The Journal of Climate Change and Health 15 (2024) 100292

Contents lists available at ScienceDirect

The Journal of Climate Change and Health

journal homepage: www.elsevier.com/joclim

Research article

Complex adaptive systems-based framework for modeling the health impacts of climate change

Byomkesh Talukder[a,b,*], Jochen E. Schubert[c], Mohammadali Tofighi[b,d], Patrick J. Likongwe[e], Eunice Y. Choi[b], Gibson Y. Mphepo[e], Ali Asgary[d], Martin J. Bunch[f], Sosten S. Chiotha[e], Richard Matthew[g], Brett F. Sanders[c,g], Keith W. Hipel[h], Gary W. vanLoon[i], James Orbinski[b,j]

[a] Department of Global Health, Florida International University, USA
[b] Dahdaleh Institute for Global Health Research, York University, Canada
[c] Department of Civil and Environmental Engineering, University of California, Irvine, USA
[d] ADERSIM & Disaster & Emergency Management, York University, Canada
[e] Leadership for Environment and Development Southern and Eastern Africa (LEAD SEA), Malawi
[f] Faculty of Environmental and Urban Change, York University, Canada
[g] Department of Urban Planning and Public Policy, University of California, Irvine, USA
[h] System Engineering Department, Waterloo University, Canada
[i] School of Environmental Studies, Queen's University, Kingston, Canada
[j] Faculty of Health, York University, Canada

ARTICLE INFO

Article History:
Received 25 May 2022
Accepted 1 December 2023
Available online 7 December 2023

Keywords:
Climate change
Health
Ecological services
Extreme weather
Infectious disease
Food security
Clinical public health
Disaster risk management
Complex adaptive systems
Agent-based modeling

ABSTRACT

Introduction: Climate change is a global phenomenon with far-reaching consequences, and its impact on human health is a growing concern. The intricate interplay of various factors makes it challenging to accurately predict and understand the implications of climate change on human well-being. Conventional methodologies have limitations in comprehensively addressing the complexity and nonlinearity inherent in the relationships between climate change and health outcomes.

Objectives: The primary objective of this paper is to develop a robust theoretical framework that can effectively analyze and interpret the intricate web of variables influencing the human health impacts of climate change. By doing so, we aim to overcome the limitations of conventional approaches and provide a more nuanced understanding of the complex relationships involved. Furthermore, we seek to explore practical applications of this theoretical framework to enhance our ability to predict, mitigate, and adapt to the diverse health challenges posed by a changing climate.

Methods: Addressing the challenges outlined in the objectives, this study introduces the Complex Adaptive Systems (CAS) framework, acknowledging its significance in capturing the nuanced dynamics of health effects linked to climate change. The research utilizes a blend of field observations, expert interviews, key informant interviews, and an extensive literature review to shape the development of the CAS framework.

Results and discussion: The proposed CAS framework categorizes findings into six key sub-systems: ecological services, extreme weather, infectious diseases, food security, disaster risk management, and clinical public health. The study employs agent-based modeling, using causal loop diagrams (CLDs) tailored for each CAS sub-system. A set of identified variables is incorporated into predictive modeling to enhance the understanding of health outcomes within the CAS framework. Through a combination of theoretical development and practical application, this paper aspires to contribute valuable insights to the interdisciplinary field of climate change and health. Integrating agent-based modeling and CLDs enhances the predictive capabilities required for effective health outcome analysis in the context of climate change.

Conclusion: This paper serves as a valuable resource for policymakers, researchers, and public health professionals by employing a CAS framework to understand and assess the complex network of health impacts associated with climate change. It offers insights into effective strategies for safeguarding human health amidst current and future climate challenges.

* Corresponding author.
E-mail address: btalukde@fiu.edu (B. Talukder).

https://doi.org/10.1016/j.joclim.2023.100292
2667-2782/

1. Introduction

Climate change affects virtually all aspects of human life and health [1]. Clear evidence of the human health impacts of climate change has been presented in many research papers [2–9] and international reports. Climate change impacts the health of individuals and populations through multiple pathways. Many independent variables lead to emergent outcomes that are difficult (or impossible) to predict with hypotheses that entail reductionism or linearity based on mechanistic understandings of reality [10]. For instance, floods induced by climate change and population displacement may impact accessibility to safe drinking water and increase infectious diseases [11]. Conversely, risk management actions and climate change adaptation policies can mitigate disaster [12]. The health impacts of climate change here also refer to complex, large-scale, non-linear interactions within which behaviors may evolve along with the potential for powerful feedback loops to rapidly precipitate catastrophe [13].

Complexity theory has evolved to study contemporary problems and investigate the interconnected nature of unpredictable phenomena [14,15]. The Complex Adaptive Systems (CAS) theoretical framework can be used to study complex contemporary problems. CAS are systems involving multiple components that react to other components in the system and the system as a whole, thereby leading to emergent phenomena [16–18]. These components are also referred to as adaptive agents or simply as agents.

The principles of CAS can be used to model the impacts of climate change and understand their human health implications. Human vulnerability to climate change is considered dynamic and depends on a place-based socio-biophysical system, affected by the continuous interaction of multiple stressors (climatic, socioeconomic, political, and cultural), as well as the interactions of components with that system [19–21]. Understanding the interrelations of agents within a CAS allows a pinpointing of areas that are priorities for adaptive learning, that can represent potential maladaptive trajectories, or that could be susceptible to positive and negative feedback [19,20]. The first step in designing a CAS for climate change health vulnerability is to produce a high-level representation of the system, capturing its major sub-systems or dimensions and their linkages [21]. Each subsystem is composed of many variables and interconnections. The second step is to generate a conceptual model of the inner workings of each sub-system [21]. Finally, more specific conceptual models may be generated addressing particular sub-systems of interest.

A collaborative approach among different stakeholders may be adopted at any stage of each system representation, and the complexity of systems representation may depend on data availability to establish relationships between variables [19–21]. For example, Groundstroem and Juhola apply systems thinking to identify climate change impacts on international bioenergy supply systems [19]. They establish an analytical framework laying out the sub-systems and interconnections of a bioenergy supply system. They rely on causal loop diagrams (CLDs) to map out the system's structure and networks to reveal causalities and feedback within the system. The result is a complex and interconnected network of social, environmental, political, and economic sub-systems, and various cascading impacts of climate change affecting the bioenergy supply [22]. Sellberg et al. (2021) analyze how a complexity perspective was used across twelve resilience assessment and planning cases in contexts of development and natural resource management in different parts of the world [23]. They found that several core complex adaptive system strategies were employed, including adapting the systems approach to a local context, identifying external drivers of change and interactions across scales (administrative to biophysical boundaries), conceptualizing social-ecological interactions, and identifying historical trends, regime shifts, and alternative future scenarios. These CAS strategies are mainly concerned with capturing the complexity of the social-ecological systems and making sense of them through meaningful interrelated simplifications. Actual system complexity is difficult to fully capture in a modeling approach, yet simplifications of system linkages can provide a better understanding of cascading impacts [19,23]. Challenges may also exist with data availability and statistical correlation methods to model aspects of the variable linkages, or shortcomings may exist when using simulated data that may not fully or reliably capture future conditions. It is generally strongly recommended that model weaknesses and limitations be identified and critically assessed, so that results can be appropriately qualified [19].

Agent-Based Modeling (ABM) is an approach capable of modeling complex systems in their disaggregate form [24–26]. Other system methods such as system dynamics [27] and network analysis [28], capture system complexity as an aggregate of its parts and have been used in modeling various aspects of public health [25,29]. However, these are less effective than ABM for capturing the non-linear relationships of a systems' agents or variables. In this paper, we present a novel framework based on CAS and ABM to model some aspects of human population health impacts of climate change. Our model reflects the values and data needs of community, government, and non-government organizations for planning actionable adaptation strategies to the short- and long-term health impacts of climate change [13,30].

