Addressing syndemic disparities in problematic alcohol use, violence, and reproductive health: A system dynamics approach

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Acknowledgement: This study was funded in part by National Institutes of Health Grant R01 DA050696 (PI Deutsch).

Abstract

Although syndemic theory is an increasingly popular approach for clarifying the nature of co-occurring health disparities within disproportionately affected populations, traditional empirical (linear, frequentist) methods often fail to capture the dynamic interactions between health conditions. System dynamics (SD) is a promising approach that can capture the causal relationships and synergistic influences that are emphasized in syndemic models, however, syndemic SD models rarely represent multimorbidity of health conditions in ways that align with syndemic theory. In this paper, we provide a comprehensive syndemic SD model that combines alcohol use, intimate partner violence (IPV), and unintended pregnancy/contraception use, with alcohol exposed pregnancy as a further symptom of this syndemic, within a Northern Plains community with a large Indigenous population (AIAN and non-AIAN). We validated the model and calibrated it against historical data for the two communities. Policy tests focused on understanding the role addressing IPV as a component of a hypothetical intervention that would reduce alcohol use, specifically among the Alcohol Use Disorder (AUD) and Alcohol Exposed Pregnancy (AEP) populations. Results indicated that while policies focusing only on reducing alcohol consumption yield much faster reduction in AUD in the short-term, addressing the endogenous IPV mechanism has higher and more sustained impact in the long run. Additionally, informed by the model, the same magnitude of policy interventions lead to disproportionate outcome between AIAN and non-AIAN populations. These results highlight the importance of considering and addressing causal relationships between health outcomes, rather than developing interventions that focus on individual health outcomes. We provide calibrated models along with the necessary files required for reproducibility of the results, hoping this research to serve as a foundation for feedback-rich quantitative syndemic SD models.

Introduction

Public health research (and related fields, e.g., epidemiology, community health, social and behavioral sciences) include a wide variety of conceptual and theoretical frameworks (e.g., models, theories, paradigms) that are used to explain underlying etiologies and external contexts driving health outcomes, and/or to evaluate implemented strategies for change. These frameworks often include complex and nested interactions between a person and their environment, such as ecological systems theory[1], social cognitive theory[2], Conceptual Framework for Action on Social determinants of Health[3], or the One Health model [4]. However, researchers often find it challenging to effectively utilize such frameworks in their research through the empirical methods that are traditionally used in such fields (e.g., frequentist statistical methods). Given these challenges, system science approaches are increasingly seen as valuable alternatives that can more effectively capture complex nonlinear public health conceptual models and identify potential leverage points for change [5, 6].

Syndemic theory, which conceptualizes multi-morbidity within specific populations and their environments [7], is one example of a complex model of health that researchers have struggled to incorporate in empirical analyses. Although this theory aligns with the growing recognition and understanding of how multiple health inequities "cluster" together within the contexts of broader structural and societal disadvantage (e.g., social determinants of health), syndemic theory focuses on specifying the nature of the relationship between multiple conditions as further defined by broader structural contexts. Specifically, syndemics are defined as "the *concentration* and deleterious *interaction* of two or more diseases or other health conditions in a population, especially as a consequence of social inequality and the unjust exercise of power" [8]. In other words, syndemic theory emphasizes a system in which co-occurring epidemics mutually cause or synergistically reinforce each other through biological and social etiological interactions on an individual level, within broader ecological levels of structural and systemic disadvantage, as a function that is greater than the sum of the outcomes themselves [9]. Given this complexity, it is understandable that recent reviews indicate that a considerable portion of syndemic research fails to meet the operational definitions and constructs of the theory itself [10]. Many researchers have inappropriately reduce the theory of syndemics down to the co-occurrence between two diseases, or have discussed syndemics as an aggregate "cumulative adversity" [11]. However, different interventions are needed to address epidemic co-occurrences based on the nature of their interrelationship (if the co-occurrence of the epidemic is truly syndemic; e.g., mutually causal, serially causal or synergistically interactive). Thus, researchers have called for new approaches that can more effectively meet the challenges of appropriately capturing syndemic relationships in public health [12], many of which involve systems science approaches (e.g., agent-based models, social network or spatial analyses) to more effectively capture dynamic behaviors of epidemics and their co-occurrences.

