Current Epidemiology Reports (2019) 6:248–262
https://doi.org/10.1007/s40471-019-00200-w

INJURY EPIDEMIOLOGY (S MARSHALL, SECTION EDITOR)

System Dynamics Applications to Injury and Violence Prevention: a Systematic Review

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Published online: 25 April 2019

Abstract

Purpose of Review System dynamics (SD) is an approach to solving problems in the context of dynamic complexity. The purpose of this review was to summarize SD applications in injury prevention and highlight opportunities for SD to contribute to injury prevention research and practice.

Recent Findings While SD has been increasingly used to study public health problems over the last few decades, uptake in the injury field has been slow. We identified 18 studies, mostly conducted in the last 10 years. Applications covered a range of topics (e.g., road traffic injury, overdose, and violence), employed different types of SD tools (i.e., qualitative and quantitative), and served a variety of research and practice purposes (e.g., deepen understanding of a problem, policy analysis).

Summary Given the many ways that SD can add value and complement traditional research and practice approaches (e.g., through novel stakeholder engagement and policy analysis tools), increased investment in SD-related capacity building and opportunities that support SD use are warranted.

Keywords System dynamics · Simulation · Injury · Violence · Systems · Complexity

Introduction

The health, social, and economic impacts of unintentional and intentional (violent) injuries are enormous. Globally, 4.8 million people died as a result of injuries and 973 million sustained injuries that warranted healthcare treatment in 2013 [1]. While international progress in injury prevention has been made over the last few decades, as evidenced by a 30% decline in the age-adjusted rate of disability-adjusted life years (DALYs) due to injuries between 1990 and 2013, these decreases have not been equitably dispersed [1]. For example, during this same time period, DALY rates attributed to injury increased in west, central, and southern sub-Saharan Africa [1]. Moreover, even in countries experiencing declines, like the USA, the overall burden remains high. More people die from injuries in the first half of their lives (ages 1–44 years) in the USA than from any other cause [2].

As with many public health problems, injury trends are relatively persistent, complex, and often resistant to attempted policy and intervention approaches [3•]. The underlying system of factors that drives injury trends is often comprised of multiple, interrelated organizational, social, cultural, and environmental factors and involves dynamically complex interactions between these factors [4, 5]. By dynamically complex, we mean that interactions are often characterized by feedback, time delays, non-linearity, adaptiveness, and other attributes that make predicting the behavior of the system of factors over time particularly difficult [6•, 7•, 8•].

Briefly, we define each of these characteristics to elucidate how such attributes of dynamic complexity can make

This article is part of the Topical Collection on *Injury Epidemiology*

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examining and responding to injury problems challenging [6•, 7•, 8•]. (1) Feedbacks refer to closed chains of causal connections in which a change in one factor sets off a series of reactions to further change that factor. For example, an increase in opioid overdose deaths could trigger a decrease in physicians' opioid prescribing, with the intent of addressing the problem (a control or balancing feedback loop). However, the decrease in opioid prescribing may in turn trigger an increase in illicit opioid use, potentially offsetting gains or even exacerbating the increase in opioid-related deaths (a reinforcing loop). (2) Time delays refer to the fact that certain factors, such as injury-related norms, attitudes, and policies, are often delayed with respect to their initial causes or inputs. For example, injury prevention legislation takes time, advocacy, and political will and may be considerably removed in time from the event(s) that initiated such action. (3) Non-linearity refers to the fact that the output observed from a system may not be proportional to any linear combination of inputs. For example, the intensity of brain injury that occurs from players' sports-related impacts can dramatically (and non-linearly) increase with each impact, especially when events occur close in time [9]. (4) Finally, adaptiveness refers to the fact that the systems are always changing and responding to new factors and feedbacks. For example, new sources of distraction for drivers arise with new technological advancements, new firearms become available with implications for violence-related outcomes, and new substances capable of causing overdose emerge, and systems react in more and less effective ways.

Traditional research tools (e.g., basic statistical measures, regression models) and frameworks (e.g., the public health approach) offer several strategies for understanding the burden of injury, examining relationships between specific risk factors and outcomes, and evaluating the impacts of public health policies designed to prevent injuries [10]. However, many of these approaches lack a perspective of, and the analytic ability to take into account, the larger system of underlying factors and the dynamic complexity of interactions among these factors that may be driving an injury problem.

System dynamics (SD) offers a set of interdisciplinary research and practice tools to complement traditional approaches [6•, 7•, 8•]. Specifically, SD can be used to help examine dynamic complexity and the effect of proposed interventions on the system's behavior over time, ultimately improving our understanding of where to intervene within the larger system to have the greatest impact.