We envision this framework to be relevant in a wide range of applications. From a public health perspective, for instance, it may be applied to assess the emergence of particular infectious diseases due to changing climate and environmental conditions at the level of individual health facilities, as well as in predicting which health facilities may be overburdened by increasing healthcare demand. Model outputs can be intersected with social condition data to identify underlying causes that predispose people to health risks associated with climate change, and to design adaptation interventions to climate change that may reduce human health impacts. A holistic assessment of the complex system causing health impacts of climate change can further identify vulnerabilities in disaster risk management and could function as a support tool to target resources to strengthen the resilience of health services. Finally, the proposed CAS based framework is intended to be executed using quantitative methods and models (e.g., ABM), and would identify data gaps that, once addressed, could contribute further to a richer and more accurate understanding of the health impacts of climate change.

The remainder of this paper is organised so that Section 2 describes the methods used for developing the conceptual CAS based framework; Section 3 presents subsystems of the relationship between climate change and human population health, a list of data sources based on a literature review to demonstrating or suggesting the quantifiability of each subsystem, and a methodology for agent-based modeling (ABM) of the subsystem; Section 4 provides a vision for how the CAS based framework may be implemented for scenario simulation and decision support, its limitations, as well as possible entry points for local expert knowledge; and Section 5 presents conclusions.

2. Methods

The motivation for this framework is based on years of accumulated field experience of the authors in Bangladesh, India, Cambodia, Malawi, South Sudan, Rwanda, Paraguay, the USA, Canada, and elsewhere [11,31–43]. A visualization of the full methodological process used to develop this framework is portrayed in Fig. 1 and is based on four steps: (i) authors' observations and knowledge gathered from long-time practical field experience with the health impacts of climate change in developing countries in terms of global, public and clinical health, sustainability of agriculture, ecological degradation, disaster management, and systems thinking about environmental health issues; (ii) narrative literature review; (iii) mobilization of

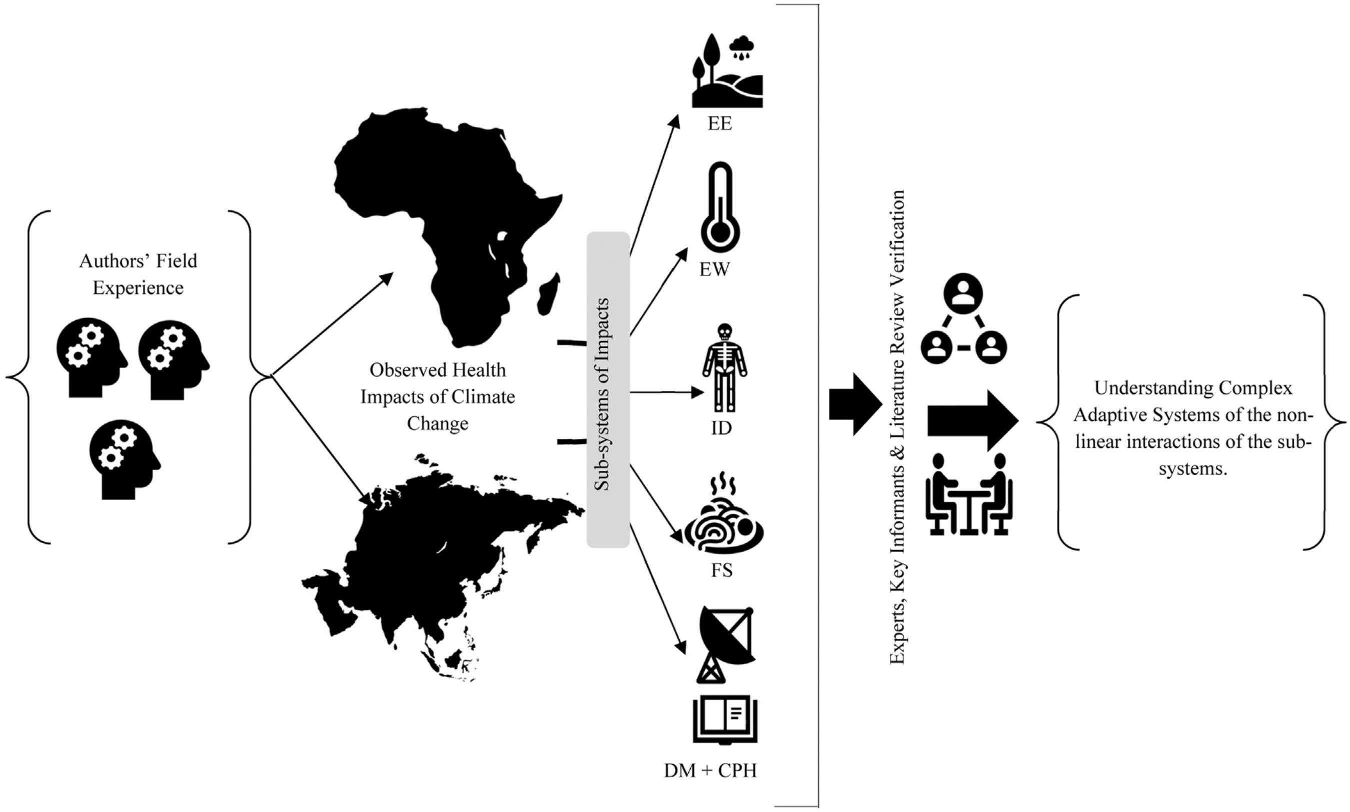

Fig. 1. Methodological flow chart for developing the framework. First, field observations allowed the authors to link the health impacts of climate change (CC) in terms of six sub-systems: ecological services (ES), extreme weather events (EW), infectious disease (ID), food security (FS), disaster risk management (DM) and clinical public health (CPH). Experts, key informants, and a literature review then verify the field observations. Following the first step, the interactions of the sub-systems are visualized and established as a complex adaptive system (CAS) of health impacts of climate change.

expert opinion by formal interview, and (iv) key informant interviews through informal discussion.

The initial approach was developed based on the field experiences of the authors. This was then augmented collaboratively through consultation with key informants from NGOs, government officials, and educators working on climate change's health impacts in coastal Bangladesh and the Lake Chilwa Basin of Malawi. Both countries are highly affected by, and have limited capacity to cope with ongoing climate change, and its associated extreme weather events [11,44–46].

Five questions guided our consultations with the experts and key informants: (i) What are the commonly occurring diseases for which climate change is a driver? (ii) How do extreme weather events affect health outcomes? (iii) How does and will climate change impact agricultural production, food security, and health? (iv) Does ecological degradation amplify the impacts of climate change on health? (v) How can disaster management and public health policy help mitigate climate change-related health impacts? Feedback from experts and key informants in Bangladesh and Malawi, as well as author field observations confirmed that climate change, and its associated extreme weather events have human health impacts which are magnified by human behavior, and many socio-ecological variables such as ecological degradation, and agriculture and public health policy.

With the goal of identifying and reviewing probable issues related to developing a CAS based framework, the authors and other experts used brainstorming and deductive (theoretical) and inductive (statistical) based reasoning as described by Rotello and Heit [47]. A targeted narrative literature review was conducted to confirm and reinforce the objectives of the study and expert and key informant inputs by classifying, assessing, and mixing the findings of high-quality studies related to one or more issues relevant to the CAS of health impacts of climate change. This literature review utilized Google Scholar, PubMed, and Web of Science to identify subsequently reviewed literature related to the topic. Key search terms included: "climate change and health," "complex adaptive systems and health," "ecological services and health," "climate change and infectious disease," "climate change and extreme weather events," "climate change, disaster management and health" and "climate change and clinical health."