As system dynamics (SD) emphasizes causal relationships and synergistic influences through multiple feedback loops, it serves as a promising strategy to model syndemics [13]. Previous SD syndemic models have focused on a variety of negative health outcomes/ co-occurring outcomes within disadvantaged, deprived, or marginalized communities [14-17]. However, the population-level focus of SD models often makes it difficult to capture different "states" of individuals experiencing multiple conditions in mutually causal or synergistically reinforcing syndemic models, particularly if conditions have varying levels of severity. Although a generic SD structure for simulating co-occurring or mutually causal conditions has been developed [18], few applied models represent multi-morbidity as via a specific syndemic structure. Here, we provide an example of an SD syndemic model that that details multi-morbidity of conditions through synergistic, mutually reinforcing relationships. The current model is grounded in the classic SAVA syndemic model used to explain HIV transmission (through an underlying syndemic between drug use, violence, and risky sexual activity) within disadvantaged communities [19], to explain alcohol exposed pregnancy (through an underlying syndemic between problematic alcohol use, intimate partner violence [IPV], and unprotected sex/unintended pregnancy) within a Northern Plains American Indian/Alaska Native (AIAN) community.

A considerable body of research has highlighted a causal relationship between problematic (heavier) alcohol use and violent behavior [20]. Within romantic relationships, alcohol use is both a precedent and antecedent of IPV perpetration and victimization [21-23]. Over time, this results in mutually reinforcing patterns of interactions [24], bolstered by the continued interpersonal and intrapersonal distress and need to cope that culminates from IPV events[25-27] that sustains this bidirectional relationship. Further, both IPV and problematic alcohol use are associated with higher rates of unintended pregnancy (e.g., reduction of contraception use, reproductive coercion [28-30]). In turn, this can exacerbate relationship-level stressors and facilitate subsequent IPV events for people in relationships with pre-existing IPV [31]. However, problematic alcohol use, IPV, and unintended pregnancy are all contexts that increase vulnerability and reduce the ability for people to seek help, creating a syndemic "system" that is resistant to change. Thus, these conditions also result in an additional "symptom" of this syndemic, alcohol use during pregnancy (alcohol exposed pregnancy, or AEP) [29].

AIAN people experience disproportionately higher rates of IPV, unintended pregnancy/unprotected sexual activity, and problematic alcohol and drug use [32-34]. Further, alcohol use during pregnancy has long been seen as a concern within AIAN communities (although it must be noted that epidemiological research indicates that Indigenous people have higher rates of binge drinking during pregnancy, but are less likely to drink during pregnancy compared to non-Indigenous people[35, 36]). However, these interrelationships are contextualized by an enduring legacy of historical trauma (e.g., histories of relocation and destruction of community land resources, experiences of violence among multiple generations within a family) and ongoing systemic oppression (e.g., a complex matrix of policies and practices that result in mistreatment and marginalization within health, justice, and economic institutions [37]). In other words, the concentration of problematic alcohol use, IPV, and unintended pregnancy experienced within Indigenous communities is further maintained by the broader contexts of inequality and the unjust exercise of power. Unfortunately, efforts to address AIAN health disparities such as problematic alcohol use or IPV rarely consider the importance of a syndemic and interactive framework, despite recognition that multi-level and systemic approaches are necessary to fully address multi-morbid disparity [38-40]. Although there has been substantial growth in improving interventions for AIAN communities via cultural grounding or adaptation of evidence-based programs, such interventions are most often based on a clinical and western understanding of health issues that compartmentalizes treatment for individual outcomes[41, 42].

