

**AN ANTHOLOGY OF
GLOBAL RISK**

EDITED BY
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13. Re-Framing the Threat of Global Warming: An Empirical Causal Loop Diagram of Climate Change, Food Insecurity and Societal Collapse

C. E. Richards, R. C. Lupton and J. M. Allwood

Highlights:

- Understanding the existential threat of climate change is essential for good risk management; however, our knowledge of the pathways through which climate change could cause societal collapse is underdeveloped. This chapter aims to identify and structure an empirical evidence base of the climate change, food insecurity, and societal collapse pathway.
- The authors first review the societal collapse and existential risk literature and define a set of determinants of societal collapse. They then develop an original methodology, using these determinants as societal collapse proxies, to identify an empirical evidence base of climate change, food insecurity, and societal collapse and structure this using a novel-format Causal Loop Diagram (CLD).
- The resulting evidence base varies in temporal and spatial distribution of study and in the type of data-driven methods used. For example, the link between *food insecurity* and

conflict was found to have been investigated mostly by statistical analyses, whereas the links between *food insecurity* and *migration*, and *food insecurity* and *natural mortality* were investigated mostly by interviews and surveys.

- The CLD documents the spread of the evidence base and enables exploration of how the effects of climate change may undermine agricultural systems and disrupt food supply, which can lead to economic shocks and socio-political instability, as well as starvation, migration and conflict.
- Suggestions are made for future work that could build on this chapter to further develop our qualitative understanding of, and quantitative complex systems modelling capabilities for analysing, the causal pathways between climate change and societal collapse. In particular, it highlights important factors at global scale and national granularity, such as the geographic distribution of population and natural resources, international interactions (such as food trade, conflict and migration), and institutional breakdown.

This chapter uses a systems dynamics approach and proposes that a Causal Loop Diagram can be utilised in order to construct an evidence base of the relationships between climate change, food insecurity and societal collapse. Novel approaches to investigating and mapping systemic and complex risk interactions are also explored in chapters throughout this volume, including Chapter 20.

1. Introduction

Despite recent social protests and climate emergency declarations, efforts to mitigate climate change to date are insufficient.¹ Greenhouse gas (GHG) emissions continue to rise and global warming above 3 °C is increasingly likely this century.² There is emerging evidence of amplifying feedbacks accelerating³ and dampening feedbacks decelerating.⁴ These feedbacks exacerbate the possibility of runaway global warming,⁵ estimated at 8 °C or greater by 2100.⁶ Such temperature increases translate to a range of real dangers,⁷ shifting the narrow climate niche within which humans have resided for millennia.⁸

Looking beyond the framing of “global warming”, there is concern that the effects of climate change may pose an existential risk to humanity, one that threatens “societal collapse” or even extinction.⁹ Understanding these worst-case scenarios is essential for good risk management.¹⁰ Improving awareness of potential pathways through which climate change poses such a risk can help inform decision-making about interventions.¹¹ Considering societal impacts that are more tangible for individuals, businesses and governments,¹² and better aligned with conventional risk priorities,¹³ may facilitate more effective action to mitigate climate change.¹⁴

A number of pathways through which climate change could cause societal collapse have been identified, one being via food insecurity.¹⁵ Climate change is predicted to undermine agricultural systems and disrupt food supply,¹⁶ which may lead to economic shocks, socio-political instability as well as starvation, migration and conflict at local through to global scale.¹⁷ While the climate science underpinning global warming estimates is well established,¹⁸ albeit subject to sensitivities, the uncertainties increase significantly when we start to consider these tangible societal impacts given the complex relationships involved.¹⁹ Our understanding of worst-case scenarios, and particularly of empirical evidence addressing the causal pathways through which climate change may cause societal collapse, is underdeveloped.²⁰

In this chapter we aim to identify and structure an empirical evidence base of the relationships between climate change, food insecurity and societal collapse. We do this using Causal Loop Diagrams (CLD), a system dynamics approach that is useful for visualising the relationships between variables in a complex system.²¹ This chapter is organised as follows. In Section 2, we review the societal collapse and existential risk literature to refine the aim introduced above. In Section 3, we develop an original methodology to establish a new empirical evidence base and create a novel-format CLD of causal pathways between climate change and societal collapse. In Section 4, we present and discuss the results from the application of this methodology to the climate change, food insecurity and societal collapse causal pathway of interest. We conclude, in Section 5, by identifying avenues of future work that may build upon this chapter.

2. Literature Review

To refine the aim of this chapter, introduced in Section 1, our review examines whether there is historical evidence of climate change as a mechanism of societal collapse and to what extent have causal pathways been documented to inform our understanding of climate change as an existential threat to contemporary society.

We first define the terms “existential risk” and “societal collapse” as used in this chapter. Adopting Ord’s definition, “an existential risk is a risk that threatens the destruction of humanity’s long-term potential” be it incomplete destruction, such as societal collapse, or complete destruction, such as extinction.²² Adopting Kemp’s definition, societal collapse is an “enduring loss of population, identity [and/or institutional] complexity”;²³ it may be abrupt or gradual, but is typically rapid because it is notably transformative, and may be experienced by a local, national or the global community of people. Fig. 1 presents a conceptual model of societal collapse, synthesised from the broader literature, to provide further contextual definition.

