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Review article

Evaluation of public health interventions from a complex systems perspective: A research methods review

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ABSTRACT

Introduction: Applying a complex systems perspective to public health evaluation may increase the relevance and strength of evidence to improve health and reduce health inequalities. In this review of methods, we aimed to: (i) classify and describe different complex systems methods in evaluation applied to public health; and (ii) examine the kinds of evaluative evidence generated by these different methods.

Methods: We adapted critical review methods to identify evaluations of public health interventions that used systems methods. We conducted expert consultation, searched electronic databases (Scopus, MEDLINE, Web of Science), and followed citations of relevant systematic reviews. Evaluations were included if they self-identified as using systems- or complexity-informed methods and if they evaluated existing or hypothetical public health interventions. Case studies were selected to illustrate different types of complex systems evaluation.

Findings: Seventy-four unique studies met our inclusion criteria. A framework was developed to map the included studies onto different stages of the evaluation process, which parallels the planning, delivery, assessment, and further delivery phases of the interventions they seek to inform; these stages include: 1) theorising; 2) prediction (simulation); 3) process evaluation; 4) impact evaluation; and 5) further prediction (simulation). Within this framework, we broadly categorised methodological approaches as mapping, modelling, network analysis and 'system framing' (the application of a complex systems perspective to a range of study designs). Studies frequently applied more than one type of systems method.

Conclusions: A range of complex systems methods can be utilised, adapted, or combined to produce different types of evaluative evidence. Further methodological innovation in systems evaluation may generate stronger evidence to improve health and reduce health inequalities in our complex world.

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1. Introduction

It has been suggested that a complex systems perspective can help public health researchers generate evidence that better accounts for the complex nature of real-world environments (Meadows and Wright, 2008; Rutter et al., 2017; Apostolopoulos et al., 2018; Chughtai and Blanchet, 2017; Diez Roux, 2011; Finegood et al., 2014). A 'complex systems perspective' involves considering the "bigger changing picture" within which attempts to improve population health occur (Egan et al., 2019, p.11). Such a perspective is not necessarily intervention focused (Shiell et al., 2008; Mowles, 2014), but it can be used to inform decisions about interventions. For example, it can potentially improve understandings about how an intervention's interactions with the wider system in which it is embedded contribute to impacts relevant to health and health inequalities (Rutter et al., 2017; Shiell et al., 2008; Mowles, 2014). However, there remains uncertainty amongst public health researchers about what applying a complex systems perspective to intervention evaluation entails, the different methods involved, and the kinds of evaluative evidence they produce (Shiell et al., 2008; Allender et al., 2015; Cabrera et al., 2008; de Savigny and Taghreed, 2009; Peters, 2014).

1.1. Complex systems

Aristotle's phrase "the whole is greater than the sum of its parts" has been used to explain what is meant by the term 'complex system' (Kania et al., 2012). A system is made up of inter-related parts, but these parts alone do not make it 'complex'. A complex system is dynamic – its behaviour changes over time. These behavioural patterns or properties emerge when the parts of a system interact within a wider whole; they are not reducible to the functions of the individual components within the system. Complex systems cannot be fully known, controlled, or predicted – but researchers and stakeholders can analyse what makes a system behave in a certain way and how it can be shifted towards more desirable behaviour patterns (Meadows and Wright, 2008).

Numerous terms are used to describe complex systems; Table 1 explains those used in this article. Cause-and-effect relationships within a complex system are likely to be 'non-linear'; that is (and unlike simpler dose-response relationships), inputs into one part of the system can lead to disproportionate impacts over time. An action within a complex system may have its impacts diminished or amplified depending on how the rest of the system responds. For example, an intervention to restrict availability of certain alcoholic beverages may (hypothetically) find its health impact diminished if producers, retailers, and customers adapt by switching to producing, promoting, and purchasing other alcoholic products (McGill et al., 2016; Sumpter et al., 2016). Conversely, the impacts may be amplified if the intervention encourages retailers to promote healthier products, consumers to make healthier choices, and policy-makers to consider further restrictions on alcohol availability.

Complex systems have both a long academic tradition (dating back to ancient philosophy) and a more recent (dating from the 20th century) resurgence as a mathematical discipline. Gates (2016) has used the terms 'systems thinking' and 'complexity science' respectively to describe these two intersecting traditions .

Systems thinking draws on a somewhat loose collection of interdisciplinary fields (Gates, 2016). Researchers select methods, theories and concepts from these fields to help them examine the wider influences and causal pathways relevant to a particular phenomenon of interest. Systems thinking is concerned with the structure of a system, understanding and defining its 'boundaries', and making sense of the relationships between 'agents' and the wider system. Many systems thinking approaches gain insight from the multiple perspectives of different stakeholders and facilitate stakeholders and evaluators in restructuring their individual and collective understanding of the system in question (Gates, 2016; Ammerman et al., 2014; Carey et al., 2015; Walton, 2014).

Table 1
Glossary of terms.

Terms	Description
Adaptation	Adjustments in system behaviour in response to interventions.
Agents	Individuals, households, institutions, or other entities.
Boundaries	Defining what to include/exclude in the system we are interested in studying.
Complex intervention	Intervention described as complex based on: • "Number of interacting components within the experimental and control interventions • Number and difficulty of behaviours required by those delivering or receiving the intervention • Number of groups or organisational levels targeted by the intervention • Number and variability of outcomes • Degree of flexibility or tailoring of the intervention permitted". (Craig et al., 2008, p.2)
Emergence	Properties of a complex system that cannot be directly predicted from the elements within it and are more than just the sum of its parts.
Feedback loop	A positive or negative response that may alter the intervention and its impacts. Feedback loops describe a situation in which a change reinforces (amplifies) or balances (inhibits) further change.
Flows	Elements in a system that can increase or decrease a stock (e.g. investment rate or demographic developments can change the number of available houses).
Non-linear relationships	Relationships within a system that do not follow a simple, constant input-output line. Cause-and-effect relationships within a system are frequently disproportionate (bigger or smaller) to the initial input of an intervention.
Stocks	Elements in a system that can be accumulated or depleted (e.g.jobs or people in good health).
System	A set of entities (e.g. people, organisations, resources) and their interconnections. Complex systems involve elements interconnected in such a way that they produce their own pattern of behaviour over time.
Whole system intervention	A complex intervention that explicitly seeks to change several different points in a particular system (e.g. a local obesity strategy that includes school, high street, governmental, and media interventions).

Complexity science typically takes a dynamic system as its principal unit of analysis. Often, such research defines and models systems, using computer simulation, to draw conclusions about how systems might behave over time. There are various ways a complex system can be modelled (Williams and Hummelbrunner, 2010); the aim of such models is not to precisely replicate the 'real world,' but rather to create a helpful abstraction in order to evaluate its potential changes and the mechanisms that drive them.

Systems thinking and complexity science are intersecting research traditions, and there are potential risks and limitations of implementing one approach without the other. For example, a computational model that is developed without a multi-perspective understanding of the system may be viewed as flawed by stakeholders, while a systems thinking approach without some formal modelling may overlook key uncertainties and system behaviour that a computational approach could identify.

1.2. Public health evaluation

Most public health evaluations do not reflect either of these two traditions (Shiell et al., 2008; Hawe et al., 2009a; Petticrew et al., 2019). Instead, where complexity is mentioned at all, public health evaluations have tended to focus on the complexity of interventions (i.e. interventions with multiple components, stakeholders, and outcomes) (Craig et al., 2008). Increasingly, there have been calls for evaluative public health research to move beyond thinking of complexity solely as a property of an intervention (Rutter et al., 2017; Diez Roux, 2011; Shiell et al., 2008; Petticrew et al., 2019; Finegood et al., 2010). If complexity

is a property of the system within which an intervention is implemented, even an apparently simple intervention can result in complex interactions and emergent outcomes across that system (Shiell et al., 2008).

In this review, we synthesise evidence from studies that report applying a complex systems perspective to evaluations of *population-level interventions that seek to modify social determinants of health to impact on non-communicable disease outcomes*. As shorthand, we use the term 'public health intervention' when referring to such interventions. We define the term 'public health evaluation' to refer to studies of public health interventions. 'Systems methods' refers to methodological approaches used to apply a complex systems perspective to evaluations. Within the public health field, previous reviews of complex systems research have focussed on specific public health issues (Kania et al., 2012; Ammerman et al., 2014; Cockrell Skinner and Foster, 2013; Dooris et al., 2014; Hoang et al., 2016; Kowalczyk et al., 2015; Lapalme et al., 2014) or on particular approaches (Atkinson et al., 2015; Bagnall et al., 2019). Three previous reviews have involved a wider scoping of literature relevant to complex systems-oriented evaluation in public health, although none limit themselves to intervention evaluations (Ammerman et al., 2014; Carey et al., 2015; Walton, 2014). One review focused on 'whole system interventions', a term that is sometimes used to describe complex interventions that attempt to change many different parts of a system simultaneously (Bagnall et al., 2019).

This review aimed to: (i) describe and classify different types of systems methods applied in published public health evaluations; and (ii) examine the kinds of evaluative evidence generated by these different methods.