Clarifying the interaction between inequities in a syndemic framework through an SD model will require careful understanding of how to effectively represent the ways in which each construct can lead to reinforcement of multi-morbidity. The current paper provides the groundwork for such an effort, focusing on a simulated stock and flow structure with simple feedback loops that represents interrelationships between (problematic) alcohol use, IPV, and contraception use, separately for AIAN and non-AIAN pregnant and non-pregnant women of childbearing aged 15-44 within a small metropolitan area in the Northern Plains United States. Through this application, we highlight the importance of addressing IPV in efforts that are geared towards reducing problematic alcohol use.

Method

Model overview

We used a system dynamics method to capture the dynamics of alcohol use among women, including both AIAN and non-AIAN populations, with particular focus to the interplay between drinking behavior, pregnancy outcomes, and treatment transitions. The model formulates changes over time in various subpopulations that we differentiate by pregnancy status (i.e., Pregnant vs. Non Pregnant), and behavioral classifications (i.e., using birth control, "BC" and not using birth control, "NBC"). The model is calibrated with data from 2016 to 2019 and its prediction forecasts 2020 to 2028.

Model structure and dynamics

The model is a system dynamics framework with interconnected stocks and flows representing population subgroups. These include never-drinkers (ND), non-risky drinkers (NRD), risky drinkers (RD), individuals with alcohol use disorder (AUD), and their respective pregnant and nonpregnant categories. In addition, each drinking stock category has a corresponding sobriety state (e.g., $Sober\ NRD$). Transitions between these stocks are governed by rates that depend on various factors, including the proportion of heavy drinkers and delays inherent in biological and treatment processes.
A distinctive feature of this model is the endogenization of IPV effects. IPV is treated as an internal mechanism that modulates the rate of abuse dynamics. In particular, the model uses nonlinear (logistic) functions, and the impact of IPV on transitions is modeled mathematically by modifying the rate at which abuse-related transitions occur.

$$F_{abuse}(t) = \frac{L}{1 + e^{K.(R(t)-x_0)}}$$

Where $R(t)$ represents the heavy drinkers ratio population over time with the corresponding parameter values of scale, L, sensitivity, K, and reference point, x_0 that determines the impact of IPV on the transition flows.

Data sources and calibration

For each model, we estimated 261 parameters using maximum likelihood method combined with the Powell search. The parameters determine the rates of population transitions among alcohol drinking stocks and birth control use behavior. They also specify the nonlinear impact of IPV on the transition rates. Further information on data sources for parameterization and calibration are found in Appendix 1.

Policy implementation

After calibrating the model, we used the estimated parameter values to predict the trajectory of the variables of interest over time, starting from 2019 to 2028. We considered the impact of two sets of policies on the simulated outcomes. The first set focuses on changing the drinking behavior in the community, which is implemented by increasing the rates of population flows from heavier drinking stocks to regular ones (e.g., RD to NRD) or to the related sobriety state (e.g., NRD to $Sober\ NRD$). The second set is centered around reducing the IPV effects, thereby improving all population level transition rates, including the alcohol related flows and the changes in birth control use behavior.
To provide a concrete examples of the policy analysis, we focus on two level of changes in each policy set for AIAN and non-AIAN population. Specifically, we focus on the population with Alcohol Use Disorder (AUD) and Alcohol Exposed Pregnancy (AEP). For the alcohol intervention, we assume 30% and 60% improvements in the transition rates that last only for one year after the start of the intervention. For the IPV reduction policy, we consider two cases of 50% and 100% reduction in the impact of IPV on the transition rates. Note that while the IPV intervention can impact both alcohol and birth control use related flows, the alcohol intervention only focuses on the flows among the drinking stocks (i.e., it does not have a direct impact on the birth control use behavior).

Results

Figure 1 illustrates the projected prevalence of AUD among AIAN and non-AIAN individuals not utilizing birth control methods from 2019 to 2028 under varying conditions of endogenous IPV reduction and alcohol intervention strategies. Each row corresponds to distinct policy interventions, ranging from no alcohol-focused intervention (panel a), a modest one-year 30% alcohol reduction intervention (panel b), to a more intense one-year 60% alcohol reduction intervention (panel c). Within each panel, we show outcomes under three different levels of IPV reduction: no reduction (0%), partial reduction (50%), and complete reduction (100%).

