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D7.1 Review of existing system dynamics models on overweight/obesity in children and adolescents

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Executive Summary

This deliverable presents a systematic review of existing studies applying System Dynamics to investigate obesity in children and adolescents. This is a component of the CO-CREATE project: Work Package 7 (A review of existing system dynamics models on overweight/obesity in children), led by the University of Oslo.

The specific research aims were to (i) identify and summarize the key characteristics of system dynamics studies on the relationship between children and adolescents' body weight status and related behaviors (i.e. eating and physical activity) and the environment they are embedded in; (ii) describe the environmental factors and dynamic mechanisms driving overweight and obesity development in children and adolescents in these studies; and (iii) identify the causal relationships through which interventions and policies can impact overweight and obesity determinants in children and adolescents. Our main outcomes of interest were children and adolescents' eating and physical activity behaviors, which directly influence obesity outcomes.

Peer-reviewed and published studies were identified resulting from searches of the Medline, Embase, PsyInfo, CINAHL, Web of Science and Scopus databases. Seventeen studies presenting system dynamics modeling were identified for inclusion in this review. A summary of the key characteristics from the included articles was presented and described using a narrative thematic approach. Then, environmental determinants and the dynamic mechanisms driving obesity in children and adolescents were identified and illustrated with a graphical representation known as a Causal Loop Diagram. Lastly, interventions and policies addressing diet and physical activity were presented according to their level of influence and impact on the intervention targets based on the causal loop diagram.

This review found that children and adolescents' food choices and physical activity, are influenced by environmental factors and these factors' influence is reinforced and counteracted by feedback loops. System dynamics is a methodology that contributes to the understanding of how environmental factors and their dynamic mechanisms drive obesity and how certain interventions and policies could alleviate the problem. The modeled interventions targeting the children and adolescents' environment, showed more downstream impact on the individual food choices and physical activity levels. This study also revealed that further research on intangible variables modeling is justified. For the practice field, evaluation of policy options using system dynamics modeling taking all this into consideration might be a way forward.

The findings presented in this review will be used as inputs for the system dynamics model that will be developed later in WP7. Furthermore, the findings of the present work will be written into a paper for publication in a scientific journal.

Table of content

List of acronyms / abbreviations

ABM = Agent-Based Modeling

BMI = Body Mass Index

CLD = Causal Loop Diagram

EBRB = Energy Balance Related Behaviors

NCD = Non-communicable diseases

PA= Physical Activity

PRISMA= Preferred Reporting In Systematic Reviews

RCTs = Randomized Controlled Trials

SD = System Dynamics

SES= Socio-Economic Status

SFD = Stock and Flow Diagram

SSB = Sugar-Sweetened Beverages

Introduction

Increasing obesity prevalence is an urgent public health problem across the world, in both children and adult populations[1–4]. Obesity has several short and long-term impacts on the health and well-being of youth[5–7], particularly, because childhood obesity often continues into adulthood[8–10]. In light of these concerns, there have been multiple efforts to combat childhood obesity ranging from clinical interventions to public policies[11]. However, efforts to address obesity have yielded few effective and scalable solutions either for clinical care interventions or public health policies. The failure of most countries to reverse and prevent the obesity epidemic using traditional single behavioral target interventions suggests that obesity is a substantially complex public health problem with multiple levels of influence[12] which need to be considered in any attempt to reverse the epidemic.

Multiple biological, psychosocial, cultural, environmental and economic drivers of behavior, underly excess energy balance [13] in children and adolescents. These drivers operate at multiple levels with a variety of mechanisms that interact with one another, including for instance, environmental factors (e.g. oversized food portions in fast food restaurants, the lack of neighborhood sidewalks and food advertising); individual or behavioral factors (e.g. higher and frequent consumption of fat and energy-dense take-away food, and the adoption of sedentary lifestyles). In this respect, interventions evaluated in studies with traditional designs such as individual-level studies that test the efficacy of vaccines or nutrition supplements[14], examined individual level behavior mostly because of the difficulty of using such methods to evaluate higher level interventions[15] e.g. policies at a national level. Public health research is dominated by randomized control trial (RCT) and epidemiologic risk factor study designs[16,17]. Generally, RCTs and other types of quasi-experimental designs are concerned with internal validity and the ability to measure intervention effects precisely[18]. However, this precision often sacrifices external validity and the ability to measure and understand contextual and ecological effects. Even where mechanisms of effect are clear, the linkages and feedback between these mechanisms are not well studied or well understood[18] which could be a contributing factor to the low level of effectiveness found in RCTs.

To study, identify, and characterize the mechanisms that drive complex public health issues such as obesity, there is a need to use study designs and methods that allow measurement of interactions among elements of complex systems, such that other aspects that go beyond the individual are considered in concert[19]. In terms of analysis the methods for studying complex problems are holistic in nature, as they examine models of systems to help identify the complex mechanisms by which they operate[20]. While traditional statistical modeling often assumes binary relationships of cause and effect where changes in dependent variables are proportional to changes in independent variables, complex systems are characterized by nonlinearity, threshold events, and chaotic behavior[21]. In fact, the different levels at which obesity drivers and interventions influence each other in direct and intended ways, as well as, indirect and unanticipated ways, lead to effects that emerge over time.

Unanticipated effects can result in policy resistance, which is the tendency for policies to be ineffective or have unintended consequences that create new problems or worsen the original problem[22,23]. For example, a school-based policy restricting unhealthy foods for lunch could cause parents to provide fast food to their children in an attempt to 'make-up for' the school's strictness.

In recognition of the complexity of public health problems, such as childhood and adolescent obesity, the application of systems science methods based on systems thinking principles, has gained increasing interest and support during recent years[24,25]. Several branches of systems science develop computer models to simulate or mimic the system under study considering the interactions among the system components. Models can be a basis for *in silico* experimental investigations which can be conducted at lower cost and in less time than trying to achieve changes in actual systems[22]. Such models can facilitate policy evaluation by expanding the boundaries of mental models and enhancing learning from evidence[23,26,27]. Systems models can help assess the potential impact of upstream interventions on the environment and their downstream effects on childhood bodyweight dynamics. Systems science methods include System Dynamics Modeling (SDM) and Agent-Based Modeling (ABM). Unlike ABM, which is an individual-based modeling technique, systems dynamics is an aggregate-level modeling type, which makes it appropriate for national level policy evaluation [28]. System dynamics is a methodology for understanding dynamic problems[29,30]; it centers on the idea that feedback structures and their interactions among component parts within a system, are responsible for the system behavior over time[31]. SD uses quantitative computer models to uncover and understand endogenous sources of complex system behavior, i.e. it seeks to find explanations for system behaviors by understanding the internal structure of a system rather than focusing on factors external to the system[32]. Ultimately, a system dynamics model allows for the exploration of scenarios, testing of assumptions and evaluation of policies[33,34].

Several systematic reviews of studies applying systems science methods on obesity research have been conducted in recent years. In 2011, Levy et al. presented an overview of the obesity simulation models published from 2006–2010. Four studies used ABM and SD methods, and these were reviewed along with other types of simulation models such as discrete-time Markov, Monte Carlo and statistically based models[13]. Skinner and Foster[24] reviewed 21 studies published before March 2012, about the causes and/or consequences of obesity from a systems science perspective. A 2015 review examined ABM of Noncommunicable Diseases (NCD), comprising studies published from 2003 to 2014; among the 22 studies included, 13 were obesity related[28]. Xue et al.[35], examined the applications of systems science methods, specifically system dynamics modeling and agent-based modeling, in obesity research published between 2000 and 2017. Recently, Morshed et al.[36], reviewed agent-based and system dynamics computational models of obesity and how they provide insights into the shared drivers of the global syndemic. They included 38 studies representing 30 computational models, of which 16 where SD models. According to the previously mentioned reviews, one the most critical population subgroups, namely children and adolescents, has received

very little attention in reviews of SD studies even though it represents a key, systemic leverage point for obesity prevention. This review covers only SD studies on childhood and adolescent obesity to fill this gap. Despite there being multiple reviews of system science studies, reviews focusing on SD remain relatively scarce and those that do exist often combine it with other approaches such as ABM. This suggests a need of conducting more SD-based reviews as this methodology could help in capturing and formalizing generic processes driving obesity at a higher level of aggregation. Besides, this could help establishing interventions, as well as, identifying case-context specific adjustments that might be needed to make the model relevant for specific population subgroups and different contexts[23,37].

Our research aims are to (i) identify and summarize the key characteristics of system dynamics-based studies on the relationship between children and adolescents' body weight status and related behaviors (i.e. eating and physical activity) and the environment they are embedded in; (ii) describe the environmental factors and dynamic mechanisms reported in these studies, driving overweight and obesity development in children and adolescents; and (iii) identify the causal relationships through which interventions and policies could impact the drivers of overweight and obesity in children and adolescents.

Methods

Design

This systematic review was conducted following the methodological guidelines recommended in the Cochrane handbook for systematic reviews of Interventions[38] and PRISMA guidance for reporting systematic reviews[39]. Using an a priori defined protocol, we identified relevant articles against inclusion and exclusion criteria. The systematic review protocol is registered on PROSPERO (registration number: CRD42019125424).