2. Methods

2.1. Study design

We applied systematic review and critical interpretive synthesis approaches to conduct a review of systems methods used in public health evaluations. The study protocol is provided in the Supporting Information 1 file. Critical reviews have been described by Dixon-Woods et al. (2006) as 'interpretive' in that they synthesise relevant examples from a complex body of literature with an intent to generate new concepts, theories, or interpretations. Interpretative synthesis may involve purposive sampling that seeks to capture the diversity of relevant examples. Interpretative synthesis is contrasted with 'aggregative' synthesis (e.g. systematic reviews of effectiveness) that attempt to test specific research hypotheses by synthesising findings from all the relevant high quality studies that can be identified (Dixon-Woods et al., 2006).

2.2. Data sources and searches

We employed a variety of search methods to identify studies. We consulted experts (n = 32) with an interest and expertise in systems-oriented public health research. We also conducted citation searches of relevant published systematic reviews beginning with two we had pre-identified (Carey et al., 2015; Walton, 2014). For our electronic search, we adapted search terms (Supporting Information 2) from those reviews and searched Scopus, MEDLINE and Web of Science, searching after the time period covered by the published systematic reviews (Carey et al., 2015; Walton, 2014). The databases were searched from January 2014 to September 2019.

2.3. Study screening

Identified studies were screened for relevance, supported by Covidence software (Veritas Health Innovation). A study was included if it met all of the following criteria:

1) Self-identifies as taking a systems or complexity-informed approach.
2) Focuses on a public health-relevant subject. We developed the following non-exhaustive list of topic areas to guide us: housing, policing, community safety, health promotion, community health, built environment, urban planning, regeneration, alcohol, obesity, food, trading standards, illicit substances, tobacco, social welfare, employment, transport, education, and environmental health. We focused on interventions that sought to modify social determinants of health and impact on non-communicable diseases.
3) Reports empirical findings to inform decision-making (i.e. not simply methodological discussion) from an evaluation of an existing or hypothetical intervention. We defined the term 'intervention' to refer to policies, initiatives, services, and activities that may be important for population health. We deliberately took a broad view of 'evaluation' that included any research intended to increase understanding of an intervention's impacts, mechanisms for impact, context, or implementation.

Primary studies from any country were eligible for inclusion, although the search was limited to English-language publications. Initially, titles and abstracts were screened to identify obviously non-eligible studies. Full text articles were then screened for relevance by two independent reviewers; a third reviewer reconciled disagreements.

2.4. Data extraction

Data extraction for each study was conducted independently by two reviewers using a table developed to capture information on each study's aim, intervention type, methods, findings, and recommendations for policy and practice. Disagreements were reconciled through consultation with a third reviewer.

2.5. Data analysis and synthesis

We developed a framework for mapping included studies onto different stages of an evaluative process from a close reading of the included studies, informed by our prior understandings of systems and evaluation. This combination of inductive and deductive interpretation fits with that found in critical interpretive synthesis and recognises that researchers cannot (and may not consider it desirable to) 'unknow' what they already know of the topic being reviewed (Dixon-Woods et al., 2006). Within this framework, we categorised studies by their methodological approach and purposively selected 'case study' papers that provided clear accounts of methods, and reported findings intended to inform policy and/or practice.

2.6. Researcher contributions

EM, TP, and VE led the review's search, selection, and data extraction process with further input from ME and MP to discuss issues and disagreements. M White, EM, ME, and TP led on the development of the framework. All authors suggested potential studies to include from their own knowledge, and provided input on the review protocol, case study selection, framework development, and manuscript drafts.

3. Findings

Seventy-four unique studies reported in 85 publications were included in the review (see Fig. 1), covering topic areas such as urban planning, transport, nutrition/obesity, sexual health, tobacco, substance abuse, school health promotion, strategies for tackling non-communicable disease, crime, violence, and anti-social behaviour. Table 2 shows the main characteristics of each included evaluation and is organised by the relevant methodological approach.

Table 3 presents a framework that includes (in the rows) five stages in an evaluation process ordered to parallel the theorising, planning,

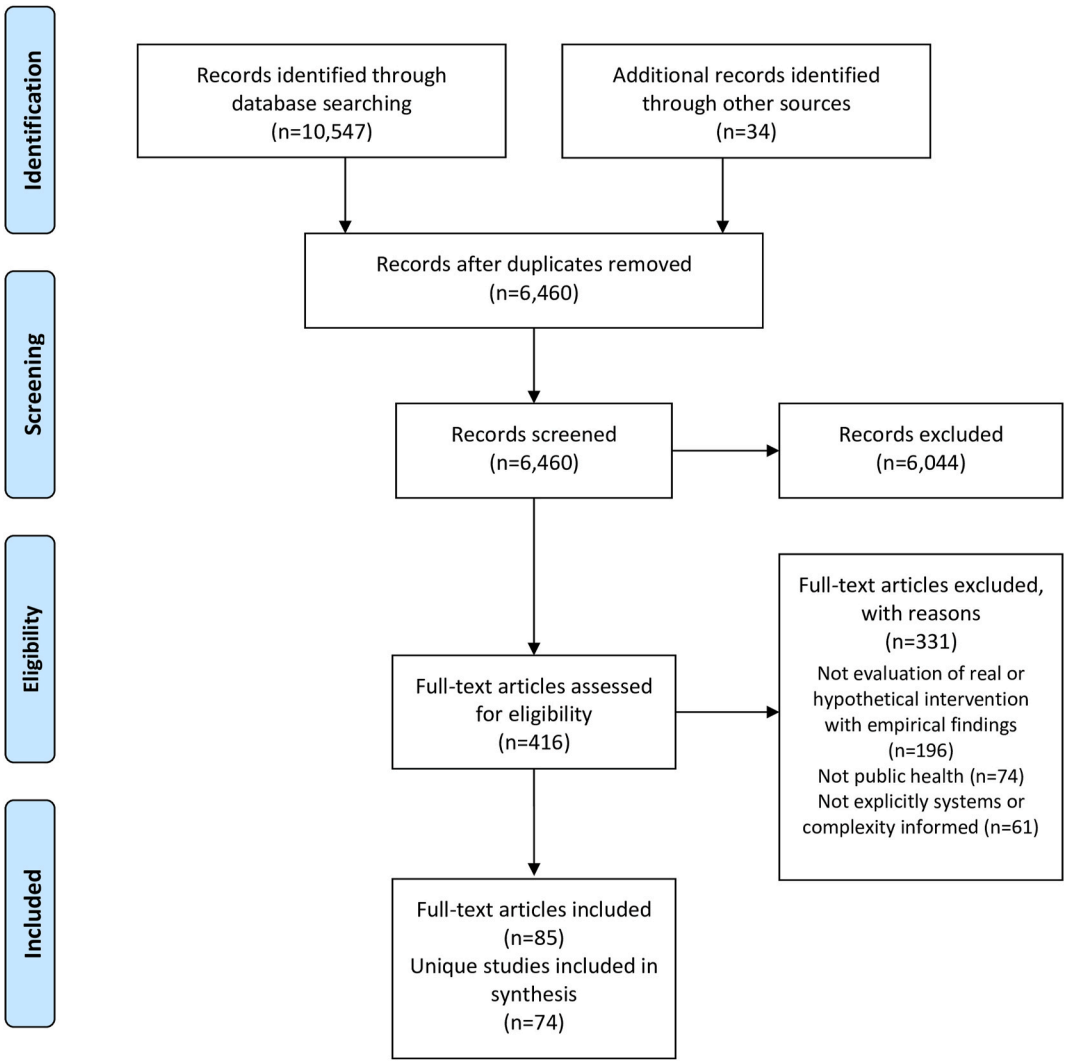

Fig. 1. Flow diagram for inclusion of studies.

delivery, assessment, and further delivery phases of the interventions they may seek to inform. The 'theorising' and 'prediction (simulation)' stages refer to studies that generate evidence to inform intervention development. The process evaluation and impact evaluation stages relate to studies that aim to generate evidence about implemented interventions; the former focuses on how the intervention is delivered, the latter on assessing its impacts. The 'further prediction (simulation)' stage relates to studies that provide evidence to inform longer-term decisions including decisions to deliver an already implemented intervention in new settings. We present this framework as a heuristic and do not suggest that the evaluative stages must occur in a sequential fashion, or all be a part of every evaluation. A particular type of systems method can be applied to more than one evaluative stage.

The columns of Table 3 describe the types of systems methods we identified from the included studies. Our typology is intended to differentiate between (i) studies that theorise and illustrate a system's boundaries and inter-related parts ('system mapping'); (ii) studies that focus on relationships between individuals or organisations relevant to a system ('network analysis'); (iii) computational models that simulate changes within a complex system over time ('system modelling'); and (iv) approaches that have emerged from the systems thinking tradition or from attempts to apply systems theories and concepts to other evaluation methods ('system framing'). This typology is, we accept, contestable given that studies often use multiple methods and the systems literature includes a large (and growing) number of methodological approaches – not all of which are amenable to simple classification. In the sections below, we provide more details of each type of systems method and consider how they have been used across the five stages of evaluation in our heuristic framework.