In the absence of any alcohol-specific intervention (panel a), prevalence patterns exhibit a sustained high trajectory of AUD across both AIAN and non-AIAN populations, population in scenarios without IPV reduction. However, even a partial (50%) reduction in IPV, substantially reduces AUD prevalence, particularly among AIAN individuals. Complete IPV reduction (100%) further enhances these benefits, which underscores the significance of addressing IPV as an influential modulator in alcohol-related health outcomes.

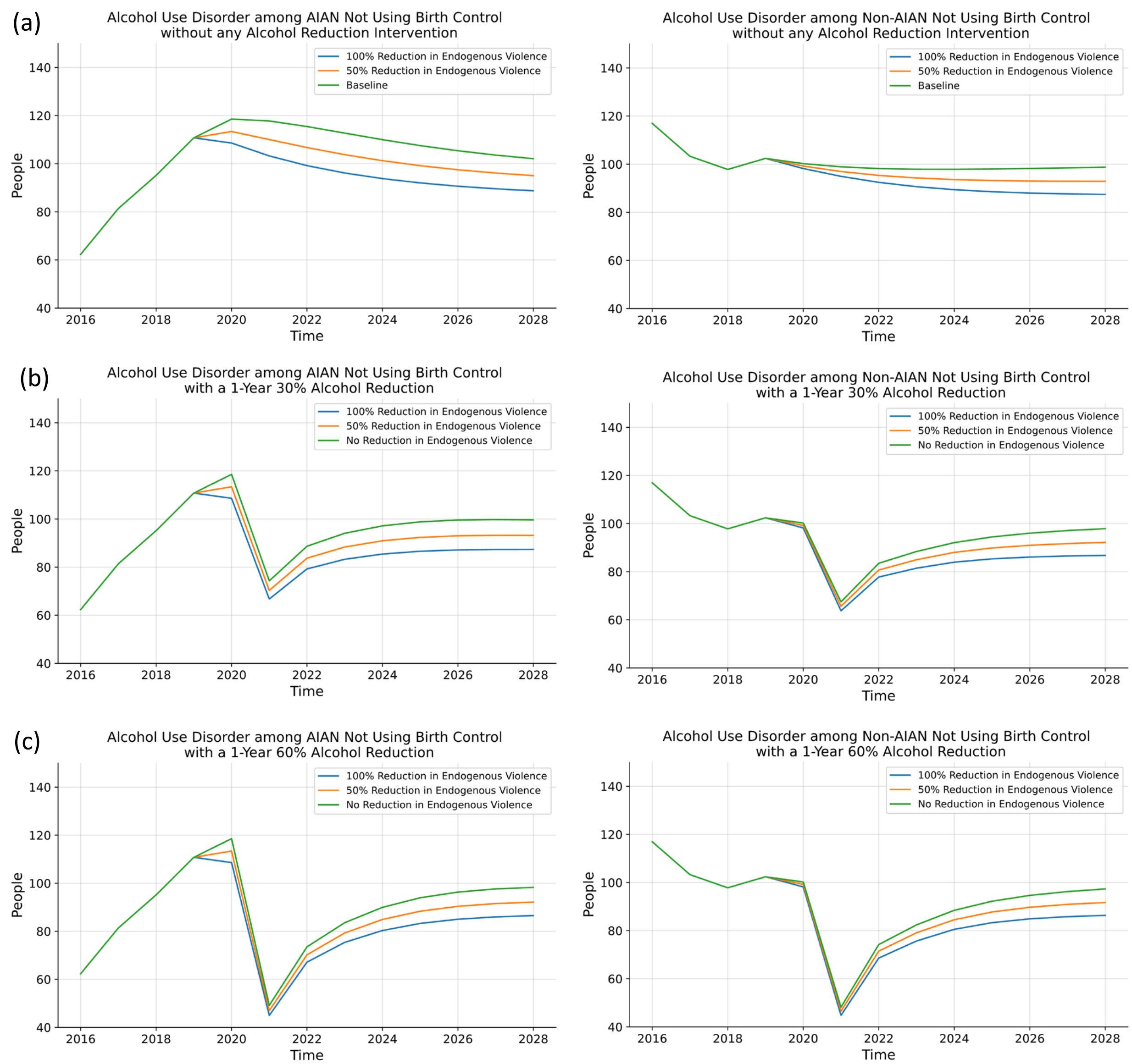

Figure 1. Projected prevalence of alcohol use disorder among AIAN (left) and non-AIAN (right) individuals not using birth control from 2019 to 2028 under different levels of endogenous violence reduction (0, 50%, and 100%). Panels (a) presents outcomes with no alcohol risk intervention, (b) incorporates a 1-year 30% alcohol reduction, and (c) applies a 1-year 60% alcohol reduction.

Introducing a moderate alcohol intervention (30% reduction, panel b) demonstrates an immediate but temporary decline in AUD prevalence, which subsequently rebounds, reflecting the transient nature of alcohol-focused interventions when implemented in isolation. Conversely, the inclusion of IPV reduction strategies produces a more persistent impact. Specifically, the synergistic effect of a 30% alcohol intervention coupled with full IPV elimination (100%) yields notably lower and more enduring AUD prevalence rates, which points to the long-term benefits of addressing IPV as an underlying driver of the behavior.