Search strategy

Using a combination of text and Medical Subject Headings (MeSH terms), the following databases were searched; MEDLINE, EMBASE, PsyINFO, CINAHL, Scopus and Web of Science. The search algorithm was structured using the following search terms: (obesity OR overweight OR adiposity) AND (children OR adolescents) AND (system dynamics OR systems modeling). The search was conducted during February – April 2019 for the whole life of each database searched. Only published and peer-reviewed studies were considered in the search strategy. The search was restricted to studies published in the English language. Additional search strategy information is reported in Appendix 1.

Study selection

Eligible studies for inclusion, were those that applied the system dynamics method to model obesity and included overweight/obesity as an element in the model or any obesity-related behaviors (i.e. diet and physical activity, screen time and sleep). Titles and abstracts from electronic database searches were imported into the reference management program ENDNOTE 9 and screened against the inclusion and exclusion criteria (Table 1). Any disagreements on selection were discussed with a second reviewer and, if agreement could not be reached, were referred to a third reviewer for a final decision.

Data Extraction

Firstly, the main reviewer screened titles and abstracts against the inclusion criteria. Secondly, the full-text version was obtained for papers that met the inclusion criteria. Thereafter, two reviewers independently extracted data from the included papers. Discrepancies between the reviewers over the extracted data was identified and resolved by discussion with a third reviewer. The data extracted from the review was arranged by i) Author(s), Year and Country, ii) Study design (aim, population groups, simulation time, model outcome, and scenarios or interventions modeled), iii) Model details (model focus, model purpose, conceptual model, key model variables, feedback loops and validation tests), and iv) Findings (results and conclusions).

Table 1 Inclusion criteria

Criteria	Inclusion	Exclusion
Population	• Studies focusing on children and adolescent populations. • Studies examining a mixture of adults and adolescents were included when the results for children and adolescents are reported separately. • No restrictions on target group characteristics such as gender, baseline weight status or country.	• Studies focusing on adult populations only
Intervention	• Studies where the modeling intervention is aimed at understanding and preventing overweight and obesity in children and adolescents, delivered alone, or in combination with one or more other intervention(s). • Focus on policies to promote healthy habits and interventions to promote physical activity. • Any behavioral, community, individual or environmental policies aimed at the prevention of overweight/obesity in children and adolescents.	• Pharmacological or surgical interventions. • Studies concerned with interventions focusing on treating children and adolescents with overweight and obesity

Comparator Interventions	• Any comparison: i.e. intervention/standard practice/enhanced practice; or other intervention(s)/strategies used for prevention of overweight and obesity in children and adolescents.	
Outcomes	• The main outcomes of interest in this review were children and adolescents' eating and physical activity behaviors, which directly influence obesity outcomes (BMI).	

Model validity assessment

Although there are guidelines for carrying out and reporting system dynamics models[40], there are no standard guidelines (such as Cochrane group's guidelines) on performing syntheses of computational modeling research or evaluating model quality[36]. Nevertheless, a model validation checklist was compiled for this review, to assess the models of the included studies based on principles developed by system dynamics practitioners[27,40,41]. This checklist was adapted for the purposes of this review. The validity of the individual models was assessed by the lead reviewer, and independently checked by a second reviewer. Studies were given a quality score based on how many criteria they met on the validation checklist. Disagreements were resolved by consensus and if necessary, a third reviewer was consulted.

Analysis

A narrative approach to synthesis was chosen[42]. Evidence on model structures driving children and adolescent obesity is presented as a thematic summary; the findings are presented in text and in summary tables. A description of the themes of the studies disclosing the environmental and individual determinants and the level of influence of the intervention's studies, is presented according to the research aims. The determinants of childhood and adolescent obesity were separated into factors affecting diet/nutrition and physical activity[43].

Drawing on the socio-ecological perspective [44–47], we grouped the studies modeling interventions according to their intervention's level of influence into three categories: 1) environmental and policy interventions; 2) organizational (or institutional) and community interventions; and 3) interpersonal and individual interventions. We furthermore allocated each intervention by whether it aimed at diet/nutrition or at physical activity. Interventions with diet/nutrition components were targeted at: improving parents' eating habits and nutrition education, planning family meals, recommending adequate food servings size and frequency, enhancing accessibility and affordability of healthy foods, improving nutritional programs at schools, encouraging decreased intake of high-fat and high-sugar foods, and increasing fruit and vegetable availability at home and school.

Interventions with physical activity components attempted to reduce sedentary behavior, improve walkability, improve physical education programs at schools, reduce screen time, engage parents in active play and promote recreation and discipline in physical activity. Illustrative diagrams and tables are presented in subsequent sections to show the thematic summaries that resulted from the review.

Causal Loop Diagram

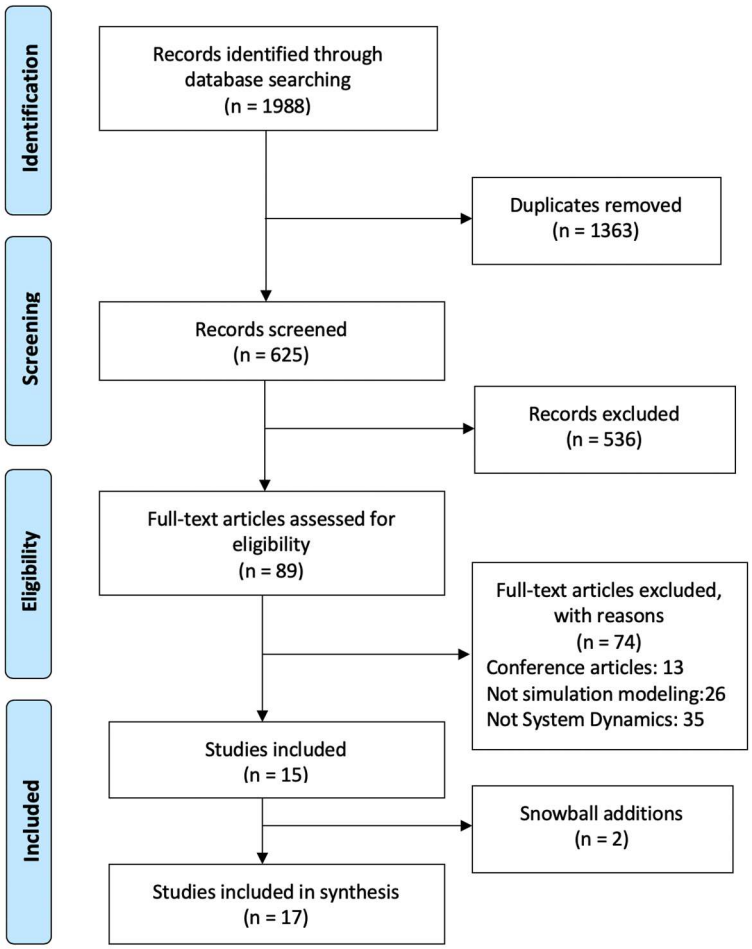
Based on the variables and causal connections affecting childhood obesity developed in the included studies, we assembled a causal loop diagram. In other words, this diagram is a compilation of system dynamics structures found in the included studies. The diagram also builds on the social ecological model for understanding childhood obesity and highlights the different levels of influence of interventions and their effect in the causal mechanisms between intervention and outcomes hypothesized in various studies. The causal loop diagramming method is adopted from the systems modeling toolbox[48,49] and has diverse applications[50,51]. Causal loop diagrams represent, in a visual manner, a possible set of causal set of causal relationships between different variables of the system[51].These diagrams provide a graphical summary of the main mechanisms obtained from the literature, finding out the empirical support for alternative pathways, collating the existing relationships modeled in the literature, highlighting the areas in need of further empirical research and allowing for future quantitative statistical and systems modeling as well as meta-analyses[52].

Results

Study selection

One thousand nine hundred and eighty-eight records were identified through database searching. A total of 625 references resulted after eliminating duplicates. After the initial screening based on titles and abstracts, 89 articles remained and were retrieved in full text for further evaluation. Of these articles, 74 were excluded in the subsequent detailed assessments. The remaining 17 studies were included in the review, which included 2 articles added from reference checking of full-text articles (see Figure 1).

Figure 1 Study selection process



Study characteristics

The summary of the key characteristics of the 17 studies included in this review is presented in Appendix 2. The majority of the studies were carried out in the United States (n=8). All the included studies were published in the last decade. The authors of the included studies chose diverse time horizons to simulate their models, ranging between 48 months to 50 years. The most popular settings of the studies were at a national level (n=7) and city/municipality (n=4). Other settings were schools (n=3), neighborhoods (n=2), and individual (n=1). Most of included studies used empirical data from governmental sources such as: the National Health and Nutrition Examination Survey (NHANES) for studies based in the United States, the Health survey for England (HSE), Australian Bureau of Statistics, New South Wales Health administrative datasets (HealthStats NSW), Colombian National Department of Statistics (DANE), World Data Bank, Statistics Canada Census and other various published sources.

Population

Six studies included children, adolescents and adults, separating them into age cohorts where each age group transferred to the next cohort over time[53–58]; ten articles included only children and adolescent populations[59–69]. Two studies included adolescents only[58,61].