3.1. *Theorising*

Theory has an important part to play across all the stages of an evaluative process, but 'Theorising' appears first in the framework because systems approaches often begin by theorising the structure of the system of interest – its boundaries, the elements that comprise it, and the way they relate to one another. Theorising research can identify potential points of intervention in the system and suggests ways in which it might interact with that system.

System mapping approaches are frequently used at this stage, particularly maps generated from structured stakeholder mapping workshops. Forty-five evaluations included in this review reported some form of system mapping, or presented some form of diagrammatic representation of a system (see Table 2). Three of these studies (including Case Study 1) gave a particularly prominent role to system mapping (Brennan et al., 2015; Thomas and Reilly, 2015; Rosas and Knight, 2019; Urwannachotima et al., 2019). However, most used system maps as a tool within the context of another method. In such studies, they were developed at an early or interim stage of an evaluation to aid study design and provide a framework for further modelling or

Table 2
Summary of included studies by methodological approach.

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
SYSTEM MAPPING AS A DISTINCT APPROACH					
Brennan et al. (2015); Thomas and Reilly (2015)	Systems thinking in 49 communities related to healthy eating, active living, and childhood obesity.	To use group model building methodology to identify and analyse the essential components of the system influencing policy and change in 49 Healthy Kids, Healthy Community sites.	Causal Loop Diagram. Concept Map.	System-wide theory of change (ToC). Learning through study participation. (Obesity). Theorising.	Implemented
Rosas and Knight (2019)	Evaluating a complex health promotion intervention: case application of three systems methods.	To determine how the complex, dynamic interactions within IM40 (a youth development intervention) might be mapped and understood.	Stock and Flow Diagram. Viable systems model. Sociogram.	System-wide ToC. Learning through study participation. Diffusion of knowledge/practice. (Youth development). Theorising.	Implemented
Urwannachotima et al. (2019)	Sugar-sweetened beverage tax and potential impact on dental caries in Thai adults: an evaluation using the group model building approach.	To elicit and represent the dynamic relationships between sugar-sweetened beverage tax, sugar consumption, and oral health outcomes in Thailand using a group model building approach.	Causal Loop Diagram.	Barriers and facilitators within, across system levels. System-wide ToC. Learning through study participation. (Unhealthy commodities; dental health). Theorising.	Implemented
NETWORK ANALYSIS					
Fuentes et al. (2018)	Development and complex dynamics at school environment.	To evaluate behavioural plasticity of social relationships between peers aged 6–7 who participated in a school-based intervention.	Sociograms.	Diffusion of knowledge/practice. Impact of intervention(s). (School health; mental health). Impact evaluation. Behavioural impacts.	Implemented
Rosas and Knight (2019)	Evaluating a complex health promotion intervention: case application of three systems methods.	To determine how the collaborative relationships among IM40 (youth development intervention) stakeholders manifested.	Stock and Flow Diagram. Viable systems model. Sociogram.	Diffusion of knowledge/practice. System-wide ToC. (Youth development). Process evaluation.	Implemented
White and Levin (2016)	Navigating the turbulent waters of school reform guided by complexity theory.	To use complexity sciences as a theoretical framework to develop, implement, and evaluate a school reform design experiment at a high school with low-income, low-performing underrepresented minority students.	Various including Concept Map, multi-mediator models and network diagrams.	Diffusion of knowledge/practice. Learning through study participation. System-wide ToC. (School health). Process evaluation.	Implemented
SYSTEM MODELLING					
Adams and Schaefer (2016)	How initial prevalence moderates network-based smoking change: Estimating contextual effects with stochastic actor-based models.	To use an empirically-grounded ABM to examine how initial smoking prevalence moderates the effectiveness of potential network-based interventions designed to change adolescent smoking behaviour.	None.	Impacts of variation in local context on interventions. (Tobacco). Prediction.	Hypothetical
Allender et al. (2019)	Translating systems thinking into practice for community action on childhood obesity.	To report on insights gained during the development, implementation, and evaluation of the first 2 years in a systems-based childhood obesity prevention initiative.	Causal Loop Diagrams referenced.	System-wide ToC. Learning through study participation. (Obesity). Theorising and process evaluation.	Implemented
Araz et al. (2018)	Complex systems modelling for evaluating potential impact of traffic safety policies: a case on drug-involved fatal crashes.	To assess the complex interrelationships and dynamics among drugged drivers, drugged driving laws, public transportation, drug use treatment, and traffic congestion, and to evaluate the impact of a drug law on drugged-related crash fatalities.	Causal Loop Diagram. Stock and Flow Diagram.	Simulated intervention impacts. System-wide ToC. (Road traffic safety). Prediction.	Hypothetical
Atkinson et al. (2018)	Impacts of licensed premises trading hour policies on alcohol-related harms.	To use an ABM to compare estimated impacts over time of a range of trading hour policy options on various indicators of acute alcohol-related harm.	None.	Simulated intervention impacts. System-wide ToC. (Substance use). Prediction.	Hypothetical
Beheshti et al. (2017)	Comparing methods of targeting obesity interventions in populations: an agent-based simulation.	To develop and use an ABM to evaluate different network-based methods of targeting obesity interventions.	None.	Diffusion of knowledge/practice. Simulated intervention impacts. System-wide ToC. (Obesity). Prediction.	Hypothetical
Biroscak et al. (2014)	Applying systems science to evaluate a community-	To identify and formulate a dynamic hypothesis that accounts			Implemented

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Table 2 (*continued*)

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
	based social marketing innovation: a case study.	for the behaviour of key community-based prevention marketing variables.	Causal Loop Diagram. Stock and Flow model referenced.	System-wide ToC. Learning through study participation. (Obesity). Further prediction.	
Caroleo et al. (2017)	Assessing the impacts of electric vehicles uptake: a system dynamics approach.	To estimate the environmental health impacts of alternative market scenarios for electric vehicles diffusion in Piedmont, Italy.	Causal Loop Diagram.	Simulated intervention impacts. System-wide ToC. (Environmental health). Prediction.	Hypothetical
Chen et al. (2018)	Obesity trend in the United States and economic intervention options to change it: a simulation study linking ecological epidemiology and system dynamics modelling.	To study the country-level dynamics and influences between population weight status and socio-economic distribution in the US; to project the potential impacts of socio-economic-based intervention options on obesity prevalence.	Concept Map.	Simulated intervention impacts. System-wide ToC. (Obesity). Prediction.	Hypothetical
Combs et al. (2019); Luke et al. (2017)	Modelling the impact of menthol sales restrictions & retailer density reduction policies: insights from Tobacco Town Minnesota. Tobacco Town: computational modelling of policy options to reduce tobacco retailer density.	To develop an ABM to project the impact of menthol cigarette sales restrictions and retailer density reduction policies for different communities and populations; to identify the behavioural mechanisms and effects of tobacco control policies designed to reduce tobacco retailer density.	None.	Simulated intervention impacts. Impacts of variation in local context on interventions. System-wide ToC.(Tobacco). Prediction.	Hypothetical
Eker et al. (2018)	Participatory system dynamics modelling for housing, energy and wellbeing interactions.	To explore the dynamic relationship between housing performance, energy, communal spaces, and wellbeing with simulation modelling.	Causal Loop Diagrams. Stock and Flow Diagram.	Barriers and facilitators within, across system levels. Simulated intervention impacts. System-wide ToC. Learning through study participation. (Built environment; housing). Prediction.	Hypothetical
Guo et al. (2016)	System dynamics-based evaluation of interventions to promote appropriate waste disposal behaviors in low-income urban areas: a Baltimore case study.	To determine what interventions are most effective at improving waste disposal practices in Baltimore, Maryland.	Stock and Flow Diagrams.	Simulated intervention impacts. System-wide ToC. (Household waste disposal). Prediction.	Hypothetical
Guzman et al. (2013)	Optimal and long-term dynamic transport policy design: seeking maximum social welfare through a pricing scheme.	To examine how forecasting, analysis, and optimisation procedures can support a decision-making process to create the best achievable transport design with regards to social welfare.	Causal Loop Diagram. Stock and Flow model referenced.	Simulated intervention impacts. System-wide ToC. (Transport). Prediction.	Hypothetical
Haghshenas et al. (2015)	Evaluation of sustainable Policy in urban transportation using system dynamics and world cities data: a case study in Isfahan.	To analyse impacts of transportation policies using a SD model based on pertinent data of world cities.	Causal Loop Diagram. Stock and Flow Diagram.	Simulated intervention impacts. System-wide ToC. (Transport). Prediction.	Hypothetical
Hirsch et al. (2010)	A system dynamics model for planning cardiovascular disease interventions.	To use a SD model to project trajectories for future incidence and prevalence of CVD under different strategies for reducing the county's CVD burden. .	Diagram presenting overview of model. Stock and Flow model referenced.	Simulated intervention impacts. System-wide ToC. (Cardiovascular disease). Prediction.	Hypothetical
Honeycutt et al. (2019)	Simulated impacts and potential cost effectiveness of Communities Putting Prevention to Work: tobacco control interventions in 21 U.S. communities, 2010–2020.	To estimate the potential long-term cost-effectiveness of Communities Putting Prevention to Work.	None.	Impact and simulated long-term impacts of intervention. (Tobacco). Further prediction	Implemented
Jalali et al. (2019)	Dynamics of intervention adoption, implementation, and maintenance inside organisations: the case of an obesity prevention initiative.	To understand the dynamics that regulate the adoption, implementation, and maintenance of organisational-level intervention programmes.	Causal Loop Diagrams. Stock and Flow Diagrams.	Simulated intervention impacts. System-wide ToC. (Obesity). Process evaluation and further prediction.	Implemented
Jin and White (2012)					Hypothetical