SD tools range from qualitative to quantitative and have public health research, practice, and communication implications. For example, a common SD tool, causal loop diagramming (CLD), involves mapping the hypothesized feedbacks and interactions between factors in a system that may be driving observed trends (e.g., suicide rates) [6•]. This type of diagramming or mapping can occur in the context of a large group of stakeholders invested in the issue (e.g., community members, experts, and policy makers) or among a small research team [11]. Depending on the audience and purpose, CLDs can increase understanding of a problem, elucidate hypotheses, improve stakeholder communication, facilitate development of a shared vision, illuminate research needs and gaps, or identify potential points of collaboration or synergy. Building from CLDs, SD simulation models can help quantitatively test hypotheses about the underlying factors, structures, and processes in a system driving an observed trend [6•]. SD simulation models provide a tool to test hypotheses involving many factors and feedbacks, develop a greater understanding of the contributions of specific inputs to a problem, examine effects of potential interventions and unintended consequences, and develop a coordinated approach to a problem. These SD tools, among others, ultimately can help advance science and practice and foster coordinated communication, around critical public health problems, like injury. We refer the interested reader to additional resources and a more thorough discussion of SD tools [6•, 8•, 12].

SD tools have been increasingly applied to a wide range of public health problems, such as diabetes [13, 14], tobacco [15], substance use [16–18], HIV/AIDS [19–22], and obesity [23, 24], to help understand the complexities driving these problems and elucidate potential policy approaches. The purpose of this systematic review was to identify, summarize, and reflect on SD applications in the injury prevention literature and highlight future opportunities for SD to contribute to injury prevention research and practice.

Methods

We sought to identify all applications of SD modeling to injury outcomes in the peer-reviewed literature between January 1958, when SD methods were first introduced, and June 2018.

Search and Study Identification Strategies

Members of our research team recently completed a systematic review of SD applications in health (defined broadly to include physical, social, and/or emotional wellness of individuals or populations) in the peer-reviewed scientific literature, searching articles written in English that were published between 1958 and 2016. This review updates and builds from that work to specifically examine injury SD applications.

A detailed description of the previous review has been documented [25]. Briefly, studies were identified through PubMed and Web of Science using three search strategies: (1) a keyword search using a range of SD-related terms; (2) a review of all articles published in the *System Dynamics Review* or accepted for presentation at a list of SD-related conferences; (3) a review of all articles citing a foundational publication in the SD field (Forrester 1961–1969; Homer

2006; Sterman 2000–2010) [3•, 6•, 7•, 26•, 27•]. Search results were restricted to health-related applications, using health-related keywords and a list of publication venues in Web of Science.

In July 2018, we updated this search to capture any articles published between 2016 and June 2018. To ensure that the health-related restriction was broad enough to capture all injury applications, we added injury and safety-related terms to the keyword search across the entire review period (1958–2018).

Articles meeting search criteria were then reviewed to determine whether they were injury-related (more on definition below) and actual SD applications, as opposed to studies that talked about the "dynamics" of a problem in a different context or solely made recommendations to include SD methods in future work. Articles that did not use some type of SD qualitative or quantitative modeling approach (e.g., CLD, stock and flow model, and group model building) were not included.

Definition of Injury

We examined all selected articles for their application to injury and violence prevention. Specifically, we included SD applications that explicitly and directly involved the study of at least one type of fatal or non-fatal injury. Adopting the World Health Organization's definition, we defined an injury as physical damage "caused by acute exposure to physical agents such as mechanical energy, heat, electricity, chemicals, and ionizing radiation interacting with the body in amounts or at rates that exceed the threshold of human tolerance. In some cases (e.g., drowning and frostbite), injuries result from the sudden lack of essential agents such as oxygen or heat" [28, 29]. The main causes of injury include both unintentional (e.g., road traffic crashes, poisoning, falls, burns, and suffocation) and violent/intentional (e.g., intimate partner violence, suicide, and child abuse) mechanisms. We did not include studies that indirectly related to injury without specifically modeling or discussing the direct link to the injury outcome, such as studies of drug trade or traffic flow that did not specifically model overdose or crash-related injuries, respectively. All potential injury-related SD applications were initially selected by one research team member, who erred on the side of inclusiveness, and final decisions were made by two members of the research team with any discrepancies discussed and agreed upon.

During our review, we identified several articles that specifically focused on occupational safety processes (e.g., construction management, mine safety). While many of these models examined underlying organizational systems and how system structures and dynamic interactions might lead to safety-related incidents, they often lacked a focus or discussion on injuries specifically [30–40]. Therefore, they were not included in this review. Other common themes in the literature with an indirect link to injury included post-disaster response planning and emergency department system management (e.g., management of wait times and patient flow) [41–49].

Abstraction

Key characteristics of the articles were abstracted by two members of the research team. Abstraction elements included the following: authors; year of publication; title; general injury topic area (e.g., road traffic injury, suicide); research team expertise (i.e., research departments/disciplines represented on core research team); purpose of the paper and purpose of the SD model; description of SD method(s) used (e.g., qualitative CLD, concept model, and tested/analyzed simulation model); setting/context (e.g., organization, community/city, and national); use of a participatory approach/stakeholder involvement; description of types of stakeholders involved, intensity of involvement, and method of stakeholder recruitment, if applicable; main findings and conclusions; and primary strengths and limitations. Additionally, reference lists of all articles were thoroughly reviewed for other relevant articles that met review inclusion criteria but had not been captured through the search strategy described above; however, no additional articles were identified.

