ORIGINAL PAPER

Depression and alcohol misuse among older adults: exploring mechanisms and policy impacts using agent-based modelling

Ivana Stankov[1] · Yong Yang[2] · Brent A. Langellier[3] · Jonathan Purtle[3] · Katherine L. Nelson[3] · Ana V. Diez Roux[1]

Abstract

Purpose To: (1) explore how multi-level factors impact the longitudinal prevalence of depression and alcohol misuse among urban older adults (≥ 65 years), and (2) simulate the impact of alcohol taxation policies and targeted interventions that increase social connectedness among excessive drinkers, socially isolated and depressed older adults; both alone and in combination.

Methods An agent-based model was developed to explore the temporal co-evolution of depression and alcohol misuse prevalence among older adults nested in a spatial network. The model was based on Los Angeles and calibrated longitudinally using data from the Multi-Ethnic Study of Atherosclerosis.

Results Interventions with a social component targeting depressed and socially isolated older adults appeared more effective in curbing depression prevalence than those focused on excessive drinkers. Targeting had similar impacts on alcohol misuse, though the effects were marginal compared to those on depression. Alcohol taxation alone had little impact on either depression or alcohol misuse trajectories.

Conclusions Interventions that improve social connectedness may reduce the prevalence of depression among older adults. Targeting considerations could play an important role in determining the success of such efforts.

Keywords Mental health · Chronic disease · Health policy · Complex systems · Agent-based model

Introduction

Populations worldwide are ageing. Globally, the proportion of older adults will nearly double between 2015 and 2050 [1], and in North America, adults over 60 years are projected to comprise 27% of the population [2].

✉ Ivana Stankov
is379@drexel.edu

1   Urban Health Collaborative, Dornsife School of Public
     Health, Drexel University, 3600 Market St, 7th Floor,
     Philadelphia, PA 19104, USA

2   Division of Social and Behavioral Science, School of Public
     Health, University of Memphis, Memphis, TN 38117, USA

3   Department of Health Management and Policy, Dornsife
     School of Public Health, Drexel University, 3215 Market St,
     Philadelphia, PA 19104, USA

With a prevalence around 13% [3], depression is the leading mental health issue among older adults [1]. Later-life depression is particularly concerning given its association with numerous comorbidities, including functional decline, all-cause mortality, and suicide [4–6]. Alcohol misuse (or excessive alcohol consumption) is also an emerging public health problem among older people [7]. According to a recent systematic review [8], the prevalence of excessive weekly alcohol consumption among North Americans aged 50–75 was among the highest reported internationally, ranging from 14 to 36% among men and 4–15% among women. In the United States, the proportion of older adults consuming alcohol to excess is projected to double by 2020 [9].

Depression and alcohol misuse often coexist, but few studies have investigated their interrelationship [9–12]. Longitudinal studies exploring this interrelationship suggest that alcohol misuse may predict depression trajectories [12–15]—lending support to the theory that depression and alcohol misuse may be mutually reinforcing.

The dynamic relations between depression and alcohol misuse—resulting from shared risk factors, complex

interactions, dependencies, and feedback loops—have important implications for policies and other population-based interventions to address one or both conditions. For example, if the two conditions are causally linked, policies implemented to reduce alcohol misuse (e.g., alcohol taxation) could also reduce depression prevalence. Similarly, interventions to reduce depression (e.g., strategies to reduce social isolation) could also affect alcohol use. Predicting these 'spillover' effects requires approaches that take into consideration the complex system of factors shaping patterns of interrelated conditions like depression and alcohol misuse.

Agent-based models (ABMs) have emerged as important tools for providing dynamic insights into the mechanisms underpinning a range of health issues and the potential impact of policies intervening on these complex systems [16]. Agent-based modelling is a computational approach that represents agents (e.g., people or households) with diverse characteristics, and their interactions with each other and their environment over time [17]. Governed by a set of rules, these interactions may result in changes in the environment and/or the agents themselves, through learning and adaptive processes in which agents' past experiences shape their future behaviour. ABMs, therefore, provide an in silico laboratory that can be used to explore the emergence of unanticipated population-level patterns that cannot be reduced to the mere sum of all individual-level interactions [17]. They are also useful in identifying the plausible impacts of policies and intervention scenarios on multiple interrelated outcomes under varying conditions. Although ABMs have been used to investigate the impact of policies on behaviours like physical activity and diet [16], their application to understand the impact of interventions on mental health issues, or multiple outcomes, remains limited [18].

Study purpose

In this paper, we present an ABM designed to advance understanding of depression and excessive alcohol consumption (referred to as 'alcohol misuse' henceforth) among urban older adults, and to explore the potential impact of alcohol taxes and interventions providing opportunities for social connection, on these outcomes. We examined taxation policies, because their effectiveness in reducing overall alcohol consumption in the general population has been well established [19]. Although the impact of alcohol taxes among older adults is under-explored [20], there is some evidence to suggest that alcohol consumption in the older demographic is sensitive to changes in alcohol pricing [21].

We focused on policies increasing social connectedness because of the high prevalence of social isolation [19] and recent policy interest in strategies to minimize loneliness among older adults [22]. While interventions seeking to increase social connectedness may reduce social isolation, an established risk factor for depression among older adults [23], they may also increase alcohol misuse via increased exposure to peers who misuse alcohol [24]. The joint implementation of both these policies, therefore, could have consequences that may not be easy to predict based on empirical studies of their separate effects. This is the context where ABM may yield the most insight.

The objectives of this study were to: (1) explore the social and environmental mechanisms that may underpin the reinforcing relation between depression and alcohol misuse among urban older adults (≥ 65 years); (2) examine the potential impact of alcohol taxation policies and targeted interventions that increase social connection among excessive drinkers, socially isolated and depressed older adults, both alone and in combination, on depression and alcohol misuse.

We delineated the boundary and scope of this model to create the most parsimonious ABM possible. This is common practice within ABM where the tension between model breadth and parsimony must be navigated in a way that "allows effective tracing from inputs via specific mechanisms to outputs of interest" [25, p. 180]. Specifically, we limited our focus to understanding overall population-level trajectories of depression and alcohol misuse. We did not focus on depression and alcohol misuse comorbidity as an outcome due to sample size limitations which reduced our capacity to reliably estimate and calibrate comorbid trajectories among older adults.

