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Moving alcohol prevention research forward—Part I: introducing a complex systems paradigm

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ABSTRACT

Background and aims The drinking environment is a complex system consisting of a number of heterogeneous, evolving and interacting components, which exhibit circular causality and emergent properties. These characteristics reduce the efficacy of commonly used research approaches, which typically do not account for the underlying dynamic complexity of alcohol consumption and the interdependent nature of diverse factors influencing misuse over time. We use alcohol misuse among college students in the United States as an example for framing our argument for a complex systems paradigm. **Methods** A complex systems paradigm, grounded in socio-ecological and complex systems theories and computational modeling and simulation, is introduced. Theoretical, conceptual, methodological and analytical underpinnings of this paradigm are described in the context of college drinking prevention research. **Results** The proposed complex systems paradigm can transcend limitations of traditional approaches, thereby fostering new directions in alcohol prevention research. By conceptualizing student alcohol misuse as a complex adaptive system, computational modeling and simulation methodologies and analytical techniques can be used. Moreover, use of participatory model-building approaches to generate simulation models can further increase stakeholder buy-in, understanding and policymaking. **Conclusions** A complex systems paradigm for research into alcohol misuse can provide a holistic understanding of the underlying drinking environment and its long-term trajectory, which can elucidate high-leverage preventive interventions.

Keywords Agent-based modeling, college drinking prevention, complex systems science, computational modeling and simulation, policy, system dynamics modeling.

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INTRODUCTION

This is the first of two papers advocating for a paradigm shift in alcohol prevention research. These two papers seek collectively to: (1) outline the inherent limitations of current approaches in alcohol prevention research and discuss how a complex systems approach addresses these shortcomings; and (2) provide readers with a basic understanding of computational simulation modeling methodologies and outline heuristic concept models, grounded in alcohol misuse among college students in the United States, demonstrating the potential of these approaches for alcohol prevention research and action.

Alcohol misuse persists as a public health problem [1]. Commonly used prevention approaches, targeting intrapersonal (e.g. drinking motives) and interpersonal (e.g. peer pressures) factors, assume linear causality (where risk exposure is proportional to outcome) and epitomize risk-factor epidemiology [2–5]. However, these approaches often fail to account substantively for the underlying dynamic complexity and the interdependent and causally linked nature of socio-structural and interpersonal factors influencing drinking over time [6]. Consequently, many extant alcohol prevention programs are low-leverage, consisting of components at proximal levels of influence (e.g. individual factors) and constrained temporally and spatially in scope and effect. Such interventions seek typically to reduce alcohol consumption or harmful consequences associated with drinking events [7–9]. These efforts have demonstrated small effects on drinking quantity, frequency and experienced consequences, with minimal impact on high-risk or heavy drinkers [10]. Additionally, in certain cases these approaches have actually produced adverse consequences [11]. It is our

contention that alcohol prevention programming has been partially ineffective because researchers, policymakers and practitioners have overlooked the dynamically complex and ecological nature of drinking. Consequently, we contend that a paradigm shift in alcohol prevention research, policy and practice may be beneficial. This new paradigm should contextualize drinking within a constellation of diverse and interacting factors, such as the macrosocial forces (e.g. structural policies) that shape the drinking environment and the stakeholders who are interested in drinking. This paradigm shift could inform high-leverage interventions, which would consist of components at structural levels of influence (e.g. policies) and target long-term change across broad swaths of individuals and communities.

Using alcohol misuse among college students in the United States as an illustrative example, our objectives are threefold: (1) to overview critically current college student alcohol misuse research; (2) to contrast current approaches with a complex systems paradigm for alcohol prevention research in college environments; and (3) to outline how a complex systems paradigm can forge new directions in alcohol prevention research.

ALCOHOL MISUSE RESEARCH IN COLLEGE ENVIRONMENTS

College student alcohol misuse contributes annually to 1825 student deaths, 600 000 physical assaults, 97 000 sexual assaults and 3.36 million impaired driving episodes, as well as numerous instances of poor academic performance, vandalism, property damage and legal involvement [12–14]. There is no single factor or determinant of whether college students will misuse alcohol and/or experience adverse consequences. Variability in college student alcohol involvement is influenced by individual- and group-level dynamics, as well as contextual, spatial, temporal and socio-structural factors. For instance, male students drink in greater quantities, drink more frequently and experience more alcohol-related consequences than their female peers [13,15], while white students drink more frequently and in greater quantities than black or Hispanic students [16]. There are also personality traits and personal characteristics, such as impulsivity, sensation-seeking and alcohol expectations, which have been linked to drinking quantity and alcohol-related adverse consequences [17,18].