Results

The combined search of keywords, specific SD-related sources, and seed articles for the period of 1958 through mid-2018 yielded 1238 unique articles (Fig. 1). The additional safety-related search terms across this period returned an additional 29 unique articles, for a total of 1267 articles reviewed. After excluding articles that did not involve an actual SD-related application and were not injury-related, 62 articles remained. Two members of the research team conducted a thorough text review of these 62 and determined that 18 [50–67] had a direct and specific link to an injury outcome and utilized a SD-related method or tool (e.g., CLD, SD simulation model). These 18 studies were included in the review (Table 1).

SD Uptake, Topics Covered, and Geographic Scale/Context

With the exception of one 1993 study related to drug use and overdose [54], we did not identify SD applications to injury outcomes in the peer-reviewed literature until 2009 (Table 1). Since 2009, one to three applications have been published each year. Topic areas included youth violence [50], domestic violence [55, 56], community violence [51], suicide [63], drug overdose [54, 64–67], occupational injury [53], road traffic

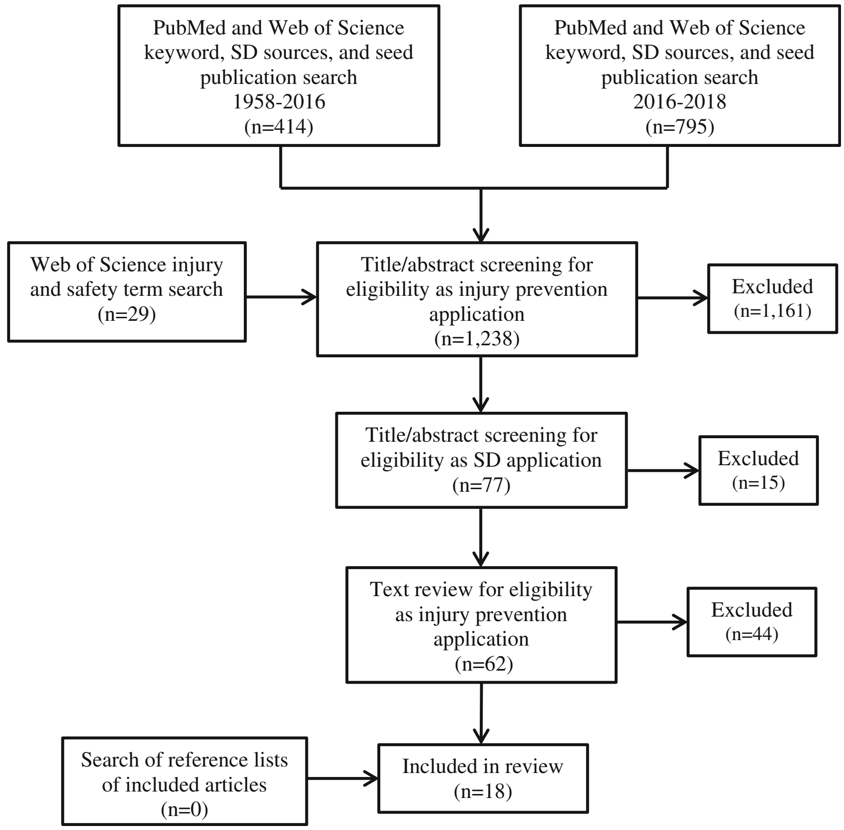

Fig. 1 Results of the systematic review: number of records identified through search strategy, screened for eligibility, and included in review of system dynamics (SD) applications to injury outcomes

injury [52, 58–62], and traumatic brain injury [57]. Studies were conducted within a variety of geographic contexts and scales. Half of the studies ($n = 9$) [50, 51, 55, 56, 58–62] were framed within the context of one or more specific communities or cities, and one-third ($n = 6$) [54, 63–67] involved a national context. The remaining three occurred within a specific organization [53] and a region of a country [52], or the context was not specified [57].

Multidisciplinary Involvement

The multidisciplinary nature of SD was observed with respect to both the core research teams, as well as the larger group of participants and stakeholders engaged. Core research teams included those with backgrounds in social work, engineering, public health, psychology, design and built environment, medicine, policy, criminal justice, statistics, and geography. Two-thirds ($n = 12$) [50, 51, 53, 56–58, 60, 62, 64–67] of the studies involved some type of larger stakeholder engagement, ranging from an expert panel or a few key informant interviews to several iterative workshops, in-depth interviews, and continued follow-up with key stakeholders representing a range of community perspectives (Table 1). In three studies [55, 59, 61], a participatory approach was not used for the specific study reviewed but was used for other components of the team's larger body of work on the injury topic.