Outcomes

The reviewed studies showed various factors that impact on children's obesity outcomes and energy-balance related behaviors (EBRB). Twelve of the 17 studies reported body mass index (BMI) and obesity prevalence[53–57,59–63,66,70]. Fourteen studies reported measures related to eating behaviors (e.g. fat intake, SSB consumption, portion sizes and meal frequency)[53,56–67,70]. Seven studies reported physical activity (PA) measures[53,54,58,61–63,68]. Five studies simulated the human energy regulation system. The model structures found in these studies generally consisted of four components: energy intake, energy expenditure, body composition and BMI impact/prevalence of obesity. Rahmandad (2014) and Hall (2013), simulated changes in body composition partitioned in Fat Mass (FM) and Fat Free Mass (FFM) and energy requirements of children at different ages; concluding that energy intake is a significant source of inertia in obesity trends. Eleven articles modeled changes in body weight at a population-level among different age groups, gender and socio-economic status[53–60,63,66,70].

Model details

The two main objectives of the all models reviewed were i) to examine etiological factors or tested interventions or policies and ii) to help predict or explain potential interventions[18]. Some studies were used for two or more purposes. Eleven studies were used to test interventions on obesity prevention and 8 to examine etiological mechanisms of obesity in childhood. Nine studies were used for predictive purposes and 4 for explanatory purposes. The most common conceptual models (i.e. representation of the concepts of the system to help building the model) of each study, were explained by using Causal Loop Diagrams (CLDs), Stock and Flow Diagrams (SFDs) and Conceptual Frameworks. Other forms of conceptual model representations include equations and textual descriptions. Most of the models (70%) were parameterized so that the error of the models' behavior with respect to the reference mode was minimized, and 57% conducted model validation tests to enhance model confidence. The most common tests performed by the authors were structure test, parameter test, extreme conditions test, sensitivity analysis and behavior reproduction.

Model validity assessment

The model validation process entails establishing sufficient confidence in a model to be prepared to use it for a particular purpose[61]. System Dynamics models are validated through structural and behavioral tests to understand their robustness and limitations[27,41]. Eight studies had an explicit description of model structure, model output, conceptual boundary, temporal boundary, level of aggregation, sources of parameter values, initial values, decisions involving calculations, exogenous variables considered, data sources and overall rationale[53,56–58,63,65,67,70]. Ten model structures were causal-descriptive, built as to how the real system operates and explained how the behavior is generated or changed[53–58,63,65,67,70]. Four studies provided a thorough description and explanation of the model validation procedure they carried out to build confidence in the model. Including tests performed, explanations of each test, graphical representation of tests[55,63,65,70]. Seven studies documented their models, providing a detailed description of the computational operations the model is designed to perform allowing an independent party to implement and simulate the model[55–58,63,65,70] (E.g. equations and algorithmic rules, all model parameters, units and initial values are fully reported and data sources). Regarding model visualization, 8 studies included comprehensive model representations such as Causal Loop Diagrams and Stock and Flow Diagrams which were shown to facilitate model reproducibility[53,54,57,58,60,63,65,68]. Model validity assessment scores and guidelines are presented in Appendix 4.

Dynamic mechanisms of childhood overweight/obesity drivers

Simulation results of the included studies suggested that obesity in children and adolescents is primarily driven by environmental elements rather than merely individual dietary and physical activity behaviors. Following obesity determinants frameworks[71], we identified environmental and individual factors driving overweight and obesity development in children and adolescents. We report them below according to whether the factor influenced diet or physical activity.

Diet/nutrition

Fourteen articles modeled obesity determinants related to diet/nutrition[53,55–67]. Six studies examined the food system setting and regulations of it, affecting overweight and obesity in children and adolescents. Struben et al.[57], modeled food supply, demand and governmental policy sectors influencing the population's health through regulating the food system. They described the attributes of nutritional market transformation (e.g. price, taste, availability, nutritional quality). Liu et al.[65], simulated the dynamics of SSB demand and the impact of utilizing the revenue from excising SSB tax to support obesity prevention interventions. Liew[64], modeled obesity trends influenced by soda consumption and school regulations affecting adolescents' food choices. Roberts et al.[63], built a model structure of the driving mechanisms of healthy choices (e.g. healthy food affordability,

availability at home and outside, and attractiveness). Abidin et al.[59,60], modeled food consumption in children as a function of portion size and number of meals which determined the consumption of total fat. Average fat portion size in different eating occasions including, home, school and outside of home meals played an important role influencing body weight and obesity prevalence.

Roberts et al.[63], studied healthy social norms influencing children's healthy weight (e.g. healthy parental influence and healthy peer influence). Likewise, they modeled parental resources such as parental employment, time and financial resources, leading to healthy food choices for their children. Carrete et al.[62], analyzed overweight and obesity in children taking into account the influence of the availability of snacks and junk food, family habits and economy, friends influence and the culture, in the development of healthy behaviors based on a socioecological framework. Safan et al.[67], studied healthy food behaviors in social settings shaped by individual characteristics (taste and food preferences), landscape macro-system forces (e.g. culture and policy) and social interactions (e.g. peer influence). They also stated that the day-to-day interactions among peers and family members shape children and adolescents' eating preferences/behaviors. Peer role-modeling has also been found to be significant in altering children's eating behaviors.

Frerichs et al.[53], simulated social transference effects of unhealthy behaviors from adult to adult, adult to child and child to child; on the population's BMI categories. Their results showed that the prevalence of obese children was more sensitive to adult to child social transmission rather than child to child. Lan et al.[61], investigated social factors influencing elementary school students' BMI values, including students' personal lifestyle, diet-related parenting behavior, advocacy and implementation of school nutrition education and students' peer interactions. Findings show that nutrition education, amongst other factors, have a strong influence in students' eating behaviors.

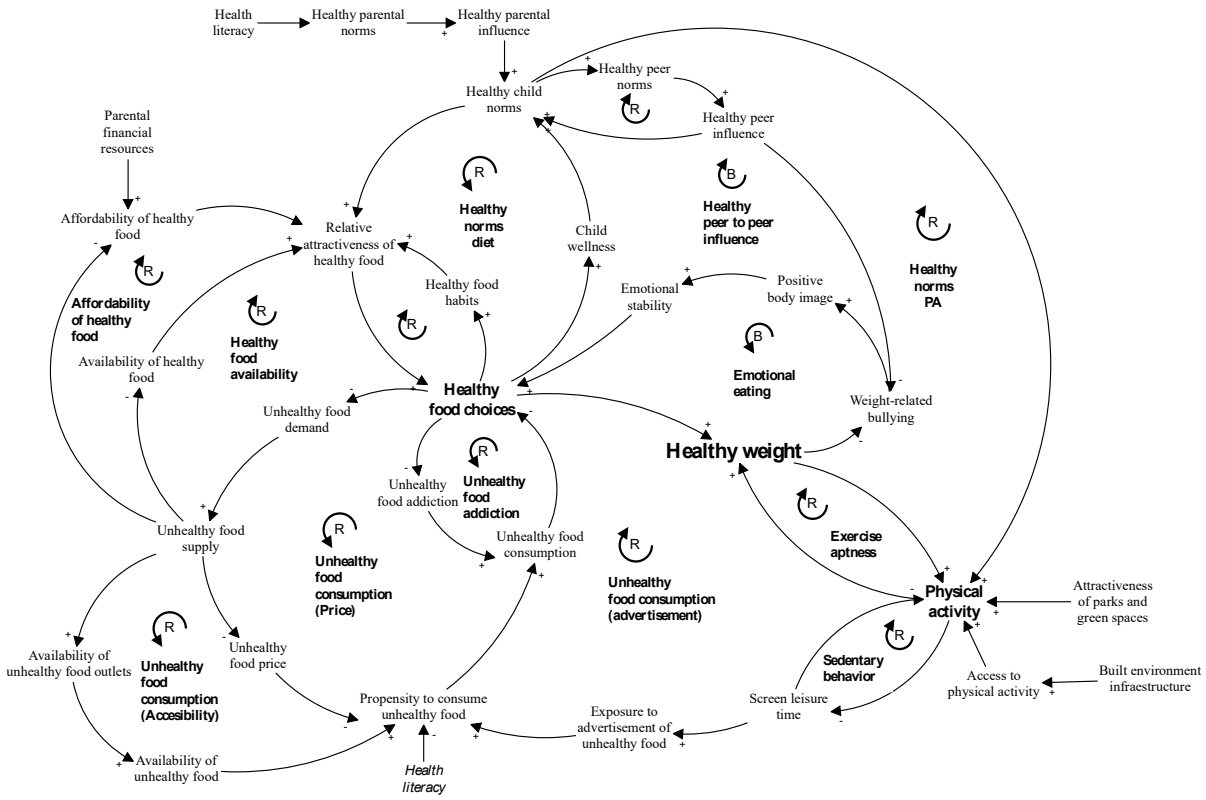
Physical activity

Six studies examined physical activity and built environments influencing childhood obesity[54,62,63,65,67,68]. Shahid & Bertazzon[68], modeled neighborhood walkability, pathway length, proximity to parks and fast food restaurants as those are considered among the most important determinants of childhood physical activity and body weight. Liu et al.[65], addressed the importance of the financial sustainability of an intervention and its interactions with other interventions. They studied how tax revenues from SSB can be used to construct affordable, attractive, accessible, safe outdoor activity spaces (parks) to increase children's physical activity levels. Carrete et al.[62] and Safan et al.[67], studied active lifestyles in social settings shaped by physical environments (e.g. available, accessible) and the availability of recreational activities on physical activity. Roberts et al.[63], modeled elements to support physical activity as walkability, green spaces, safety of built environment, active transport and sports infrastructure.