(*continued on next page*)

Table 2 (*continued*)

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
	An agent-based model of the influence of neighbourhood design on daily trip patterns.	To explore the influences of neighbourhood design on trip and traffic patterns with an emphasis on pedestrian movements.	Spatial patterning image.	Simulated intervention impacts. (Urban planning). Prediction.	
Kasman et al. (2019)	Activating a community: an agent-based model of Romp & Chomp, a whole-of-community childhood obesity intervention.	To explore stakeholder-driven community diffusion by employing an ABM to retrospectively simulate a successful whole-of-community childhood intervention.	None.	Diffusion of knowledge/practice. Impacts of variation in local context on interventions. System-wide ToC. (Obesity). Process evaluation.	Implemented
Keyes et al. (2019a)	Assessing the impact of alcohol taxation on rates of violent victimization in a large urban area: an agent-based modelling approach.	To use simulation to estimate the impact of alcohol taxation on drinking, non-fatal violent victimization and homicide in New York City.	Diagram depicting relationships between agents, social network and neighbourhood characteristics.	Simulated intervention impacts. Impacts of variation in local context on interventions. System-wide ToC. (Violence prevention). Prediction.	Hypothetical
Keyes et al. (2019b)	Simulating the suicide prevention effects of firearms restrictions based on psychiatric hospitalization and treatment records: social benefits and unintended consequences.	To estimate the number of lives saved from firearms suicide with expansions of gun restrictions based on mental health compared with the number who would be unnecessarily restricted.	None.	Simulated intervention impacts. System-wide ToC. (Suicide prevention). Prediction.	Hypothetical
Koh et al. (2019)	Examining disparities in food accessibility among households in Columbus, Ohio: an agent-based model.	To evaluate the effect of complex interactions among household and environmental-level factors on household-level food availability via a simulation model, the Food Accessibility Agent-based Model in Central Columbus, Ohio; to test impacts of novel interventions for reducing disparities in food availability.	Concept map. Spatial patterning image.	Simulated intervention impacts. System-wide ToC. (Food security). Prediction.	Hypothetical
Kuo et al. (2016)	Framing the local context and estimating the health impact of CPPW obesity prevention strategies in Los Angeles County, 2010–2012.	To determine the county-wide health effects of obesity prevention strategies in 3 programme focus areas in LA County.	None.	Simulated intervention impacts. Impacts of variation in local context on interventions. (Obesity). Further prediction.	Implemented
Lee et al. (2018)	Simulating the impact of sugar-sweetened beverage warning labels in three cities.	To determine the impacts of sugar-sweetened beverage warning labels on overweight and obesity prevalence among adolescents in Baltimore, Philadelphia and San Francisco.	Diagram of model depicting agents in their environment.	Simulated intervention impacts. Impacts of variation in local context on interventions. System-wide ToC. (Obesity). Prediction.	Hypothetical
Li et al. (2018)	Assessing the role of access and price on the consumption of fruits and vegetables across New York City using agent-based modelling.	To develop and use an ABM to provide insights on how to increase the consumption of fruits and vegetables in New York City by simulating populations, food consumption decisions, local food environments, interventions, and their complex interactions in different neighbourhoods.	None.	Impacts of variation in local context on interventions. Diffusion of knowledge/practice. (Nutrition). Prediction.	Hypothetical
Lich et al. (2017)	Extending systems thinking in planning and evaluation using group concept mMapping and system dynamics to tackle complex problems.	To combine group concept modelling and SD modelling to survey, organise, and prioritise factors contributing to outcomes with a broad, diverse group of stakeholders.	Concept Map, Causal Loop Diagram, Stock and Flow Diagram.	System-wide ToC. Learning through study participation. Intervention impacts. Further prediction. (Mental health).	Implemented
Loyo et al. (2013)	From model to action: using a system dynamics model of chronic disease risks to align community action.	To use a SD model as a catalyst to align multiple stakeholders to develop a comprehensive strategy for reducing chronic diseases and related costs in Austin, Texas.	Concept Map. Other maps referenced but not specified.	Simulated intervention impacts. (Chronic disease). Prediction.	Hypothetical
Lyon et al. (2016)	Modelling the impact of school-based universal depression screening on additional service capacity needs: a system dynamics approach.	To use SD modelling to assess the anticipated impacts of two service improvement approaches for a universal depression screening program on service need and use in a high school.	Stock and Flow Diagram.	Simulated intervention impacts. System-wide ToC. (Mental health). Prediction.	Hypothetical
Manohar et al. (2014)	Evaluation of policies to reduce transportation	To use SDs to evaluate the impact of road expansion, public transit	None.	Simulated intervention impacts. (Transport pollution). Prediction.	Hypothetical

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Table 2 (*continued*)

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
	pollution using system dynamics.	incentive, and enforcement of quality norms on pollution caused by road transportation.			
Nyabadza and Coetzee (2017)	A systems dynamic model for drug abuse and drug-related crime in the Western Cape Province of South Africa.	To use SD to investigate the relationship between substance abuse and drug-related crimes in the Western Cape of South Africa and the predicted impact of increasing convictions and correctional service referrals to rehabilitation services, and reducing relapsing in this setting.	Stock and Flow Diagram.	Simulated intervention impacts. System-wide ToC. (Substance use, crime). Prediction.	Hypothetical
Safan et al. (2018)	Modelling the diet dynamics of children: the roles of socialization and the school environment.	To evaluate the roles of socialization and school environment on the diet dynamics of children.	Diagram of modified social-ecological theory.	System-wide ToC. (Diet). Prediction.	Hypothetical
Scott et al. (2016)	The effects of extended public transport operating hours and venue lockout policies on drinking-related harms in Melbourne, Australia: results from SimDrink, an agent-based simulation model.	To use computer simulation to test the effects of improved public transport and venue lockouts on verbal aggression, consumption-related harms, and transport-related harms among a population of young adults engaging in heavy drinking in Melbourne.	None.	Simulated intervention impacts. (Substance use, transport). Prediction.	Hypothetical
Soler et al. (2016)	Community-based interventions to decrease obesity and tobacco exposure and reduce health care costs: outcome estimates from Communities Putting Prevention to Work for 2010–2020.	To estimate short-term and long-term benefits of the Communities Putting Prevention to Work by modelling the impact of the intervention on risk behaviours and on reductions in health and economic outcomes.	None.	Simulated intervention impacts. (Obesity and tobacco). Further prediction.	Implemented
Spicer et al. (2012)	Bars on blocks: cellular automata model of crime and liquor licenced establishment density	To use a complex systems approach to explore how varying liquor licensing density impact crime.	Diagram of system-wide processes occurring at each time step.	Simulated intervention impacts. (Substance use, crime). Precision.	Hypothetical
Tengs et al. (2001)	The cost-effectiveness of intensive national school-based anti-tobacco education: results from the Tobacco Policy Model.	To evaluate the cost-effectiveness of enhanced nationwide school-based anti-tobacco education relative to the status quo.	None.	Simulated intervention impacts. Impacts of variation in local context on interventions. (Tobacco). Prediction.	Hypothetical
Tobias et al. (2010)	Application of a system dynamics model to inform investment in smoking cessation services in New Zealand.	To estimate the long-term effects of smoking cessation interventions to inform government decision-making regarding investment in tobacco control in New Zealand.	Stock and Flow Diagram.	Simulated intervention impacts. System-wide ToC. (Tobacco). Prediction.	Hypothetical
Wakeland et al. (2013)	Modelling the impact of simulated educational interventions on the use and abuse of pharmaceutical opioids in the United States: a report on initial efforts.	To simulate the effects of three educational interventions in a SD model of the medical use, trafficking, and nonmedical use of pharmaceutical opioid.	Stock and Flow Diagram.	Simulated intervention impacts. System-wide ToC. (Substance use). Prediction.	Hypothetical
White and Levin (2016)	Navigating the turbulent waters of school reform guided by complexity theory.	To develop ABMs that capture important dynamic properties of a school reform design at different tipping points (purposeful perturbations).	Various including Concept Map, multi-mediator models and network diagrams.	Simulated intervention impacts. Learning through study participation. System-wide ToC. (School health). Further prediction.	Implemented
Yang et al. (2014)	Examining the impact of the Walking School Bus with an agent-based model.	To use an ABM to examine the impact of the Walking Cchool Bus on children's active travel to school.	None.	Simulated intervention impacts. System-wide ToC. (Child health). Prediction.	Implemented
Yonas et al. (2013)	Dynamic simulation of crime perpetration and reporting to examine community intervention strategies.	To develop a conceptual computational ABM to explore community-wide versus spatially focused crime reporting interventions to reduce community crime perpetrated by youth.	Spatial patterning image.	Simulated intervention impacts. (Violent crime). Prediction.	Hypothetical
York et al. (2017)	Infrastructure implications of a green economy transition in the	To model the impacts of investment in public passenger transport, freight rail systems, or a	Causal Loop Diagram. Stock and Flow model referenced.	Simulated intervention impacts. (Transport). Prediction.	Hypothetical