In addition to the person-specific factors, social network dynamics exert major influence on drinking patterns of students. For instance, peer influence can come in the form of direct/experienced pressure (e.g. being offered a drink) and indirect/perceived pressure (e.g. social norms) [3]. Students also demonstrate a penchant for self-selecting into peer groups with others who have similar drinking behaviors [19]. Additionally, varied individual and social factors influence drinking patterns and associated adverse consequences among college students, ranging from drinking motives to residence type [17]. Furthermore, an assortment of physical and environmental characteristics impact student drinking, such as organizational properties (e.g. 2- or 4-year designation), physical properties (e.g. campus size) and community planning/zoning properties (e.g. alcohol outlet density) [20]. Multiple socio-structural influences, including those within business (e.g. pricing), legal (e.g. merchant compliance checks) and campus/community planning (e.g. availability of alternate transportation) domains, further influence alcohol misuse [4,21]. Thus, the underlying etiology of student alcohol involvement is widespread and entrenched in the nexus of university-community social, political, legal, economic and physical environments. Figure 1 presents a heuristic diagram of the diverse influences which constitute the college drinking environment, grounded in social ecological models of community health promotion [22,23] that drive current alcohol prevention research.

To date, a bevy of prevention programs have been developed to reduce college student alcohol misuse and associated consequences. CollegeAIM, a college alcohol intervention matrix developed by the National Institute on Alcohol Abuse and Alcoholism (NIAAA), outlines the array of individual- and environmental-level strategies which have been implemented and describes their characteristics [24]. Historically, efforts to minimize problematic alcohol consumption among students have been focused primarily on the individual [25–27]. Colleges have also sought to establish campus alcohol-control policies [28]. A wide variety of university alcohol policies have been implemented, such as banning alcohol for all students on-campus [29], providing alcohol-free housing on-campus [30], restricting where alcohol may be consumed [28] and establishing amnesty policies [31]. Community organizing and mobilizing approaches, in which partnerships with community stakeholders are established and leveraged, have also been promising [32–34]. Despite the wide scope of these prevention programs, strategies missing from CollegeAIM are the very ones which NIAAA contends are most needed: 'Research on drinking among college students must take into account the multiple developmental, individual, and environmental factors (*and their interactions*) [emphasis added] that appear to affect whether and how much college students drink' [35]. Alcohol prevention researchers have echoed these sentiments, asserting 'heavy drinking and associated problems continue unabated, with few exceptions, at colleges that are most in need of intervention. …colleges may require stronger, more consistent, and *more comprehensive approaches* [emphasis added], with increased emphasis on the alcohol environment' [36].