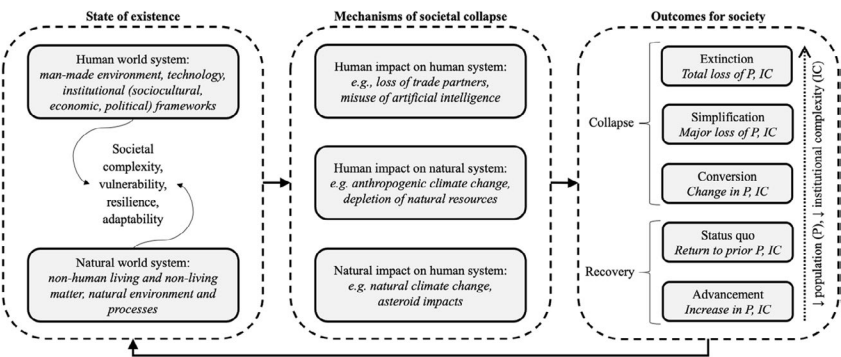


Fig. 1: Conceptual model of the overarching process of societal collapse.

The rise and fall of civilisations has been documented since the earliest recordings of history and is increasingly studied to inform our understanding of societal collapse.²⁴ We consider two types of historical studies that provide insight into climate change as a mechanism of societal collapse in the past. We note that other mechanisms are also discussed in the literature, and there is debate about the role of different mechanisms in particular societal collapse events.

The first type of historical study empirically investigates an individual societal collapse event using primary sources, including anthropological, archaeological and paleontological data. Based on such data analysis, natural climate change has been asserted as a mechanism of societal collapse in many of these case studies, as established by de Menocal²⁵ and Weiss and Bradley.²⁶ For example, Hodell et al.,²⁷ Haug et al.,²⁸ and Medina-Elizalde and Rohling²⁹ analyse paleoclimate data alongside the archaeological record to show that drought conditions, driven by climate change likely due to solar forcing, contributed to the collapse of the Classic Maya civilisation of Mesoamerica in ~8–10th century CE. Weiss et al.,³⁰ Cullen et al.,³¹ and Cookson et al.³² show that regional aridity, driven by climate change likely due to volcanic forcing, contributed to the collapse of multiple societies across Mesopotamia, including the Akkadian Empire in ~22nd century BCE. Similarly, natural climate change has been implicated in the collapse of multiple Late Bronze Age societies around the Mediterranean,³³ including Mycenaean Kingdoms in ~12th century BCE,³⁴ the Harappan Civilization of South Asia in ~19th century BCE,³⁵ the Angkor Empire of Southeast Asia in ~15th century CE,³⁶ multiple Chinese Dynasties³⁷ and civilisations along the Silk Road³⁸ during the previous millennium, the Norse Vikings of Greenland in ~16th century AD,³⁹ and the Tiwanaku Empire of Pre-Columbian South America in ~10th century CE⁴⁰ amongst others.

This first type of studies establishes precedence of natural climate change as a mechanism of societal collapse throughout history, demonstrating the risk that anthropogenic climate change similarly poses to contemporary society. However, the events examined occurred more than 100 years ago, with most dating back to ancient history, when societies were relatively isolated. Because these case studies pre-date contemporary society, they do not provide empirical evidence of anthropogenic climate change in context of today's highly interconnected society.⁴¹

Statistical evaluation of the frequency and significance of natural climate change relative to other mechanisms of societal collapse identified across these case studies has not yet been established within the literature. However, the second type of historical study does qualitatively examine collections of these case studies to develop

theories of predominant modes of societal collapse. Three major modes are observed, as follows.

Fagan⁴² and McMichael⁴³ focus on natural impact on the human system across multiple civilisations, concluding that natural climate change is predominant having significantly influenced human existence throughout history. Over the past 12,000 years, the natural and human systems developed within the stable climate niche of the Holocene Epoch.⁴⁴ The associated geographic endowments governed human transition from band societies based on foraging to complex societies based on agriculture. Unfavourable subtle (e.g. weather variations) and drastic (e.g. natural disasters) shifts in climate influenced the collapse of complex societies either by direct loss of life or indirectly via resource insecurity. In particular, in this mode, typically, the loss of agriculture led to de-population via famine, migration or conflict due to food insecurity.

Ponting,⁴⁵ Wright,⁴⁶ and Diamond⁴⁷ focus on human impact on the natural system across multiple civilisations, concluding that human overpopulation and overexploitation relative to the carrying capacity of the environment is predominant. Societal collapse via environmental degradation often involved unsustainable agriculture, exacerbated by natural climate change, leading to de-population as well as institutional breakdown via loss of economic stability and socio-political dysfunction due to magnified inequality. This mode aligns with early “Malthusian catastrophe”,⁴⁸ “tragedy of the commons”,⁴⁹ and “overshoot-and-collapse”⁵⁰ theories.