Methods

Key components of the model design are presented using the 'PARTE' framework: Properties of agents; Actions or behaviours modelled; Rules which govern such behaviour; Time; and the Environment in which agents are embedded [25].

Agent properties and actions

The ABM included 540 agents (older adults ≥ 65 years) and the alcohol outlets in their neighbourhoods. Each time step (i.e., each week), agents were probabilistically assigned an alcohol consumption status (excessive drinker or not) based on individual factors, such as their affinity for excessive consumption (> 7 standard drinks per week [7]) and depression (CES-D ≥ 16 [26]), and also the alcohol consumption of their friends and cohabitants. Also considered were environmental influences, such as alcohol pricing and access to alcohol retailers. Agents' depression status was determined by considering their past predisposition toward depression, level of social connectedness, and affinity toward excessive

drinking. Table 1 provides a summary of the data and studies used to inform these model parameters. In the interest of parsimony, certain predictors of depression and alcohol use, such as educational attainment, gender, and physical health were omitted from our ABM, because they were not deemed critical to addressing the central aims of the paper.

Model environment

Environmental factors (i.e., price of alcohol and access to retailers) are important determinants of drinking. The model environment was therefore designed to reflect the distribution of older adults and alcohol retailers in the study region. Each agent was randomly assigned a residence on a 42×56 toroidal (i.e., donut-shaped) surface akin to the model by Gopalakrishnan et al. [27], each unit representing half a mile. These dimensions were informed by the 21 by 28-mile area of Los Angeles (LA) County inhabited by 540 older adults assessed at all exams of the Multi-Ethnic Study of Atherosclerosis (MESA). MESA is a longitudinal cohort study investigating associations between lifestyle factors and cardiovascular disease across six US cities, including Los Angeles [28]. Participants between 45 and 84 years old were assessed at baseline (Exam 1) from 2000 to 2002, and

Table 1 Summary of model parameter values at baseline, and the data/empirical sources informing these

Parameter	Definition and values	Data and empirical foundation
Individual attributes		
w_i	Weekly income (USD/week) $w_i \in (24, 1082)$	Informed by baseline MESA data[a]. Values were drawn at random, for HD zone residents, from a normal distribution with mean = 215, SD = 180; and for LD zone residents, from a normal distribution with mean = 298, SD = 257. Values remain constant
Sp_i	Cohabitation status Categorical $\in [0, 1]$ (if lives with someone = 1; if not = 0)	Randomly assigned with proportion living with someone = 0.564, informed by baseline MESA data[a]. Values remain constant
Sp_{Ai}	Cohabitant's excessive alcohol consumption status Categorical $\in [0, 1]$ (if cohabitant drinks to excess = 1; if not = 0)	Randomly assigned with proportion of cohabitants drinking to excess (> 7 standard drinks per week) = 0.037, informed by baseline prevalence of excessive drinking in the MESA population[a]. Assignment is independent of agent's own alcohol consumption status. Values remain constant
$p(A_{it-1})$	Past affinity for excessive alcohol consumption $p(A_{it-1}) \in [0, 1]$ $p(A_{it-1}) = 0.037$ at baseline	Baseline proportion of excessive drinking (> 7 standard drinkers per week) in the MESA population[a] was used to initialize the model. Values updated over time
$p(A_{it})$	Current affinity for excessive alcohol consumption $p(A_{it}) \in [0, 1]$ $p(A_{it}) = 0.037$ at baseline	Baseline proportion of excessive drinking (> 7 standard drinkers per week) in the MESA population[a] was used to initialize the model. Values updated over time
$p(D_{it-1})$	Past predisposition toward developing depression $p(D_{it-1}) \in [0, 1]$ $p(D_{it-1}) = 0.161$ at baseline	Baseline proportion of clinically depressed (CES-D > 16) older adults in the MESA population[a] was used to initialize the model. Values updated over time
$p(D_{it})$	Current predisposition toward developing depression $p(D_{it}) \in [0, 1]$ $p(D_{it}) = 0.161$ at baseline	Baseline proportion of clinically depressed (CES-D > 16) older adults in the MESA population[a] was used to initialize the model. Values updated over time
n_{Sn_i}	Number of people in agent i's personal network	Randomly assigned. Values remain constant
S_q	Strength of tie between agent i and any given agent q in its personal network	Drawn at random from uniform distribution $\in [0,1)$ Study by Onnela et al. [32]. Values remain constant
Environmental attributes		
Ap	Price of eight standard drinks of alcohol (USD), representing the lower range of excessive weekly alcohol consumption among older adults $Ap = \$13.44$ at baseline	Study by DiLoreto et al. [33] and US recommendations for alcohol consumption for those > 60 year [7]. Values remain constant
Personal network attributes		
	Random spatial network with average degree of connectivity = 5 people	Study by Lambiotte et al. [31] and Wrzus et al. [30]. Values remains constant

HD high density, *LD* low density, *SD* standard deviation, *MESA* Multi-Ethnic Study of Atherosclerosis, *CES-D* Center for Epidemiologic Studies Depression Scale

[a]Refers to baseline MESA data of older adults residing in Los Angeles (n = 540)

followed up at 1.5–2-year intervals (Exams 2–5). The LA site was the focus of this ABM, because it had the largest sample of older adults with available data on depression and drinking patterns. These data were collected using the Center for Epidemiologic Studies Depression (CES-D) Scale [29] and a personal history questionnaire which sought to establish participants' usual amount of alcoholic drinks consumed per week. The use of the MESA data was approved by the Institutional Review Board at Drexel University.

The model environment was divided into two zones: one with a high density of alcohol outlets (HD zone), and the other a low density (LD zone). Supplement A1 describes the spatial data used to inform the ABM environment. Agents in each alcohol zone were uniquely assigned a weekly income based on the corresponding income distribution of older adults in MESA (see Supplement A2 for more information on these distributions). Other individual-level characteristics assigned to agents included their cohabitation status, the excessive drinking status of their spouse/cohabitant (if they had one), their own predisposition toward depression, and excessive alcohol consumption (Table 1).