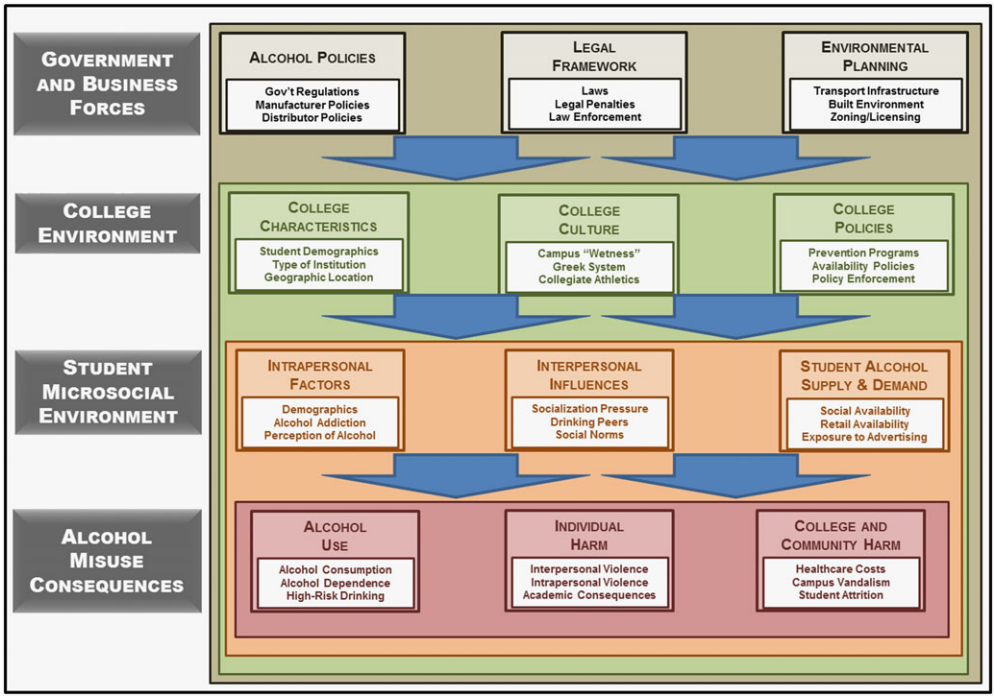

Figure 1 Heuristic example of socio-ecological influences on alcohol misuse in college environments. [Colour figure can be viewed at wileyonlinelibrary.com]

While alcohol prevention strategies are generally ineffective at addressing multiple levels of influence simultaneously, current prevention efforts also demonstrate counterproductive qualities. For instance, normative re-education programs are a common strategy employed on campuses to deter excessive alcohol consumption [37]. These programs seek to distribute information outlining accurate levels of student alcohol consumption, such as typical quantity consumed [24]. An underlying theoretical assumption of this approach is that students increase their own alcohol consumption levels to meet what they (mis)believe is the exaggerated alcohol use 'norm' among their peers. Given that the vast majority of students believe their peers drink at higher levels than themselves [38], accurate information may result in decreased consumption. While national evaluations of these approaches find no meaningful differences at schools with social norms programs [39] and CollegeAIM identifies this approach as having the lowest level of effectiveness [24], what is more noteworthy are the potential unintended consequences of these programs. These programs may result in boomerang effects wherein those exposed to normative re-education actually increase their alcohol consumption [40–42]. These concerns have led researchers to assert 'widespread use of social norms campaigns needs to be scrutinized' [40] and 'there may be so little to be gained in terms of improved consumer knowledge that the potential cost of oppositional attitudes or behavior should receive substantial attention' [42]. These campaigns are not the only prevention strategies which have resulted in undesirable unintended consequences [42]. For instance, while countries with greater alcohol-impaired driving roadside checks have lower overall rates of driving under the influence of alcohol, people who have been checked previously for alcohol-impaired driving within the past 3 years exhibit a greater likelihood of being convicted of impaired driving [43]. Additionally, college students who employ serious harm reduction (SHR) and limiting/stopping (LS) protective behavioral strategies during drinking episodes actually drink in greater quantities and experience more alcohol-related consequences. Moreover, friends' use of SHR is also associated with increased alcohol consumption [11].

Given the inherently systemic and complex nature of college student drinking—especially regarding the interdependence and interactions of multiple causal risk factors which occur across broad and varied spatiotemporal scales—this public health problem requires comprehensive and dynamic conceptualizations [6]. However, the bulk of extant research and action is incapable of capturing such dynamics. For example, current mental, theoretical and conceptual models, which are static, siloed and narrowly bounded, are incompatible with the systemic and dynamic complexity of college drinking [44]. Moreover, the prevalent methodologies, which are based on reductionism and linear causality and seek to maximize internal validity via various forms of experimental designs [45], cannot capture

macrostructural domains, contextual effects or ecological effects that unfold across different spatiotemporal boundaries [46,47].

Within this traditional epistemological framework, analytical approaches are similarly constrained. Based on probability theory and macroscopic laws of averages [48], the general linear model (GLM) [49] and especially regression modeling, has marked alcohol prevention research. As with any statistical technique, the GLM relies upon a number of fundamental assumptions which must be met to ensure that the conclusions reached following its application are trustworthy. Among the most important of these assumptions are related to linearity and non-collinearity. Although non-collinearity can be tested for and mitigated prior to finalizing models, and more advanced techniques are better able to handle non-linearity, it is our contention that the dynamic complexity of college student drinking makes reliance upon the GLM problematic [49]. Overall, approaches grounded in the GLM are not well-equipped to capture hetereogeneity, feedback loops or other non-linearities [47,50–52]. Even advanced analytical techniques, such as structural equation modeling or latent class analysis, cannot capture these non-linear characteristics fully due to the fundamental limitations of the GLM [47,52]. Simply put, traditional statistical modeling cannot identify, model, capture, control, manage and/or explain dynamically complex problems effectively [48], such as college drinking.