In their 12-volume *magnum opus* exploring the rise and fall of 28 civilizations, Toynbee concludes that “great civilizations are not murdered [but rather] they take their own lives.”⁵¹ Building on this, Tainter,⁵² Acemoglu and Robinson,⁵³ and Johnson⁵⁴ focus on human impact on the human system across multiple civilisations, concluding that societal complexity in relation to problem-solving inability (e.g. environmental degradation) and institutional dysfunction (e.g. inequality and oligarchy internally, trade ally and hostile neighbour relations externally) is predominant. As a society becomes more complex, it reaches a point beyond which “continued investment in complexity as a problem-solving strategy yields a declining marginal return” and it will be at risk of collapsing under its own weight via

institutional breakdown and de-population.⁵⁵ This mode aligns with “energy returned on energy invested” theory,⁵⁶ applied to explore societal collapse by Homer-Dixon.⁵⁷

Diamond,⁵⁸ Turchin,⁵⁹ and Schwartz and Nichols⁶⁰ examine why some civilisations have been able to thrive or recover, rather than collapse. They similarly conclude that societies have flourished due to combinations of favourable geographic endowment, managing their existence within the carrying capacity of the natural system, and co-operative action in problem-solving.

This second type of studies highlights that societal collapse involves a complex nexus of factors and dynamically interlinked events. For instance, Gibbon details how all three of the modes, described in the preceding five paragraphs, contributed to the collapse of the Roman Empire.⁶¹ These modes of societal collapse, although based on empirical evidence pre-dating contemporary society, describe key aspects of the anthropogenic climate change problem faced today. While these studies describe causal pathways of relevance, to the best of our knowledge, no study has used CLDs to untangle the complexity and give structure to the dense information in this evidence base.

Across these historical studies, we observe no apparent temporal or spatial influence on the occurrence of societal collapse. Rather, societal collapse has been described as occurring in various forms, whether it be by known “white-swan” or surprise “black swan” events,⁶² in different geographic locations and times throughout history. Additionally, a quantitative statistical analysis by Arbesman shows that societal collapse has occurred randomly and independent of civilisation life-spans.⁶³ These qualitative and quantitative observations highlight that any society may be susceptible to collapse, much in-line with the *Red Queen Hypothesis* of the *Law of Extinction*.⁶⁴

From these historical studies, we observe sets of secondary determinants for each of the primary determinants introduced in Fig. 1, which are defined in Fig. 2. Considering a geographically bounded society, *emigration* refers to any permanent departure of population including both voluntary or forced migration, *conflict mortality* accounts for deaths directly arising from any form of domestic or international conflict (e.g. due to war), and *natural mortality* accounts for deaths related to domestic environmental conditions (e.g. due to famine). The

loss of socio-cultural norms, political structures or economic value accounts for that which notably transforms the identity and institutions of the society.

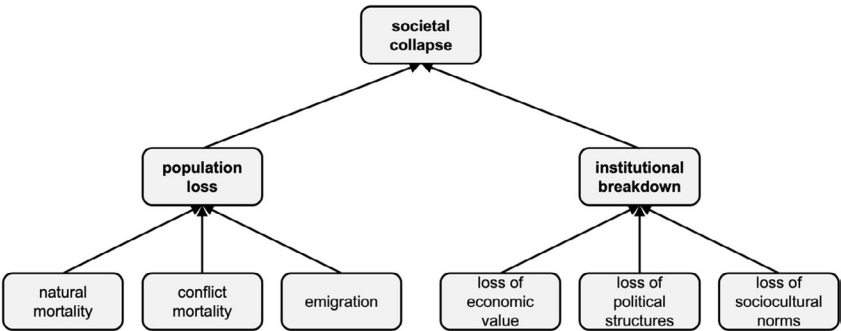


Fig. 2: Primary and secondary determinants of societal collapse for a bounded society.

In addition to these historical studies, we consider the relatively nascent studies of existential risks (X-risks) that provide insight into how climate change may trigger societal collapse in the future.

Comprehensive surveys of X-risks reveal mechanisms that could cause the collapse of contemporary society. Bostrom and Ćirković,⁶⁵ Rees,⁶⁶ and Ord⁶⁷ provide eminent scholarly treatment of the field, drawing from the academic literature. The World Economic Forum⁶⁸ and Global Challenges Foundation⁶⁹ produce global risk reports drawing from decision-makers and experts across intergovernmental and non-governmental organisations. These surveys establish that many historically observed mechanisms of societal collapse, including natural climate change, remain applicable as X-risks today. However, the state of existence of contemporary society has led to a different landscape in which these mechanisms apply, and to a number of unprecedented mechanisms, including anthropogenic climate change. Ehrlich and Ehrlich⁷⁰ and Häggström⁷¹ note that although increased complexity, such as globalisation and technological advancement, can increase a society’s resilience and adaptability, it can also increase vulnerability. For example, globalisation increases resilience to local agricultural production shocks through access to global markets; however, it also increases vulnerability through exposure to sudden reversal in connectivity, such as trade restrictions.⁷² Some geoengineering technologies, for example, may

enable society to mitigate and adapt to climate change; however, they may also increase vulnerability to termination shocks, where failure of the technology exposes society to sudden temperature increases.⁷³ In this highly interconnected landscape, “synchronous”⁷⁴ and “cascading”⁷⁵ failures create the potential for mechanisms and outcomes of societal collapse, once contained to a single localised civilisation, to rapidly spread across multiple nations and impact humanity on a global scale.