Meisel et al.[54] proposed attributes that may have an effect on transference rates (TRs) among BMI categories such as: leisure time physical activity, transportation physical activity and screen time. This was done to track the number of individuals who met the requirements of each attribute as they moved from one BMI category to the other, as these attributes were found to be important relative to obesity transitions. Roberts et al.[63] and Lan et al.[61], included mental health in their models and how it is influenced by bullying and body image but also how improving mental health would lead to higher physical activity levels. Lan et al.[61] also found that the educational attainment and socioeconomic status of parents, play an important role in the amount of physical activity their children engage in.

Based on the main dynamic mechanisms identified in the studies between the environmental and individual determinants of childhood and adolescent obesity a causal loop diagram was assembled (Figure 2).

Figure 2 Causal Loop Diagram



Interventions and policies addressing childhood overweight/obesity

To address our third research aim, we present the identified interventions and policies modeled in the included studies and divided them according to their level of influence (see Table 2). Note that several studies evaluated more than one category of interventions. Further information on each intervention can be found in Appendix 3.

Environmental and policy interventions

We identified six studies modeling environmental and policy interventions[57,58,62–65]. These interventions consisted of local and national policies, laws that regulate or support healthy actions and practices for obesity prevention. Examples are: the imposition of fiscal measures (i.e. taxes and/or subsidies), promoting a healthy lifestyle, the adoption of mandatory nutritional guidelines, the implementation of educational campaigns to increase health information and knowledge at a population level, increasing healthy food affordability and availability in schools and other public institutions (fruit and vegetables subsidies, food provision, vending machines regulations, among others), and the regulation of food advertisement to children across all media types.

Five studies described environmental interventions to promote physical activity[58,62,63,65,68]. These included investment in physical activity infrastructure, advertisement campaigns to promote active lifestyles and the development of urban planning of built infrastructure to support physical activity such as: active transportation (bike pathways and improved sidewalks), outdoor recreational areas (parks) and sport facilities.

Organizational and community interventions

Five studies included community-based interventions in their models[58,62,63,66,68]. These interventions targeted families, specifically parents, focusing on health-focused behaviors rather than weight-focused approaches. The community programs included: nutrition education programs for children and parents, family engagement, healthy food environments in schools and other public institutions, improved access to healthy foods, and campaigns to raise awareness of childhood obesity. Three studies proposed interventions concerned with improving eating behaviors and four studies focused on creating a local environment that emphasized and supported a physically active lifestyle.

Interpersonal and individual interventions

Seven articles addressed individual and interpersonal interventions[53,59–64]. The proposed interventions in this category directed efforts towards providing a supportive environment that leads to internalization of healthy eating and physical activity behaviors. Examples are guidance on a healthy diet and physical activity and school and family-based weight management interventions to prevent the transition from overweight to obese. Seven studies focused on diet/nutrition[53,59–64] and two on physical activity[62,63] interventions.

Table 2 Interventions and policies

	Name of intervention	Intervention target	Reference
Environmental and policy			
Diet/Nutrition	Fiscal measures on nutrition (taxes and subsidies)	- Unhealthy food price - Affordability of healthy food	57,63,65
	Marketing nutrition campaigns	- Exposure to advertisement of unhealthy food - Relative attractiveness of healthy food	57,58,62,63
	Health promotion on nutrition	- Relative healthy food attractiveness - Health literacy	57,58,62
	Product innovation	- Relative attractiveness of healthy food	57
	Mass media campaign	- Relative attractiveness of healthy food - Health literacy	62
	Healthy food availability measures	- Availability of healthy food	58,63
	Unhealthy food restriction measures	- Availability of unhealthy food	64
Physical Activity	Investment in PA spaces	- Built environment infrastructure	62,65
	PA advertising campaigns	- Attractiveness of parks and green spaces - Physical activity	63
	Urban planning policies	- Access to Physical Activity	58,63,68
Organizational and community			
Diet/Nutrition	School nutrition programs	- Health literacy	62
	School nutrition policies	- Health literacy	66

	Community-based prevention programs	- Health literacy	63
Physical Activity	School PA policies	- Physical activity - Healthy child norms	66
	Neighborhood walkability	- Access to physical activity - Availability of unhealthy food outlets	68
	Community-based prevention programs	- Health literacy - screen leisure time	58,63
Interpersonal and individual			
Diet/Nutrition	Routine advise and clinical service on nutrition	- Health literacy - healthy peer influence	63
	Healthy eating behavior educational programs	- Health literacy - Healthy child norms - Positive body image	62
	Low calorie diet	- Healthy child norms	59,60
	Awareness programs on nutrition	- Health literacy - relative attractiveness of healthy food	64
	School nutrition education	- Health literacy	61
Physical Activity	Routine advice and clinical service on active lifestyle	- Healthy child norms	62
	Recreational PA	- Physical activity - screen leisure time	63

Discussion

Obesity is indisputably a complex problem; that is one which has components interacting at various levels and whose behavior is emergent. As a complex problem, it is therefore necessary to study obesity as part of a 'system' rather than decomposing it and studying its individual parts [72]; traditional study designs and analytic tools will provide a limited part of the picture[73]. Rather, a complex problem like obesity requires a systemic approach towards childhood obesity prevention. System dynamics is a systems-based methodology that makes it possible to explicitly include interaction among different variables as well as non-linearity, delays, and feedback loops present in complex systems[74]. By doing so, it helps to improve the understanding of the causal relationships of obesity sources and allows policy planners and other stakeholders to better anticipate the multiple effects of interventions on obesity and other non-communicable diseases in the short and long term[75].

According to the insights provided by the causal loop diagram (Figure 2), the main feedback loops controlling the system were in their majority reinforcing negative influences. This indicates that there are multiple powerful vicious cycles intensifying unhealthy behaviors. Some of the major reinforcing feedback loops were related to the commercial food environment, which were driven by the price of unhealthy food, availability of unhealthy food and the 'addiction' created by unhealthy food consumption. Another important feature was the sedentary behavior loop. This loop was driven by screen leisure time which led to more exposure to advertisements for unhealthy food, leading the individual to greater individual propensity to consume unhealthy food. Physical activity was also influenced by the quality (attractiveness and accessibility) of the built infrastructure. The reinforcing feedback loops related to the social norms of the individuals, focused on the health literacy of parents which would shape the children and adolescents' norms when deciding to choose healthy food and an active lifestyle. Factors like parental financial resources and the availability of healthy food, influenced the relative appeal of healthy food, which would create healthy food habits at the same time. In addition, the emotional eating and peer-to-peer influence loops were identified as the only two balancing feedback loops, which controlled the emotional state of children and adolescents with respect to peer influence, body image and emotional stability towards food choices and physical activity. This suggests that the emotional eating component of obesity, could be effectively stabilized through children and adolescent's emotional health as well as healthy peer influence.

The interventions modeled in the included studies targeting determinants in the food market system and built environment, focused mainly on developing policies at a national level to control nutrition regulations, taxes, restriction of unhealthy food and beverages population-wide education programs and urban planning policies to improve built environments. When modeled, these interventions showed more downstream impact on the individual food choices and physical activity levels. However, these are also the most difficult to implement due to their cost, need of resources and

inherent complexity. As such authors of these studies emphasized that governmental support for these interventions were crucial[54,55,57,58,60,63]. Authors also noted that interventions are more effective when implemented in combination rather than individually[53,55–57,60,66,67]. On the other hand, interventions aiming to influence the social norms loops and emotional eating loop, consisted of creating community-based programs to engage families, schools and neighborhoods to incentivize nutrition and physical activity knowledge and best practices. These interventions appeared to be the easier and less costly to implement but their impact on healthy weight may be somewhat limited when the food market system and built environment are still boosting unhealthy food choices and sedentary behavior.

Studies assessing the possibility of reaching obesity prevalence targets set by governments found that first, the target would not be reached if intervention strategies remain unchanged; and second, the target would be achieved eventually but over longer than anticipated time scales [60,63]. This denotes that there are elements in the system preventing the interventions from closing the gap between the desired goal and the actual state of the systems such as: delays, nonlinearities and feedback loops that have not been accounted for.

Findings of this review suggest that System Dynamics has contributed to the understanding of how environmental factors and their dynamic mechanisms drive obesity and how certain interventions and policies could alleviate the problem. In addition, SD models are able to capture mental models and perceptions as well as hard measures – i.e. total fat content and norms and perceptions[53,60,63,67,70]. The application of System Dynamics to obesity research among children and adolescents integrates multiple theoretical frameworks and includes relevant empirical data that could be useful for policy evaluation. However, there are several apparent gaps in the SD models presented within the studies reviewed for this report. Notably, intangible variables such as stress and self-esteem, have not been clearly defined and quantified in SD models. Indeed, the studies reviewed failed to thoroughly examine the mental health and social interaction feedback loops which have been frequently acknowledged to be an important influence in obesity[52,61,63,76,77], whilst poorly studied and formalized. These gaps not only represent a large limitation in the papers reviewed by not accounting for such variables, but also the formalization of these variables would contribute greatly to the obesity research by supporting other research areas like psychology and behavioral sciences. Finally, during the review process, it was observed that none of the reviewed studies included a comparative cost-effectiveness analysis of the interventions in the model simulations. This omission provides a good opportunity for further research which would add an important dimension to assessing potential interventions using SD[47,78].