Restricted by such limitations, alcohol prevention research has generated modest successes decreasing college student alcohol misuse beyond short periods of time [24]. While short-term positive outcomes may be achieved in some instances, the inherent shortcomings of approaches employed result in a partial understanding of college drinking [24] as they omit socio-structural forces and spatiotemporal scales that exert profound influences in shaping alcohol misuse. These paradigmatic shortcomings have brought about an incommensurability [53] between epistemology and reality. In other words, the true nature of college drinking is fundamentally different than the linear and reductionist assumptions underpinning the bulk of alcohol prevention research; thus, a paradigm shift is necessary. The introduction and integration of a complex systems paradigm in alcohol prevention research has the potential to forge new research and intervention directions.

A PARADIGM SHIFT IN ALCOHOL PREVENTION RESEARCH

Alcohol misuse in college environments is a 'problem of organized complexity' [54] that can be understood as systems made up of a large number of heterogeneous, evolving and interacting components [55]. In contrast to traditional prevention approaches grounded in linear causality, alcohol misuse is characterized by circular causality (in the form of feedback loops), where an initial factor ripples through a chain of causation over time, context and space. This ripple is subsequently influencing, and being influenced by, several distinct (yet linked) factors [44]. These multi-layered system clusters exhibit bidirectional exchanges [56] where decentralized elements within each cluster influence other elements or systems within and across other clusters over time. Further complexity stems from heterogeneity in the delay between causes and effects. These constant feedbacks and complex dynamics result in adaptation and co-evolution among included components, where the system self-organizes and produces unpredictable outcomes. In other words, outcomes emerge from the interactions of factors to produce novel and often unexpected patterns and properties which are difficult to predict or understand using linear and static conceptualizations accurately [57,58]. Consider the following heuristic example: changes in a public policy [e.g. US federal government lowers the minimum legal drinking age (MLDA) to 18 years][1] would result in perturbations throughout the college drinking system and result subsequently in a range of impacts, including: economic-level impacts, such as alcohol industry adaptations (e.g. alcohol companies altering advertising strategies), and individual-level impacts, such as student adaptations (e.g. shifting of drinking venues from residences to bars, thereby increasing impaired driving frequency). Moreover, the variety of 'responses'/ripples resulting from a change to the national MLDA would lead consequently to additional 'feedback' to policymakers, who may have to create and/or adapt additional legislation in response. The cycle continues with each change at any level; hence, the term 'feedback loop'. Thus, circular action chains continue in perpetuity, or until the system changes.

Such an architecture contains characteristics of a complex adaptive system (CAS), exemplified by non-linear, adaptive and dynamic interactions among its parts, and the generation of self-organizing, non-reductive and unpredictable phenomena [59]. Within this CAS, individual clusters, elements within clusters and smaller or larger systems exhibit similar characteristics themselves, thus leading to the conceptualization of college drinking as a complex adaptive system of systems (CASoS) [60]. Figure 2 presents a heuristic diagram of the college drinking environment as CASoS. The contrasting difference between this figure and Fig. 1 is dynamic complexity, exemplified by circular causal interactions (feedback loops) across various spatiotemporal scales.

[1]The Amethyst Initiative, launched in 2008 and currently supported by 136 College and University presidents, seeks to enact this policy change. See: http://www.theamethystinitiative.org/