Works by Lynas,⁷⁶ Wallace-Wells⁷⁷ and Gowdy⁷⁸ draw on the scientific climate change literature to explore hypothetical futures under best- to worst-case scenarios. The scenarios consider the feedbacks within the natural system that could worsen, as well as the potential for humans to mitigate, anthropogenic climate change. Shifts in average weather (e.g. temperature) and natural disasters (e.g. floods) affected by climate change could impact human mortality directly. These two effects, coupled with sea level rise due to melting of ice caps, could indirectly impact human mortality via degradation of the natural world system (e.g. land quality) and the human world system (e.g. infrastructure failures) resulting in resource and service insecurity. This insecurity could impact institutional stability, resulting in economic loss, political dysfunction and social unrest, as well as migration and conflict. The hypothetical outcomes for contemporary society against the threat of anthropogenic climate change range from dystopian (collapse) to utopian (recovery).

These futures studies identify endpoints of different causal pathways between anthropogenic climate change effects and potential impacts on the human world system, with the latter reflecting key determinants of societal collapse observed in the historical studies. Scholars have made limited in-roads to empirically investigating the top-level relationships between some of these endpoints using recent datasets. The direct links between climate change and the endpoint impacts of mortality, conflict and migration are, respectively, examined by Mora et al.,⁷⁹ Hsiang et al.⁸⁰ and Hauer et al.⁸¹ The feedback between migration and conflict driven by climate change is examined by Abel et al.⁸² The direct links between climate change and the endpoint impacts of economic loss, political instability and shifts in cultural norms are examined by Burke et al.,⁸³ Sofuoğlu and Ay,⁸⁴ and Adger et al.⁸⁵ respectively. However, the complex bottom-level links between and surrounding these endpoints

are generally ill understood,⁸⁶ and the strength of empirical evidence is poorly documented from a systems science perspective.⁸⁷ To the best of our knowledge, no study has empirically examined how the impacts of climate change could explicitly translate into societal collapse for contemporary society. We do not have a clear picture of climate change as a systemic risk to our globalised society, particularly at spatial scales accounting for the heterogeneity of individual identity, business governance and policymaking across nations, and international exchanges. This limits our ability to understand feedbacks, identify intervention points, develop quantitative models and inform strategies to minimise the risk of societal collapse occurring in the future.⁸⁸

Given the insights from this review, we refine the aim of this chapter as follows. Firstly, the empirical evidence base should specifically address contemporary society. Secondly, the CLD should be constructed at a scale and granularity that addresses the heterogenous characteristics of nations and international interactions. The refined aim of this chapter is thus to identify an empirical evidence base of climate change, food insecurity and societal collapse in contemporary society and structure the evidence base with a CLD defined at global scale and national granularity.

3. Methodology

A two-stage framework, consisting of five steps, was developed to achieve the aim of this chapter. For each step, below, we first introduce it generically and then describe its application to our specific analysis of the climate change, food insecurity and societal collapse causal pathway.

3.1. Stage 1: Establishing an empirical evidence base of societal collapse in contemporary society

Step I deploys societal collapse proxies via a key word search to identify “evidence points”, which in this instance may be considered data points, in the form of publications that empirically examine the causal pathway of interest in contemporary society.

The determinants defined in Fig. 2 provide these societal collapse proxies to establish the new empirical evidence base in lieu of historical

societal collapse events pre-dating contemporary society. The *population loss* set are straightforward to isolate, consistent to measure across nations and describe tangible consequences. The *institutional breakdown* set are relatively less so. Thus, the societal collapse proxies adopted in this study were *natural mortality* (i.e. *starvation*, with respect to food insecurity), *conflict mortality* and *emigration*; subsequent studies could use the *institutional breakdown* set. Key words were selected based on terminology of climate change, food insecurity and the societal collapse proxies. Peer-reviewed journal articles were chosen as the form of evidence point in this study; subsequent studies could use other publications, such as books and reports.

The keyword search was performed in Scopus. A record of the search is contained in the Supplementary Information (A.). Approximately 3,000 publications were reviewed by reading the title, abstract and main body as needed. Evidence points were selected based on satisfaction of the following criteria: the publication (a) is a peer-reviewed, English-language, journal article; (b) uses empirical, data driven methods; (c) examines the period from 1990 to present (2019), representative of contemporary society; and (d) primarily examines the causal pathway of interest. We made an exception to (a) to include the most recent *Limits to Growth* book,⁸⁹ which was not itself a search result but documents the World3 model that was identified in the search results. We note that (b) precluded selection of review or essay-style publications; however, we found that these were often discussed in the literature review of selected evidence points, so were, nonetheless, accounted for indirectly.

This step resulted in a new empirical evidence base consisting of 41 evidence points, which are summarised in Fig. 4.

Step II defines a custom colour-coded typology for the new empirical evidence base. This typology is used in Stage 2, to construct a final CLD (f-CLD) in a novel format showing the spread of the evidence base across the system.

In this study, we were interested in the methodological spread as this provides information on data that may be useful for future studies. Four methodological categories were identified in the new empirical evidence base. Each evidence point was classified into one of these categories and assigned a colour coding, namely: quantitative complex systems model — red; statistical analysis of quantitative dataset — blue; collection /

analysis of qualitative interview / survey data — green; quantitative data-led case study / scenario — yellow.