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Table 2 (*continued*)

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
	Western Cape province of South Africa.	combination of these on the green economy infrastructure in the Western Cape, South Africa.			
Zhang et al. (2014)	Impact of different policies on unhealthy dietary behaviors in an urban adult population: an agent-based simulation model.	To contrast the potential of different approaches aimed at tackling unhealthy dietary behaviours in a population of urban US adults and examine how individual beliefs are influenced by interventions in the social network or food environment	None.	Simulated intervention impacts. (Obesity). Prediction.	Hypothetical
SYSTEM FRAMING					
Alfandari (2017, 2019)	Systemic barriers to effective utilization of decision making tools in child protection practice.	To qualitatively evaluate how and if a national reform in Israeli child protection decision making committees strengthened professional judgment through introducing a new standard tools package.	None.	Barriers and facilitators within, across system levels. (Social care). Process evaluation.	Implemented
Bartelink et al. (2019); Bartelink et al. (2018)	Process evaluation of the healthy primary School of the Future: The key learning points.	To explore the processes through which 'Healthy Primary School of the Future' and the school context adapt to one another to generate and share knowledge and experiences on how to implement changes in the complex school system.	Diagram of programme theory incorporating feedback loops.	Barriers and facilitators within, across system levels. System-wide ToC. (Health promotion). Process evaluation.	Implemented
Blackman et al. (2011)	A Qualitative Comparative Analysis of factors associated with trends in narrowing health inequalities in England.	To use Qualitative Comparative Analysis to explore the conditions associated with the narrowing of premature mortality from cardiovascular disease and cancer in deprived English local authorities compared to the national average.	None.	Impacts of variation in local context on interventions. (Cardiovascular disease, cancer). Impact evaluation.	Implemented
Blackman et al. (2013)	Using Qualitative Comparative Analysis to understand complex policy problems.	To use Qualitative Comparative Analysis to understand what conditions are associated with narrowing or not narrowing the gap between teenage conceptions in deprived local authority areas in England compared to the national average.	None.	Impacts of variation in local context on interventions.(Sexual health). Impact evaluation.	Implemented
Burman and Aphane (2016)	Leadership emergence: the application of the Cynefin framework during a bio-social HIV/ AIDS risk-reduction pilot.	To use the Cynefin framework to situate emergent knowledge action spaces into appropriate decision-making domains, which can then be used to develop subsequent phases of interventions.	Cynefin framework diagram.	Learning through study participation. (School health, sexual health). Process evaluation.	Implemented
(Crane et al., 2019a) Crane et al. (2019b))	Evaluation of Get Healthy at Work, a state-wide workplace health promotion program in Australia.	To evaluate the state-wide implementation of a complex initiative to reduce workers' risk of chronic disease in Australia and to assess its short-term impacts at the business level.	Diagram of programme implementation levels and interaction points; programme cycle.	Barriers and facilitators within, across system levels. System-wide ToC. Implementation variation. (Health promotion). Process evaluation.	Implemented
Czaja et al. (2016)	Characterizing implementation strategies using a systems engineering survey and interview tool: a comparison across 10 prevention programs for drug abuse and HIV sexual risk behaviour'.	To determine how a systems engineering approach can be used to identify the requirements for implementing prevention programs, focused on the prevention of drug or HIV sex risk behaviours.	Diagram of system elements and levels.	Barriers and facilitators within, across system levels. System-wide ToC. (Substance use, sexual health). Process evaluation.	Implemented
Dickson-Gomez et al. (2018)	A social systems analysis of implementation of El Salvador's national HIV combination prevention: a research agenda for evaluating Global Health Initiatives.	To examine the implementation of a national HIV combination prevention strategy in El Salvador funded by the Global Fund to Fight AIDS, Tuberculosis and Malaria.	Diagram of pathways to system goals with feedback loops.	Barriers and facilitators within, across system levels. System-wide ToC. (Sexual health). Process evaluation.	Implemented
Durie and Wyatt (2013)	Connecting communities and complexity: a case	To evaluate a learning programme designed to create	None.	Barriers and facilitators within, across system levels. System-wide	Implemented

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Table 2 (*continued*)

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
	study in creating the conditions for transformational change.	transformational community change.		ToC. Learning through study participation. (Community transformation). Process evaluation.	
Evans et al. (2015)	Implementation of a school-based social and emotional learning intervention: understanding diffusion processes within complex systems.	To use a formative process evaluation to examine how the Student Assistance Programme changed as it moved through different phases of the diffusion of innovations framework.	None.	Impacts of variation in local context on interventions. (School health). Process evaluation.	Implemented
Fahey et al. (2003, 2004)	Applying systems modelling to public health.	To demonstrate the value of using soft systems methodology to enhance the understandings of a proposed public health network.	Conceptual model and soft systems model of public health network. Input/output process model.	System-wide ToC. Barriers and facilitators within, across system levels. (Public health network). Theorising.	Hypothetical
Figueiro et al. (2017)	A tool for exploring the dynamics of innovative interventions for public health: the critical event card.	To describe the development and proof of concept process of 'the critical event card', which supports the representation and analysis of complex interventions' evolution, based on critical events.	Bespoke timeline of critical events across the system showing interaction between elements.	Diffusion of knowledge/practice. System-wide ToC. Learning through study participation. (Public health strategy). Process evaluation.	Implemented
Fisher et al. (2016)	Social determinants in an Australian urban region: a 'complexity' lens.	To use a complexity lens to assess the extent to which an alliance of health and human service networks promotes effective action on the social determinants of health in an Australian urban region and to identify potential barriers to the alliance.	Diagram of interactions between elements within and across system levels.	Barriers and facilitators within, across system levels. Diffusion of knowledge/practice. System-wide ToC. (Urban Planning). Process evaluation.	Implemented
Grant (2015)	European Healthy City Network Phase V: patterns emerging for healthy urban planning.	To conduct a Realist analysis into the challenges and emergent developments in Phase V of the WHO European Healthy Cities Network.	Conceptual framework of system activities and levels.	Barriers and facilitators within, across system levels. System-wide ToC. (Urban planning). Process evaluation.	Implemented
Haggard et al. (2015)	Implementation of a multicomponent Responsible Beverage Service programme in Sweden - a qualitative study of promoting and hindering factors.	To identify factors that promote or hinder implementation of a multicomponent Responsible Beverage Service programme in Swedish municipalities.	None.	Barriers and facilitators within, across system levels. (Substance use). Process evaluation.	Implemented
Kearney et al. (2016)	Applying systems theory to the evaluation of a whole school approach to violence prevention	To use conceptual approaches from systems science to examine how multiple systems layers interacted and influenced each other within the context of a whole school approach to violence prevention.	None.	Barriers and facilitators within, across system levels. Impacts of variation in local context on interventions. System-wide ToC. (Violence prevention). Process evaluation.	Implemented
Igras et al. (2014)	Systems approach to monitoring and evaluation guides scale up of the Standard Days Method of family planning in Rwanda.	To describe how a successful pilot program to integrate the Standard Days Method of family planning into existing Ministry of Health services was scaled up nationally in Rwanda.	None.	Barriers and facilitators within, across system levels. Learning through study participation. System-wide ToC. (Sexual health). Process evaluation.	Implemented
Knai et al. (2018)	The Public Health Responsibility Deal: Using a systems-level analysis to understand the lack of impact on alcohol, food, physical activity, and workplace health sub-systems.	To understand: 1) the causal pathways involved in the RD and how did they help or hinder it; 2) the RD structures, processes and interests at play; 3) the feedback loops, and if they suppressed or potentiated the effects of the RD on the outcomes of interest; and 4) how resilient the system was to change and its ability to 'absorb' externally directed change.	Causal Loop Diagram.	Barriers and facilitators within, across system levels. System-wide ToC. (Public private partnership). Process evaluation.	Implemented
McGill et al. (2016); Sumpter et al. (2016)	Consequences of removing cheap, super-strength beer and cider: a qualitative study of a UK local alcohol availability intervention. Reducing the Strength: a mixed methods evaluation of	To determine how a systems perspective can be used to explore the intervention's intended and unintended consequences within the local system and the effect of the intervention on alcohol availability.	Diagram of theories of change at different system levels.	System-wide ToC. Unplanned events and consequences. Diffusion of knowledge/practice. (Substance use). Process evaluation.	Implemented

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Table 2 (*continued*)