Agents were assigned social ties (i.e., to other agents within the model), representing personal networks comprising family members and close friends. The decision to embed agents in a personal network as opposed to a broader social network is grounded in the idea that personal networks function as resources, enabling an "exchange of support among closer network members" [30, p. 54]. The average number of connections between agents in the network was five, because a recent meta-analysis of 277 studies found that the average personal network of adults ≥ 65 years included five friends [30]. Given the influential role of environmental factors in the model, social ties were spatially constrained. The spatial conditioning of network ties was modelled after a study of mobile phone network users. This study [31] found that the probability that any two members of the same phone network were connected was directly proportional to the inverse of the square distance between them. Therefore, within the ABM, the greater the distance between any two agents, the less likely it was that they were socially connected. The strength of each social tie was randomly assigned a unique value between zero and one, resulting in a 'weighted' network. This random assignment was informed by research which found that the strength of ties (defined as the number of calls and texts exchanged between members of a phone network) was independent of distance [32]. For simplicity, we also assumed that the social ties and their strengths did not change over time. This assumption was made because the model simulated a relatively short time span (i.e., 5 years). Although the personal networks of some older adults may be disrupted during this period, overall, we did not think that the average node degree within the entire network would change substantially during this relatively short time interval. We also assumed that the social ties were symmetrical. That is, that the tie strength, and by extension, the influence exerted by agent A on agent B, is the same as that exerted by agent B on agent A. Supplement A3 describes the personal network and the basis for its creation in greater depth. Cohabitants were not represented as links in the spatial network; they were separately considered.

Model time and rules

Each simulation was run for 5 years (260 weeks) in Netlogo v5.3.1 [34]. Each time step (i.e., each week), agent's behaviour and depression state were updated based on a set of rules which consider the agent's past experiences and their interactions with members of their social network. Each time step was operationalized as 1 week, because alcohol-related decision-making and consumption operate on a finer temporal scale than changes in depression, which can be a chronic condition.

Drinking behaviour

Consistent with the literature, a core assumption in the model was that cohabiting with a drinker [35–37], and having a high proportion of social connections that drink to excess [24, 38], increased an agent' risk of alcohol misuse. At each time step, each agent's alcohol misuse was probabilistically determined by considering seven factors spanning individual, environmental, and social domains: (1–2) predisposition toward excessive alcohol consumption and depression; (3) presence or absence of cohabitants and their drinking status; (4–5) drinking status and strength of ties to excessive drinkers in personal network; (6) proximity to nearest alcohol outlet; and (7) the relative cost of alcohol, which expresses alcohol price in relation to an agent's income.

Evolution of depression

An agent's predisposition to developing depression at any given time was determined by considering time-varying individual-level and social factors. Predisposition to depression and affinity for alcohol misuse increased agents' likelihood of developing depression. The combined influence of social factors (e.g., network size and strength of social ties) simultaneously mitigated the temporal likelihood of developing depression.

The parameters and equations governing agents' drinking and depression status are detailed in Supplement A4.

The causal loop diagram (CLD) in Fig. 1 depicts the interrelationships between excessive alcohol consumption and depression, including factors hypothesised to influence their co-evolution. As such, the CLD along with agent's
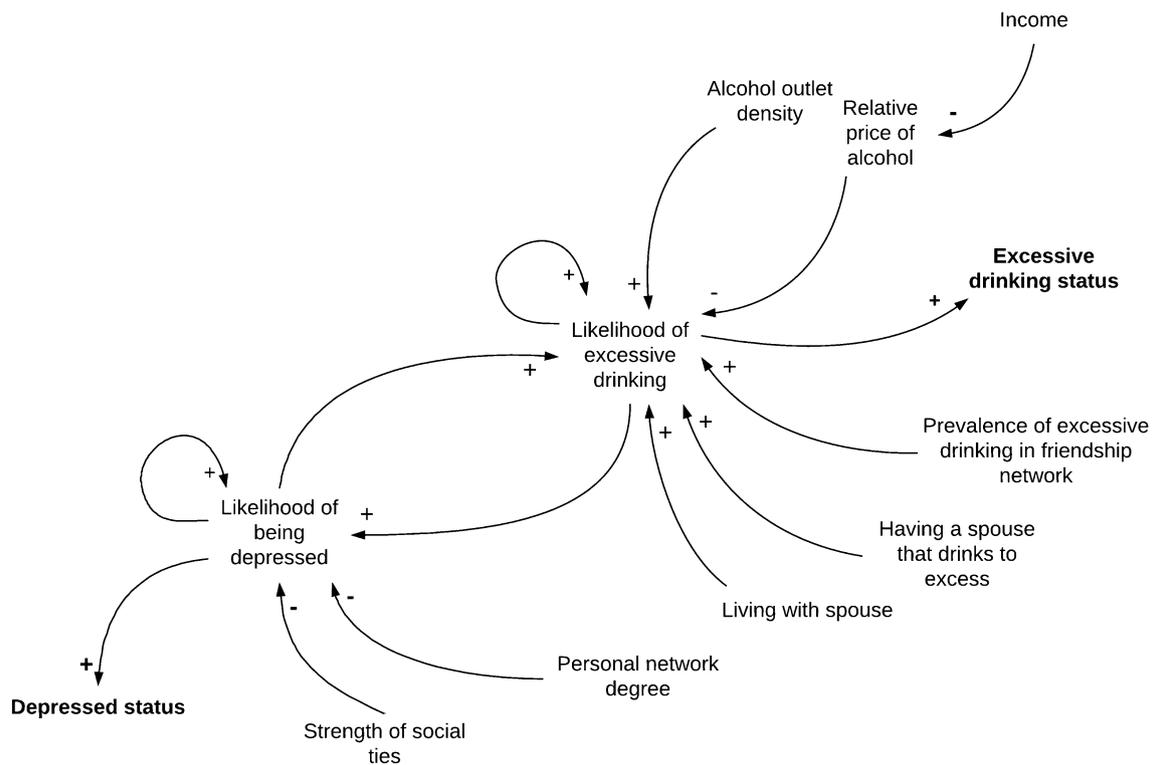
Fig. 1 Causal loop diagram of key factors influencing the assignment of excessive drinking and depression status

traits, namely, agent's individual-level characteristics and the rules governing their behaviour, represent an empirically informed preliminary theory that was tested through pattern-oriented modelling (POM), which includes parameter calibration [39].