Strengths and limitations

To our knowledge, this is the first systematic review focusing on system dynamics-based studies incorporating the dynamic relationships of determinants of and interventions addressing childhood and adolescent obesity. This review used a systematic search and review protocol with strict inclusion and exclusion criteria across multiple databases. Additionally, reference lists of studies selected for inclusion were manually searched. At all stages, the study selection process was performed by two reviewers independently and was clearly defined and is fully reproducible. Even though there are no available quality assessment guidelines to assess SD models, this review applied a compiled checklist of validity assessment based on principles developed by SD authors [27,40,41].

The results of this review should be assessed with some caution. In particular, we only included studies written in English and grey literature was not included. Second, it was challenging to give a validity score to the models because there are no standard quality assessment guidelines to evaluate system dynamics studies, these studies are heterogeneous (i.e. model purpose, intervention type, level of aggregation, etc.) and model documentation was not fully reported. Finally, we did not systematically and critically assess the assumptions and evidence used to parameterize and calibrate the models.

Conclusion

This review found that children and adolescents' food choices and physical activity, are influenced by environmental factors and these factors' influence is reinforced and counteracted by feedback loops. This indicates that there are multiple powerful vicious cycles intensifying unhealthy behaviors. System dynamics is a methodology that contributes to the understanding of how environmental factors and their dynamic mechanisms drive obesity and how certain interventions and policies could alleviate the problem. The modeled interventions targeting the children and adolescents' environment, showed more downstream impact on the individual food choices and physical activity levels. This study also revealed that modeling intangible variables such as stress and self-esteem, have not been modeled in depth, yet it seems to be fundamental for obesity prevention in children and adolescents. This suggests that further research on intangible variables modeling in this context is justified. For the practice field, evaluation of policy options using system dynamics modeling taking all this into consideration might be a way forward.

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Appendices

Appendix 1. Search strategy

Medline

1. Overweight/
2. Weight Gain/
3. (overweight or obesity or obese or pediatric obesity or childhood obesity or adiposity or weight gain or body mass index or BMI).ti,ab,kw.
4. 1 or 2 or 3
5. Child/
6. Adolescent/
7. (child or children or childhood or adolesc* or young adult or young people or youth or teen*).ti,ab,kw.
8. 5 or 6 or 7
9. Nonlinear Dynamics/
10. Computer Simulation/
11. Systems Analysis/
12. (nonlinear dynamics or dynamic simulation model* or systems thinking or system dynamics or systems dynamics or system dynamics model or systems modeling or dynamic behavior or systems modeling or dynamic behaviour).ti,ab,kw.
13. 9 or 10 or 11 or 12
14. 4 and 8 and 13
15. limit 14 to english language

Web of Science/Scopus

Concept	Query search
Obesity	obesity OR overweight OR obese OR "pediatric obesity" OR "childhood obesity" OR "child obesity" OR "body mass index" OR BMI OR "weight gain" OR adiposity
	AND
Children and adolescents	child* OR adolescen* OR youth OR teen* OR “young people” OR "young adults"
	AND
System Dynamics Modeling and similar terms	“nonlinear dynamics" OR "dynamic simulation model*" OR "systems thinking" OR "system dynamics" OR "systems dynamics" OR "system dynamics model*" OR "systems modeling" OR "dynamic behavior" OR "systems modelling" OR "dynamic behavior"

Appendix 2. Study key characteristics

		Study Overview					Model Description						Findings
	Reference, Year, Country	**Study aims**	**Target population groups**	**Simulation time**	**Model outcome**	**Simulations, Scenarios and/or interventions tested**	**Model focus**	**Model Purpose**	**Conceptual model**	**Key stocks**	**Feedback loops**	**Validation tests**	**Results and conclusions**
1	Abidin et al., 2014 United Kingdom	To simulate the effects of changes in eating behavior of British children on weight and obesity; and identify how long will it take to remove obesity as a public health concern by 2020, using system dynamics optimization.	British child population by gender and three age bands (2-4 years, 5-10 years and 11-15 years)	1970-2030	Average weight (AW), average body mass index (ABMI) and the prevalence of obesity (POB)	BMI reduction and POB measurement using an optimization process: - Phase 1 (1970–2012): represents the past and present situations that lead to obesity. - Phase 2: refers to the capability of the ICOD model to reverse the future of AW, ABMI and POB trends.	Energy balance (human energy regulation system	Intervention testing Predictive	Conceptual framework presented in four sectors: food intake, energy expenditure, physical measurement and BMI impact	Average of fat portion size from outside meal, average weight, average height and prevalence of obesity.	Three reinforcing loops RL1, RL1, RL1 (food consumption loop) and one balancing loop BL (energy balance loop)	Structure tests and behavior reproduction	Simulation results indicated that 2020 target will not be achieved until 2026 at the earliest, suggesting a longer period may be needed to reduce obesity. Failure to achieve the target might be due to focusing policy interventions related to obesity to individual choices instead of environmental factors. Finally, attention should be directed to interventions to improving outside food sources for children.

2	Abidin et al., 2014 United Kingdom	To compare and determine the effective strategy for obesity prevention by improving the consumption of portion size and meal frequency.	Child population aged between 2 to 15 years old.	1970-2030	Eating behavior: Body weight and BMI.	Compared simulation runs: Base run: without policy change Strategy 1: the effect of reducing portion size for an outside meal parameter (50% reduction), on Average weight and Average BMI. Strategy 2: the effect of reducing the frequency of meals parameter (50% reduction), on Average weight and Average BMI.	Energy balance (human energy regulation system	Etiology & Intervention testing	Causal Loop Diagram	Prevalence of obesity, Average weight, average height.	Three reinforcing loops RL1, RL1, RL1 and one balancing loop (energy balance loop)	Parameter and structure verification, Behavior reproduction	Findings from the experiments found that almost 5% reduction occurs in AW and ABMI by 2030, via reducing meal frequency compared to portion size strategy, which undergoes nearly 3% reduction. Simulation analysis demonstrated that reducing meal frequency is the most effective strategy for obesity prevention. A developed understanding between the effect of meal frequency and portion size on weight and BMI changes may prove helpful for obesity prevention programs.
3	Carrete et al., 2017 Mexico	To contribute to the understanding of how	Elementary school students	2000-2050	Eating behavior (weight and BMI)	The effects that the major elements of each	The Social Ecology Framework (SEF)	Etiology & Intervention testing	Based on a framework consisting of four levels:	Macro level influenced by: National	Not specified	Not stated by the authors	This research shows the existence of counteracting

		elements of the socioecological system shape individual behaviors by analyzing overweight and obesity from a sociological perspective that takes into account the influence of relevant social factors regarding the development of healthy behavior patterns of urban Mexican children.	from 9 to 12 years old		and physical activity and obesity prevalence.	subsystem of the socioecological framework, have on childhood overweight. Scenario 1: Reliance on governmental policies. Scenario 2: Family engagement Scenario 3: Family and governmental policies aligned		Predictive	micro, meso, exo and macro systems	policies, Culture Exo level influenced by: Local policies, Availability of recreational activities, Availability of junk food. Meso level influenced by: School intervention, Social influence. Micro level influenced by: Family habits and economy, Friends influence.			efforts at the micro (family) and macro (governmental policies) levels that need to be aligned to reduce rates of obesity and overweight. Moreover, the use of the systems approach for framing and understanding how the interrelationships of socioecological elements derive in synergic or antagonistic effects, helps to predict the long-term effect of governmental actions and school interventions.
4	Frerichs et al., 2013 United States	(1) to assess the sensitivity of childhood overweight and obesity prevalence to peer and adult social	Children and adults by age groups	10 years	Overweight and obesity prevalence (BMI and percentile	The impact of varying model parameters of social transmission and weight loss behavior rates to test	Population cohorts based on health status related to weight	Etiology & Intervention testing Predictive	Causal loop diagram of adult and child social transmission of obesity	Health status related to weight (i.e., normal weight, overweight, and obese adults and	Two reinforcing loops: (1) a loop between the increase in overweight and obesity that leads to a	Behavior reproduction, sensitivity analysis	Childhood obesity prevalence may be more sensitive to changes in adult-to-child social transmission rates compared to child-to-child rates.

		transmission rates, and (2) to test the effect of combinations of prevention and treatment interventions on the prevalence of childhood overweight and obesity.			guidelines)	the effect of combinations of behavioral and treatment interventions. The model includes an explicit intervention impact parameter to capture the potential to actively engage targeted individuals to model and encourage healthy behaviors among the other age group at varying degrees.				similarly normal weight, overweight, and obese children).	rise in the likelihood of social transmission, and (2) a loop from the increase in overweight and obesity that leads to a decrease in normal weight population, which leads to a subsequent increase in the likelihood of maintained social transmission.		Combinations of prevention and treatment generally have greater impact than either alone. However, the additional complexity of adult and child influences and social transmission resulted in changes to an alternative's impact depending on varying influence of adult and child interventions on each other. Intervention combinations that focus more heavily on adults may result in greater reductions in childhood obesity than those that target children only if adult interventions have higher residual impact on children.