SD Tools Applied and Findings Elicited

One-third ($n = 6$) [51, 53, 57, 59–61] of the reviewed articles used CLD and mapping techniques to develop a deeper understanding of hypothesized factors, feedbacks, and the system structure driving an injury problem; to refine a hypothesized map for other contexts or communities; to elucidate data gaps and research needs; or to develop a shared framework among diverse stakeholders (Table 1). Eleven (61%) articles [50, 54–56, 58, 62–67] involved building and testing a SD simulation model, typically, but not always, after CLD or map development. Simulation models were built to increase understanding of a specific injury problem or observed unintended consequence, explore the choice and timing of different intervention strategies, test the generalizability of the model structure across different contexts (e.g., cities), or provide a decision support tool for injury prevention stakeholders. Finally, one study [52] involved construction of SD simulation concept models to demonstrate the utility of SD methods for traffic safety policy analysis. Table 1 includes brief summaries of the specific insights revealed by study.

Primary Strengths and Limitations

There were several similar strengths and weaknesses expressed by the authors. One of the most common strengths

Table 1 Studies included in the systematic review of system dynamics (SD) applications to injury outcomes ($n = 18$)

Citation	Injury topic	Purpose of model	System dynamics tool(s)	Participatory process	Main results	Strengths and limitations (as noted by authors)
Bridgewater et al. (2010) [50]	Youth violence	Increase understanding of youth violence and inform community strategic planning	Tested and analyzed model	-Interviews with gang and mental health experts and survivors of gang violence -Project briefings with community members and stakeholders -Diagramming with community residents -Focus groups with current and former gang members	Focal areas for prevention include movement of youth between different levels of violence (e.g., into and out of gangs) and the effects of individual- and community-level trauma on violence	Strengths: -Involvement of gang members -Commitment to community relationships and engagement Limitations: -Lengthy process to engage community
Frerichs et al. (2016) [51]	Community violence	Develop a deeper understanding of key determinants of community violence transmission and racial inequities	Diagram	Workshop with key stakeholders (research, law enforcement, schools, housing, prior gang-involved youth, etc.)	Key factors identified as affecting community violence include isolation and mental health, gun ownership, normalization of violence, social support, racial inequalities, and structural violence	Strengths: -Rich discussions of difficult topics among diverse stakeholders -Integration of critical race theory -Adapted workshop scripts to improve cultural relevance Limitations: -Missing variables and poorly clarified relationships in diagram due to challenges in group facilitation and diagramming
Goh and Love (2012) [52]	Road traffic injury	Demonstrate how SD can facilitate macro-level traffic safety policy analysis	Concept/demonstration model	N/A	Advantages of SD for road traffic safety include incorporation or non-linear relationships and wide range of variables, develop user-friendly interface, potential to educate policymakers on the impact of traffic safety policy, and promotion of a holistic view of the transport system	Strengths: -Demonstration of simulation model creation with corresponding policy analysis -Transparent display of model equations and parameters Limitations: -Not study-specific. Discussion of larger SD simulation limitations: reliance on time specifications, deterministic nature of models that does not readily take into account uncertainty, challenges with structural validity of SD models
Goh et al. (2012) [53]	Occupational injury	Increase understanding of factors influencing occupational health safety performance of a drilling and mining contractor	Diagram	Workshop with a variety of managers	Key hypothesized factors affecting the disabling injury frequency rate included efforts to meet safety targets, tensions between production and safety, client demands, and desire to win future contracts	Strengths: -Developed tool for hypothesizing factors influencing safety management -Provided a dynamic and holistic view of related issues -Provided basis for developing prevention strategies and

Table 1 (continued)

Citation	Injury topic	Purpose of model	System dynamics tool(s)	Participatory process	Main results	Strengths and limitations (as noted by authors)
						informing discussions with senior management of organization Limitations: -None stated
Homer (1993) [54]	Drug use (and overdose)	Generate estimates and projections of cocaine use and knowledge of underlying processes to overcome limitations of self-report data	Tested and analyzed model	N/A	-Consequences of cocaine use, like overdose/ morbidity, mortality, arrests, and effects on price, feed back to affect future use -Increasing gap over time between actual and self-reported cocaine use -Projected continuation of existing trend in shift from casual powder cocaine to compulsive crack cocaine use, resulting in overall increase in cocaine use	Strengths: -Captured detailed projections -Projections based on endogenous feedback loops with minimal assumptions -Series of model evaluations and revisions Limitations: -Simplification of reality -Model may fail to capture relationships that are important in the future
Hovmand and Ford (2009) [55]	Domestic violence	Evaluate the effect of the timing of three community interventions on improving offender accountability and victim safety	Tested and analyzed model	N/A	Increases in first arrests for primary aggressors and decreases in first arrests for primary victims observed when interventions to increase victim advocacy and cooperation between law enforcement and victim advocates occurred 5 years before a mandatory arrest policy	Strengths: -Explored complex patterns of dynamic behavior -Showed that it can be problematic to only consider one outcome -Addressed limitations of traditional linear, reductionist approaches Limitations: -None stated
Hovmand et al. (2009) [56]	Domestic violence	Provide an explanation of underlying mechanisms driving the dynamics of increasing victim arrests after implementation of mandatory arrest policies for domestic violence	Tested and analyzed model	Interviews with domestic violence victim advocates and prosecutor office staff	Mechanisms underlying domestic violence victim arrests shift over time from initial increase in arrest rate to decline in stock of victims at risk of arrest to erosion of cooperation between law enforcement and victim advocates, resulting in overall increase in victim arrests	Strengths -Illustrated inherent complexities and temporal nature of social mechanisms -Demonstrated importance of feedback loops and stocks/flows -Highlighted importance of law enforcement and victim advocate cooperation Limitations: -None stated
Kenzie et al. (2018) [57]	Traumatic brain injury	Depict relationships between variables influencing concussion pathophysiology and symptomology across multiple scales	Diagram	-Interviews with researchers and clinicians -Feedback solicited at conferences and from Brain Trauma Evidence-Based Consortium	-Diagram includes increasing time scales and variables at several scales of biological organization (cellular, network, experiential, and social) that affect traumatic brain injury	Strengths: -Provided a foundation for a unifying framework for concussion research -Provided proof of concept for future systems-oriented work -Thorough review of the literature -Expert input across disciplines