Model calibration

Parameters for the relative weights of individual, social, and environmental influences on drinking behaviour, and the characteristics of the depression function including the intercept and mitigating influence of social factors on depression growth could not be informed by empirical data. Thus, plausible values of these parameters were determined through calibration. In calibration, unknown model parameters are systematically varied over a defined range to identify values that maximize the model's fit to the data [39]. Where many plausible configurations of values existed, higher weights were assigned to individual-level influences than social and environmental factors. This decision was based on multi-level studies which tend to show stronger and more consistent effects for individual-level compared to social and environmental factors [40]. To enable calibration, excessive alcohol consumption and depression prevalence were simulated over 5 years. These trajectories were then contemporaneously compared to 5-year depression and

alcohol misuse prevalence trends among older adults residing in LA, estimated from MESA data. According to Railsback and Grimm, through this form of POM, "we accept agent traits as theory when they cause the ABM to reproduce the set of patterns that we choose" [39, pp. 243–244]. In other words, when the ABM can adequately reproduce the patterning of depression and alcohol misuse observed within the real-world (i.e., those estimated from the MESA data), we take this as support for the relationships within the CLD and other aspects of model specification (e.g., agent characteristics and parameter weights).

Sensitivity analysis

We conducted a sensitivity analysis to test the model's sensitivity to changes in two key attributes of the spatial network; the average node degree and the distribution of tie strengths. As described, agents had an average of five friends and the strength of each social tie was randomly assigned a unique value between zero and one, resulting in a 'weighted' network. The sensitivity analysis was designed to test the sensitivity of each outcome, namely depression and alcohol misuse prevalence, to small changes in the average node degree and the distribution of tie strengths in the network (i.e., making all social ties the same strength (0.5), resulting in an 'unweighted' network). First, we simulated depression

and alcohol misuse prevalence trajectories by varying the average node degree by 5, 10, and 20%, above and below the reference value (i.e., an average degree of five [30]), holding all other parameter values constant. Using these data, we calculated the sensitivity by approximating the partial derivate of each outcome (i.e., the time averaged effect of 500 repeated runs) in relation to the average node degree, as described by Railsback and Grimm [39]. The smaller the sensitivity value, the lower the relative uncertainty in the parameter value and therefore the lower the model's sensitivity to changes in that parameter. Finally, we tested the model's temporal sensitivity to parameter interactions. Specifically, we explored how the model's sensitivity to the average node degree changed over time, depending on a weighted versus an unweighted network.

Simulated policies and interventions

We used the calibrated model to examine the potential impact of two types of intervention scenarios—alcohol taxes and social connection interventions; simulated both alone and in combination, on trends in depression and alcohol misuse.

Alcohol taxes are important policy levers [20] that can reduce alcohol consumption. Because the magnitude of alcohol taxes varies widely by country and beverage type [41], we simulated a range of taxes representing a: 50, 80, 100, and 400% relative increase in the baseline price of alcohol.

Social connection interventions (i.e., the impact of giving individuals one new friend) have shown promise in reducing depression among older adults [42]. We explored the impact of social connection on the complex dynamics between depression and drinking behaviour. For example, while reducing social isolation may lower depression risk, increasing connection to excessive drinkers may promote alcohol misuse among those previously drinking in moderation. Moreover, these relationships may, themselves, be modified in complex ways by alcohol taxes. Our model examined social connection interventions targeting excessive drinkers, depressed older adults, and those who were relatively isolated—defined as having fewer than five social ties. We also investigated whether connecting individuals to non-excessive drinkers, rather than randomly selected people (i.e., regardless of alcohol misuse status), was more effective in curbing alcohol misuse and depression prevalence.

We elected to simulate policies and corresponding impacts as though they were implemented in year 2, rather than predicting long-term impacts beyond the model's calibrated 5-year timeframe. In this way, we could compare a 'baseline trajectory' (i.e., the calibrated model run over 5 years) with alternate scenarios which represent how the observed 5-year alcohol misuse and depression prevalence trends might have been impacted had a given policy been implemented in year 2. Each policy was simulated 50 times to account for random variation.

Results

The calibrated model demonstrated a good fit to 5-year depression and alcohol misuse prevalence trends estimated from MESA (Fig. 2a, c) . The mean-squared errors between the simulated output and prevalence rates estimated using the data were ≤ 0.06 for both depression and excessive alcohol consumption trajectories (Fig. 2b, d). The outcomes of the sensitivity analyses suggest that the model is relatively insensitive to changes in the distribution of tie strengths for both depression and alcohol misuse (Supplement A5; Figs. 1, 2). Depression prevalence, however, shows modest sensitivity to changes in average node degree, both in the weighted and unweighted network, particularly when the average node degree is reduced to four people (Supplement A5; Table 1 and Fig. 1).

The results of the alcohol tax scenarios (Fig. 3a, b) indicate that taxation reduced alcohol consumption, although the effect was small and only clearly apparent for the most extreme tax. No significant impact on the prevalence of depression was observed for any of the tax scenarios.

The social connection interventions, which afforded agents' one additional friend, decreased depression prevalence. Of the three targeted approaches, actions directed at relatively isolated older adults appeared most effective (one percentage point reduction), followed by interventions targeting those with depression (Fig. 3c). These two interventions were both more effective in decreasing overall depression prevalence than efforts targeting excessive drinkers. Interestingly, the impact of the social connection interventions on depression was unaffected when agents who were excessive drinkers were excluded as potential new social ties. Moreover, social connection interventions did not impact alcohol misuse (Fig. 3d), even when relatively isolated individuals or excessive drinkers were connected to another person independent of drinking status.