5	Roberts et al., 2018 Australia	The aim of the study is to support the Australian Government and stakeholders responsible to achieve a target to reduce the population prevalence of childhood overweight and obesity by 5 percentage points by 2025. A system dynamics model was developed to address the question of what combination of high-level strategies is needed to meet the target.	Children between 0 and 17 years of age	2010-2030	The proportion of overweight and obese children aged 5 to 16 living in NSW from 2016 to 2025 Other outcomes: awareness of healthy food and behaviors, engagement with services, consumption of sugar-sweetened beverages and energy expenditure	Interventions: 1) Increased healthy food choices in Government settings (2) Settings-based, state-wide primary prevention programmes (3) Prenatal and post-natal interventions (4) Advertising bans across all media types (5) Sugar-sweetened beverage tax (6) Healthy food subsidies (7) Social marketing campaigns (8) Routine advice and clinical service delivery. (9) Environments to support	population level modeling based on weight status	Intervention testing Predictive	Collaboratively built conceptual model of the risk factors and pathways of OB, and of mechanisms for interventions	Overweight/obesity percentage by age, energy balance (intake and expenditure), community education and information, awareness, healthy food affordability, healthy food availability out of home, healthy food at home, program adoption, community infrastructure, relative walkability, NSW population.	Not specified	Sensitivity analysis and behavior reproduction	While the model demonstrates that it is theoretically possible to achieve the target of a 5% reduction in childhood overweight and obesity in NSW by the end of 2025, substantial cross portfolio policy actions will be required. The collective impact of 'business as usual' interventions (i.e. continuing NSW Health programmes to address childhood overweight and obesity at their current levels of reach and adoption) was found to be insufficient to achieve the target. The model outcomes also provided guidance regarding the

						physical activity.							timing of intervention effects, with model outputs forecasting that there will be little discernible impact until 2020.
6	Lan et al., 2014	To investigate the factors affecting elementary school students' BMI values.	Elementary school students	48 months	BMI values	Simulation tests were conducted to analyze: 1)The influence of students' concepts of health on obesity. 2) The influence of the educational attainment and socio-economic status of parents on the amount of physical activity of students. 3) The influence of	Stock and flow diagram based on causal loop diagram	Etiology & Intervention testing Explanatory	Causal loop diagrams	Students' concept of health, Obesity levels and nutrition education.	- R1: Diet-associated parenting behaviors and students' BMI values. - R2: Students' perception of self-body image and BMI values. - R3: Effectiveness of the implementation of school nutrition education and students' concepts of health. - R4: Students' experience of	Behavior reproduction	Students with more adequate concepts of health usually have better eating behaviors and attitudes and consequently have less chance of becoming obese. In addition, parents with a high socioeconomic background usually have a better concept of health. Therefore, parents having a high educational attainment and socioeconomic status imply a higher amount of physical activity of their children.

						the implementation of school nutrition education on students' high-calorie diets.					being ridiculed due to their body shapes and high calorie diets.		Finally, this study verified that the implementation of school nutrition education has a certain effect on curbing the frequency of students' intake of high-calorie diets.
7	Liew. 2018 United States	To project the prevalence of soda consumption and obesity given the declining trends in soda consumption and permission to purchase soda pop or fruit drinks, as well as, the expected percentages increase in people between ages 15 to 19 and students in grades 9-12 with obesity.	Students between 15 to 19 years old	20 years	Change in soda consumption and obesity in adolescents	Soda consumption, school permission to sell soft drinks percentage of obesity increase in students in grades 9-12	Mathematical modeling	Etiology & intervention testing Predictive	Conceptual model	Soda consumers, schools permitting the sales of soda pop or fruit drinks and number of adolescents with obesity.	Not specified	Not stated by the authors	Results suggest that the number of soda consumers is projected to decrease over time while the reverse is true for adolescent obesity. Another finding is that permitting the sales of soda pop or fruit drinks in schools' vending machines has the potential to influence students' choice of beverage consumption. Despite the declining trends in the number of soda consumers and schools that permit the sales of

													soda pop and fruit drinks, policies to promote healthy beverage consumption and restrict the sales of soda pop or fruit drinks in schools' vending machines should be continued.
8	Meisel et al., 2018 Colombia The nutritional stage dynamics model of the Colombian population	To investigate the nutritional stage dynamics within the urban population of Colombia using a System Dynamics model. Specific objectives: (1) to estimate the transference rates (TRs) between BMI categories by age and SES, (2) to identify the population subgroups towards which intervention efforts should	Colombian urban population by age groups (0-59 years),	2005-2030	Transference rates between BMI categories by age group and SES	1.- Rate of people transitioning from overweight to not overweight category 2.- Rate of people transitioning from obese to overweight category 3.- Combination of 1 and 2 4.- Rate of people transitioning from obese to overweight and from	population aging cohorts based on BMI categories (not overweight, overweight and obese) and Socio-Economic Status (SES	Etiology Predictive	Overview of the SD structure	Weight status categories by age and socioeconomic status (SES)	Not specified	Integration error, parameter assessment, extreme conditions, behavior reproduction and sensitivity analysis	The model results indicate that the most vulnerable and poorest groups display higher Transference Rates (TRs) to overweight and obese, whereas wealthiest groups show the highest prevalence of overweight and obesity. Despite this, the main public health policies in Colombia targeting the lowest SES population are related to undernutrition and

		be targeted, and 3) to monitor the potential effect of public health policy interventions aimed at preventing overweight and obesity across age and SES categories.				overweight to not overweight among individuals aged 5-14 years and 15-24 years.							integrated policies for the whole spectrum of malnutrition are not effectively implemented. Finally, the prevalence of overweight and obesity among children aged 0 to 14 years do not follow the patterns observed in other middle-income countries in Latin America.
9	Meisel et al., 2016 Colombia The nutritional stage dynamics model of the Colombian population	To capture the transitions of the population by BMI categories within the Colombian urban population.	Colombia population by age groups, gender and BMI categories (not overweight, overweight and obese)	2005-2030	Transference rates between BMI categories by age group	1) the TR from overweight to not overweight is increased from 2011 to 2030; 2) The TR from obese to overweight is increased 2011 to 2030; and 3) the TRs from obese to overweight and from	Population level modeling based on BMI categories (not overweight, overweight and obese)	Etiology Explanatory	Overview of the stock and flow structure	Not overweight, overweight and obese. Not overweight, overweight and oberse who met LTPA, PFSD, ST and TPA	Not specified	Not stated by the authors	The simulation results show that the prevalence of overweight and obesity will increase in 6.2 and 7.5 percent by 2015, and 13.4 and 18.9 percent by 2030, respectively, if the estimated Transmission Rates (TRs) do not change.

						overweight to not Overweight, are changed to a value of 0.01 from 2011 to 2030.							
10	Liu et al., 2016 United States	To inform policymakers' understanding of how allocating revenue collected by SSB taxation across sustainable implementation strategies might maximize benefits of such taxation for childhood obesity prevention.	2-19 age kids (boys) & adolescent population	20 years	Childhood obesity prevention	The model captures the implementation of three interventions: (a) levying an excise tax on SSBs; (b) allotting SSB tax revenue to construct safer outdoor activity spaces; and (c) allocating SSB tax revenue to subsidize an unserved population composed primarily of children and adolescents with vegetables	Policy modeling	Etiology & intervention testing Predictive	Conceptual Framework	Revenue from Excise tax, Budget for building healthy environment, realized demand, Budget allocated for building park, Net added park land areas, Budget allocated for subsidizing kids and adolescent, Realized energy intake from SSB, Cumulative reduced energy intake with SSB reduction for	Not specified	Integration error, behavior reproduction and sensitivity analysis	This framework helps researchers and policymakers to understand and anticipate the possible counter-intuitive behaviors caused by implementation-related factors such as delays and other uncertainties and it allows them to design and implement reliable implementation strategies for childhood obesity prevention.

						and fruits (VF) at school.				boys, Energy expenditure.			
11	Powell et al., 2017 United States	Simulated the potential impact of a given policy intervention or combination of policy interventions on the prevalence of obesity in childhood in Georgia through 2034.	Georgia children and adolescents (up to 18 years)	20 years	Obesity prevalence (specifically, BMI for age percentiles)	1.- No policy change. 2.- Individual and combination of interventions regarding: Physical Education, Recess and After-School Programs.	Not specified	Intervention testing Predictive	Text	Not specified	Not specified	Not stated by the authors	With no policy change, the prevalence of obesity among children and adolescents aged 18 in Georgia would hold at 18% from 2014 through 2034. Mandated daily physical education and integrating moderate to vigorous physical activity into elementary classrooms would have the largest potential impact on reducing the prevalence of childhood obesity in Georgia. However, a variety of policy interventions will be necessary to significantly reduce childhood obesity.