Author(s) (Date)	Title	Research aim	System diagram	Types of findings (Topic area). Evaluation stage.	Implemented/ Hypothetical intervention
	alcohol retailers' willingness to voluntarily reduce the availability of low cost, high strength beers and ciders in two UK local authorities				
Orton et al. (2017)	Putting context centre stage: evidence from a systems evaluation of an area based empowerment initiative in England.	To assess how a systems approach can be used to help understand how change processes that emerge as social initiatives embed and co-evolve within a series of local contexts.	None.	Impacts of variation in local context on interventions. System-wide ToC. (Community empowerment). Process evaluation.	Implemented
Pérez-Escamilla et al. (2017)	Scaling up Integrated Early Childhood Development programs: lessons from four countries.	To examine the process of scaling up major country-level early childhood development programmes through the application of a complex adaptive systems framework.	None.	Barriers and facilitators within, across system levels. System-wide ToC. (Child development). Process evaluation.	Implemented
Pérez-Escamilla et al. (2018)	Prevention of childhood obesity and food policies in Latin America: from research to practice	To identify and examine key elements to translating research into effective obesity policies in Latin America using a complex adaptive systems framework.	None.	Barriers and facilitators within, across system levels. System-wide ToC. (Obesity). Process evaluation.	Implemented
Rosas and Knight (2019)	Evaluating a complex health promotion intervention: case application of three systems methods.	To determine how the collaborative relationships among IM40 (youth development intervention) stakeholders manifested.	Stock and Flow Diagram. Viable systems model. Sociogram.	Diffusion of knowledge/practice. System-wide ToC. (Youth development). Process evaluation.	Implemented
Rothwell et al. (2010)	Implementing a social-ecological model of health in Wales.	To assess the implementation of the Welsh Network of Healthy School Schemes at national, local and school levels, using a systems approach.	Diagram of system structure and interactions.	Barriers and facilitators within, across system levels. Diffusion of knowledge/practice. System-wide ToC. (Health promotion School health). Process evaluation.	Implemented
Schelbe et al. (2018)	Systems theory as a framework for examining a college campus-based support program for the former foster youth.	To describe the application of systems theory as a framework for examining a college campus-based support program for former foster youth.	None.	Learning through study participation. System-wide ToC. (Youth support). Process evaluation.	Implemented
Shankardass et al. (2018)	The implementation of Health in All Policies initiatives: A systems framework for government action.	To present a systems framework to evaluate the implementation of Health in All Policies initiatives and to apply the framework to the Finnish policy 'Health 2015'.	Diagram of system structure.	Barriers and facilitators within, across system levels. System-wide ToC. (Health equity policy). Process evaluation.	Implemented
Stevens and Salmon (2014)	Safe places for pedestrians: using cognitive work analysis to consider the relationships between the engineering and urban design of footpaths.	To demonstrate how work domain analysis can bring together into one analysis the often-competing requirements and contexts of the engineering and technical standards of footpaths with their urban design potential.	Diagram of work domain analysis showing system interactions.	System-wide ToC. Impacts of variation in local context on interventions. (Transport). Process evaluation.	Implemented
van Twist et al. (2015)	Assessing and appraising the effects of policy for wicked issues: including unforeseen achievements in the evaluation of the district policy for deprived areas in The Netherlands.	To use a case of urban regeneration projects to study how unplanned and unforeseen events and consequences of policy were accounted—or neglected—in the evaluation methods and to present an alternative approach that considers policy "by-effects".	None.	Unplanned events and consequences. (Urban planning). Process evaluation.	Implemented
Walton (2016)	Setting the context for using complexity theory in evaluation: boundaries, governance and utilization.	To consider how programme framing and governance can help or hinder application of complexity theory to public health evaluation and policy, using a school health promotion intervention case study.	None.	Barriers and facilitators within, across system levels. Diffusion of knowledge/practice. (School Health) Process evaluation.	Implemented
White et al. (2017); Law et al. (2020a, 2020b); Pell et al. (2019); Scarborough et al. (2020)	Evaluation of the health impacts of the UK Treasury Soft Drinks Industry Levy (SDIL).	To conceptualise the SDIL as a series of events introduced into a complex system, to assess how the intervention affects economic, social and health outcomes and to model future health impacts.	System map depicting system-wide theory of change.	System-wide ToC. Intermediate outcomes. Unintended consequences. Impact of intervention(s). (Obesity). Process and impact evaluation.	Implemented

Table 3
Heuristic framework mapping systems methods against stages of evaluation.

Stages of evaluation	Aim	System mapping	Network analysis	System modelling	System framing
Theorising	Identify and compare stakeholder understandings of a complex system.	●			●
	Identify and compare stakeholder understandings of how a planned/hypothesised intervention might interact within a complex system.	●			●
Prediction (simulation)	Hypothesise and simulate how an intervention may impact on and interact with a complex system.			●	
	Hypothesise and simulate how agents within a complex system react and interact in response to an intervention.			●	
Process evaluation	Understand how an implemented intervention has impacts within a complex system in the real world, including impacts of variation in local context.	●	●	●	●
Impact evaluation	Quantify the impacts of an implemented intervention on key system parameters in the real world.		●		●
Further prediction (simulation)	Hypothesise and simulate how an intervention may impact on and interact with a complex system over a longer time horizon or in a different context.			●	
	Hypothesise and simulate how agents within a complex system might react and interact in response to an intervention over a longer time horizon or in a different context.			●	

qualitative analysis. Mapping workshops were also used to bring stakeholders together to help them understand each other's perspectives and encourage joint decision-making (Rosas and Knight, 2019; Urwannachotima et al., 2019).

System maps are well established within complexity science and take various forms. System maps developed for modelling presented variables known as 'stocks' and 'flows' (see Table 1) (Rosas and Knight, 2019; Araz et al., 2018; Eker et al., 2018; Guo et al., 2016; Haghshenas et al., 2015; Jalali et al., 2019; Lich et al., 2017; Lyon et al., 2016; Nyabadza and Coetzee, 2017; Tobias et al., 2010; Wakeland et al., 2013). Twelve evaluations presented causal loop diagrams, which omit some of the details found in stock and flow diagrams and have a particular focus on identifying feedback loops (Brennan et al., 2015; Urwannachotima et al., 2019; Araz et al., 2018; Biroscak et al., 2014; Caroleo et al., 2017; Eker et al., 2018; Guzman et al., 2013; Haghshenas et al., 2015; Jalali et al., 2019; Lich et al., 2017; York et al., 2017; Knai et al., 2018). Six studies presented concept maps, used to illustrate a wide array of factors relevant to a particular intervention (Brennan et al., 2015; White and Levin, 2016; Chen et al., 2018; Koh et al., 2019; Lich et al., 2017; Loyo et al., 2013). Two network analysis studies presented sociograms: maps showing relationships between agents such as people or organisations (Rosas and Knight, 2019; Fuentes et al., 2018).

Eleven studies presented *ad hoc* systems diagrams, designed by evaluators specifically for their studies (McGill et al., 2016; Bartelink et al., 2019; Crane et al., 2019a; Crane et al., 2019b; Czaja et al., 2016; Dickson-Gomez et al., 2018; Figueiro et al., 2017; Fisher et al., 2016; Grant, 2015; Rothwell et al., 2010; Shankardass et al., 2018; White et al., 2017). The studies that developed these maps did not appear to have collected data using formally structured mapping workshops. Instead, they typically collected data through a range of qualitative methods (document analysis, interviews, and focus groups). Three studies drew on systems frameworks originally developed for business and administration (soft systems methodology (Fahey et al., 2003; Fahey et al., 2004); 'Cynefin' (Burman and Aphane, 2016); and the 'viable systems model' (Rosas and Knight, 2019)) and presented visual aids associated with the literature on these frameworks.

Case Study 1: System mapping
Systems thinking in 49 communities related to healthy eating, active living and childhood obesity (Brennan et al., 2015)
Aim
To develop causal maps for 49 Healthy Kids, Healthy Communities (HKHC) in order to create a synthesised causal map that identifies the common variables and major system feedback structures.
Intervention
A community partnership implemented in 49 areas in the US and Puerto Rico to create policy, system, and environmental changes to improve eating and promote active living. The intervention was aimed at children and families, with a particular emphasis on children at highest risk of obesity.

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Methods
In each HKHC area, a half-day group model building workshop was held with a range of participants, including: residents, elected officials, representatives from government, community organisations, businesses, and researchers. Participants created behaviour-over-time graphs to map variables that affect or are affected by healthy eating, active living, and childhood obesity. Participants then created a causal loop diagram which mapped the causal relationships between the variables identified. Evaluators subsequently created a synthesised causal loop diagram based on each community's diagram.
Findings
The creation of the maps allowed participants to share and develop theories of change from a systems perspective and prompted participants to consider how best to intervene in the system and further reinforce what was already working within the system.