Table 1 (continued)

Citation	Injury topic	Purpose of model	System dynamics tool(s)	Participatory process	Main results	Strengths and limitations (as noted by authors)
					-Coping, adaptation, and treatment interventions may facilitate concussion recovery	Limitations: -Diagram is a representation of modelers' understanding of a system at one point in time and does not include every relevant variable -Lack of clarity regarding relevance of broadly defined traumatic brain injury research to concussion and mild TBI specifically -Diagram is static and does not depict changes in system structure over time
MacMillan et al. (2014) [58]	Bicyclist road traffic injury	Simulate five cost-effective policies to increase bicycle commuting in a car-dominated city	Tested and analyzed model	-Interviews with a variety of stakeholders (low-income families, regional transport policymakers, local businesses, local government, etc.) -Workshops with selected stakeholders	-The currently planned Regional Cycling Network strategy is unlikely to meet its targets and may not result in reductions in the bicyclist injury rate, according to the model -Projected decrease in bicyclist injury rate may occur with implementation of segregated bicycle lanes, self-explaining roads, and/or a combination of the two, with overall cost savings	Strengths: -First integrated assessment of active transport policy -Incorporated multiple outcomes -Improved knowledge from combined stakeholder knowledge, regional data, and empirical evidence -Nuanced approach to modeling key phenomena (e.g., "safety in numbers") -Sensitivity analyses of structural and parametric uncertainty Limitations -Narrow definition of bicyclist injury -Relative risks from cohort studies used in model may overestimate mortality benefit of commuter bicycling
MacMillan et al. (2016) [59]	Bicyclist road traffic injury	Examine the relationship between changes in the prevalence of bicycling and media coverage of bicycling-related road traffic crashes	Diagram; analysis of specific, hypothesized SD relationships using regression	N/A	-As bicycling trips increased, fatalities remained stable, but fatalities covered in media increased as bicycling became more "newsworthy" -Increased coverage of fatalities may lead to increase in articles campaigning for improved bicycling conditions	Strengths: -Linked police records of road traffic crashes to media coverage -Examined long time period (two decades) -Use of motorcyclist fatalities as control group -Examined a "qualitative" relationship in SD model that usually lacks quantification Limitations:

Table 1 (continued)

Citation	Injury topic	Purpose of model	System dynamics tool(s)	Participatory process	Main results	Strengths and limitations (as noted by authors)
						-Only used one newspaper in each city to examine media coverage -Exposure of public to bicycling fatalities may occur outside of print newspaper -Only examined fatal bicyclist injuries -Did not examine context or tone of media coverage -Only focused on one aspect of the relationship between bicyclist fatalities and media coverage
MacMillan and Woodcock (2017) [60]	Bicyclist road traffic injury	Develop agreement on effective policies for achieving sustained increases in bicycling transport in three urban cities	Diagram	-Interviews with a variety of stakeholders (research, community advocacy, health, etc.) -Workshops with selected stakeholders	-Increasing number of bicyclists increases political will to improve infrastructure -"Safety in numbers" and normalizing bicycling reduce injuries and deaths -Demographic and infrastructure differences across the three cities caused notable differences in diagram feedback loops	Strengths: -Represented perspective of a wide range of stakeholders -Workshops allowed for transdisciplinary conversation and group learning -Tested a causal theory across different contexts/cities Limitations: -Need to extend to more contexts to improve generalizability -Feedback loops may be contradicted by existing data and still need to be tested
MacMillan et al. (2018) [61]	Bicyclist road traffic injury	Develop a causal theory for the relationships between active travel and walking and bicycling infrastructure to inform the outcomes to track in a future intervention study	Diagram	N/A	Outcomes to be measured included physical health outcomes (diabetes, injury), risk factors (physical inactivity, air pollution), social and environmental health outcomes (social connection), and other individual- and area-level measures	Strengths: -Key tool for visualizing relationships between infrastructure for bicycling and a range of outcomes -Combination of subjective and objective measures -Broad range of outcome measures Limitations: -None stated
McClure et al. (2015) [62]	Road traffic injury	Refine an understanding of the features of the land use/transport system that optimize health in six cities	Tested and analyzed model	Input from researchers, policymakers, and practitioners	Combined policy to reduce travel mode risk and change transport mode distribution (from individual motorized to mass transport and active transport) resulted in the largest proportion of road traffic deaths prevented in most cities	Strengths: -Incorporated non-linear relationships -Thorough assessment of model validity -Used parsimonious set of variables and simple set of relationships Limitations:

