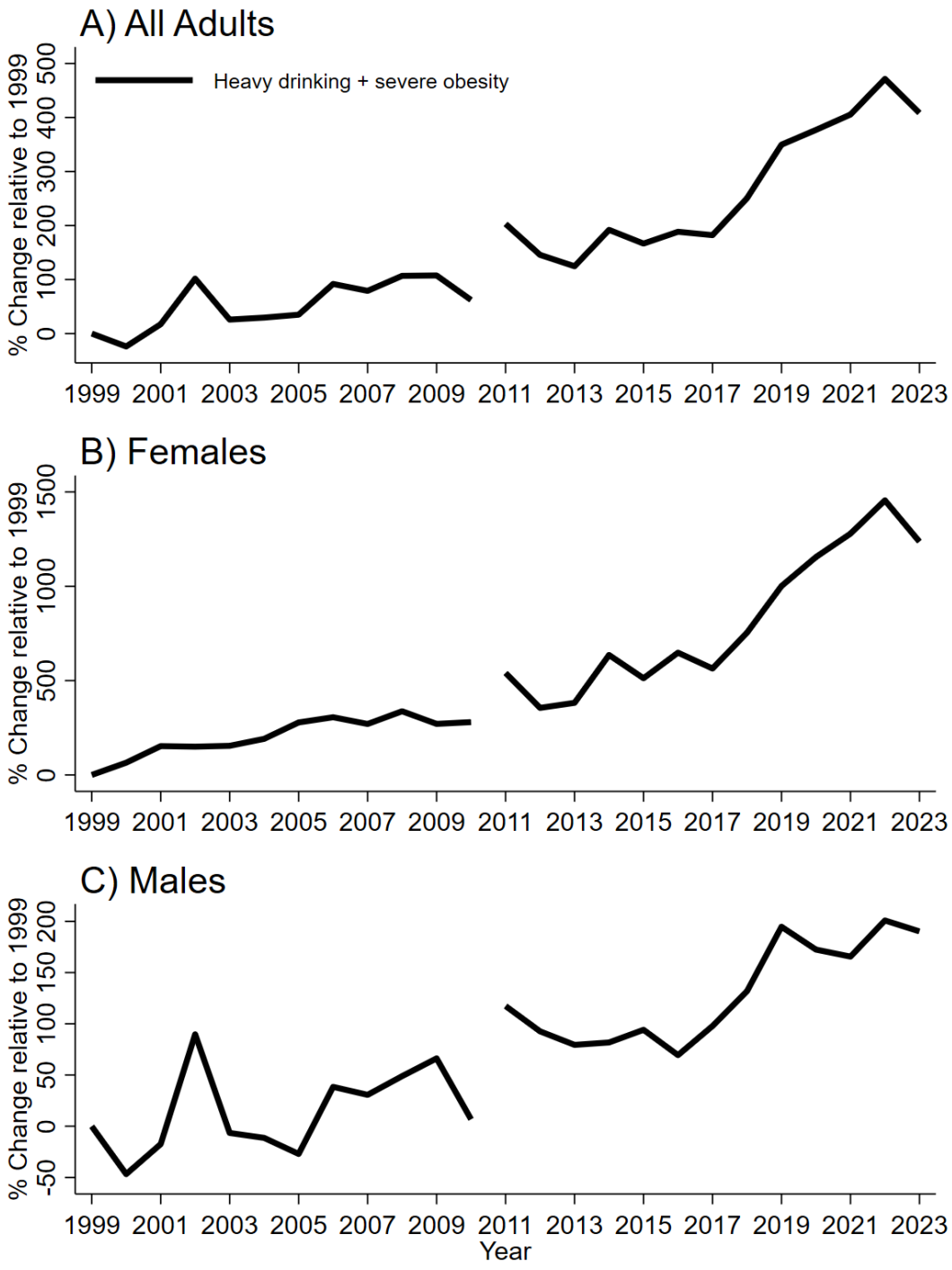


Fig. S3. Trends in combined heavy drinking and severe obesity prevalence. *Notes:* Changes are indexed relative to 1999. Data are from the Behavioral Risk Factor Surveillance System (BRFSS) and age- and sex-adjusted to the U.S. 2000 standard population (Panel A). Panels B and C present trends age-adjusted trends stratified by sex. The series are shown in two segments reflecting a switch from landline to cellphone-based sampling in 2011.