The resulting typology of the new empirical evidence base is shown in Fig. 4.

3.2. Stage 2: Constructing a novel-format causal loop diagram from the empirical evidence base

Step III involves creating an individual CLD (i-CLD) for each evidence point to clearly structure the complex causal relationships examined. These i-CLDs provide the building blocks from which to construct the f-CLD in Step IV.

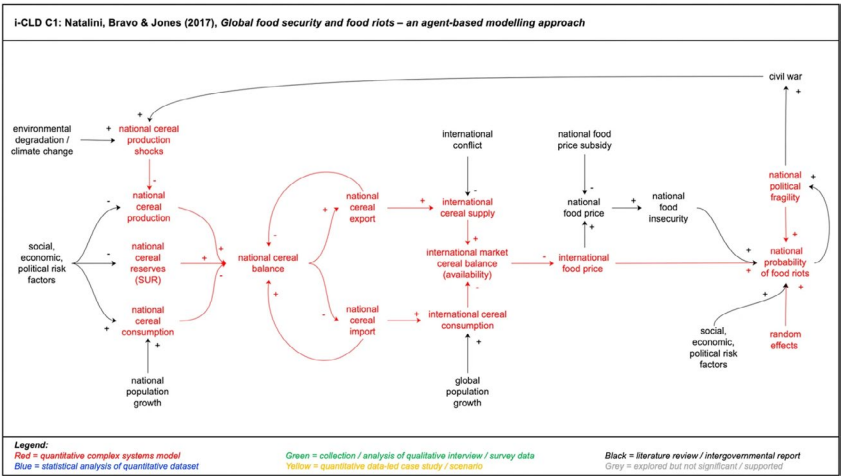


Fig. 3: One of the i-CLDs created for each of the 41 evidence points in the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society.

The process to create an i-CLD is as follows. The corresponding evidence point was examined in its entirety to identify and record key information in the form of variables (nodes), links (arrowed lines) and relationship notation (positive or negative). Key information derived from the original data-driven content, i.e. the main analysis, of the evidence point was colour coded in the i-CLD according to the typology classification established in Step II. Any relationships hypothesised but

not supported by the main analysis were coloured grey. Key information derived from other content, i.e. the literature review, of the evidence point was coloured black. The scale and granularity of the i-CLD was recorded as detailed in the evidence point. This process was repeated for each evidence point in isolation until a complete set of i-CLDs was produced for the new empirical evidence base.

All 41 i-CLDs created in this study are contained in the Supplementary Information (B.). One of the i-CLDs is shown in Fig. 3 as an example.

Step IV reconciles the set of i-CLDs into a standardised format in order to construct the f-CLD of the system of interest at the desired scale and granularity.

The standardisation process has two aspects. One aspect is related to component (variables and links) definition, necessary to maximise clarity of the f-CLD while covering all information contained in the evidence base. This addresses the typical challenge of CLDs becoming dense and overcomplicated, which decreases their utility. The other aspect is related to level of aggregation, necessary to ensure the f-CLD conveys information at the intended scale and granularity. The standardisation is an iterative process, as follows.

The ~950 variables from the set of 41 i-CLDs were recorded on a blank worksheet for the f-CLD, without links between them. A clustering approach was used to reconcile these variables into like groups. For each group, an overarching major node was isolated and the i-CLD variables in the group were virtually deposited into a matrix for that major node. For example, *drought*, *sea level rise* and *crop disease* were some of the i-CLD variables clustered into an *environmental risk factors* f-CLD major node matrix. The f-CLD major nodes were defined at a level of aggregation representative of a nation. Doing so effectively scaled down any global or regional aggregation, and scaled up any sub-national or local aggregation, in the i-CLD variables. For example, *household food imports* was an i-CLD variable of local aggregation that was scaled up to national *food imports (trade)* in the f-CLD.

The ~1150 links from the set of 41 i-CLDs were reconciled into arrowed lines between the major nodes in the f-CLD. This sometimes-required interpretation of implied causality in the i-CLD relationships in order to route them across the major nodes in the f-CLD. For example,

where an i-CLD showed a direct link from *international food price* to *conflict* variables, this was routed using arrowed lines from *international food price* to *national food price* to *food accessibility* to *food insecurity* and finally to *conflict* major nodes defined in the f-CLD. Where there was a discrepancy between relationship descriptions, the relationship with the most supporting i-CLDs was adopted.

The interim f-CLD produced at the end of each standardisation iteration was examined to determine whether the major node definition could be refined to maximise clarity. For example, in one iteration *water* and *land* were defined as separate major nodes, but examination determined that each had the same arrowed lines to other major nodes; therefore, another iteration was undertaken with *water* and *land* now clustered under a single *natural resources* major node in order to minimise redundant arrowed lines. This process was iterated several times until an f-CLD had been constructed at an appropriate level of detail for this study. Additionally, relevant literature reviewed in Section 2⁹⁰ was cross-referenced, but not included as evidence points, to ensure comprehensive coverage of key relationships in the f-CLD.

The standard-format f-CLD, consisting of uncoloured and unweighted components, resulting at the end of this step is contained in the Supplementary Information (C.).