3. Results

The authors' experience, expert knowledge and opinion, key informant interviews, and the literature review provided data and information to identify and link six major sub-systems of a CAS as these relate to the human health impacts of climate change:(i) ecological services [48], (ii) extreme weather events [49], (iii) infectious diseases [49], (iv) food security [49], (v) clinical public health [3], and (vi) disaster risk management [3,48].

A useful visual tool to represent the complex interactions between changing climatic conditions and health outcomes are causal loop diagrams (CLDs) [50,51]. "Cause and effect" indicates that one element must lead to another either in absolute (deterministic) or probable (stochastic) ways [52]. CLDs help identify the circular nature of complex cause-and-effect relationships [53], show the big picture for understanding the interrelationship of the elements, and facilitate recognition of the system structure that generates overall health impacts while providing a descriptive and visual model of the CAS of health impacts of climate change. A high-level CLD of the linkages between the sub-systems is shown in Fig. 2X. The CLD demonstrates the interaction of the six sub-systems in a complex web and the positive and negative relationship(s) to one another. Hence, the health impacts of climate change can be viewed as the outcomes of the

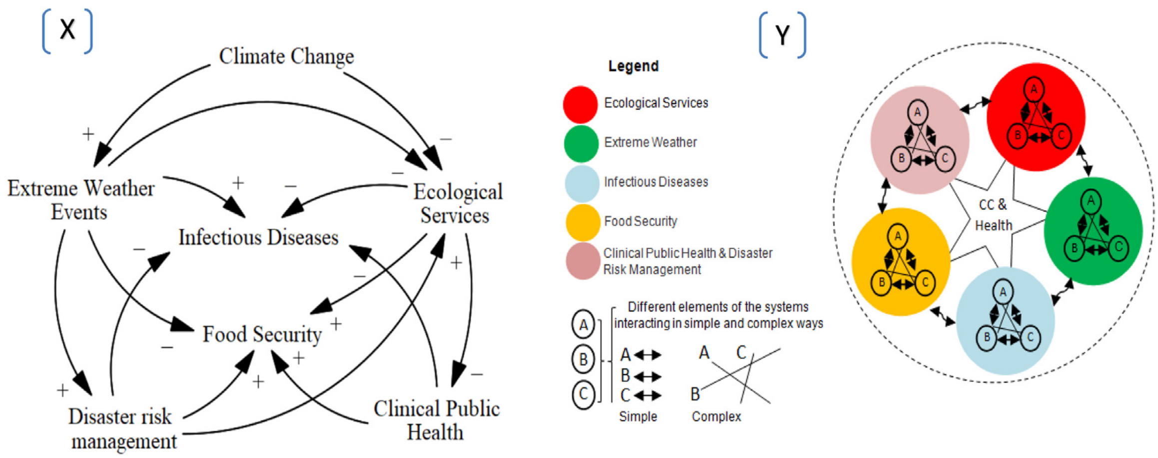

Fig. 2. Schematic of the effects of climate change on health as a complex adaptive system (CAS). Part [X], the causal loop diagram (CLD) or systems thinking diagram [55], captures the interactions of the six sub-systems (i.e., ecological services, extreme weather events, infectious disease, food security, disaster risk management, and clinical public health) and represents the descriptive model of a CAS of the health impacts of climate change. It shows that the sub-systems are connected in a complex way. For example, climate change increases extreme weather events and reduces agricultural production, leading to food insecurity, and food insecurity leads to clinical public health issues such as malnutrition. The impacts of extreme weather events may be countered with the robust design of public health services and policy. In part [Y], A, B, and C represent different variables of each sub-system. These variables interact within the individual system and with the adjacent variables of other sub-systems, and all sub-systems interact with each other as a whole. Thus, the CAS model captures the overall health impacts on agents (individual or population) from climate change.

complex causal inter-relationships, interactions, and interconnectivity of elements within and between these six sub-systems [17,54].

The high-level CLD of the health impacts of climate change can be used as a guide to further break down each sub-system into many lower-level elements, which interact with each other inside and outside the dimensions of the high-level subsystems in non-linear and dynamic relationships [17,23,56–58]. Conceptually, this is shown in Fig. 2Y.

Through an extensive narrative literature review and based on the authors' field experience in Bangladesh, India, Malawi, and Paraguay, we developed CLDs relative to the six sub-systems that are integral in capturing the interconnectedness between climate change and population health in these countries: ecological services, extreme weather, infectious disease, food security, clinical public health, and disaster management.

3.1. CLDs of the health impacts of climate change

In Sections 3.1.1 to 3.1.6, the CLDs of the health impacts of climate change are illustrated with respect to the six sub-systems. The CLDs below have been developed based on knowledge acquired in Bangladesh and Malawi and therefore, reflect system dynamics pertaining to those regions. Here, they are used to exemplify the proposed framework and will require modification for different geographical areas. In the following CLDs, positive causal links (marked by a plus sign [+] to mean "same direction") represent a positive correlation between variables, so that an increase in variable "A" leads to a rise in variable "B," and a decrease in "A" leads to a reduction in "B". It is essential to understand that the plus sign at the arrowhead does not necessarily mean that the variables are increasing, only that they are changing in the same direction (i.e., increase or decrease together). Negative causal links (marked by a minus sign [−] to mean "opposite") represent a negative or inverse correlation, so that an increase in variable "A" leads to a decrease in variable "B." [59]

3.1.1. Ecological services

Ecological services are the central pillars of all life [60]. The Millennium Ecosystem Assessment (MA) proposed four ecosystem services categories: regulating, provisioning, supporting, and cultural [61]. *Regulatory services* include flood and disease regulation, water purification, pest control, disease control, disaster mitigation and prevention [62]. *Provisioning services* make available food and essential nutrients, medicines and medicinal compounds, fuel, energy, livelihoods, and cultural and spiritual enrichment for humans [62]. Provisioning services contribute to cleaning water and air [62,63] and, in this way, have positive health effects [2]. Both regulatory and provisioning services have direct and indirect consequences for human health and well-being, and each is an important component of the epidemiological puzzle that can act to stem the tide of infectious and non-communicable diseases [62].

As shown in Fig. 3., climate change impacts provisioning and regulatory ecological services in several ways [64,65]. Ongoing climate change has a negative effect on habitat and vegetation health, reducing biodiversity and air quality while increasing the spread of pests. Changes to the hydrologic cycle and extreme weather events further affect food production and the availability of clean water, allowing human disease and illness to increase. In particular, ecosystem modifications help spread pathogens into new ecological niches [5]. However, "healthy ecosystems and environments are necessary for the survival of humans and other organisms, and thus constitute the basis of sustainable development" [66]. Ecological degradation has been associated with increased global connectivity, encouraged the intermixing of human and animal habitats, and has amplified climate change impacts on migration, all of which have affected human well-being, as many wildlife species are or have become reservoirs of pathogens that threaten human health [67].