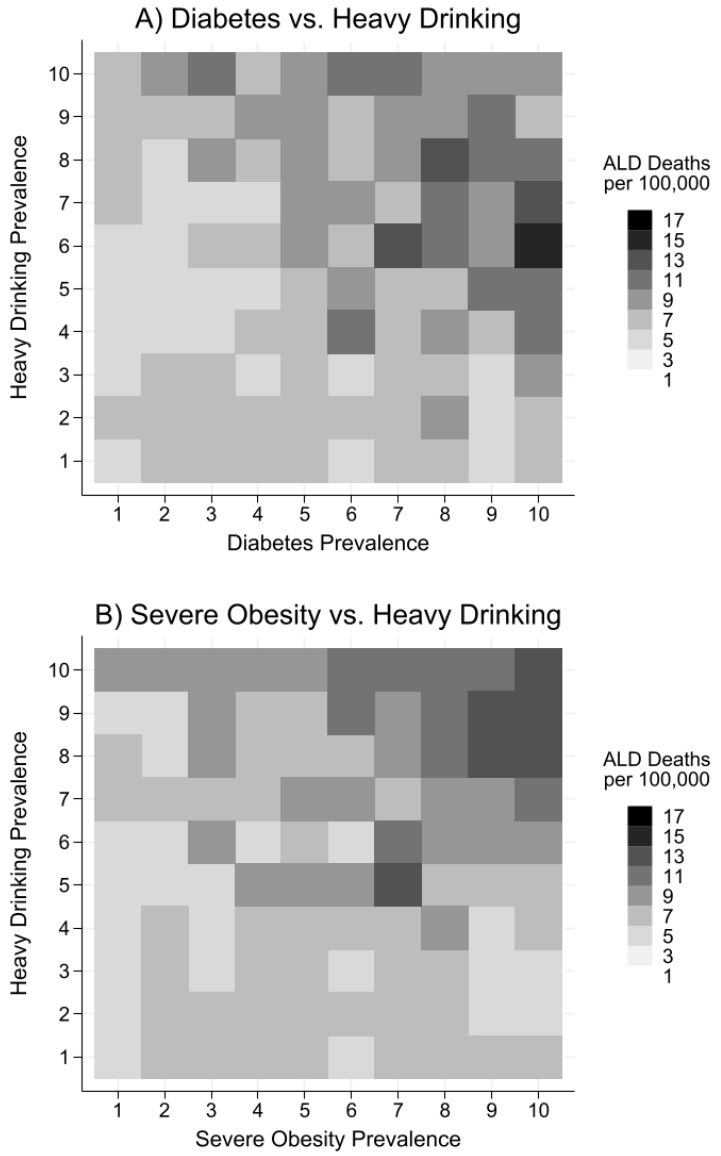


Fig. S4. Heat maps of ALD mortality over diabetes, severe obesity, and heavy drinking prevalence. *Notes:* ALD death rates are shown for state-year observations binned into deciles of heavy drinking and severe obesity (Panel A) or diabetes (panel B) prevalence. Mortality rates are highest in the top right quadrant where both prevalences are elevated and considerably lower where only one is elevated. Mortality rates are from the NCHS and age- and sex-adjusted to the 2000 U.S. standard population; heavy drinking, severe obesity, and diabetes prevalence measures are from the Behavioral Risk Factor Surveillance System (BRFSS).