3.2. Prediction (simulation)

Most of the modelling studies included in this review were used to simulate the impacts of interventions yet to be implemented (see Table 2). Models cannot truly capture the complexities and unpredictability of the real world, but they may be of use to decision-makers in anticipating likely impacts of interventions. Agent-based models (ABMs) were typically used to hypothesise and simulate how agents within a system might react and interact in response to an intervention (White and Levin, 2016; Adams and Schaefer, 2016; Atkinson et al., 2018; Beheshti et al., 2017; Combs et al., 2019; Luke et al., 2017; Jin and White, 2012; Kasman et al., 2019; Keyes et al., 2019a, 2019b; Koh et al., 2019; Lee et al., 2018; Li et al., 2018; Scott et al., 2016; Spicer et al., 2012; Yang et al., 2014; Yonas et al., 2013; Zhang et al., 2014). System dynamics (SD) modelling was used to hypothesise and simulate how an intervention may impact on and interact within a wider complex system (Allender et al., 2019; Araz et al., 2018; Biroscak et al., 2014; Caroleo et al., 2017; Chen et al., 2018; Eker et al., 2018; Guo et al., 2016; Guzman et al., 2013; Haghshenas et al., 2015; Hirsch et al., 2010; Honeycutt et al., 2019; Jalali et al., 2019; Kuo et al., 2016; Lich et al., 2017; Loyo et al., 2013; Lyon et al., 2016; Manohar et al., 2014; Nyabadza and Coetzee, 2017; Soler et al., 2016; Tengs et al., 2001; Tobias et al., 2010; Wakeland et al., 2013; York et al., 2017). Other forms of modelling could also potentially inform decisions about planned interventions (e.g. microsimulation), but here we have focused on modelling approaches found in studies that met our review's inclusion criteria.

Although different in their approach, both ABMs and SD models allow researchers to run 'what if' simulations – varying values in parts of the model to simulate the unfolding effects of interventions (Forrester, 1961, 2007). Different interventions or combinations of interventions can be modelled and compared (Hirsch et al., 2010), or tested in models

designed to simulate different contextual characteristics. For example, we identified studies that simulated the impact of a hypothesised sugar-sweetened beverage intervention in three cities (Lee et al., 2018) and the impact of high street tobacco restrictions in different communities (Combs et al., 2019).

Agent-based modelling is a bottom-up modelling approach, where behaviours at the micro-level (individual agent) lead to macro-level changes emerging over time (Railsback and Grimm, 2011). The aim of the method is to observe whether simple, rule-based patterns of behaviour can be identified that, collectively and over time, generate complex system behaviour. Researchers define behavioural rules according to a pre-specified hypothesis or theory. They can then test the degree to which, if the agents in the model act according to the rules, the emergent behavioural and outcome patterns in the model resemble the observed real-life system behaviour (Weimer et al., 2016). ABMs are sometimes used to examine agents' spatial movements, and this was reflected in some of our included studies (Lee et al., 2018; Scott et al., 2016; Yonas et al., 2013; Zhang et al., 2014), whilst others focused on agent behaviours within social environments.

In contrast, SD modelling is a 'top-down' modelling approach, used to analyse problems from a macro perspective and develop a more holistic view of the structures behind a complex phenomenon (Swanson, 2002). It typically involves an initial mapping of a system followed by computational modelling of causal relationships between system elements quantified using evidence from primary or secondary data, or expert-elicited assumptions. Twenty-three SD modelling studies were included in this review. Most (n = 16) were used to model hypothetical interventions. Case Study 2 gives an example of a SD model that compared the predicted impacts of multi-intervention policies for reducing cardiovascular disease (Hirsch et al., 2010).

Case study 2: System dynamics modelling

A system dynamics model for planning cardiovascular disease (CVD) intervention (Hirsch et al., 2010)

Intervention

The study simulated three hypothetical strategies for reducing CVD in El Paso County, Colorado: (i) 14 lifestyle and environment interventions; (ii) those 14 interventions and (for those with CVD) 5 health care interventions; (iii) the 14 lifestyle and environment and 5 health care interventions – but this time the health care interventions were available to the whole population.

Aim

To evaluate the potential impacts of various intervention strategies for reducing the county's CVD burden.

Data

The authors took an existing model of CVD causal factors and recalibrated it to reflect the local population. Data from a wide range of sources were used including local population estimates, public health surveillance data, and health service data relevant to CVD risk factors, prevalence, and outcomes.

Findings

Strategy 3 combining lifestyle, environment, and health care for all produced the largest reduction in CVD events and deaths as well as total consequence costs by 2020. However, it required a large expansion in primary care considered potentially unfeasible by the researchers. In comparison, Strategy 2 was found to be almost as effective but required a much smaller (and so potentially more feasible) increase in primary care.

3.3. Process evaluation

Process evaluations, as described in our framework, focus on assessing *how* an implemented intervention impacts upon a system, considering contextual factors, implementation, and how the wider system responds and adapts. We recognise that there is some subjectivity involved in decisions as to what constitutes a process and what constitutes an impact; depending on the theory of change or the goal of an intervention (which may vary for different stakeholders), some process indicators may well be considered impacts.

All the methodological approaches we categorised in this paper were used to examine processes from a complex systems perspective; arguably, this is an inherent feature across systems approaches (Rutter et al., 2017). For example, studies that map or model implemented interventions can potentially generate insights into implementation processes, and how contextual factors may have influenced implementation (Urwannachotima et al., 2019; Jalali et al., 2019; Kasman et al., 2019).

Process evaluations are a common feature of public health intervention evaluation (Moore et al., 2014), but they do not typically include system maps, modelling or the explicit application of systems theories and concepts. They are more likely to involve qualitative or mixed-methods approaches (e.g. qualitative data from implementers and users, and quantitative data on intervention delivery) (Moore et al., 2014). However, our review identified 16 qualitative studies (Alfandari, 2017, 2019; Burman and Aphane, 2016; Czaja et al., 2016; Dickson-Gomez et al., 2018; Durie and Wyatt, 2013; Evans et al., 2015; Figueiro et al., 2017; Fisher et al., 2016; Orton et al., 2017; Pérez-Escamilla et al., 2017; Pérez-Escamilla et al., 2018; Schelbe et al., 2018; Shankardass et al., 2018; van Twist et al., 2015; Walton, 2016) and a smaller number of mixed methods process evaluations (McGill et al., 2016; Sumpter et al., 2016; Bartelink et al., 2018, 2019; Crane et al., 2019a, 2019b; Grant, 2015; Haggard et al., 2015; Kearney et al., 2016; Igras et al., 2014; Knai et al., 2018) that did explicitly seek to apply a complex systems perspective. These studies are included under the heading 'system framing' as they seek to gain insights from different stakeholders' perspectives and consider how an intervention interacts with different elements of a theorised wider system. The application of systems thinking concepts and theories played a relatively minor role in some of the included studies (Alfandari, 2017; Haggard et al., 2015), but a greater role in others.

Examples of process evaluations that substantially incorporated system framing into the study design include Case Study 3, which described how specific systems theories and concepts were integrated into its methods and analysis (Schelbe et al., 2018). In addition, Grant (2015) conducted a realist analysis of city planning and urban design interventions that identified barriers and facilitators across system levels.

Studies that draw from the systems thinking tradition often include an element of participatory action research (Burns, 2007), bringing stakeholders together and providing opportunities for them to learn from each other and from research about ongoing processes affecting their work, so that they can take action to improve problem situations. Soft systems methodology and developmental evaluation are well known examples of this kind of approach (Fahey et al., 2003, 2004; Checkland and Poulter, 2006; Patton, 2010). Amongst the studies included in this review, there are examples of what could be broadly described as action research. Rosas and Knight (2019) developed continuous learning cycles for their evaluation of a youth development intervention, where a series of different methods (e.g. system mapping, viable system modelling and network analysis) were applied to examine emerging issues identified through stakeholder participation. Burman and Aphane (2016) applied the Cynefin framework to help stakeholders understand processes and act during the implementation of a school health intervention.

Case Study 3: System framing

Systems theory as a framework for examining a college campus-based support program for the former foster youth (Schelbe et al., 2018)

Aim

To describe the application of systems theory as a framework for examining a college campus-based support program for former foster youth.

Intervention

The Student Enrichment Program (STEP) was a community programme embedded in a local community college. The programme aimed to improve post-secondary educational outcomes for former foster youth at a community college. Students were provided with financial, academic, and social/emotional support.

Methods

Interviews with current and former STEP students, mentors, collaborative members, and independent living program staff. Member checking was also conducted with the programme leader and programme coordinator.

Findings

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The authors utilised systems theory as a framework to understand how the STEP functioned. Systems theory focussed their analysis on the programme's components, how different stakeholders related to each other, with a specific emphasis on the boundaries between stakeholders the impact of those boundaries on their interactions. The authors drew on the concepts of closed and open systems, and feedback, to explore how the programme interacted and was influenced by its location in the broader context of a community college.

3.4. Impact evaluation

In our framework, we describe impact evaluations as studies that seek to quantify the impacts of interventions on key system parameters in the real world. Our emphasis on 'real world' rules out modelling studies that use simulations to examine potential impacts. Simulations can (to greater or lesser degrees) incorporate 'real world' data obtained from research and other sources. However, we felt it important to distinguish simulations from evaluations that focus on calculating estimates of effect based on directly observed measurements of impact.

We identified relatively few studies to populate the impact evaluation stage of our framework (Fuentes et al., 2018; Blackman, Jonathan, and Byrne, 2011; Blackman et al., 2013; White et al., 2017; Law et al., 2020a; Law et al., 2020b; Scarborough et al., 2020). This is partly a result of our decision to locate the modelling studies elsewhere in the framework. It also reflects a historic lack of engagement from public health evaluators with complex systems approaches (Shiell et al., 2008; Hawe et al., 2009a, 2009b). Impact evaluations are sometimes framed as antithetical to complex systems approaches (Mowles, 2014). For example, Mowles (2014) argues that they insufficiently account for the complex, emergent, and unpredictable nature of human interaction.