3.1.2. Extreme weather events

Extreme weather events are defined as anomalies denoting a significant departure from long-period average weather observations such as atmospheric temperature, wind speed, and precipitation. Droughts, periods of extreme heat or cold, and floods are examples of extreme weather events [7], and with accelerating climate change, the frequency and magnitude of these events are likely to increase [44,68,69]. Extreme weather events have profound impacts on health [70] and the environment [71], affecting "individual fitness, population dynamics, distribution and abundance of species, and ecosystem structure and function" [72]. For example, extreme heat and cold cause immediate rises in weather-related mortality [73,74]. More broadly, natural hazards, including floods, tsunamis, earthquakes, tropical cyclones (e.g., hurricanes and typhoons), and tornadoes have been secondarily associated with infectious diseases, including diarrheal diseases, acute respiratory infections, malaria, leptospirosis,

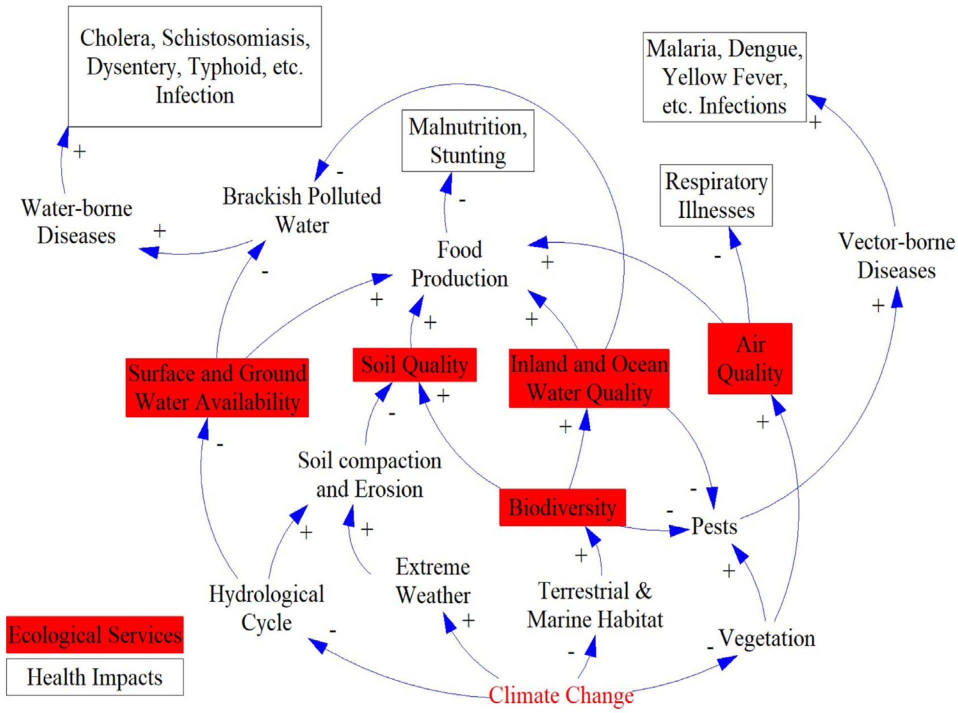

Fig. 3. Causal loop diagram of health impacts of climate change in relation to ecological degradation.

measles, dengue fever, viral hepatitis, typhoid fever, meningitis, tetanus and cutaneous mucormycosis [75,76].

Extreme weather events can cause severe crop damage and jeopardize agricultural production and socio-economic development, and directly affect livelihoods and food security [77–79] . One review estimates that, 83 % of the damage and losses caused by droughts are in agriculture, and that by 2050 crop yields are projected to decrease by 25 % if climate change is not mitigated. Extreme weather events damage crops and leave households vulnerable to weather shocks [80]. Damaged crops lead to food insecurity, eventually leading to poor nutrition and clinical public health impacts. Extreme weather events can also cause food safety issues. For example, in some settings, Salmonella has become prevalent in lettuce and green onion products because of drought followed by heavy rainfall [81]. Some examples of how extreme weather may impact health are shown in Fig. 4.

3.1.3. Infectious diseases

CLDs of the health impacts of climate change concerning infectious diseases are presented in Fig. 5. Climate change and other anthropogenic activities (such as agriculture) play a significant role in infectious disease emergence [82–84] and in the spread and re-emergence of infectious diseases in natural and socio-ecological systems [85]. Among infectious diseases, vector-borne (e.g.: mosquito-borne) diseases, including malaria, dengue, viral encephalitis [86], yellow fever [87], and West Nile virus [88] are among those most sensitive to a changing climate [89]. For example, “globally, temperature increases of 2–3 °C would increase the number of people who, in climatic terms, are at risk of malaria by around 35 %, i.e., by several hundred million, as the seasonal duration of malaria would increase in many currently endemic areas” [90]. A changing climate will also influence the incidence of water-borne infectious diseases such as cholera [11,91,92] and diarrheal disease [88]. Climate change has increased the risk of floods, and with these, the spread of multiple infectious diseases such as malaria, dengue, hepatitis A, cholera, schistosomiasis, and diarrhea. Moreover, skin and soft tissue infections, conjunctivitis, and dermatitis are related to flood events [93].

3.1.4. Food security

The CLD in Fig. 6 depicts the causes and effects of climate change on food security (sustainable agriculture), and human health. Climate change will negatively affect food systems [94–96] and thus food security [97–101]. Food security affects individual and population health [96,102], which depends on access to adequate, affordable, good-quality, and nutritious food [103]. However, climate change potentially affects all aspects of food security, including food access, utilization, and price stability [104]. Climate change also increases the occurrence of food safety hazards at various stages of the food chain, from primary production through consumption [105]. Increasing CO_2 threatens human nutrition by reducing zinc and iron in C_3 grains and legumes (e.g., wheat, rice, oats, barley, potatoes, soybeans, cassava, etc.), the primary dietary source of zinc and iron for billions of people and the deficiency of zinc and iron in crops is a substantial global public health problem [106]. Food insecurity leads to undernutrition [107], which has short-term mortality, morbidity, and disability consequences. There are also long-term consequences for adult height, intellectual ability, reproductive performance, and metabolic and cardiovascular disease [108].

Natural disasters jeopardize agricultural production and development [109], and as described above, climate change tends to increase the frequency and intensity of weather-related natural disasters [110]. Natural disasters significantly impact the agricultural sector by directly damaging livestock, crops and the ecosystems that support their supply chain and agriculture, affecting livelihoods, food security, and nutrition [77,111,109].

3.1.5. Disaster risk management

Realistic disaster risk management plans enable societies to prepare for and mitigate the severe effects of extreme weather events. The CLD of health impacts of climate change in relation to disaster management and clinical public health is shown in Fig. 7. Climate change has significantly increased the extent and magnitude of disasters [112]. Appropriate disaster preparedness can maintain food supply and thus food security and individual and population health. Disasters have the greatest impacts on the poor and most vulnerable