The combined impact of the most extreme tax policy with any social connection intervention (Fig. 4a, b) did not appear to impact the prevalence of depression and alcohol misuse beyond levels observed from the simulated implementation of each intervention alone (Fig. 4b vs 3b). Similar results were observed in analyses restricted to relatively isolated individuals (Fig. 4c, d). However, there was some evidence that the combined strategy had a slightly smaller impact on reducing the prevalence of alcohol misuse among relatively isolated older adults than the general population (Fig. 4d compared to Fig. 4b).
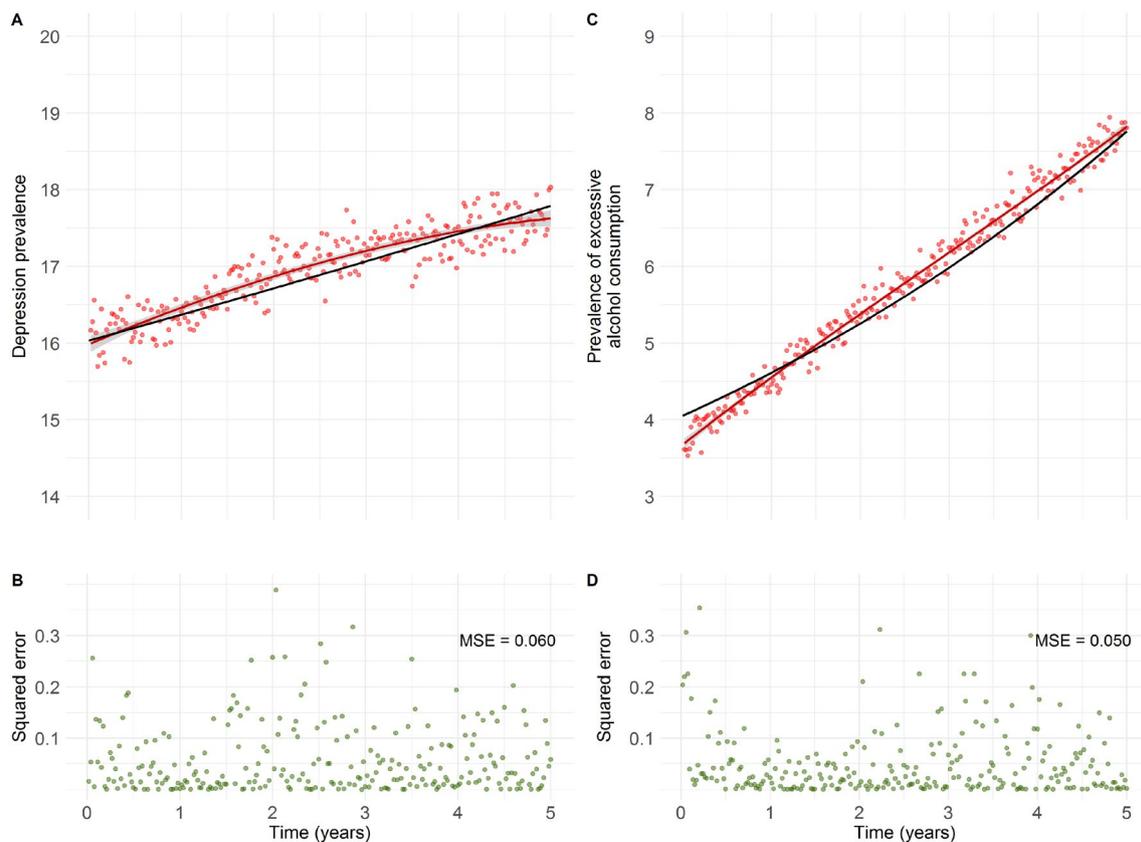
Fig. 2 Fit between the model simulated output (red) and depression and excessive alcohol consumption trajectories estimated using MESA data (black) from older adults residing in Los Angeles County

Discussion

The calibrated model successfully reproduced depression and alcohol misuse prevalence trends observed among older adults in LA. The ABM's empirical grounding and the observed alignment between the model's simulated output and the data lend support to the theory underpinning the model. Namely, the notion that depression and alcohol misuse could be interrelated and that the individual, social, and environmental factors depicted in the CLD and characterised in Table 1 plausibly influence their co-evolution. The simulated scenarios aligned with expectations: the impact of alcohol taxes was greatest on levels of alcohol misuse, while social interventions were more effective at decreasing depression prevalence [20, 42]. While several of the simulated alcohol taxes were largely ineffective, the most extreme forms of taxation along with the social connectedness interventions produced modest effects which, at the population-level, demonstrate their potential as approaches for reducing depression and alcohol misuse among older adults.

The weights assigned to individual, social, and environmental factors played an important role in the dynamics between depression and alcohol misuse, and in turn,

on the estimated prevalence trends for drinking behaviour and depression in the model. Yet, the real-world values of these parameters remain unknown. The POM and calibration techniques which iteratively explored the depression and alcohol misuse patterns that emerged from different weights assigned to key factors and processes within the model (e.g., the weight of influence of depression on the likelihood of alcohol misuse and vice versa) suggest that the parameter values that best fit the data were quite small. This finding lends some support to the theory that depression and alcohol misuse could be interrelated, but that the feedback effect may be slight.

The simulated alcohol taxes exhibited an inverse dose–response relationship with alcohol misuse; the higher the taxes, the lower the levels of alcohol misuse observed—a finding consistent with the empirical literature [43]. A systematic review by Elder et al. estimates that a 3–10% decrease in population-level alcohol consumption may be expected for every 10% increase in alcohol cost [20]. We are unaware of any studies that evaluate alcohol price elasticity for older adults [20], and as such, it remains unclear to what extent the impacts reported by Elder et al. can be generalised to older demographics. In our simulations, alcohol misuse
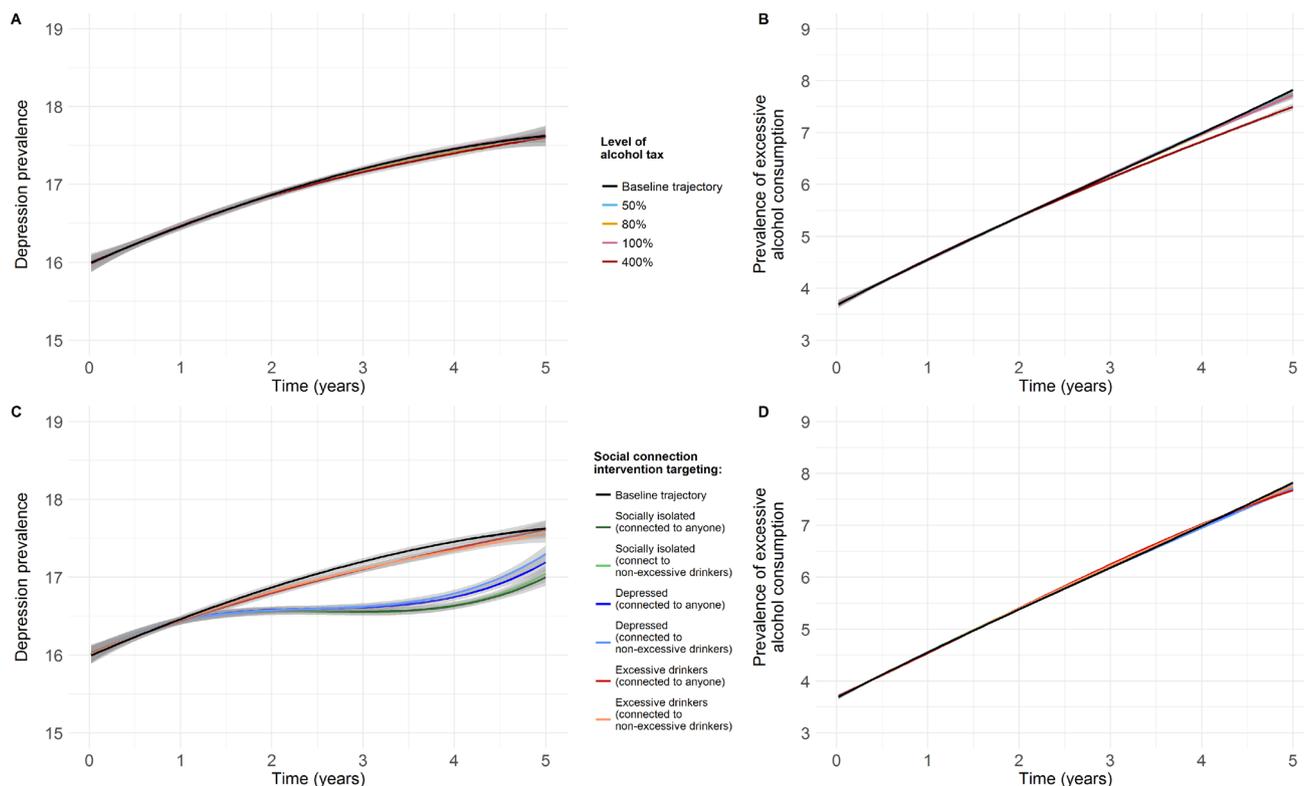
Fig. 3 The impact of raising alcohol taxes, in year 2, by 50, 80, 100, and 400% on **a** overall depression and **b** alcohol misuse prevalence, and the impact of variously targeted social connection interventions, implemented in year 2, on **c** overall depression and **d** alcohol misuse prevalence