Tab. S1. Poisson Regression Estimates of the Association Between Heavy Drinking Prevalence, Obesity Prevalence, and ALD Mortality Rates, 1999-2023. *Notes:* Poisson pseudo-maximum likelihood (PPML) estimates with 95% confidence intervals in brackets. The dependent variable is the ALD mortality rate per 100,000 adults. The independent variables are heavy drinking prevalence, obesity prevalence, and their interaction. All measures are among adults ages 18+ and age- and sex-adjusted to the U.S. 2000 standard population using 5-year age groups. Models include state and year fixed effects and are weighted by state adult population. Standard errors are clustered at the state level. * p<0.10, ** p<0.05, *** p<0.01.

	(1)	(2)	(3)	(4)
Heavy drinking	2.059***		1.304**	-3.870
	[0.860,3.257]		[0.126,2.482]	[-9.339,1.598]
Obesity		3.430***	3.295***	1.947***
		[2.427,4.433]	[2.356,4.234]	[0.560,3.334]
Heavy drinking × Obesity				22.982*
				[-2.331,48.295]
State fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	1,231	1,231	1,231	1,231

Tab. S2. Alternative Specifications for the Relationship Between Heavy Drinking Prevalence, Obesity Prevalence, and ALD Mortality Rates. *Notes:* Poisson pseudo-maximum likelihood estimates with 95% confidence intervals in brackets. The dependent variable is the ALD mortality rate per 100,000 adults. The independent variables are heavy drinking prevalence, obesity prevalence, and their interaction. All measures are among adults ages 18+ and age- and sex-adjusted to the U.S. 2000 standard population using 5-year age groups. Column (1) adds race/ethnicity controls (proportion non-Hispanic Black, Hispanic, and non-Hispanic Other, with non-Hispanic White as the reference category) to the baseline specification. Columns (2) and (3) replace contemporaneous measures of heavy drinking and obesity prevalence with 3-year and 5-year lags, respectively, to account for disease latency in the obesity-ALD pathway. Column (4) restricts the sample to 2011–2023 to address the BRFSS methodological redesign in 2011. Column (5) restricts the sample to 1999–2019 to exclude mortality trends during the COVID-19 period. All models include state and year fixed effects and are weighted by state adult population. Standard errors are clustered at the state level. * p<0.10, ** p<0.05, *** p<0.01.

	+ controls	3-year lag	5-year lag	Post-redesign	Pre-COVID
	(1)	(2)	(3)	(4)	(5)
Heavy drinking	-5.618**	-2.276	0.425	-14.867**	-3.278
	[-10.424,-0.812]	[-6.690,2.139]	[-4.827,5.677]	[-26.806,-2.928]	[-8.638,2.082]
Obesity	-0.438	2.483***	2.895***	-1.336	1.677**
	[-2.547,1.672]	[1.027,3.939]	[1.041,4.750]	[-4.236,1.565]	[0.114,3.240]
Heavy drinking × Obesity	21.243**	18.633*	7.065	50.903**	17.401
	[0.431,42.056]	[-3.437,40.703]	[-17.130,31.261]	[9.545,92.260]	[-6.868,41.669]
% non-Hispanic Black	4.876***				
	[2.256,7.497]				
% Hispanic	-3.889***				
	[-6.265,-1.513]				
% non-Hispanic Other	-4.684**				
	[-9.202,-0.166]				
State fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	1,231	1,076	975	659	1,030

Tab. S3. Alternative Metabolic Risk Measures: Diabetes and Severe Obesity as Predictors of ALD Mortality Rates, 1999–2023. *Notes:* Poisson pseudo-maximum likelihood estimates with 95% confidence intervals in brackets. The dependent variable is the ALD mortality rate per 100,000 adults. Columns (1) and (2) replace obesity prevalence with diabetes prevalence as an alternative measure of metabolic vulnerability; column (2) adds a heavy drinking × diabetes interaction term. Columns (3) and (4) replace obesity prevalence with severe obesity prevalence (BMI ≥ 40) as an alternative measure of metabolic vulnerability; column (4) adds a heavy drinking × severe obesity interaction term. All measures are among adults ages 18+ and age- and sex-adjusted to the U.S. 2000 standard population using 5-year age groups. All models include state and year fixed effects and are weighted by state adult population. Standard errors are clustered at the state level. * p<0.10, ** p<0.05, *** p<0.01.