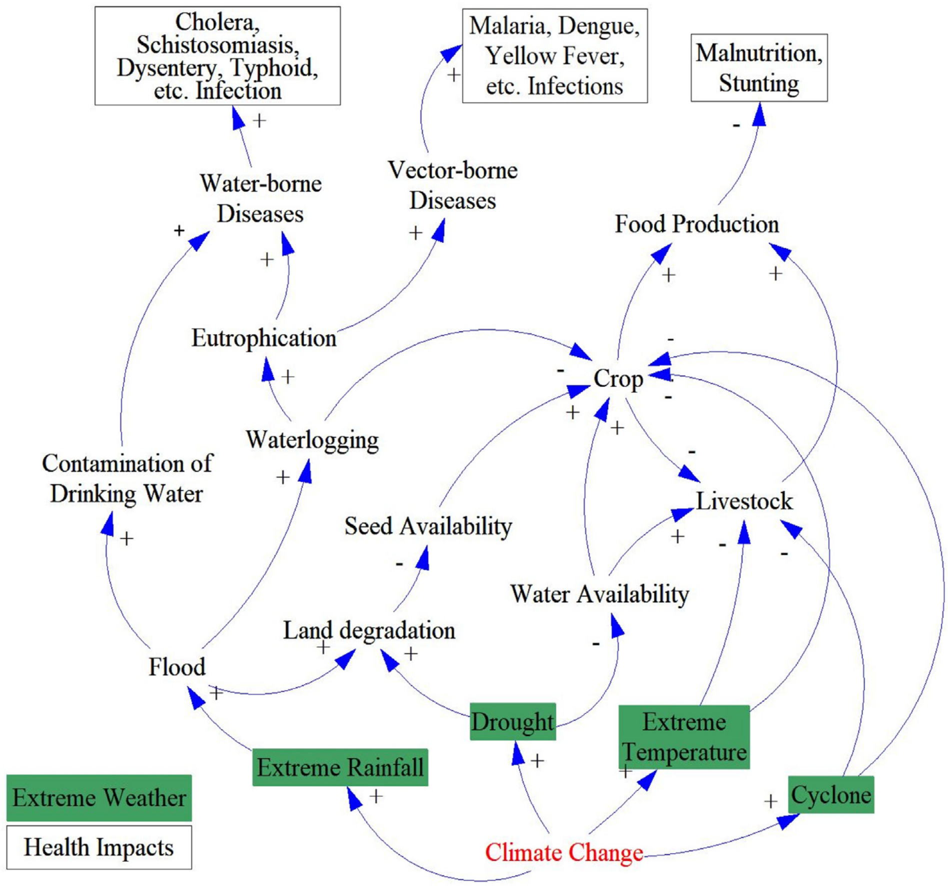

Fig. 4. Causal loop diagram of health impacts of climate change in relation to extreme weather events.

people [113]. Effective disaster management is crucial in reducing the risks and effects of climate change on socioecological systems [114]. For example, building resilient infrastructure, deploying early warning systems, implementing well-informed community preparedness plans, and developing sound emergency response procedures can lessen the impacts of natural disasters by reducing loss of life and preventing damage to sanitation, health, and food supply infrastructure.

3.1.6. Clinical public health

Clinical public health systems and their resilience determine the magnitude of a health crisis associated with a disaster, as shown in the CLD in Fig. 7. Effective health care in a disaster critically depends on an appropriate disaster preparedness of a health system, the broader social systems, and how these intersect to promote health and resilience before, during and after a crisis [91,115,116].

Contributing factors to disease transmission after disasters include for example: environmental risk factors; type of endemic organisms; population demographics and characteristics such as crowding; the pre-event structure and functionality of a clinical public health system and its facilities; levels of immunization, and the magnitude of the disaster [117]. Risk factors for disease outbreaks after disasters are associated primarily with poor potable water and or population displacement and the availability of hygienic sanitation facilities. The capacity to rapidly re-establish effective primary healthcare delivery post-disaster is vital to reduce the risk of communicable diseases and death in the affected population [76,118].

3.2. Selection of variables

The CLDs presented in Sections 3.1.1 to 3.1.6 help identify vital representative variables from the six sub-systems that can be used to model the health impacts of climate change in a CAS based framework. Using the CLDs, literature review, discussion with key informants, and formal interviews with experts, a set of representative variables that affect the health of agents (individual and population) are identified and listed in Table 1 to demonstrate the potential value of this approach. In total, 92 variables are identified that address ecological services (10 variables), extreme weather events (9 variables), infectious diseases (11 variables), food security (18 variables), disaster management (23 variables), and clinical public health (21 variables). Two criteria were considered in selecting variables: (i) the capacity of the variables to represent quantifiable influences of complex relationships and (ii) their significance in capturing maximum impacts on agents. The variables identified here are not comprehensive. Instead, they are an illustrative selection based on an assumed/hypothetical location (informed by the authors' experience, especially in Bangladesh and Malawi) where floods and droughts occur with increasing frequency due to climate change-related extreme weather events. These are causally associated with population displacement, disruption in health services, increases in specific infectious diseases, and acute and chronic undernutrition. The targeted health impacts in this location are (i) infectious diseases: malaria, cholera, schistosomiasis, and acute diarrheal disease; (ii) food security outcomes: protein energy malnutrition and growth stunting in children; and (iii) potable water and sanitation and hygiene.

Variables/indicators play a helpful role in highlighting and quantifying problems, identifying trends, and contributing to the process of priority setting, policy formulation and evaluation, and monitoring of progress. Most importantly, breaking down a system into multiple variables and associated linkages helps simplify its complexity while paradoxically demonstrating complexity by tying together the elements of the six sub-systems [160]. Only well-defined and carefully

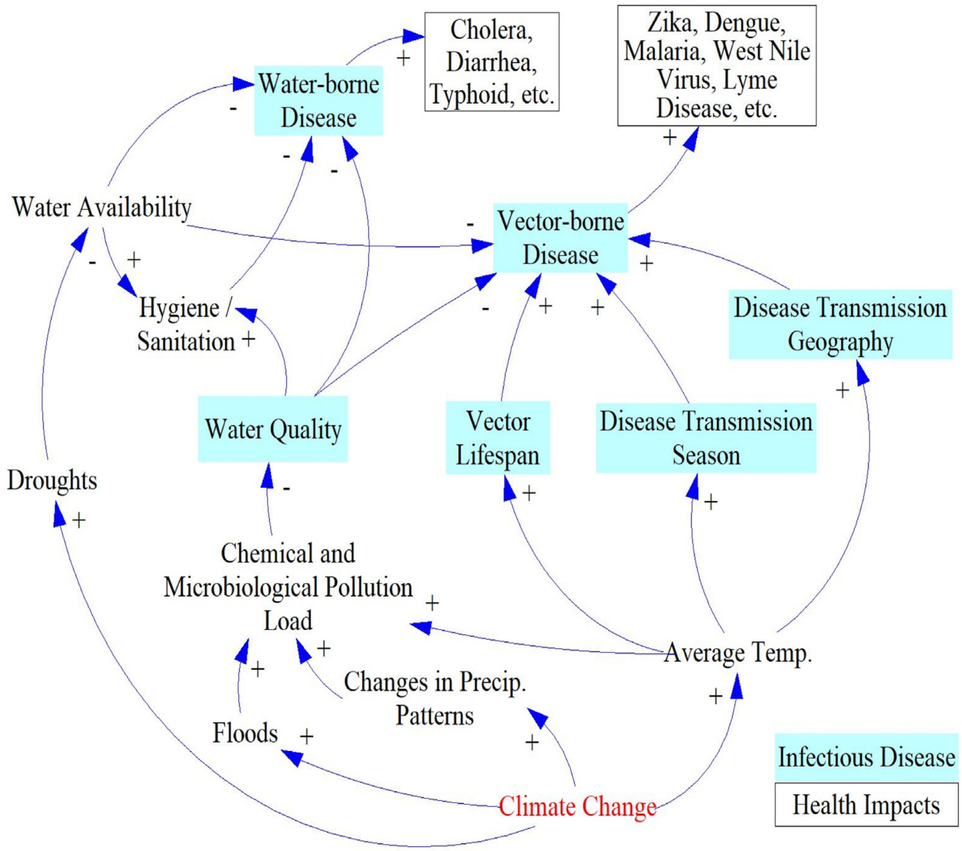

Fig. 5. Causal loop diagram of health impacts of climate change in relation to infectious disease.

selected variables provide meaningful insight for a model to be useful in decision-making and policy development [160]. The variables suggested here are within the boundaries of the intended geographic region, and more may be available from further local sources. The variables may be different in other scenarios since the health impacts of climate change vary depending on the specific scenarios and their geography.

3.3. Proposed modeling framework

In this section, a framework of CAS modeling [161] of the health impacts of climate change is presented based on the background discussion in Section 1.0, the methodology in Section 2.0, and the results in Sections 3.1 and 3.2.