among older adults was less sensitive to changes in alcohol pricing than those of Elder et al. [20]. However, we caution that our model was not designed to estimate price elasticity, but to qualitatively contrast the plausible effects of various interventions. Nevertheless, an important insight was that taxation did not significantly influence depression prevalence, despite the empirically informed relation between depression and alcohol misuse built into our model.

To date, a few studies have examined the effects of increasing social connectedness on depression among older people [42]. Dickens et al. [42] report that some 40% of 32 studies considered depression as an outcome in their systematic review of interventions addressing social isolation among older adults. Of these, only four reported statistically significant impacts on depression. Our ABM's findings generally align with this literature. Specifically, the simulated social interventions, which variously connected at-risk subgroups of older adults with one other person, appeared effective in decreasing depression prevalence both overall and among relatively isolated individuals. Interestingly, targeting played an important role in determining the relative effectiveness of these interventions on depression outcomes. Namely, social interventions targeting relatively isolated and depressed individuals appeared more effective, than those targeting excessive drinkers. One possible explanation for

this is the relatively low prevalence of alcohol misuse among agents, resulting in the targeting of a much smaller population subset compared to the depressed and socially isolated groups. Analogously, intervention scenarios in which older adults were connected to non-excessive drinkers did not appear to be more effective in reducing the prevalence of depression than scenarios in which connections were random. This finding may also be explained by the relatively low prevalence of alcohol misuse. Specifically, social interventions which created ties between agents independent of drinking status tended to connect agents to non-excessive drinkers simply because of their high prevalence.

In contrast, none of the social interventions affected alcohol misuse. This finding is surprising as the social interventions tested, directly influenced at least two factors—personal network degree and the proportion of excessive drinkers in an agent's network—implicated in the causal path between alcohol misuse and depression (CLD in Fig. 1). The observation that these interventions did not shift population levels of alcohol misuse, despite modest changes to depression prevalence, may reflect the relatively weak feedback mechanism found to be underpinning the co-evolution of these two outcomes. Furthermore, the fact that social interventions combined with the most extreme alcohol tax policy appeared no greater than any one of these
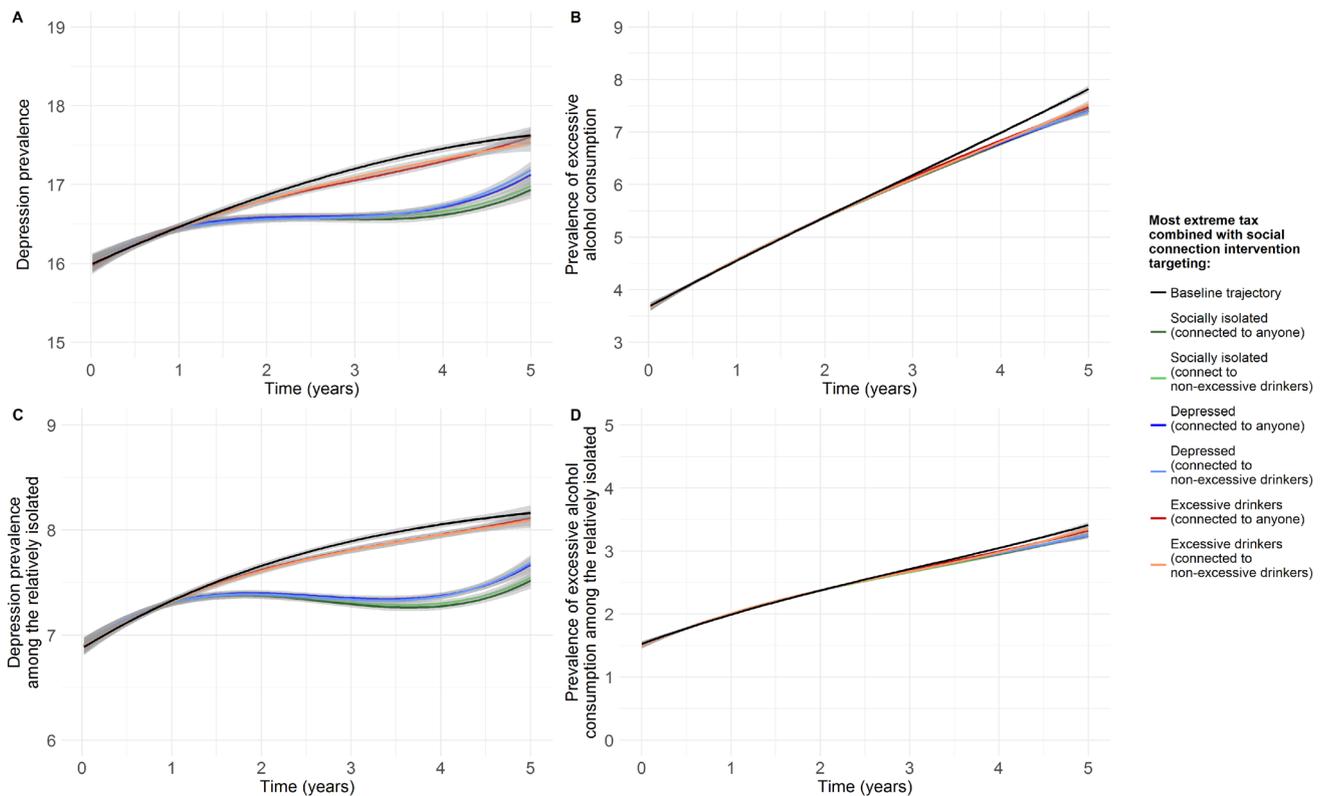
Fig. 4 The impact of combining variously targeted social connection interventions with the most extreme alcohol tax, in year 2, on **a** overall depression and **b** overall alcohol misuse prevalence; and **c** depression and **d** alcohol misuse prevalence among relatively isolated older adults