Table 1 (continued)

Citation	Injury topic	Purpose of model	System dynamics tool(s)	Participatory process	Main results	Strengths and limitations (as noted by authors)
						-Need to extend to more contexts to improve generalizability -Some variables omitted from the model for a variety of reasons
Page et al. (2017) [63]	Suicide	Investigate impacts of a combination of current suicide prevention strategies and develop a decision support tool for policymakers and communities	Tested and analyzed model	N/A	General practitioner training and coordinated aftercare resulted in largest reductions in suicide	Strengths: -Mathematically rigorous approach to modeling suicide trends -Model consistent with observed data -Developed a useful decision support tool -Model available to public for testing different scenarios Limitations: -Simplification of reality -Undercounting of suicide in data used to calibrate model -Interventions incorporated into model are a limited set of potentially important interventions -Potentially limited generalizability
Wakeland et al. (2011) [64]	Opioid overdose	Illustrate a system-level, simulation based approach for evaluating mitigation strategies to address the increase in prescription opioid abuse, addiction, and overdose deaths	Tested and analyzed model	Input from panel of experts in SD modeling, chronic pain treatment, drug diversion, and drug addiction	-May be difficult to minimize overdose deaths without adversely affecting access to pharmaceutical treatment for chronic pain patients -Highly effective tamper-resistant opioid formulations could reduce proportion of medical user deaths from unintentional overdose but would not reduce overall overdose deaths -Physician education programs may reduce total number of unintentional overdose deaths but could reduce access to opioid treatment for those who may need it	Strengths: -Recognized complex interconnections and feedback loops -Examined multiple metrics of opioid overdose deaths Limitations: -Lack of empirical support for some parameters -Model did not align with historical data and may not have been calibrated accurately -Focused on chronic pain only (not acute pain) -Did not account for poly-drug use or impact of treatment programs
Wakeland et al. (2013) [65]	Opioid overdose	Compare the effect of three education interventions on prescription opioid overdose deaths	Tested and analyzed model	Input from experts in policy and prescription opioid use and abuse	-Prescriber-level education is more effective in reducing prescription opioid overdose deaths than patient-level education -However, prescriber-level interventions might also result in increase in chronic pain patients	Strengths: -Provided foundation for additional models Limitations: -Lack of empirical support for some parameters

Table 1 (continued)

Citation	Injury topic	Purpose of model	System dynamics tool(s)	Participatory process	Main results	Strengths and limitations (as noted by authors)
					being denied potentially beneficial therapies	-Some potentially important variables excluded due to lack of evidence -Did not examine poly-drug or heroin use -Did not include variables related to treatment or secular trends -Focused on chronic pain only (not acute pain)
Wakeland et al. (2015) [66]	Opioid overdose	Increase understanding of the complex interactions and underlying processes that contribute to non-medical prescription opioid use and overdose death and allow experimentation with three supply-side interventions	Tested and analyzed model	Interviews with researchers and practitioners with knowledge in pain medicine, pharmaceutical abuse liability, substance abuse, public health, and economics	Combination of tamper-resistant drug formulations and informal sharing supply interventions (removing availability through drug take back events and reducing sharing of leftover prescriptions) resulted in greatest reduction in overdose deaths	Strengths: -Evidence that creation of overall system-level theory of drug diversion and abuse is feasible -Provided broad view of the structure of the system to help explain underlying processes and feedback loops that create complex behavior -Simulated complex feedback relationships that have no analytical solution -Process of constructing model provided an opportunity to assess gaps in knowledge Limitations: -Lack of empirical support for some parameters -Evaluated a short timeframe not long enough for cohort effects to be fully realized
Wakeland et al. (2016) [67]	Opioid overdose	Increase understanding of prescription drug abuse; create a working theory about the system of pain treatment, medication diversion, and abuse and unintentional overdose deaths; and evaluate the effect of potential interventions	Tested and analyzed model	Input from expert panel	-Both supply and demand factors likely contributed to increase in non-medical use of prescription opioids -Reduction in popularity of non-medical use and prescription drug monitoring programs demonstrate considerable leverage -Multiple metrics are needed to provide a balanced policy assessment	Strengths: -Model aligned with observed data -Focused on both supply and demand -Examined multiple metrics of opioid overdose deaths Limitations: -Lack of empirical support for some parameters -Focused on drug trafficking as opposed to interpersonal sharing which may have exaggerated impact of profit motives -Focused on chronic pain only (not acute pain)

was the richness in perspectives and expert knowledge contributed through multidisciplinary stakeholder involvement (Table 1). Other strengths included increased ability to visualize the "bigger picture" and create a unified framework around a specific injury problem, to examine non-linear and complex hypothesized relationships, to explicitly highlight the importance of specific research needs and data gaps, and to create hands-on tools to foster active learning about a problem and potential intervention effects. Common limitations included lack of empirical support for specific model parameters and relationships, lengthy processes involved in building relationships and engaging with a wide range of stakeholders, generalizability concerns of models, potential oversimplification of models, and lack of model alignment with historical data (i.e., poor model calibration).