To reiterate, the health impacts of climate change are the outcomes of linear and non-linear dynamic relationships with the agents within the six sub-systems that generate macro-level phenomena [162]. The health impacts of climate change depend on the interactions of various components (variables) of the sub-systems in ways that create feedback and cascading effects on the components of the sub-systems. The interactions of the units of each sub-system can lead to a nonlinear transformation to macro-level phenomena (emergent properties) [163]. The health impact of climate change is a complex phenomenon, and modeling it requires a method capable of capturing the linear and non-linear interactions of the agents and the relationships of the sub-systems [164]. In this modeling framework, a system dynamics-integrated ABM is proposed for modeling the complex interactions of the variables in Table 1 with agents (individual and population) within a region of concern.

Using the variables identified in Table 1 for ecological services {10 parameters: ($ES_1 \ldots ES_{10}$)}, extreme weather events {09 parameters: ($EW_1 \ldots EW_9$)}, infectious disease {11 parameters ($ID_1 \ldots ID_{11}$)}, food security {18 parameters ($FS_1 \ldots FS_{18}$)}, disaster management {23 parameters ($DM_1 \ldots DM_{23}$)} and clinical public health {21 parameters ($CH_1 \ldots CH_{21}$)} and the core concepts of agent-based modeling, the proposed framework is hypothetically illustrated in Fig. 8. These variables and their variations can represent the actions and interactions of autonomous agents at different levels of granularity, as individuals or collective entities, and at different spatial scales, to understand the emerging behavior of a system and what shapes its outcomes. Depending on the level of granularity of agents and the scale of their interaction, different CLDs and sets of variables may need to be defined for each agent for adoption into ABM. Various commercial and open-source software packages offer the ability to perform agent-based modeling (e.g., AnyLogic, AgentScript, GAMA Platform), and the authors recommend model validation to be included in the model setup procedure as a way to quantify the implications of limited data and statistical correlation between sub-system variables [19].

4. Discussion

To determine the health impacts on agents, the presented framework requires consideration of the overall cause-and-effect relationship of the interconnected variables chosen to represent the six sub-systems. More specifically, each set of agents (e.g., industry sectors, population age groups, health center catchments) will require their own set of sub-system variables, and interactions between agents will also have to be considered. Therefore, selecting and parameterizing appropriate variables is essential for this framework.

The success of this CAS based framework depends on the range and quality of the data available to represent system variables. In other words, discovering insights into the dynamics of climate change-driven health impacts depends on the ability to represent

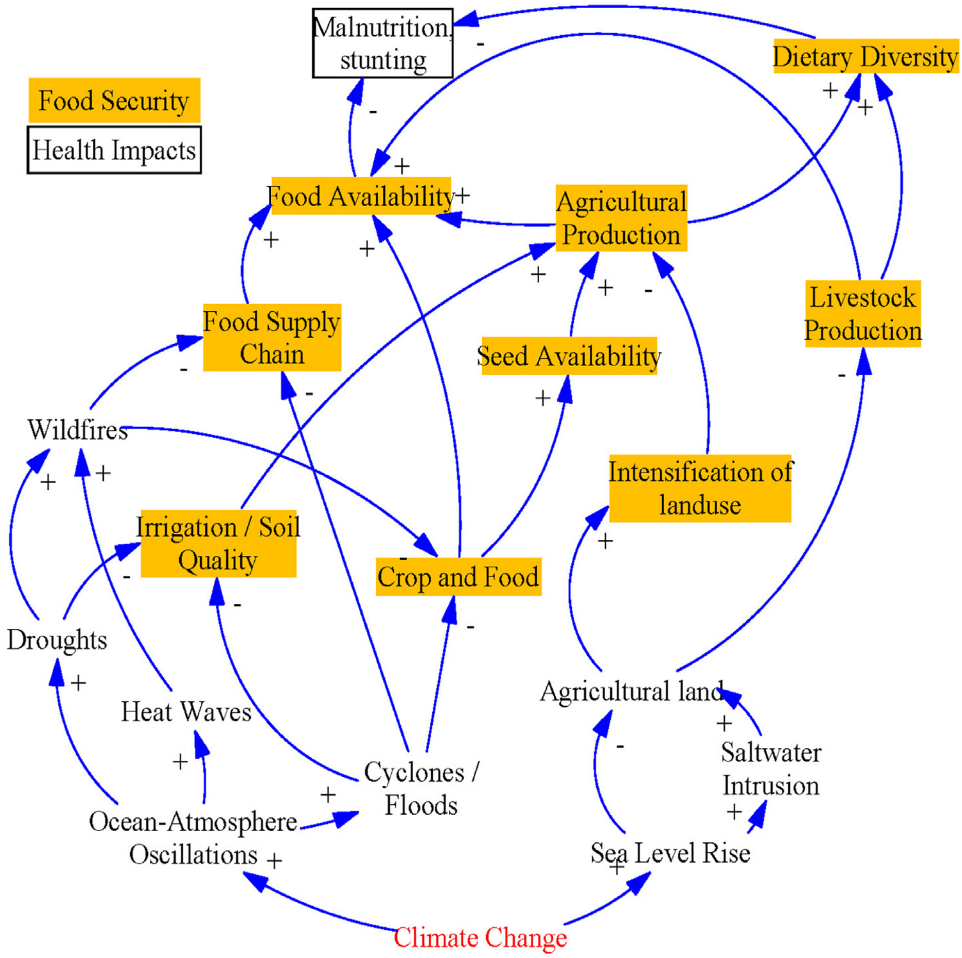

Fig. 6. Causal loop diagram of health impacts of climate change in relation to food security.

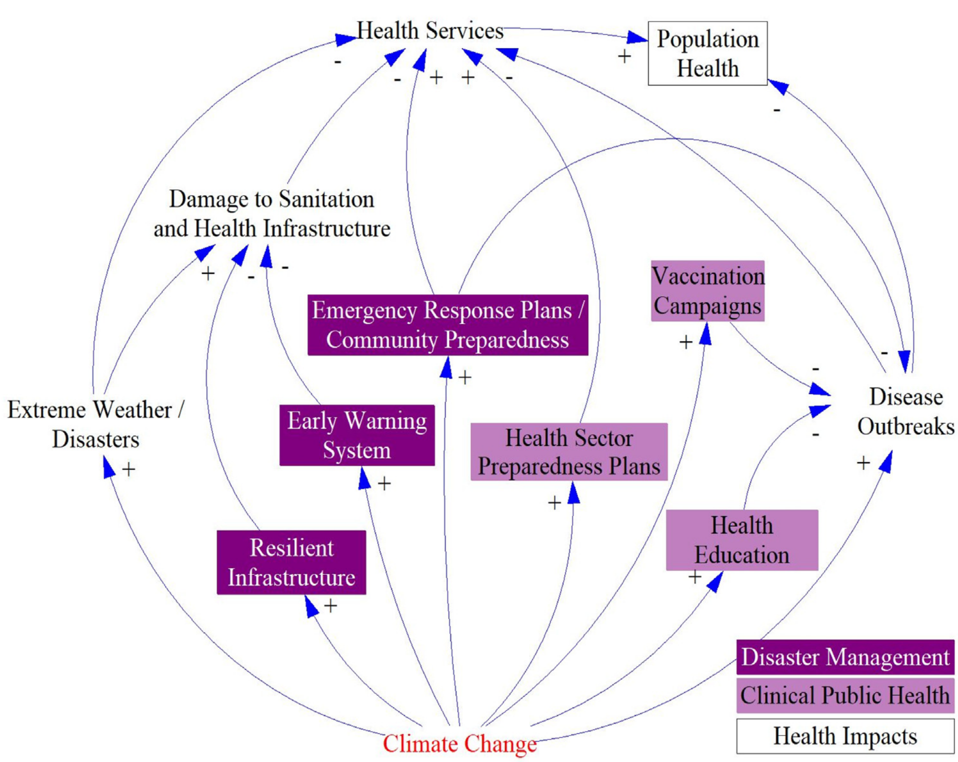

Fig. 7. Causal loop diagram of health impacts of climate change in relation to disaster management and clinical public health