The most intensive intervention scenario (60% alcohol reduction in panel c) further exemplifies this dynamic. Although this high-intensity alcohol-focused strategy initially achieves substantial reductions in AUD, similar to the 30% reduction intervention, its effect diminishes over time. Nevertheless, pairing this approach with IPV reduction has higher impact in reducing AUD. Across all scenarios, reductions in IPV consistently produce a more persistent reduction in the AUD population. Note that in all scenarios, since the effect of alcohol reduction treatment fades away by 2028, AUD reaches to the same levels that are achieved by IPV-only reduction interventions.

Figure 2 compares four interventions—two that target alcohol (30% or 60% reduction) and two that target IPV (50% or 100% reduction)—and illustrates clear differences in their timing and durability. In the early phase, alcohol interventions lead to an immediate drop in AUD prevalence, reflecting how reduced drinking quickly diminishes the size of heavier-drinking stocks. By contrast, IPV-focused interventions, which mitigate deeper feedback within the system, show slower initial effects. However, as time progresses and the short-lived impact of alcohol measures tapers off, scenarios lacking IPV reduction revert toward higher levels of AUD, often exceeding even moderate IPV-intervention scenarios. This discrepancy underscores the significance of addressing IPV as an endogenous driver that continually reinforces harmful drinking patterns.

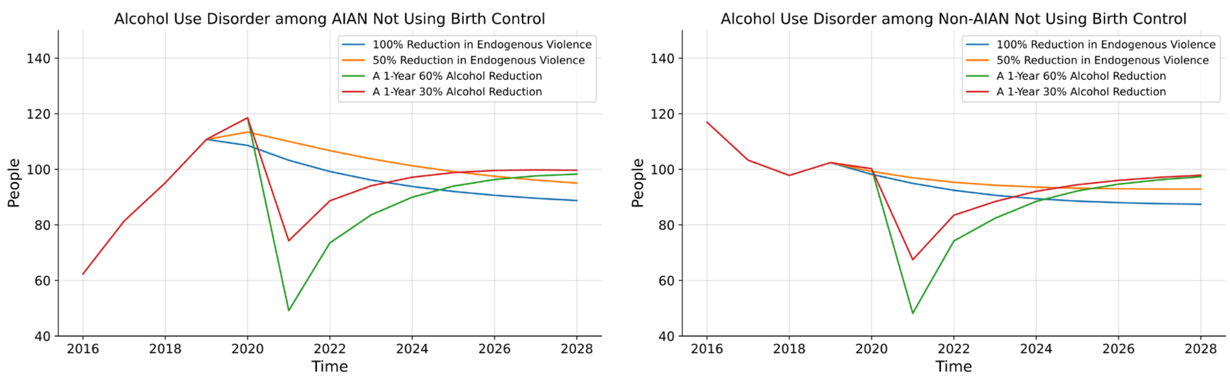

Figure 2. Scenario analysis comparing projected AUD cases among AIAN and Non-AIAN populations not using birth control under four intervention strategies: complete and partial reductions in endogenous IPV, and short-term (one-year) alcohol consumption reductions.