implemented alone could also be explained by this relatively weak feedback process.

Our model has a number of strengths, primarily, its dynamic exploration of the interrelationship between two outcomes, a focus which has been called for in public health [17, 44]. In addition, with its focus on depression and alcohol misuse among older adults, the model affords numerous insights into the mechanisms underpinning the co-evolution of two pressing public health issues, as well as the social and environmental factors that may influence their temporal development. Further model strengths include its empirical foundations and the data-driven characterization of the environment and the agents embedded within it. The model could, therefore, be used to simulate the potential effectiveness of a range of realistic intervention scenarios on the population-level burden of these conditions. By limiting reference to a specific time frame for which data were available, the model also allowed a direct comparison between a baseline trajectory (which was well calibrated to these data) and the potential impact of simulated interventions.

The findings of this study ought to be considered with some limitations in mind. The model's generalizability may be limited, because it was calibrated to depression and alcohol misuse trajectories using data from older adults residing in LA and participating in the MESA study. The prevalence rates of depression within this population are, on average, slightly higher than those estimated using 1998–2008 data from the US Health and Retirement Study (HRS) (i.e., 17% in MESA vs 15% in HRS) [45]. Alcohol misuse prevalence rates within the model were, on average, also lower than 2005–2006 data from the National Survey on Drug Use and Health, which estimated the prevalence of at-risk drinking (defined as ≥ 2 drinks per day; a definition comparable to that used within the model) among older adults at around 13% for men and 8% for women [46].

As with all ABMs, simplifying assumptions were made during model development. We assumed that alcohol misuse could be directly transmitted among individuals in the same personal network, but that depression was only indirectly transmitted through drinking behaviour. Gender, education, physical health, and alcohol retailer type (i.e., on- versus off-premise outlets) were not considered in the model. Another assumption was that personal networks remain static over the simulated 5-year period. As such, the influence of temporal changes to cohabitation and the potential impact of discordant alcohol use and depression states on the maintenance of and/or damage to social ties could not be explored. Sensitivity analyses, however, suggest that model outcomes

were relatively insensitive to small changes in the average node degree of the network. The need to calibrate the weight parameters in the model represents another limitation. While the estimated values of these parameters suggest that depression and alcohol misuse may be weakly interrelated, we cannot be certain that this finding reflects the true nature of these causal relations. More data and empirical research are required to clarify these issues.

Conclusions and future directions

This model suggests that depression and alcohol misuse are interrelated though the strength of the feedback interactions between them may not be strong. The ABM also suggests that alcohol misuse patterns among older adults may be relatively insensitive to changes in alcohol pricing. Moreover, social interventions targeting relatively isolated and depressed older adults to increase their social connectedness may be effective in reducing the prevalence of depression overall and among relatively isolated individuals.

Several important questions remain, highlighting the need for future research on older adults. First, data collection enabling empirical research of longitudinal associations between alcohol misuse and depression among older adults is required to enhance the precision of weight parameters in the model and the outcomes of simulated policy scenarios. These data would further enhance calibration of the ABM, thereby enhancing its capacity to explore the impact of policies and interventions on depression and alcohol misuse comorbidity. Second, studies evaluating the impact of alcohol taxes and alcohol outlet density on drinking patterns among older adults, by gender, and across the socioeconomic spectrum, are also needed to gauge the potential effectiveness of prospective policies on alcohol misuse. Third, future extensions of the model should include physical health and its dynamic influence on both depression and alcohol misuse trajectories. Finally, while the model appeared relatively insensitive to small changes in the average node degree of the network, a dynamic exploration of social connections among older adults, including factors driving the formation and erosion of personal ties, and their influence on depression and alcohol misuse is required. A deeper knowledge of such mechanisms would enable a richer exploration of the interrelationship between alcohol misuse and depression in this population.

Compliance with ethical standards

References

1. World Health Organisation (2017) Mental health of older adults: Fact sheet [Press release]. http://www.who.int/mediacentre/factsheets/fs381/en/. Accessed 14 July 2018
2. United Nations (2014) Population facts: population ageing and sustainable development. United Nations, Department of Economic and Scoial Affairs, Population Division. pp 1–4. http://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2014-4Rev1.pdf. Accessed 29 Mar 2018
3. Beekman ATF, Copeland J, Prince MJ (2018) Review of community prevalence of depression in later life. Br J Psychiatry 174(4):307–311
4. Schulz R et al (2000) Association between depression and mortality in older adults: the cardiovascular health study. Arch Intern Med 160(12):1761–1768
5. Lenze EJ et al (2001) The association of late-life depression and anxiety with physical disability: a review of the literature and prospectus for future research. Am J Geriatr Psychiatry 9(2):113–135
6. Blazer DG (2003) Depression in late life: review and commentary. J Gerontol Ser A 58(3):M249–M265
7. Center for Substance Abuse Treatment (1998) Substance abuse among older adults. In: Treatment improvement protocol (TIP) series. Substance Abuse and Mental Health Services Administration, Rockville, p 204. https://www.ncbi.nlm.nih.gov/books/NBK64419/pdf/Bookshelf_NBK64419.pdf. Accessed 18 Apr 2018
8. Gell L, Meier PS, Goyder E (2015) Alcohol consumption among the over 50 s: international comparisons. Alcohol Alcohol 50(1):1–10
9. Wu LT, Blazer DG (2014) Substance use disorders and psychiatric comorbidity in mid and later life: a review. Int J Epidemiol 43(2):304–317
10. St John PD, Montgomery PR, Tyas SL (2009) Alcohol misuse, gender and depressive symptoms in community-dwelling seniors. Int J Geriatr Psychiatry 24(4):369–375