12	Rahmandad, 2014 United States	Developed a mechanism-based model spanning full individual life and capturing changes in body weight, composition and height dynamics, including variations across individuals with respect to gender and race.	Population sub-groups: Gender, age (infants, children and adults) and race.	0-12 Months (Infant) 0-20 Years (Child) 17-80 Years (Adult)	Growth and weight (BMI)	The model replicates key trends in human growth including A) Changes in energy requirements from birth to old ages. B) Short and long-term dynamics of body weight and composition. C) Stunted growth with chronic malnutrition and potential for catch up growth	Energy balance and population cohorts	Etiology Explanatory	Equations	Body weight partitioned in Fat Mass (FM), Fat Free Mass (FFM) and Height (H).	Not specified	Not stated by the author	The model can address diverse policy questions. For example, even without further rise in obesity, the gap between healthy and actual Body Mass Indexes (BMIs) has embedded, for different population groups, a surplus of 14%–24% in energy intake which will be a source of significant inertia in obesity trends. Also, energy deficit percentage needed to reduce BMI by one unit is found to be relatively constant across ages.
13	Safan et al., 2018 United States	To evaluate the role of socialization and school environments on the diet dynamics in children's	Different population groups including children.	Not stated	Diet behavior in schools	Evaluation of four models in order to evaluate different combinations of changes in social	Population cohorts divided by "Moderately" healthy eaters, "Less"	Etiology Predictive	Socio-ecological Theory Framework	Moderately, Less and Healthy individuals.	Not specified	Not stated by the authors	It was found that some level of standard education was better than none at all albeit not that effective.

		schools settings.				interactions and school environments in response to the implementation of different school nutrition education programmesandpolicies targeting different levels of the socio ecological framework.	healthy eaters and "Healthy" eaters						Even a low rate of recidivism lead to a constant proportion of L-eaters, which increases under the presence of negative peer influence. Positive peer influence and food association learning can significantly modify the culture of eaters and thus, promote healthier eating behaviors among children. Lastly, sustained healthy eating behaviors could be achieved by conditioned food preference learning.
14	Shahid & Bertazzon, 2015 Canada	To evaluate the impact of targeting neighborhood walkability in different neighborhoods	Children (4.5-6 years old) and obese)	2009-2015	Childhood obesity rates	Three scenarios where analyzed: Base scenario (no intervention) and two	Population cohorts by Age category (Healthy weight, overweigh	Intervention testing	Not stated	Healthy-weight, overweight and obese children.	Not specified	Not stated by the authors	The simulated intervention yielded a modest but measurable reduction in the number of obese children over a short time period.

		on childhood obesity.				walkscore scenarios (10-point increase and 20-point increase), were computed for the 24 identified neighborhoods.	t and obese) Socioeconomic status						Further, it reduced the significance of walkability as a risk factor in the targeted neighborhoods, thereby exposing other critical factors that could be targeted by subsequent interventions. Conclusion: local walkability interventions can achieve measurable declines in childhood obesity rates
15	Struben et al., 2014 Canada	To analyze how supply, demand, and governmental policy endogenously evolve and collectively influence population health and shape the nutritional quality of	Canadian population (Segmented by age and gender)	2010-2050	BMI	1) No intervention, projections based on 2010 calorie consumption. 2) Industry self-regulation efforts. 3) Governmental policies.	Food market and population modeling	Etiology & Intervention testing Predictive	Nutrition Market Transformation conceptual model	Serving size, propensity to consider a category, energy stored, population, attribute-related capabilities.	Social Exposure R1 Learning and R&D R2a Industry marketing R2b Market Return R3a Capability productivity R3b Saturation B3a B3b	Behavior reproduction, sensitivity analyses	Results show how single-pronged initiatives, whether designed and deployed under governmental or private sector leadership, are ineffective, failure-prone, and costly. Transforming value chains and markets and affecting consumer demand

		consumed food portfolios.				4) Market and government stimuli of nutritious food product innovation.							and behavior in nutrition- and health-sensitive directions requires implementation of multiple aligned interventions, such as temporary marketing initiatives, consumer education, and R&D commitments so as to benefit from synergies across sectors.
16	Hall et al., 2013 United States	Developed a model of childhood energy balance and bodyweight dynamics that accounts for healthy growth and development of obesity and makes quantitative predictions about weight management interventions.	Children and adolescents (5-18 years)	20 years	Bodyweight dynamics and obesity development	Used a reference childhood body composition data to calibrate the growth model and simulate the changing proportion of fat and fat-free mass deposition with age and the increasing energy density of fat-	Energy balance (Human weight regulation system)	Etiology Explanatory	Equations	- Energy intake and expenditure Fat-free mass - Body fat mass - Excess of body weight - Excess of energy intake	Not specified	Behavior reproduction mathematical validation	The model accurately simulated the changes in body composition and energy expenditure reported in reference data during healthy growth and predicted increases in energy intake from ages 5–18 years of roughly 1200 kcal per day in boys and 900 kcal per

						free mass. Then, the model simulations were compared with studies that accurately measured children and adolescent body composition at different ages.							day in girls. Development of childhood obesity necessitated a substantially greater excess energy intake than for development of adult obesity. Furthermore, excess energy intake in overweight and obese children calculated by the model greatly exceeded the typical energy balance calculated on the basis of growth charts..
17	Kuo et al. 2016 United States	To address the range and health impacts of obesity prevention strategies in local communities in Los Angeles County (LAC) for 3 program focus areas	Adults and youth by sex and age group (18-29, 30-64, >65)	50 years	Obesity prevalence, dietary behavior and physical activity	Implemented strategies for the 3 focus areas: physical activity-promotion, health marketing, and creation of healthy food	Population level modeling and weight dynamics	Intervention testing Predictive	Causal loops diagrams from PRISM reference guide	Youth population, Non CVD adult population, Post-CVD adult population. Non obese youth, obese youth, non obese non CVD adults,	Not specified	Behavior reproduction and sensitivity analysis	Implemented strategies in LAC ranged from best practices in healthy food procurement to completed shared-use agreements to a series of strategically designed health marketing

						environments .				obese non CVD adults, non obese post CVD adults, obese post CVD adults.			campaigns on healthy eating. On the basis of PRISM simulations, these highlighted program activities have the potential to reduce by 2040 the number of youth (−29 870) and adults (−94 136) with obesity, youth (−112 453) and adults (−855 855) below recommended levels of physical activity, and youth (−14 544) and adults (−28 835) who consumed excess junk food, as compared with baseline.

Appendix 3. Intervention Characteristics

Reference	Intervention [1]	Description
Environmental and policy Interventions: *Diet/Nutrition (n=6)*		
Liu et al. (2016)	Fiscal measures on nutrition	- allocating revenue collected by SSB taxation may maximize the benefits (reducing SSB consumption, construct safer outdoor activity spaces; and to subsidize vegetables and fruits to children and adolescents at school), of such taxation for the prevention of childhood obesity.
Roberts et al. (2018)	Fiscal measures on nutrition	- the introduction of a 20% caloric tax on sugar-sweetened beverages (SSBs) may increase the sales price of these products, resulting in a reduction in purchase and consumption.
Struben et al. (2014)	Fiscal measures on nutrition	-increase affordability of healthy food through the application of subsidies. -caloric tax imposed, increasing with caloric density of servings ($1 for each 25 exceeding desired 400 calories per serving).
Struben et al. (2014)	Marketing nutrition campaign	-aggressive marketing campaigns for high nutritional quality (HN) product categories. -voluntary reduction of low nutritional quality (LN) product category advertising. -dedicated investment to improve taste, availability of HN products.
Carrete et al. (2017)	Marketing nutrition campaign	-define better policies to control food marketing and advertising
Kuo et al. (2016)	Marketing nutrition campaign	-health marketing campaign focused on a variety of public health issues including high sugar-sweetened “sugary” beverages and sodium consumption through traditional media and multimedia approaches (e.g. Twitter, Facebook, videos, online applications, Websites).
Roberts et al. (2018)	Marketing nutrition campaign	-government social marketing campaigns delivered through TV, radio, outdoor advertising, social media, etc. This may raise awareness of the risks of unhealthy food and an inactive lifestyle and the benefits of healthy food and active lifestyle.

		-a reduction in advertising of unhealthy food and beverages to children, through various media. This may result in effects of purchasing and consequent consumption of energy dense, nutrient poor products.
Struben et al. (2014)	Health promotion on nutrition	-aggressive promotion campaigns for HN product categories. -regulated reduction of LN product category advertising. -aggressive promotion campaigns to increase awareness for importance of nutritional quality and provide related product information through, for example, food labeling.
Kuo et al. (2016)	Health promotion on nutrition	-recommend and implement healthy nutrition standards (i.e. codified limits on calories and other nutrients such as sodium) and other healthy procurement practices (e.g. menu labeling, product placement)
Carrete et al. (2017)	Health promotion on nutrition	-coordinate the programs and resources of public institutions (e.g. ministries of education and health), to support national strategies. -Provide incentives and guidelines to food manufacturers and restaurants to enhance offerings of healthy foods and beverages. -increase the number of nutritional centers and promote an orientation toward preventing chronic diseases and improving wellbeing via healthy habits.
Struben et al. (2014)	Product innovation	-market and government stimuli of nutritious food product innovation.
Carrete et al. (2017)	Mass media campaigns	-increase the diffusion of national strategies using mass media, opinion leaders and community experiences.
Roberts et al. (2018)	Healthy food availability measures	-healthy food availability in governmental settings (e.g. schools hospitals and other services). This may be through food provision, vending machines and shops within facilities.
Liew (2018)	Unhealthy food restriction measures	- restricting soda pop or fruit drinks sales in schools vending machines.