In the long run, cutting back on IPV exerts a sustained influence by dampening the pathways that would otherwise perpetuate or escalate drinking behavior. Even partial (50%) IPV reduction yields lower cumulative AUD levels than do scenarios with short-term alcohol interventions alone. This difference is especially pronounced among AIAN populations, where baseline AUD rates are higher. The model thus suggests that while alcohol-centric policies can generate quick, short-term wins, strategies that reduce IPV offer more persistent benefits by systematically weakening the reinforcing feedbacks behind heavy drinking.

Figure 3 compares a scenario in which both a one-year 60% alcohol reduction and complete IPV reduction are implemented, against a baseline with no interventions. The combined approach produces the largest and most enduring decline in AUD for both AIAN and non-AIAN populations, demonstrating clear synergy: even as the short-term alcohol intervention wanes, ongoing IPV reduction tempers the reinforcing loops that sustain unhealthy drinking. This indicates that layering IPV-reduction measures onto alcohol-focused policies can substantially accelerate improvements and prevent the AUD rebound observed when only alcohol consumption is addressed.

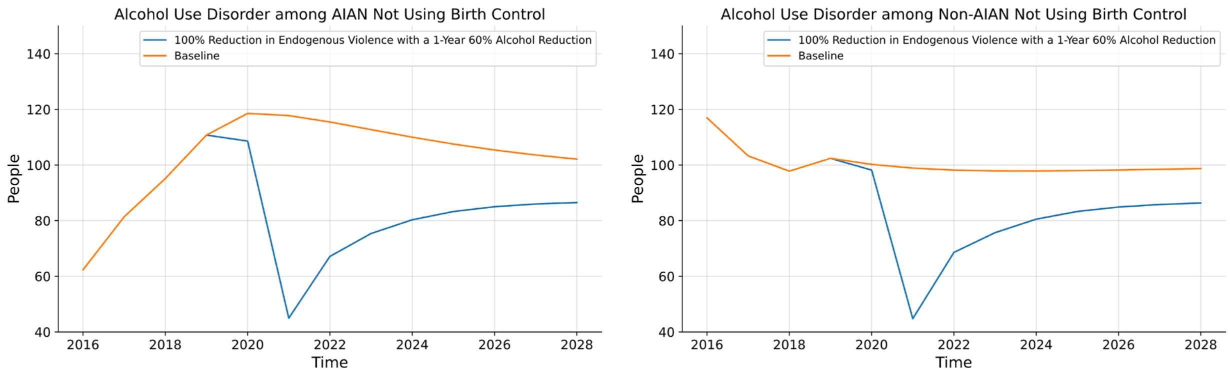

Figure 3. Comparative trajectories of Alcohol Use Disorder among AIAN and Non-AIAN individuals not using birth control under the combined intervention scenario of complete endogenous IPV reduction and a one-year 60% alcohol consumption reduction versus the baseline scenario.

However, implementing such a dual strategy in practice can be challenging. IPV reduction, while impactful, typically demands larger investments, more time, and strong community alignment—factors that can slow initial uptake. Meanwhile, heavy drinking can reemerge if policy resources for maintaining alcohol-focused programs are limited. Figure 3 thus highlights a trade-off: although combined measures offer the greatest total benefit, resource constraints and system inertia may necessitate prioritizing interventions. As a result, it crucial to weigh the short-term efficacy of an alcohol-only approach against the deeper, more durable benefits that arise when simultaneous IPV reduction is sustained over time. Figure 4 tracks the proportion of alcohol-exposed pregnancies (AEP) under the same four policy scenarios—two centered on short-term alcohol reductions (30% or 60%) and two involving IPV reductions (50% or 100%). Similar to previous results, the alcohol-only interventions produce an immediate drop that fades quickly, leading to a subsequent rebound. By contrast, IPV-focused interventions have a slower but more durable effect on curbing AEP in the long run. Crucially, this comparison is the first to demonstrate explicitly how the same magnitude of policy measures can yield different net impacts across AIAN and non-AIAN populations; AEP rates for AIAN tend to remain higher and exhibit less short-term benefit from alcohol-only policies, underscoring deeper structural challenges.