11. Devanand DP (2002) Comorbid psychiatric disorders in late life depression. Biol Psychiatry 52(3):236–242

12. Brennan PL et al (2015) Alcohol use predicts 10-year depressive symptom trajectories in the Health and Retirement Study. J Aging Health 28(5):911–932

13. Peirce RS et al (2000) A longitudinal model of social contact, social support, depression, and alcohol use. Health Psychol 19(1):28–38

14. Hartka E et al (2010) A meta-analysis of depressive symptomatology and alcohol consumption over time. Br J Addict 86(10):1283–1298

15. Gilman SE, Abraham HD (2001) A longitudinal study of the order of onset of alcohol dependence and major depression. Drug Alcohol Depend 63(3):277–286

16. Nianogo RA, Arah OA (2015) Agent-based modeling of noncommunicable diseases: a systematic review. Am J Public Health 105(3):e20–e31

17. Tracy M, Cerdá M, Keyes KM (2018) Agent-based modeling in public health: current applications and future directions. Annu Rev Public Health 39(1):77–94

18. Langellier BA et al (2019) Complex systems approaches to understand drivers of mental health and inform mental health policy: a systematic review. Adm Policy Ment Health 46(2):128–144

19. Wagenaar AC, Salois MJ, Komro KA (2009) Effects of beverage alcohol price and tax levels on drinking: a meta-analysis of 1003 estimates from 112 studies. Addiction 104(2):179–190

20. Elder RW et al (2010) The effectiveness of tax policy interventions for reducing excessive alcohol consumption and related harms. Am J Prev Med 38(2):217–229

21. Xu X, Chaloupka FJ (2011) The effects of prices on alcohol use and its consequences. Alcohol Res Health 34(2):236–245

22. Cox J (2017) Combatting loneliness one conversation at a time: a call to action. Commission on loneliness, pp 1–21. https://www.ageuk.org.uk/globalassets/age-uk/documents/reports-and-publications/reports-and-briefings/active-communities/rb_dec17_jocox_commission_finalreport.pdf. Accessed 5 Aug 2018

23. Choi H, Irwin MR, Cho HJ (2015) Impact of social isolation on behavioral health in elderly: systematic review. World J Psychiatry 5(4):432–438

24. Preston P, Goodfellow M (2006) Cohort comparisons: social learning explanations for alcohol use among adolescents and older adults. Addict Behav 31(12):2268–2283

25. Hammond RA (2015) Appendix A: considerations and best practices in agent-based modeling to inform policy. In: Wallace R, Geller A, Ogawa V (eds) Assessing the use of agent-based models for tobacco regulation. National Academies Press (US): Washington, DC

26. Lewinsohn PM et al (1997) Center for Epidemiologic Studies Depression Scale (CES-D) as a screening instrument for depression among community-residing older adults. Psychol Aging 12(2):277–287

27. Gopalakrishnan V, Kim M, An G (2013) Using an agent-based model to examine the role of dynamic bacterial virulence potential in the pathogenesis of surgical site infection. Adv Wound Care 2(9):510–526

28. Bild DE et al (2002) Multi-ethnic study of atherosclerosis: objectives and design. Am J Epidemiol 156(9):871–881

29. Radloff LS (1977) The CES-D Scale: a self-report depression scale for research in the general population. Appl Psychol Meas 1(3):385–401

30. Wrzus C et al (2013) Social network changes and life events across the life span: a meta-analysis. Psychol Bull 139(1):53–80

31. Lambiotte R et al (2008) Geographical dispersal of mobile communication networks. Phys A 387(21):5317–5325

32. Onnela J-P et al (2011) Geographic constraints on social network groups. PLoS One 6(4):e16939

33. DiLoreto JT et al (2012) Assessment of the average price and ethanol content of alcoholic beverages by brand—United States, 2011. Alcohol Clin Exp Res 36(7):1288–1297

34. Wilensky U (1999) Center for connected learning and computer-based modeling. Netlogo. Northwestern University, Evanston

35. Hajat S et al (2004) Patterns and determinants of alcohol consumption in people aged 75 years and older: results from the MRC trial of assessment and management of older people in the community. Age Ageing 33(2):170–177

36. Kharicha K et al (2007) Health risk appraisal in older people 1: are older people living alone an "at-risk" group? Br J Gen Pract 57(537):271–276

37. Weyerer S et al (2009) At-risk alcohol drinking in primary care patients aged 75 years and older. Int J Geriatr Psychiatry 24(12):1376–1385

38. Kelly S et al (2018) Alcohol and older people: a systematic review of barriers, facilitators and context of drinking in older people and implications for intervention design. PLoS One 13(1):e0191189

39. Railsback SF, Grimm V (2012) Agent-based and individual-based modeling: a practical introduction. Princeton University Press, Princeton

40. Brennan PL, Moos RH, Mertens JR (1994) Personal and environmental risk factors as predictors of alcohol use, depression, and treatment-seeking: a longitudinal analysis of late-life problem drinkers. J Subst Abuse 6(2):191–208

41. World Health Organisation (2004) global status report: alcohol policy. World Health Organisation, Geneva

42. Dickens AP et al (2011) Interventions targeting social isolation in older people: a systematic review. BMC Public Health 11(1):647

43. Martineau F et al (2013) Population-level interventions to reduce alcohol-related harm: an overview of systematic reviews. Prev Med 57(4):278–296

44. Yang Y (2017) Using agent-based modeling to study multiple risk factors and multiple health outcomes at multiple levels. Ann N Y Acad Sci 1408(1):7–14

45. Zivin K et al (2013) Trends in depressive symptom burden among older adults in the United States from 1998 to 2008. J Gen Intern Med 28(12):1611–1619

46. Balzer DG, Wu L-T (2009) The epidemiology of at-risk and binge drinking among middle-aged and elderly community adults: national Survey on Drug Use and Health. Am J Psychiatry 166(10):1162–1169