Step V maps each i-CLD to the f-CLD using a weighted (line thickness) typology (colour-coded) approach. This visually documents the spread of the evidence base across the system described by the f-CLD.

The process to map an i-CLD to the f-CLD is as follows. Each variable (node) of the i-CLD was assigned to its corresponding major node(s) in the f-CLD. Each link (arrowed line) of the i-CLD was assigned to a corresponding route along the arrowed lines in the f-CLD. Each time an arrowed line in the f-CLD had an i-CLD link assigned to it, an incremental weighting of one-unit line thickness in the corresponding typology colour-coding of the i-CLD link was added to the f-CLD arrowed line. This process was repeated for each of the 41 i-CLDs until all had been mapped to the f-CLD. A record of this process for each of the 41 i-CLDs is contained in the Supplementary Information (D.).

The novel-format f-CLD, consisting of colour-coded and weighted components, resulting at the end of this final step is presented in Fig. 5.

4. Results and Discussion

The new empirical evidence base and novel-format CLD of climate change, food insecurity and societal collapse in contemporary society resulting from the application of our original methodology (Section 3) are discussed in turn below.

4.1. Empirical evidence base of climate change, food insecurity and societal collapse in contemporary society

The new empirical evidence base (Section 3, Step I), along with its colour-coded typology (Section 3, Step II), is presented in Fig. 4. It consists of 41 evidence points, of which 9 examine the *natural mortality* (i.e. *starvation*, with respect to food insecurity), 20 the *conflict mortality* and 12 the *emigration* societal collapse proxy, alongside other human and natural world system factors. We discuss three key aspects of the evidence base, namely temporal and spatial distribution, data-driven method distribution, and advantages of each data-driven methods, below.

The temporal scale and granularity of study varies across the evidence base; however, our methodology limited the possible scale of study to the period from 1990 to present, representative of contemporary society. Within this period, approximately half of the evidence points cover a scale of less than one decade and the other half a scale of greater than one decade. Approximately half of the evidence points conduct analyses at yearly granularity and the other half conduct analyses at granularity greater than one year, with only a few studies conducting analyses at monthly granularity. The spatial scale and granularity of study varies across the evidence base. Approximately one third of the evidence points investigate the system at a global scale, with the remaining two thirds focusing on regional or national scales, primarily in Africa as well as the Middle East and Asia. Approximately half of the evidence points analyse the causal pathway at sub-national granularity, with the other half primarily focusing on national-level granularity. This variation provided different coverage of the complex relationships within the system, which was informative for constructing our CLD.

The distribution of data-driven methods used across the evidence base is notably different for each societal collapse proxy. Evidence points for *natural mortality* mostly use collection/analysis of interview/survey data. This is likely because the minimum daily food intake for human survival is well established;⁹¹ as such, statistical analysis of food and mortality data sets would not yield significantly new insights into thresholds whereas interviews/surveys can provide insight into an individual's circumstances influencing this relationship. Evidence points for *conflict mortality* mostly use statistical analysis of existing datasets. This likely reflects the interest in rigorously curated conflict datasets, such as UCDP/PRIO,⁹² across the conflict and peace fields. Evidence points for *emigration* mostly use collection/analysis of interview/survey data, likely because this provides nuanced insight into an individual's decision to migrate. It may also be due to data availability and quality challenges that limit quantitative statistical analyses, which are being addressed by groups such as the International Organization for Migration's Global Migration Data Analysis Centre.⁹³ Amongst these data challenges, it is important to recognise the issue of reconciling different types of voluntary and forced migration with causal drivers, given the complex social, economic and political factors at play; this challenge similarly applies to the other societal collapse proxies but is particularly noted in the migration studies. We observe from these studies that a food insecurity threshold for *natural mortality* is well established but thresholds for *conflict mortality* and *emigration* are not. Indeed, distinguishing causal drivers within datasets and defining quantitative thresholds for these determinants remains a "grand challenge".⁹⁴