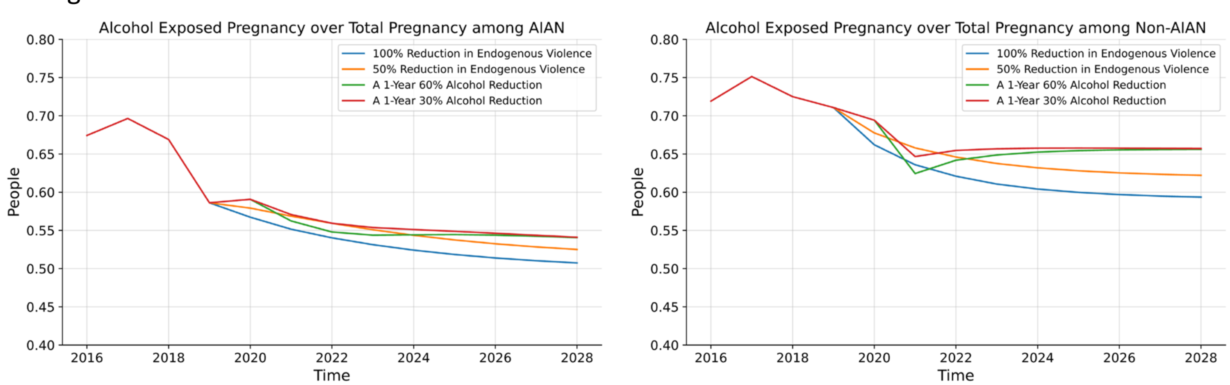

Figure 4. Comparative projections of alcohol-exposed pregnancies as a proportion of total pregnancies among AIAN and Non-AIAN populations under four scenarios: complete and partial reductions in endogenous violence, and short-term (one-year) reductions in alcohol consumption.

Notably, non-AIAN populations appear more responsive in the short run to alcohol-centric measures, making such interventions seem initially favorable if resources or time are limited. Still, Figure 4 confirms that reducing the endogenous violence mechanism is ultimately more transformative. Even partial violence reduction (50%) sustains a lower overall AEP burden than do one-year alcohol cuts alone, which underscores the importance of tackling root drivers. Although short-lived alcohol reductions may offer a near-term boost, especially in some subpopulations, interventions that address violence directly produce broader and more enduring benefits for reducing alcohol-exposed pregnancies.

Discussion

In this paper, we used a system dynamics approach to examine how IPV and problematic alcohol use interact in shaping population level health outcomes and behavior. By modeling key feedback loops from the proportion of heavy drinkers to the IPV effect, we showed how the endogenous impact can have a long lasting outcome. Specifically, we showed that interventions that solely focus on reducing alcohol use can produce short-term gains but will lead to to rebound effects once the intervention subsides, especially in communities that have high rates of IPV. In contrast, IPV mitigation helps address deeper systemic drivers that reinforce heavier drinking and perpetuate syndemic risk.

In line with extensive evidence linking heavier alcohol use to IPV[22, 23, 27], our findings suggest that IPV-focused interventions establish a more resilient outcome over time. In other words, IPV reduction intervention dampens the core mechanism fueling reciprocal escalation between alcohol misuse and IPV, which makes the overall system less prone to relapse. Moreover, addressing both problematic alcohol use and IPV simultaneously proved especially effective. When feedback mechanism perpetuating harmful drinking are weakened at the same time that IPV is controlled, reductions in alcohol-related harms become both larger and more sustainable.