Table 2 Advantages of using system dynamics approaches for injury prevention research and practice, as demonstrated in 18 reviewed studies

- Engage critical stakeholders, especially frequently marginalized populations, in understanding causes and identifying solutions
- Develop a shared vision and unified framework of a complex, multilevel problem to elucidate data and knowledge gaps and advance research
- Account for policy and intervention effects on multiple outcomes and metrics, fostering transparency in weighing options and considering trade-offs
- Account for the timing of intervention implementation
- Recognize and explore unintended or weak effects of policies and interventions
- Leverage the generalizability of underlying system structures driving injury trends
- Support policy decision-making with transparent, hands-on tools

Discussion

We found limited uptake of SD tools and methods in the injury prevention field over the past several decades. While SD methods were first developed in the mid-1950s [68], they were largely applied within economics, engineering, operations, management, business, and mathematics fields for many years. It was not until the late 1970s and early 1980s that researchers began using SD tools to study public health problems [3], and uptake in injury prevention has appeared even more recently, within the past 10 years.

Although relatively few in number ($n = 18$), SD applications to injury have covered a range of topics and contexts, employed different SD tools and approaches, and served a variety of research and practice purposes. We found that applications covered both unintentional injury (e.g., road traffic injury, overdose) and intentional or violence-related injury (e.g., youth, domestic, and community violence) and occurred across a wide range of scales, from an organizational to a national level. Likewise, the SD tools applied extended from qualitative CLDs and mapping approaches to quantitative simulation and empirical decision support tool development, with a range of implications for both research and practice.

During our review of these specific studies, we noted seven noteworthy advantages of taking an SD approach to injury research, or using SD-related tools (Table 2). These are discussed in detail below.

Engage Critical Stakeholders, Especially Frequently Marginalized Populations, in Understanding Causes and Identifying Solutions Two-thirds of the studies reviewed took an SD modeling approach that integrated stakeholder perspectives. Two studies in particular leveraged key SD diagramming techniques to advance difficult discussions around violence, race, and inequality [50, 51]. Bridgewater et al. (2010) [50] engaged active gang-involved youth, family mental health experts, survivors of gang violence, community residents, and community-based agencies to explore strategies for reducing youth violence in Boston; stakeholders were continuously involved, using SD tools, throughout the project. Similarly, Frerichs et al. (2016) [51] fostered rich discussions among law enforcement, schools, housing, grassroots community organizations, religious institutions, and prior gang-involved youth to advance discussions around community violence in Rochester, NY. Both projects recognized the ability of community-based involvement to improve the accuracy of model development and to increase the likelihood of intervention uptake. Additionally, both projects recognized the strength of SD tools to act as interventions in and of themselves by promoting restorative conversations among key stakeholders. The use of SD-related diagramming and other tools holds great, and currently underutilized, potential for advancing prevention work in injury-related areas that may be divisive or prone to stigma (e.g., gun control, intimate partner violence, and drug disorder and overdose).

Develop a Shared Vision and Unified Framework of a Complex, Multilevel Problem to Elucidate Data and Knowledge Gaps and Advance Research Kenzie et al. (2018) [57] provide an exemplary application of using SD to synthesize research on contributors to concussion occurring on different scales (e.g., cellular, environmental, and social). Using SD diagramming and drawing on experts across disciplines, the team created a unifying framework for interdisciplinary communication and collaboration with clear identification of research gaps and needs. Given the complex, interacting, and multilevel causes of injury outcomes (e.g., falls, overdose, and suicide), similar diagramming focused on other types of injury could accelerate advancements in these areas.

Account for Policy and Intervention Effects on Multiple Outcomes and Metrics, Fostering Transparency in Weighing Options and Considering Trade-offs Several of the papers reviewed demonstrated the importance of evaluating an intervention from multiple perspectives by incorporating multiple outcome measures into SD modeling efforts [56, 62, 64, 65, 67]. For example, through their SD simulation model, Wakeland et al. (2011) [64] demonstrated how specific interventions focused on reducing opioid misuse in the medical sector could increase illicit opioid use or result in barriers to therapeutic care for chronic pain patients. Additionally, McClure et al. (2015) [62] highlighted the need to focus not only on road safety risks but also risks associated with chronic disease development when examining the effect of land use and transport policies on population health. The inherent ability of SD to incorporate multiple metrics, outcomes, and perspectives is a critical benefit, given that understanding and weighing trade-offs is fundamental to almost any injury intervention selection (e.g., interventions in sports-related injuries, pedestrian travel, and medication use).