	(1)	(2)	(3)	(4)
Heavy drinking	1.713***	2.830	1.180*	-0.944
	[0.580,2.846]	[-2.424,8.084]	[-0.006,2.366]	[-3.666,1.777]
Diabetes	4.295***	5.176***		
	[1.698,6.893]	[1.510,8.842]		
Heavy drinking × Diabetes		-14.747		
		[-82.479,52.984]		
Severe obesity			7.981***	4.025**
			[4.428,11.535]	[0.306,7.744]
Heavy drinking × Severe obesity				68.680
				[-18.741,156.102]
State fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	1,231	1,231	1,231	1,231

Tab. S4. Alternative Drinking Measures: Binge Drinking and Per Capita Alcohol Consumption as Predictors of ALD Mortality Rates. *Notes:* Poisson pseudo-maximum likelihood estimates with 95% confidence intervals in brackets. The dependent variable is the ALD mortality rate per 100,000 adults. Columns (1) and (2) replace heavy drinking prevalence with binge drinking prevalence as an alternative measure of alcohol consumption; column (2) adds a binge drinking × obesity interaction term. Columns (3) and (4) replace heavy drinking prevalence with NIAAA per capita ethanol consumption (gallons) as an alternative measure of alcohol consumption; column (4) adds a per capita alcohol consumption × obesity interaction term. Binge drinking specifications cover 2006–2023, as the BRFSS binge drinking measure was not consistently defined for females prior to 2006. Per capita alcohol consumption specifications cover 1999–2022, the most recent year for which NIAAA data are available. ALD mortality rates and binge drinking prevalence are among adults ages 18+ and age- and sex-adjusted to the U.S. 2000 standard population using 5-year age groups. All models include state and year fixed effects and are weighted by state adult population. Standard errors are clustered at the state level. * p<0.10, ** p<0.05, *** p<0.01.

	(1)	(2)	(3)	(4)
Binge drinking	0.728	0.390		
	[-0.575,2.030]	[-4.099,4.879]		
Obese	3.161***	2.980**	3.012***	3.025***
	[2.241,4.081]	[0.140,5.819]	[2.146,3.877]	[0.748,5.302]
Binge drinking × Obese		1.240		
		[-14.807,17.286]		
Alcohol per capita			-0.103	-0.102
			[-0.366,0.160]	[-0.509,0.306]
Alcohol per capita × Obese				-0.006
				[-0.915,0.904]
State fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	914	914	1,221	1,221

Tab. S5. Illustrative Policy Counterfactuals: Predicted Reductions in ALD Deaths from a 10 Percent Reduction in Heavy Drinking or Obesity Prevalence at 2023 Levels. *Notes:* Each row presents a counterfactual scenario: (1) the predicted reduction in ALD deaths per 100,000 from a 10 percent reduction in heavy drinking prevalence; (2) the predicted reduction from a 10 percent reduction in obesity prevalence; and (3) the predicted reduction from a simultaneous 10 percent reduction in both. The first column shows average marginal effects based on Equation 1 with 95% confidence intervals in brackets. The second column shows the implied change in total ALD deaths, calculated by applying the average marginal effect to the 2023 U.S. adult population. Average marginal effects are evaluated at 2023 state-level values of heavy drinking and obesity prevalence, weighted by state adult population. 95% confidence intervals are derived from the delta method.

	Average marginal effect	Implied change in deaths
Effect of 10% reduction in heavy drinking prevalence	-0.123 [-0.227,-0.019]	-316
Effect of 10% reduction in obesity prevalence	-0.589 [-0.775,-0.404]	-1,517
Effect of 10% reduction in both	-0.677 [-0.891,-0.463]	-1,744