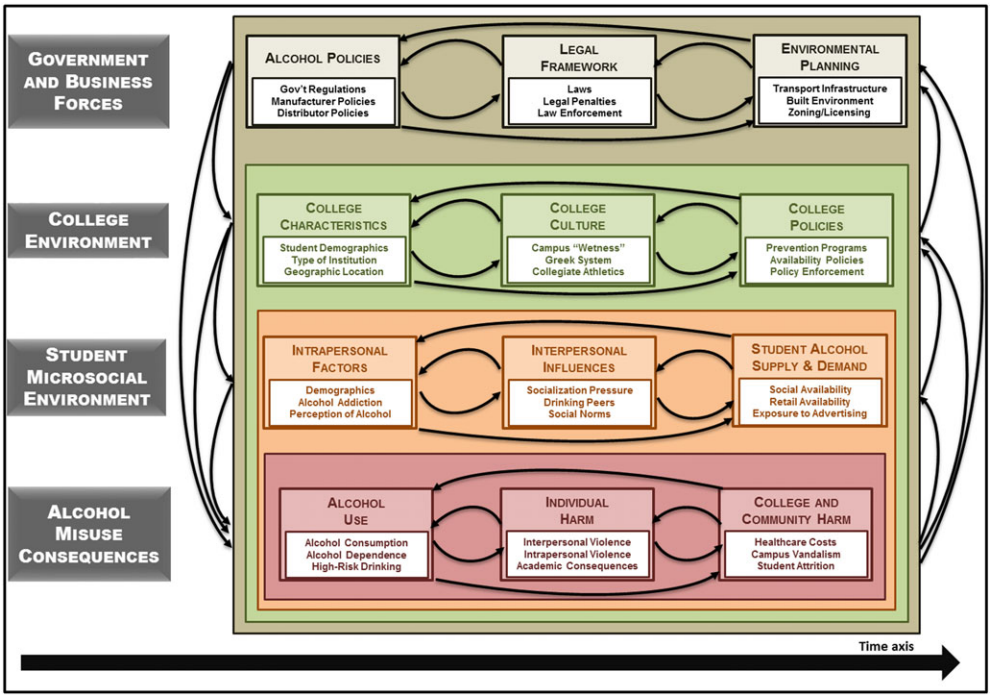

Figure 2 Heuristic example of alcohol misuse in college environments as a complex adaptive system of systems. [Colour figure can be viewed at wileyonlinelibrary.com]

A complex systems paradigm in college drinking prevention research integrates a wide array of theoretical perspectives, the underpinnings of which are grounded in a synergy of: (a) ecosocial theory (e.g. life-course, political economy, embodiment and spatiotemporal scales); (b) syndemic theory (e.g. mutually enhancing exacerbating factors and dynamic feedbacks); (c) social ecology (i.e. biological, social, institutional and cultural contexts of people–environment relationships); and (d) complex systems theory (e.g. non-linearity, emergence, self-organization, phase transitions, adaptation and resilience) [56,61–65]. A complex systems paradigm incorporates a transdisciplinary framework holistically [66], which integrates social, health, natural and computational sciences.

While the aforementioned 'complexity turn' [67] can make great contributions to alcohol prevention research, it is the advent of computational modeling and simulation [5,68] that can result in great leaps forward [69]. The notion that we cannot truly understand complex social phenomena (e.g. college drinking) until we reproduce their causes is not novel [70–72]. The investigation of problems that exhibit organized complexity has been made feasible by the proliferation of computational advances, which allow us to grow computer-based (*in-silico*) social structures and demonstrate that certain sets of micro-specifications are sufficient to generate macro-phenomena of interest.

Computational modeling and simulation [5,68] enables us to overcome shortcomings of conventional mental models, thus allowing us to foresee novel events that traditional quantitative models cannot [73]. Computational modeling and simulation can capture vexing non-linearities by including hypothesized causal factors across multiple levels and spatiotemporal scales, account for inter-relationships, feedbacks and interactions among these factors and also provide insights into the emerging aggregate patterns which these complex systems produce [52]. In this way, computational modeling and simulation provides a framework for assessing, organizing and synthesizing factors throughout multiple levels of influence using insights drawn via diverse research approaches (e.g. from different methodologies/analytical techniques). Further, as computational modeling and simulation function as a virtual world, we can test limitless counterfactual scenarios in controlled experiments [44,73–75]. Thus, prior to implementing an intervention, researchers can estimate its effects and outcomes.

While computational modeling and simulation approaches often share similarities with other methodologies, they distinguish themselves in critical ways. As with other approaches, each computational modeling and simulation technique offers strengths and weaknesses, and the choice of technique depends upon the research questions [76]. Among the most prevalent techniques is system dynamics modeling, which focuses on aggregate phenomena [47]. System dynamics modeling emphasizes structural factors influencing individual behavior and, through simulation, allows researchers to explore multiple hypotheses and generate 'dynamic hypotheses' (hypotheses which evolve over

time) [46,77]. In Part II, we provide a more nuanced discussion of system dynamics modeling and how it may be applied in alcohol prevention research.