Account for the Timing of Intervention Implementation SD simulation models run across a user-specified time frame. The longitudinal nature of such modeling tools allows researchers to explore critical questions about intervention timing, recognizing the importance of not only *which* interventions are implemented but also *when* interventions are implemented. Hovmand et al. (2009) [55] explored the sequence and timing of three domestic violence interventions, finding that interventions that build victim advocacy efforts and foster cooperation between police and victim advocates prior to implementation of a mandatory arrest policy for domestic violence can lead to reductions in victim arrests, as compared with other iterations of intervention sequencing. The ability of SD to incorporate intervention timing and to factor in how events leading up to and immediately following intervention implementation can change the underlying state of the system holds enormous potential for optimizing intervention deployment to increase potential impact on injuries.

Recognize and Explore Unintended or Weak Effects of Policies and Interventions Hovmand et al. (2009) [56] provide a clear example of how SD can be used to hypothesize about unintended policy effects. Using a range of data sources and stakeholder input, the researchers sought to explore the underlying system creating an increase in domestic violence victim arrests after implementation of mandatory arrest policies for domestic violence events. Additionally, Wakeland et al. [64, 66] demonstrated how efforts to increase prescriptions of tamper-resistant opioid medications could shift opioid use and misuse behaviors to other parts of the system, resulting in very little reduction in overdose deaths. Finally, Macmillan et al. demonstrated that a city's planned approach to foster bicycle use and reduce injuries would likely not meet anticipated government-set targets; however, modeling efforts revealed that a more ambitious approach could result in improved outcomes in a cost-effective manner [58]. These studies and others provide useful examples of using SD to enrich injury intervention understanding, planning, and evaluation.

Leverage the Generalizability of Underlying System Structures Driving Injury Trends Two of the articles developed underlying, hypothesized model structures for explaining bicycling and road transport use and safety. The researchers then tested the generalizability of underlying structures across cities, acknowledging that specific parameter values and the dominance of specific feedback loops might vary but that underlying structures can be robust. For example, Macmillan and Woodcock (2017) [60] developed initial support for an underlying causal model of bicycling in higher-income cities, finding slight variations according to bicycling prevalence in cities. McClure et al. (2015) [62] tested a model of land transport and health across several major cities, finding that the underlying model structure was consistent with several trends across six major cities. SD applications that develop and test generalizable model structures for persistent injury problems may serve as an efficient starting point for model development in other contexts by reducing the time and cost of development. While there is often value added by engaging key stakeholders in a specific context, and model adjustment is often needed when starting from a generalized structure, SD simulation models are time and resource intensive. The ability to develop relatively generalizable structures that serve as informed starting points may not only lower the burden of SD simulation uptake but also provide critical insights on recurring underlying drivers and patterns.

Support Policy Decision-Making with Transparent, Hands-on Tools Finally, Page et al. (2017) [63] developed a transparent SD model that incorporated key evidence on suicide prevention strategies. The research team then created a user-friendly version of the model, making it available as a decision support tool for stakeholders to ask "what if" questions related to different combinations of policy implementation. As with any model, the SD tool developed was a simplification of reality. However, in contrast to some other modeling approaches, the hands-on tool and associated documentation made limitations and assumptions exceptionally transparent. The tool can be used to foster decision-maker engagement, active inquiry, and informed decisions about resource and intervention prioritization. Development of user-friendly SD tools for other injury outcomes could be a fruitful path forward, helping to further discussions and transparency between researchers and practitioners.

Limitations of Review

This review was limited to articles published in the peer-reviewed literature, written in English, and indexed in PubMed or Web of Science. Web of Science, in particular, was included, as SD researchers working on health and safety problems may publish outside of traditional public health and injury prevention journals. Still, it is possible that our review may have missed pertinent SD applications to injury problems. In Liu et al.'s (2018) [69] review of SD applications in the population health literature, they highlight the fact that many SD researchers are employed in the private sector, which could result in SD applications appearing less frequently in the published literature. Finally, as with any review, there is a possibility that relevant studies were missed in our review of potential articles or that we did not correctly capture specific study details during data abstraction.

Conclusions

SD has been increasingly used to study public health problems and interventions over the last few decades; however, uptake in the injury field has been slow. While barriers to adoption exist, including few training programs in systems science methods, facilitators of SD use are becoming more prevalent, including specific funding calls for systems science applications. Given the many ways that SD can add value and complement traditional approaches in the injury field, as demonstrated above (e.g., methods to visualize and explore complexity, policy decision support tools), increased investment in building capacity to utilize SD tools and creating opportunities for use is warranted. As injury continues to represent one of our largest public health problems, innovative methods, like SD, are needed to foster new insights on intervention and policy creation, prioritization, and implementation to ultimately support prevention progress.

Funding Information Financial support for this work was provided by the University of North Carolina at Chapel Hill Injury Prevention Research Center through an award (R49/CE0042479) from the Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.

Compliance with Ethical Standards

Conflict of Interest The authors declared that they have no conflict of interest.

Human and Animal Rights and Informed Consent All reported studies/experiments with human or animal subjects performed by the authors have been previously published and complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

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For the interested reader, foundational books and papers in the field of system dynamics are marked with a •.

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