However, this review does include examples of public health impact evaluations that self-report applying a complex systems perspective. Two studies by Blackman et al. (2011, 2013) used qualitative comparative analysis (QCA) to assess impacts of contextual variation on impacts of interventions relevant to cardiovascular disease (2011) and sexual health (2013). QCA is a methodology that combines qualitative and quantitative analysis to examine how combinations of contextual factors affect impacts across multiple cases (Rihoux, 2006). In our expert consultations for this review, opinions differed as to whether, or to what extent, QCA should be considered a complex systems approach. QCA does consider how combinations of factors interact to influence outcomes, but does not generally explore aspects of complexity such as emergence in detail. Many QCA studies make no explicit claim to be taking a complex systems approach and were therefore excluded from this review.

Fuentes et al. (2018) conducted a network analysis evaluation of a school intervention that measured impacts on social relationships. Network analysis involves identifying agents (sometimes called 'actors') within a network, collecting data on their relational links with each other, and analysing these links through data visualisation (e.g. a network map called a 'sociogram') and statistical modelling (Moreno, 1960). In public health research, the agents in question tend to be individuals or organisations – often key stakeholders within a particular system of interest. Fuentes et al.'s study is unique amongst the network analyses we identified as it involved a pre- and post-controlled design (see Case Study 4) (Fuentes et al., 2018). The other network analysis studies we included had no control and were used within the context of a process evaluation to study diffusion of information, behaviours or innovative practices (Williams and Hummelbrunner, 2010; Rosas and Knight, 2019; White and Levin, 2016).

We also identified published studies from an ongoing evaluation (projected end date December 2021) of the impacts of 'UK Treasury Soft Drinks Industry Levy (SDIL).' So far, the evaluation has reported intermediate outcomes (Pell et al., 2019; Scarborough et al., 2020) and economic impacts (Law et al., 2020a, 2020b), and plans to report on the system mapping process that underpins the evaluation, as well as findings on health relevant impacts, modelling of longer term health impacts, and evidence synthesis of these multiple approaches in future publications (White et al., 2017).

Case Study 4: Network analysis

Development and complex dynamics at school environment (Fuentes et al., 2018)

Aim

To evaluate behavioural plasticity of social relationships between peers in 6-7-year-olds who participated in an intervention with cooperative and self-awareness activities, conducted in a school context.

Intervention

Children (aged 6 and 7) engaged in 8 1-hour long sessions, which included mindfulness-based practices and social/collaborative activities. The control group engaged in their normal classroom activities.

Methods

Children were individually interviewed before and after the intervention using a sociometric questionnaire. Children were asked which peers they would and would not like to play with in order to create a sociogram for each child. Complex network and game theory were used to evaluate pre-post-intervention variations compared to the control.

Findings

Social network diversity and the quality of positive relationships improved after the intervention in the experimental group, whereas no such changes were observed in the control group.

3.5. Further prediction (simulation)

Not all the included modelling studies tested hypothetical interventions. Some agent-based and system dynamics modelling studies focused on previously implemented interventions and simulated system-level impacts in new scenarios, where an intervention was rolled out to a different locality and population (White and Levin, 2016; Kasman et al., 2019; Yang et al., 2014; Allender et al., 2019; Biroscak et al., 2014; Honeycutt et al., 2019; Jalali et al., 2019; Kuo et al., 2016; Lich et al., 2017; Soler et al., 2016). As these kinds of modelling methods have already been presented in the section on prediction (simulation), we will not discuss them further here. However, we do provide an example (in Case Study 5) of an ABM that simulated the further implementation of an intervention in 3 different cities (Lee et al., 2018).

Case Study 5: Agent-based modelling

Simulating the impact of sugar-sweetened beverage warning labels in three cities (Lee et al., 2018)

Aim

To model the impact of sugar-sweetened beverage (SSB) warning labels on overweight and obesity prevalence among adolescents in three U.S. cities.

Intervention

Scenarios modelled how adolescent overweight/obesity prevalence could be affected by different levels of efficacy for a food labelling intervention (based on findings from previous studies), compliance of food retailers, compensatory eating, and population characteristics such as illiteracy rates and socio-economic status.

Methods

ABMs were developed to represent the intervention's implementation in three cities, using data from a wide range of sources, including the National Health and Nutrition Examination Survey for height, weight, and SSB consumption and purchasing habits, the U.S. Census Bureau for sociodemographic characteristics, and sources for the location of food retailers.

Findings

Modelling estimated that implementing SSB warning labels at all SSB-retailing stores would lower overweight/obesity prevalence and BMI among adolescents in all three cities. The reduction persisted in varying circumstances (i.e. lower store compliance, literacy and label efficacy, low social economic status population, and compensatory eating), with literacy rate and label efficacy identified as potential drivers.

4. Discussion

We have reviewed public health evaluations that reported applying a complex systems perspective. We have categorised the methodological approaches used in these studies, which included system mapping, network analysis, system modelling, and system framing. We then

mapped these methods onto a framework that summarises the functions such studies have in generating evidence at different stages of an evaluative process: 1) theorising; 2) prediction (simulation); 3) process evaluation; 4) impact evaluation; and 5) further prediction (simulation).

Several of these types of methods – notably the structured system mapping and modelling methods – are well established within complexity science (Gates, 2016), although they may be new to many public health evaluators. Other study methods we identified demonstrate a particular tension evident in efforts to apply complex systems perspectives to evaluation: namely, a fuzzy and contested sense of what constitutes and what does not constitute a complex systems approach. This tension is evident in impact evaluations, but we also found it in some of the process evaluation methods. It is, perhaps, to be expected as different research traditions and paradigms intersect, with the result that new approaches are developed, established methods are adapted and disciplinary boundaries become contested (Gates, 2017).

While we identified a large number of examples of complex systems approaches to public health evaluation, we also recognise that such approaches are relatively uncommon (Rutter et al., 2017) and present challenges to evaluators and decision makers, including possibly long evaluative time scales (Rutter et al., 2017), the need for adaptive and agile evaluation methodology (Bicket et al., 2020), and the ability to determine and capture multiple impacts that cannot be reduced to a single outcome measure (Hawe et al., 2009a).

The task of identifying public health evaluations that take a systems perspective involves a number of challenges and decision-points: notably, deciding (i) whether or not some studies that explicitly reported taking a complex systems perspective were justified in doing so (Moore et al., 2019); and (ii) whether the inverse applied (i.e. some studies were compatible with a complex systems perspective but were excluded from the review because they did not explicitly report doing so). This tension around the reporting of methods is not unique to systems evaluations, but is arguably amplified by the large number of approaches associated with systems thinking and complexity science traditions, as well as by research innovations that seeks to apply a systems perspective to methods that were not originally developed with that perspective in mind (Bartelink et al., 2019; Blackman et al., 2013; Grant, 2015).

We also note that there are a number of other approaches to researching systems that have been used in public health, but did not meet the inclusion criteria to be included in this review. They include (to name a few): critical system heuristics (Buse, 2013), microsimulation (Pearson-Stuttard et al., 2018), and strategic assumption surfacing and testing (Williams and Hummelbrunner, 2010).

Taken together, we suggest that there are a number of areas for further development in public health evaluation from a complex systems perspective. First, we identified relatively fewer examples of complex systems impact evaluations. This could be an area for future methodological development. Second, there are a number of complex systems methodological approaches that have not yet been applied to public health evaluation, but may generate useful evidence for decision-making. Evaluators wishing to apply a complex systems perspective could usefully test out and reflect on the application of these methods in public health evaluation. Finally, more consideration could usefully be given as to how to present findings from complex systems evaluation so that they can be used by decision makers to improve public health decision making.

4.1. Review strengths and limitations

The aim of this review was to contrast different methods in complex systems evaluations of public health interventions, rather than attempt to identify every published example of an evaluation that met a pre-specified definition. We conducted a systematic search which included expert consultations. Nevertheless, there may be relevant studies that our search did not identify. We searched for studies that self-identified as taking a systems or complexity-informed approach, rather than searching for specific methods associated with a complex systems perspective. We may therefore have missed papers that do not use language and methods that are compatible with systems thinking. We kept our definition of a public health evaluation broad and are aware that some evaluators would limit their definition to process and impact evaluations. We think our decisions are justifiable; had we only focused on a narrowly conceived definition of process and impact evaluations we would have excluded the modelling methods, which have a prominent position in complexity science. If public health evaluation is to embrace complexity science, we suggest that a willingness to broaden definitions of 'evaluation' may be a pre-requisite.

5. Conclusions

We have reviewed studies that self-identified as applying complex systems approach to public health evaluation, developed a framework that maps this body of literature onto five different stages of the evaluative process, and categorised studies by their predominant methodological approach. We believe the findings of this review could help introduce a wider public health audience to the different kinds of systems evaluation that have been used within their discipline and provide some guidance to evaluators wishing to engage with this innovative area of public health evaluation. Through methodological innovation, it is hoped that better evaluations can lead to better informed decisions on how to improve health and reduce health inequalities in our complex world.

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Appendix A. Supplementary data

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