#	Proxy Examined	Typology Classification	Evidence Point Reference	Spatial Scale	Spatial Granularity	Temporal Period	Temporal Granularity
N1	Natural mortality	Model (SDM)	Meadows et al, 2004	Global	Global	1900-2004, fwd sim.	Yearly
N2		Statistical analysis	Agboola, 2017	Global (114 countries)	National	1995-2009	Yearly
N3			Lee et al, 2016	Global (95 countries)	National	2001-2011	Yearly
N4		Interview/survey	Campbell et al, 2009	Indonesia	Sub-national	2000-2003	Period
N5			Fiedlerjohann et al, 2016	India	Sub-national	2002-2008	Period
N6			Gundersen et al, 2018	Canada	Sub-national	2005, 2007-2010	Period
N7			Nandy et al, 2016	Nigeria, Ethiopia	Sub-national	2000-2013	Yearly
N8			Sati & Vangchhia, 2016	India	Sub-national	2014	Period
N9			Walker et al, 2019	USA	National	2003-10	Period
C1	Conflict mortality	Model (ABM)	Natalini et al, 2017	Global (213 countries)	National	2005-2013, fwd sim.	Monthly, yearly
C2		Statistical analysis	Arezki & Brueckner, 2014	Global (60 countries)	National	1970-2007	Yearly
C3			Bellemare, 2014	Global	Global	1990-2011	Monthly
C4			Berazneva & Lee, 2013	Africa (14 countries)	National	2007-2008	Period
C5			Caruso et al, 2016	Indonesia	Sub-national	1993-2003	Yearly
C6			Hendrix & Haggard, 2015	Africa, Asia (49 countries, 55 cities)	Sub-national	1961-2010	Yearly
C7			Jones et al, 2017	Africa	National	1991-2011	Monthly
C8			Korten & Biagazzi, 2016	Global	0.5<0.5 deg.	1991-2008	Yearly
C9			Maystadt et al, 2014	Global (arab world vs rest of world)	National	1960-2010	Yearly
C10			Natalini et al, 2015	Africa, Asia, MiddleEast (25 countries)	National	2005-2011	Monthly, yearly
C11			Newman, 2018	Global (79 countries)	National	2005-2015	Yearly
C12			Pinstrup-Andersen & Shimokawa, 2008	Global (146 countries)	National	1980-2005	Yearly
C13			Raleigh et al, 2015	Africa (24 countries, 113 markets)	Sub-national	1997-2010	Monthly
C14			Smith, 2014	Africa (40 countries)	National	1990-2012	Monthly
C15			van Weezel, 2016	Africa (45 countries)	National	1990-2011	Monthly
C16			Weinberg & Bakker, 2015	Global (71 countries)	National	1972-2007	Yearly
C17			Wischnath & Buhaug, 2014	India	Sub-national	1980-2011	Yearly
C18		Interview/survey	Legwegoh et al, 2015	Cameroon	Sub-national	2008	Period
C19		Data-led/scenario	Lunt et al, 2016	Global	National	2016, projection	Period
C20			Sternberg, 2012	Global (Egypt, China)	National	2010-2011	Period
E1	Emigration	Model (ABM)	Smith, 2014	Tanzania	Sub-national	2012, fwd sim.	Period, yearly
E2		Interview/survey	Affli et al, 2014	Tanzania	Sub-national	2012	Period
E3			Etzold et al, 2014	Bangladesh	Sub-national	2011	Period
E4			Jacobson et al, 2019	Cambodia	Sub-national	2016	Period
E5			Milan & Ho 2014	Peru	Sub-national	2011	Period
E6			Milan & Ruano, 2014	Guatemala	Sub-national	2011	Period
E7			Murell & Affli, 2014	India	Sub-national	2011	Period
E8			Pariter-Brick & Eggerman, 1997	Nepal	Sub-national	1996 (assumed)	Period
E9			Rademacher-Schulz et al, 2014	Northern Ghana	Sub-national	2011	Period
E10			Warner & Affli, 2014	Global (S/SEAsia, SSAfrica, LatAm)	Sub-national	2011-2012	Period
E11		Data-led/scenario	Doos, 1994	Global	Global, national	1990-94, projection	Yearly
E12			Puma et al, 2018	Global	National	2011-2018	Yearly

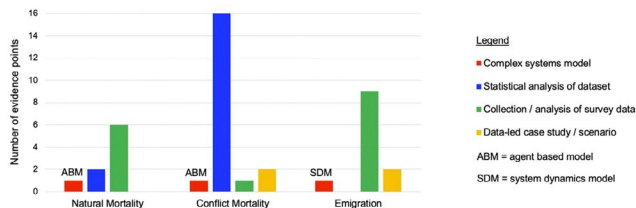


Fig. 4: Summary and custom colour-coded typology of the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society. A full reference list is contained in Supplementary Information (E.)

Each data-driven method offers different advantages. The complex systems models each describe “chunks” of the system at different scale and granularity. The models provide mathematical definition, are calibrated to real-world data and enable quantitative simulation of key relationships in the system. The statistical analyses quantitatively examine relationships between a dependent variable and one or more independent variables within the system, which can be used as a mathematical basis for extending modelling capabilities. The collection/

analysis of interview/survey data provides insight into qualitative aspects of human perspective and decision-making that quantitative data sets cannot provide directly. The data-led case study/scenarios combine quantitative data with qualitative expert interpretation to better understand global trends and forecasts. These latter two methods can also be used to inform the development of modelling capabilities, the scenarios analysed by such models and their application in decision-making processes. Collectively, these different data-driven methods can yield useful insights into the nuances of relationships in the system of interest.

4.2. Causal loop diagram of the climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity

The main result of this chapter is the CLD (the f-CLD from Section 3, Step V), presented in Fig. 5. It structures the relationships between climate change, food insecurity and societal collapse as described in our new empirical evidence base (presented in Fig. 4 and discussed in Section 4.1). We discuss three key aspects of the CLD, namely insights related to the spread of empirical evidence, the qualitative complex system depicted, and quantitative complex system modelling, below, alongside consideration of well-established benefits and limitations of CLDs.

Our CLD is presented in a novel format that documents the spread of our empirical evidence base. We use line thickness and colour, respectively, to depict the density and type of the data-driven methods used by the empirical evidence points to analyse a given link between two variables.