Table 1
Potential variables to be considered in complex adaptive system modeling of health impacts of climate change

Sub-Systems	Variables	Unit	SOV	NOV	Reference
Ecological Services	Shannon Biodiversity Index	% year^{-1}	ES_1	10	[119,120]
	Rate of land cover fragmentation	% year^{-1}	ES_2		[121]
	Water Quality Index (WQI)*	ND	ES_3		[122]
	Trophic State Index (TSI)	ND	ES_4		[123]
	Soil Quality Index**	ND	ES_5		[124]
	Soil moisture	% Water	ES_6		[125]
	Soil erosion rate	km^2/year	ES_7		[126]
	Storage of aquifer	m^3	ES_8		[127]
	Horton–Strahler number***	ND	ES_9		[128]
	Natural Soil Drainage Index (DI)	ND	ES_{10}		[129]
Extreme Weather Events	Rainfall Index	mm/year	EW_1	9	[130]
	Simple daily intensity index (SDII)	mm/day	EW_2		[131]
	Flood intensity	ND	EW_3		[132]
	Duration of waterlogging	day	EW_4		[133]
	Aggregate Drought Index (ADI)	ND	EW_5		[134]
	Warm spell duration indicator (WSDI)	day	EW_6		[135]
	Cyclone intensity (Saffir-Simpson scale)	Ordinal	EW_7		[136,137]
	Accumulated Cyclone Energy (ACE)	knot^2	EW_8		[138]
	Heat Index	°C	EW_9		[139]
Infectious Diseases (malaria, cholera, schistosomiasis, diarrhea)	Disease transmission	People/day	ID_1	11	[140,141]
	People affected by Malaria	People	ID_2		[142]
	People affected by Diarrhea	People	ID_3		SA*
	People affected by Schistosomiasis	People	ID_4		SA*
	People affected by Cholera	People	ID_5		SA*
	Drinking water quality	Ordinal	ID_6		[122]
	Sources of household water	% of source	ID_7		SA*
	Sources of agricultural water	% of source	ID_8		[143]
	Unique distribution of infectious disease	Global Moran's I statistic	ID_9		[144]
	Household location (sound vs. degraded land)	People/km^2	ID_{10}		[145]
	Rural Water Livelihood Index (RWLI)	Ordinal	ID_{11}		[146]
Food Security (Agriculture)	Yields per hectare for major staple crops	Kg/ha	FS_1	18	[147,148]
	Productivity (protein)	ton	FS_2		[149]
	Productivity (energy)/calorie availability	Calorie	FS_3		
	Food loss	ton	FS_4		[150]
	Livestock Production Index	ND	FS_5		[145]
	Irrigated land	ha	FS_6		[145]
	Caloric intake per capita per household	Cal/person	FS_7		[151]
	Household level of food insecurity	Ordinal	FS_8		
	Household dietary diversity	Ordinal	FS_9		[97]
	Food Security Index	Ordinal	FS_{10}		[150]
	Intensification of land use	Ordinal	FS_{11}		[150]
	Farmers affected by flood, drought, and heat protection systems	%	FS_{12}		[148]
	Diversity of local food system	Ordinal	FS_{13}		[152]
	Effectiveness of food supply chain	PMS	FS_{14}		[153]
	Land under rainfed irrigation	%	FS_{15}		SA*
	Arable land equipped for irrigation	%	FS_{16}		[97]
	Seed availability	Yes/No#	FS_{17}		SA*
	Nitrogen use efficiency in agricultural systems	%	FS_{18}		] [148,154]
Disaster Management	Vulnerable population	%	DM_1	23	[155]
	Population density	People/sq km	DM_2		[156]
	Exposure (% agricultural land) / Damaged crop area	%	DM_3		[156]
	Emergency response - hospital bed per 100,000 residents	%	DM_4		[156]
	Emergency response - physicians per 100,000 residents	%	DM_5		[156]
	Healthcare resources available for disaster risk management	Unit	DM_6		SA*
	Disaster communication	Yes/No	DM_7		[148,157]
	Coverage by national health emergency and disaster risk management programmes	Yes/No	DM_8		SA*
	Level of preparedness	Ordinal	DM_9		SA*
	Direct agricultural loss due to hazardous events	%	DM_{10}		[113]
	Area covered by community-based disaster risk management	%	DM_{11}		[158]
	Area covered by early warning system	%	DM_{12}		[158]
	Population below a particular flood line (100-year flood, 10 years)	%	DM_{13}		[158]
	Age dependency ratio	%	DM_{14}		[157]
	Previous disaster experience	Yes/No	DM_{15}		[159]
	Access to all-weather roads	Yes/No	DM_{16}		[148]
	Early warning standards and guides developed and disseminated	Yes/No	DM_{17}		[155]
	Community participation	Yes/No	DM_{18}		SA*
	Community volunteer systems	Yes/No	DM_{19}		SA*
	Awareness	Ordinal	DM_{20}		SA*
	Flood forecast systems	Yes/No	DM_{21}		SA*
	Agriculture planning after the disaster	Yes/No	DM_{22}		SA*
	Agriculture preparedness systems	Yes/No	DM_{23}		SA*
Clinical Public Health	Number of people per household	Number	CH_1	21	SA*
	Spatial distribution of population	People/sq km	CH_2		SA*

(*continued*)

Undernourishment	%	CH_3	[97,147]
Stunted (< 5 years)	%	CH_4	[98,149,]
Wasting (< 5 years)	%	CH_5	[148]
Population with access to potable water	%	CH_6	[150]
Households under basic sanitation	%	CH_7	[97,148]
Population maintaining adequate hygiene	%	CH_8	[148]
Households with healthcare facilities	%	CH_9	
Disease surveillance system	Ordinal	CH_{10}	[114]
Status of health sector preparedness plans	Ordinal	CH_{11}	[114]
Community assessments of risks and vulnerabilities	Ordinal	CH_{12}	[114]
Administrative and financial support	Ordinal	CH_{13}	[114]
Training for staff of essential community-level health facilities	Ordinal	CH_{14}	[114]
Standing order for health emergency management	Number/Population	CH_{15}	[114]
Community preparedness and response	Yes/No	CH_{16}	[114]
Spatial distribution of disease outbreaks	People/ sq km	CH_{17}	[147]
Individual and public health curriculum in education	Yes/No	CH_{18}	SA*
Effectiveness of health governance	Ordinal	CH_{19}	SA*
Political stability	Yes/No	CH_{20}	[150]
Insecticide-treated bed nets (ITNs)	Unit	CH_{21}	-

Note: S. System = Sub-Systems, SOV = Symbol of Variables, NOV = Number of variables, Ordinal (1-5), ND = Non-dimensional, # Yes/No = 2/1. Note: * WQI should be specified based on the water usage, such as drinking, agricultural, and fishes in the lake will have to be pacified. ** Soil quality for agricultural use and hazardous material must be pacified. *** An index for surface water body distribution. *SA = Suggested by Authors.