Despite the clear benefits of leveraging computational modeling and simulation, in the domain of alcohol prevention research these approaches remain largely underdeveloped, unintegrated into conceptual frameworks and research designs and grounded inadequately in social ecology that underpins alcohol prevention. As a result, these methodologies have been mechanistic and compartmentalized, instead of being integrated within the epistemology of alcohol prevention research. While limited, existing applications in alcohol prevention research are highly encouraging. For example, The National Institute of Alcohol Abuse and Alcoholism funded the Simulated Community System of Alcohol Use and Abuse model [78,79] and the ecological model of college drinking [80–84]—both grounded in deterministic mathematical modeling. Further, current transdisciplinary work has used dynamical systems modeling to deconstruct the etiological ecology of drinking events [85–87]. Internationally, the Sheffield Alcohol Policy Model (SAPM) delves into the consequences of alcohol consumption in Great Britain [88]. Additionally, agent-based modeling has been employed to examine how environmental and social dynamics influence general population [89] and college drinking [90], as well as spatial dynamics and social processes of college drinking events [91–93]. There are even fewer instances of system dynamics modeling approaches [6,94–96]. These extant examples suggest the tremendous promise of computational modeling and simulation in alcohol prevention research.

The underutilization of complex systems approaches in alcohol prevention research may be exacerbated by inherent challenges and limitations of systems science and studying complex systems in general [51,97]. For example, complexity is itself difficult to describe, and several of its conceptual underpinnings (e.g. emergence) are still poorly understood [97–99]. Computational modeling and simulation can be difficult, as overly simplistic models may be incomplete or even incorrect, while large and complicated models become difficult to test and validate completely [5,46]. Further, integrating concepts such as heterogeneity into models may be difficult and can result in larger, slower and more labor-intensive models [100]. However, as these approaches become more commonplace, ingenuity and necessity will probably mitigate these and other limitations.

THE PROMISE OF A COMPLEX SYSTEMS PARADIGM IN ALCOHOL PREVENTION RESEARCH

It is noteworthy that the aforementioned shortcomings of traditional approaches are not unique to alcohol prevention research. Contemporary public health problems are often defined by their resistance to interventions, where problematic systems 'resist' changes imposed on them [73,101]. These system responses render many interventions ineffectual or even exacerbating [73,101]. This so-called 'policy resistance' [73] generates a discouraging illusion of intractability and stems from the incompatibility of a reductionist paradigm to understand the dynamically complex problems to which it is applied. Resulting interventions generally address symptoms rather than the wide array of interacting root causes, which limits programmatic outcomes and positive population health impacts [73].

As an alternate paradigm, complex systems science diverges theoretically, methodologically and analytically from the common college drinking prevention research and intervention strategies which have defined the field historically. By infusing a complex systems paradigm, and thereby viewing college student alcohol misuse through these new paradigmatic 'lenses', future research endeavors can capture more accurately the dynamic complexity of these problems and facilitate substantive advances in both basic and applied knowledge. Corresponding interventions, shaped by a superior understanding of the overarching CASoS [60] which shape college student alcohol misuse, can then account more accurately for the dynamic complexity which marks these issues. In particular, the application of computational modeling and simulation methodologies provide means to address college student alcohol misuse by providing *in-silico* laboratories for hypothesis testing and identification of leverage points [102], which can guide policy and intervention decisions [73].

Further, complex systems approaches have the potential to result in greater stakeholder involvement and feedback. Specifically, the participatory process of group model building (e.g. community-based system dynamics [103]), engages and empowers stakeholders, as they are active collaborators when a simulation model is constructed [102]. Once feedback is obtained, the simulation model can then be tested across broad spatiotemporal horizons without the ethical, financial or practical restrictions inherent in traditional quantitative applied public health research [5,46]. Many modeling tools allow researchers to create models 'in action' [51], which can be manipulated and understood easily by stakeholders. The resulting accessibility and palatability removes barriers in understanding and provides a neutral environment where stakeholders themselves can explore the problem and devise and test solutions [104,105]. For example, simulation models can be presented as a 'game' to stakeholders, who are then tasked with identifying the most effective solutions [90,106]. Such innovative uses of simulation modeling provide powerful learning and policymaking tools [51,100].

CONCLUSION

The dynamic complexity and nagging persistence of college student alcohol misuse outlined herein serves as rationale for a paradigm shift away from our static, reductionist and linearity roots. If college administrators, community leaders and public health officials wish to reduce alcohol misuse college students and ultimately see return on investment for the resources allocated to address this problem, now is the time to embrace innovative approaches. A complex systems paradigm, grounded in transdisciplinary frameworks, socio-ecological and complex systems theories, and computational modeling and simulation, can foster new directions in alcohol prevention research—regardless of context—and bring about positive population health impacts.

Declaration of interests

None.

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