Further, our results show how these interventions work differently across AIAN and non-AIAN populations such that health disparities surround more than just the gap in adverse outcomes experienced by different groups. They also emerge in how well or poorly interventions perform within each group. Despite the same policy levers being applied, our model consistently revealed that AIAN populations saw less pronounced benefits under short-term alcohol reduction strategies compared to non-AIAN counterparts. This indicates that not only one group start at higher baseline risk, but the very policies designed to mitigate those risks can be less potent if they fail to account for underlying structural factors. Considering a syndemic theory framework [9], health disparities for AIAN, compared to non AIAN populations are not only a function of disproportionately higher rates of individual negative health outcomes. Rather, the synergistic relationship between disparities, as contextualized by concentrated disadvantage, results in a qualitatively different system driving health outcomes, which will further require accounting for synergistic effects.

Third, although prior interventions have addressed both alcohol use and contraception utilization [43], they often struggle to generate robust, lasting effects when they overlook the pervasive role of IPV[44]. In our model, this gap is evident as heavy drinking and (lack of) contraception use reinforce each other through feedback mechanisms that are further magnified by intimate partner IPV. Ignoring the IPV component means that interventions fail to break the cycle, driving sustained alcohol use and inconsistent contraceptive practices. Consequently, while efforts to reduce drinking or increase contraception use can still help, they are likely to be undermined if the broader context of IPV remains unaddressed.

Fourth, intervention decisions often hinge on how resource-intensive they are for the implementing community. Low-burden strategies that promise quick wins can appear attractive, especially in contexts with limited capacity or infrastructure. However, through these simulation results, we show that targeting only one issue, e.g., problematic alcohol use, may not lead to the sustained improvements seen when deeper structural factors such as IPV are also addressed. In AIAN communities, where maintaining effective services can be an ongoing challenge[45, 46], selecting interventions that tackle multiple, closely interconnected disparities could ultimately be more impactful. Therefore, an approach that weights both short-term feasibility and longer-term efficacy may better serve populations experiencing inequalities.

The current model has limitations. Given changes over time in the data used to inform models, especially for the year 2020 and beyond (see Appendix 1), we were only able to develop a full dataset for years 2016-2019. Further, although we were able to create a nuanced stock-and-flow model for alcohol use, we had a fairly simplified construct for IPV (e.g., percentage of people per stock experiencing violence), given a) the data we had available to parameterize the model, b) the focus on alcohol/substance exposed pregnancy as the ultimate "problem" of focus in the project this model was developed for, and c) the need to consider areas we could conserve the number of model parameters. However, IPV is a multidimensional construct that has a nuanced relationship with problematic alcohol use based on this multidimensionality. Further model development that can better capture this dimensionality (and the multi-morbidity between different types of IPV and alcohol use) would provide important insight into more specific types of interventions that may be effective. Finally, the AIAN and non-AIAN models represent the same small metropolitan area. Although there are evident disparities in all three main syndemic-related outcomes between AIAN and non-AIAN populations within this community, it is difficult to understand how effectively we captured the true "community" effects (e.g., aggregate violence, aggregate heavy drinking). However, by separating the models entirely, this creates an assumption that only people from the same racial group will be influential on the population. Indeed, future research could instead consider the potential role of how this disparity between groups within the overall population may result in further negative effects of stigmatization and bias that reinforce existing disparities.

Future extensions of this model could integrate additional institutional variables and structural factors that shape the interplay between alcohol use and IPV as areas of either systemic resilience or leverage point opportunities for change. Systems such as the criminal-legal or child welfare systems may exacerbate stressors and/or provide avenues for intervention[47, 48], thus requiring deliberate representation in a feedback-driven framework. Likewise, bridging resources, such as integrated services for victims or combined IPV prevention and alcohol recovery programs, might interact synergistically and pointing new leverage points. Gradually adding these elements would offer a more comprehensive and detailed understanding of how interdependent forces perpetuate or mitigate problematic drinking, while also guiding policy and program development to more effectively address IPV within vulnerable communities.

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