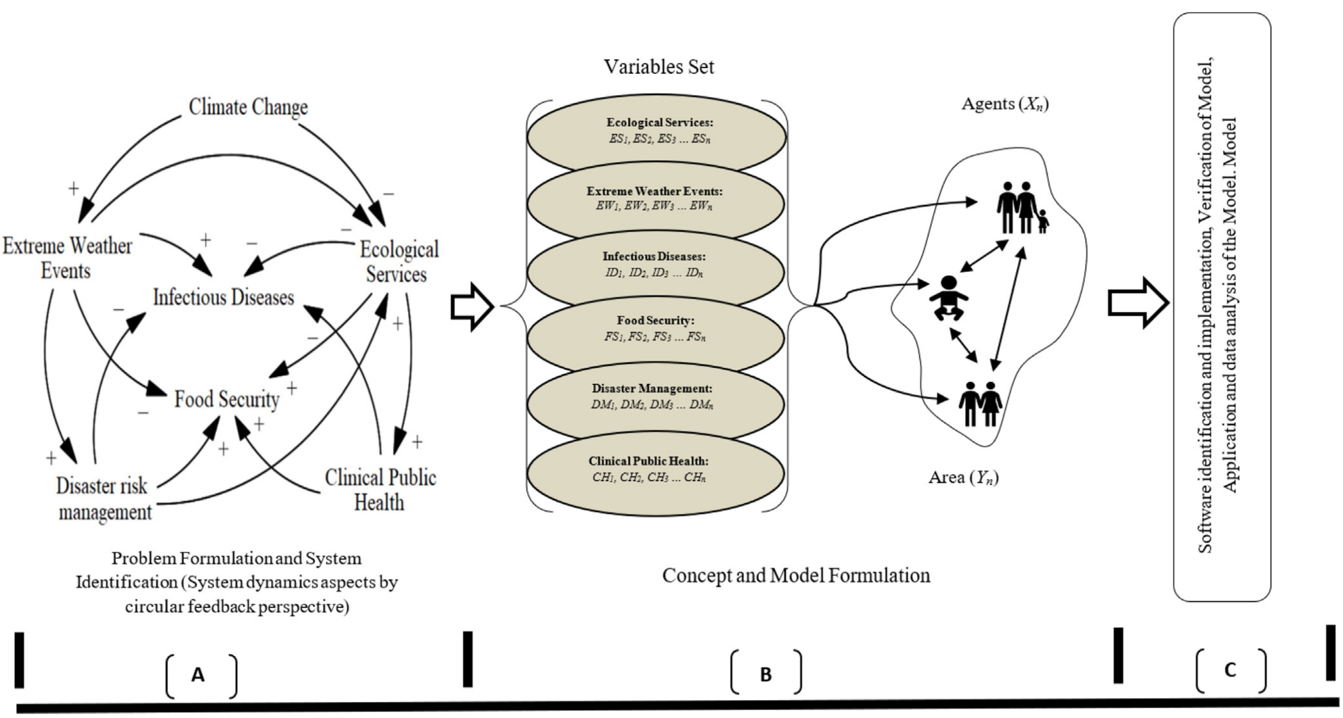

Fig. 8. A step-by-step illustration of a hypothetical agent-based model. Ecological services, extreme weather events, infectious diseases, food security, clinical public health, and disaster management influence climate change and health impacts. This hypothetical agent-based climate change and health impacts model incorporates the six sub-systems' static and time-varying causal variables. Part [A] represents the CAS and linkage between each sub-system as an aggregate system modeling approach. In part [B], the interaction of the agents and sub-system variables is used for the model formulation of the disaggregated parts of a system. In part [C], the model's final process and its purpose are presented. This hypothetical model represents potential outcomes of the health impacts of climate change on agents of an area Y_a where X_n of the population is living.

meaningful deterministic or statistical relationships between variables for the agents of interest.

The proposed CAS based framework is not restricted by the particular agent (e.g., governments vs individuals, vs watersheds) of the sub-systems. It can integrate various types or scales of agents and variables and allow users to think about the problems of climate change and health holistically. Physicians, climatologists, biologists, and social scientists can use this CAS based framework to explore different realizations of health outcomes from climate change scenarios by developing "What-If' analysis by adjusting the values of the CLD variables. For example, testing prolonged drought periods could directly inform malnutrition potential by examining the climate change impacts on water supply and farming and agriculture (see Fig. 4). Such a scenario can be further expanded by testing actions mitigating the effects of droughts. For example, the *Food Security* CLD could be used to simulate a quantification of how much farming and agriculture could vary dependence on local water supply during drought conditions to maintain minimum or maximum positive health outcomes. Thus, the CAS based framework can be an accessible scenario planning tool to explore the health impacts of climate change, with a view to understanding and identifying solutions within this complex system.

The proposed framework is expected to guide the development of a multi-agent-based simulation model. This could be used to support decisions about ecological services or adapt clinical public health interventions that seek to ameliorate the health impacts of climate change. Simulations generated by such an ABM can also be used to formulate multi-sector adaptation policies.

Evidence- and data-based step-by-step definition of the six subsystems and their identified agents ensure a broadly applicable decision model that various stakeholders, including researchers, government and non-government practitioners, and policy makers, can use. The ABM simulation model could help stakeholders understand and act on factors that shape the health impacts of climate change; facilitate knowledge sharing and mobilization among various organizations and generate new knowledge and information to facilitate practical implementation of adaptation strategies.

Agent-based modeling of the health impacts of climate change is a predictive process for forecasting future climatic influences on infectious diseases, malnutrition, and other aspects of human health [165]. The proposed model highlights the need for a more complex, multi-disciplinary, and operationally focused understanding of the causal dynamics contributing to climate change's health impacts. It can also highlight the multiple sub-system effects of carefully targeted and sequenced treatment, prevention, and ecological adaptation interventions. Modeling the health impacts of climate change can reveal the causal links shaping health outcomes and can also offer a collective narrative of the complex relationship of variables and agents. This model is not a goal in itself, but can help identify the actions needed to reduce impacts using systems thinking for community-based health adaptation.

5. Conclusion

Climate change will continue to affect human health through extreme weather events, changing patterns of infectious diseases, and impacts on food security, livelihoods and population displacement. These impacts are already profoundly inequitable and will accelerate among poor and vulnerable people. Climate, biospheric and ecological factors, as well as disaster management, and clinical public health planning will largely determine the overall health impacts of climate change. For example, changing temperature and precipitation will affect vector-borne disease ecology and related human infectious disease impacts, and will be influenced by human treatment, prevention and adaptation choices and interventions.

Applying transdisciplinary perspectives is vital to identifying and understanding complex causal relationships, and to designing and implementing effective prevention and adaptation interventions (including early warning systems and responses). This is one of the greatest challenges for global health. Considering the complexity of climate change and its health impacts, we used field observations, expert input, key informant interviews, and a comprehensive literature review to capture these dynamics, and propose a CAS based framework with six subsystems. We propose and conceptually develop the use of the framework as a foundation for agent-based modeling of health outcomes, with causal loop diagrams (CLDs) designed for each CAS sub-system and a set of context specific variables identified for use in predictive modeling. The CAS based framework can be a valuable resource for policymakers, researchers, and public health professionals seeking to assess, mitigate and adapt to the multifaceted challenges posed by climate change.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Byomkesh Talukder: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jochen E. Schubert:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Mohammadali Tofighi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Patrick J. Likongwe:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation. **Eunice Y. Choi:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Gibson Y. Mphepo:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Ali Asgary:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Funding acquisition, Formal analysis. **Martin J. Bunch:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Conceptualization. **Sosten S. Chiotha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Funding acquisition, Data curation, Conceptualization. **Richard Matthew:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization. **Brett F. Sanders:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Keith W. Hipel:** Writing – review & editing, Writing – original draft, Supervision. **Gary W. vanLoon:** Writing – review & editing, Writing – original draft, Validation, Supervision. **James Orbinski:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Acknowledgement

This paper has been funded by the Wellcome Trust, UK, and the Dahdaleh Institute for Dahdaleh Institute for Global Health Research (yorku.ca), York University, Canada.

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