Kuo et al. (2016)	Healthy food availability measures	-healthy corner store conversions (e.g. increase access to fresh fruit and vegetables, improve product placement of healthy food and beverage option, decrease unhealthy food marketing) across low-income neighborhoods.
Environmental and policy Interventions: *Physical Activity (n=5)*		
Carrete et al. (2017)	Investment in PA spaces	- invest in physical infrastructure (e.g. sport centers, schools, public parks, etc) and extensively promote engagement in PA.
Liu et al. (2016)	Investment in PA spaces	-using revenue of sugar tax to construct affordable, accessible, safe outdoor activity spaces (parks).
Roberts et al. (2018)	PA advertisement campaign	- government social marketing campaigns delivered through TV, radio, outdoor advertising, social media, etc. This may raise awareness of the risks of unhealthy food and an inactive lifestyle and the benefits of healthy food and active lifestyle.
Roberts et al. (2018)	Urban planning policies	-environments to support physical activity can include making physical activity (both planned and incidental) easier and more inviting for the population. This can include increasing walkability, providing exercise and active transport infrastructure (e.g. bike paths and improved pavements) and increasing the number, quality and accessibility of sporting infrastructure.
Kuo et al. (2016)	Urban planning policies	-developed land use and/or transportation strategies (e.g. bicycle master plans, transit-oriented districts, “complete streets” policies) to increase pedestrian activity and biking in the city.
Shahid & Bertazzon (2015)	Urban planning policies	-improving neighborhood walkability, parks proximity, pathway length and reduce fast food proximity reduce obesity in children.

Organizational and community Interventions: *Diet/Nutrition (n=3)*		
Carrete et al. (2009)	School nutrition programs	- design a plan that parents can use to check which foods and in what quantities to feed their children as well as established appointments with a school nutritionist to check plan. -meetings with parents to inform them about height, BMI and other measures of their children and explain how to use, maintain and improve these measures.
Powell et al. (2009)	School nutrition policies	- require all food served in school cafeteria lines to meet the USDA School Nutrition Guidelines. -counselling of overweight and obese children.
Roberts et al. (2008)	Community-based prevention programs	- programs primarily delivered through settings such as early childcare centers, primary and high schools and junior community sport clubs.
Organizational and community Interventions: *Physical Activity (n=4)*		
Powell et al. (2017)	School policies on PA	- integration of health education into existing curriculum (mandate daily physical education, enhance PA classes, incorporate PA into classroom activities). - active after-school programs of physical activity
Shahid & Bertazzon (2015)	Neighborhood walkability	- improve neighborhood walkability, parks proximity, pathway length and reduce fast food proximity to motivate children to engage in a higher level of physical activity and reduce obesity.
Kuo et al. (2016)	Community-based prevention programs	- integrated staff development trainings and resources to support teacher capacity to implement existing, evidence-based physical education requirements at 50-70 public schools with high rates of childhood obesity. - increase public access to a variety of existing physical activity venues (ie, largely parks located on school facilities) in >10 schools across 5 school districts located in communities with few recreational venues to increase youth and adult opportunities for free or low-cost physical activity during non-school hours.

Roberts et al. (2018)	Community-based prevention programs	- programs primarily delivered through settings such as early childcare centers, primary and high schools and junior community sport clubs.
Individual and interpersonal Interventions: *Diet/Nutrition (n=7)*		
Abidin et al. (2014a, b)	Low calorie diet	- reducing portion size and meal frequency inside and outside of home.
Roberts et al. (2018)	Routine advice and clinical service delivery	- provision of information and advice for parents on lifestyle (and particularly diet), developments of new tools and training for health and community professionals.
Carrete et al. (2017)	Healthy eating behavior educational programs	- modify the current teaching scheme by adopting the "learning-by-doing" paradigm and implement practical projects to improve self-efficacy about food selection and meal preparation -develop materials for children to continuously highlight the importance of eating well to feel and look good (e.g., posters with attractive silhouettes and the consequences of poor alimentary habits) -work with families to manage competition benchmarks by reducing the emotional cost of eating traditional Mexican dishes and high-energy appetizers. Provide personal advice with regard to 1) how to reduce sugar and fat content and add vegetables to dishes; 2) how to prepare tasty, nutritious dishes at low cost and with little effort; and 3) where to buy nutritious food -encourage parents to practice healthy behaviors at home by emphasizing how they can be fun and make one feel and look good, instead of emphasizing health risks or normative attitudes
Frierichs et al. (2013)	Community prevention programs	- no description (presumably based on seeking to educate and change attitudes about healthy lifestyles addressed particularly to parents)
Liew (2018)	Awareness programs on nutrition	-increasing adolescents' awareness on healthy beverage consumption - promote healthy eating habits
Lan et al. (2013)	Nutrition education	- school nutrition education on students' diets through diet tips, nutrition-related knowledge and advocacy of nutrition education.

Individual and interpersonal Interventions: *Physical activity (n=2)*		
Carrete et al. (2017)	Recreational PA	- Instruct parents to limit the time that children spent in sedentary activities (e.g video games, computer and TV) and substitute these with recreational PA
Roberts et al. (2018)	Routine advice and clinical	- provision of information and advice for parents on lifestyle, developments of new tools and training for health and community professionals.

[1] Names for interventions were based on how these were termed in the publications from which they were extracted.

Appendix 4. Model validity assessment scores and guidelines

Criteria	Validation Score								
	Abidin et al., 2014a	Abidin et al., 2014b	Carrete et al., 2017	Frerichs et al., 2013	Roberts et al., 2018	Lan et al., 2014	Liew 2018	Meisel et al., 2018	Meisel et al., 2016
Description of model assumptions	2	1	1	3	3	1	2	2	2
Model structure is consistent with relevant descriptive knowledge of the system	2	2	2	3	3	1	1	3	3
Description of the process used to test and build confidence in the model	2	2	0	1	3	0	0	3	0
Model results are reproducible	1	1	1	2	3	0	0	3	2
Model documentation	1	0	0	2	3	0	0	3	2
Good model visualization	3	2	2	3	3	2	1	0	3
Total Model Assessment Score	**11**	**8**	**6**	**14**	**18**	**4**	**4**	**14**	**12**

Criteria	Validation Score							
	Liu et al., 2016	Powell et al., 2017	Rahmandad 2014	Safan et al., 2018	Shahid and Bertazzon 2015	Struben et al., 2014	Hall et al., 2013	Kuo et al., 2016
Description of model assumptions	3	1	3	3	2	3	3	3
Model structure is consistent with relevant descriptive knowledge of the system	3	2	3	3	2	3	3	3
Description of the process used to test and build confidence in the model	3	0	2	0	1	2	3	1
Model results are reproducible	3	0	3	3	2	3	3	3
Model documentation	3	0	3	2	1	3	3	3
Good model visualization	3	0	0	1	3	3	0	3
Total Model Assessment Score	**18**	**3**	**14**	**12**	**11**	**17**	**15**	**16**

Criteria	0= Not at all	1= Very slightly	2= Moderately	3= Complete
Description of model assumptions	No mention at all	Basic description of model assumptions.	States main model assumptions but not not complete.	Explicit description of model structure, model output, conceptual boundary, temporal boundary (e.g. time horizon, time step), level of aggregation, sources of parameter values, initial values, decisions involving calculations, exogenous variables considered, data sources and overall rationale.
Model structure is consistent with relevant descriptive knowledge of the system	No grounding of model structure in primary or secondary data	The model structure is fairly consistent with relevant descriptive knowledge of the system to some extent	The model structure is mainly representative of the descriptive knowledge of the system.	The model structure is causal-descriptive, built as to how the real system actually operates and explains how the behavior is generated/changed. Includes: CLD, SFD, policy structures diagrams, equations, literature and uses interviews/workshops to solicit expert opinion or participation in system processes.
Description of the process used to test and build confidence in the model	No mention at all	General mention of model validation procedure.	Discussion of some model validation tests but not in detail. E.g. Structure and behavioral validations was conducted.	Thorough description and explanation of the model validation procedure carried out in the study. Including: tests performed, explanations of each test, graphical representation of tests.
Model results are reproducible	No CLD/SFD shown, no documentation	Some diagrams and formulations are shown	The description of calculations and visual representations are sufficient to allow an independent party to implement and simulate the model	Detailed explanation of calculations and visual representations are fully reported to allow an independent party to implement and simulate the model.
Model documentation	No mention at all (Appendix or supplementary material)	Only available by request	Minimum model reporting requirements are available. E.g. equations and algorithmic rules, all model parameters, units and initial values are fully reported.	Detailed description of the computational operations the model is designed to perform. E.g. equations and algorithmic rules, all model parameters, units and initial values are fully reported. Besides the minimum requirements the documentation contains sources of data, definitions of all variables used in the model and source code of the modeling platform are available.
Good model visualization	Model is not visible nor understandable.	Some diagrams are shown but are not easy to understand. E.g. crossing causal links or overlapping variable names.	Most important model visual representations are shown but not complete	Comprehensive model presentations including Causal Loop Diagrams and Stock and Flow Diagrams are shown to facilitate model reproducibility (E.g. The diagrams are clear and show the main feedback loops or cross-sector relationships in the system)

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