Doing this aids comprehension of where existing work has been focused with respect to the climate change, food insecurity and societal collapse causal pathway. It may also help with the identification of gaps in existing analyses. For example, we can see that the link between *food insecurity* and *conflict* has been investigated mostly by evidence points using statistical analyses (blue), whereas the links between *food insecurity* and *migration*, and *food insecurity* and *natural mortality*, have been investigated mostly by evidence points using interviews/surveys (green). This hints that it

may be useful to investigate the former using quantitative statistics, and the latter using qualitative interviews/surveys, to gain further insights offered by the different data-driven methods as described in Section 4.1.

It is important to recognise that our CLD may show negligible density for important links or even be missing important variables and/or links, either because they have not yet been studied or because our key word search failed to identify evidence points that have studied them. For example, our study focused on the climate change, food insecurity and societal collapse causal pathway, so the density of our empirical evidence is concentrated along links central to this pathway, whereas the links between peripheral variables in the system, such as between *fertility* and *births*, show a lower density of empirical evidence. Similarly, our use of the *population loss* set of societal collapse proxies means that the evidence base details *natural mortality*, *conflict mortality* and *emigration*, whereas the *institutional breakdown* set are not detailed. In considering this issue, our methodology attempted to maximise the rigour and transparency of our study by documenting the spread of our empirical evidence base to help make the reader aware of exactly how much and what type of evidence was supporting the CLD presented here.

Further, we can see that while empirical studies have linked *climate change* via *food insecurity* to our societal collapse proxies of *natural mortality*, *conflict mortality* and *emigration*, we found no empirical studies linking these proxies to the explicit term of *societal collapse*. This was expected given the motivation of this study (Section 1) and is due to the fact that there are no contemporary events of societal collapse, under the same definition as those in the historical studies pre-dating contemporary society, that enable these links to be empirically studied.⁹⁵

Having considered the spread of empirical evidence, we now consider the complex system documented. A key benefit of CLDs is that they simply present a myriad of information in a single diagram; in doing so, CLDs enable comprehension of the structure and behaviour of complex systems, including feedbacks, intervention points and far-reaching interdependencies.⁹⁶ Our CLD visually depicts a system of 39 variables, 105 links and 32,000 feedback loops,⁹⁷ integrating information from different fields including climate science, food security, conflict, migration and health research.

Walking through the CLD at a high-level, we can see how *population growth* and *lifestyle emissions*, influenced by *institutional/demographic factors* (e.g. emission reduction incentives), combine to directly drive *climate change*. Similarly, they indirectly drive *climate change* via *consumer demand* on *food production*, which produces emissions directly (e.g. ruminant livestock) and indirectly via *industrial capital/output* (e.g. processing factories). The *environmental risk factors* (e.g. extreme weather events) of *climate change* may cause losses of *food production* either directly (e.g. plant disease) or indirectly via *agricultural input availability* (e.g. loss of water source for irrigation). A country's *food availability* is influenced by domestic *food production* and international *food trade*. *Food accessibility* is influenced by its *food price*, which responds to domestic (e.g. *cost of food production and distribution*) and international (e.g. *international food price*) markets, and *institutional/demographic factors* (e.g. food subsidies). *Food utilisation* is influenced by *infrastructure/services* (e.g. education) and *institutional/demographic factors* (e.g. cultural traditions). *Food insecurity* is underpinned by these three pillars of *food availability*, *food accessibility* and *food utilisation*. For a given country, *food insecurity* can drive *natural mortality* (i.e. *starvation*), *conflict* and *migration*, contributing to *population loss*, as well as economic shocks and socio-political instability, contributing to *institutional breakdown*, which exacerbates the risk of *societal collapse*.

Beyond a given country suffering increased *natural mortality*, famines (i.e. *food insecurity*) can place pressure on international humanitarian efforts (i.e. *institutional risk factors*). *Conflict* may occur domestically or internationally and can feedback to exacerbate *food insecurity* and institutional fragility (i.e. *institutional risk factors*). Potential mass *emigration* can increase pressure on *food availability*, *natural resources* and *infrastructure/services* in the destination nation, which can lead to socio-cultural tensions (i.e. *institutional risk factors*) that fuel *conflict*. *Food insecurity* can also directly contribute to *institutional risk factors* such as social unrest, political instability and economic inequality, which increase the risk of *societal collapse* due to *institutional breakdown*, that may also cascade internationally. While already fragile states are expected to be hit the worst directly, these insights reveal the indirect ramifications of

climate change on our globalised society,⁹⁸ with serious consequences for humanity's "existential security".⁹⁹

While some of these relationships may appear obvious, it is the act of bringing this information, which may otherwise be siloed and thus preventing consideration of the full story, together in one place that is of value.¹⁰⁰ In doing so, our CLD attempts to provide readers with the opportunity to explore the climate change, food insecurity and societal collapse causal pathway, consider worst-case scenarios that we want to avoid, develop transformative narratives of "where we want to go" and think about interventions that may help us attain this desired future.¹⁰¹

It is important to appreciate that CLDs are only as good as their information inputs; our CLD documents relationships based on information portrayed in our empirical evidence base as well as our interpretation of that information. As such, there exist challenges and limitations.¹⁰² For instance, CLDs may mask variability of relationships in different contexts and locations, because they can only depict a single scale and granularity. The portrayal of explicit causality between variables in a CLD is a challenge as this can often work in both directions rather than one. CLDs can often become either too complicated or too simplified, which undermines their usefulness. In considering each of these issues, our original methodology attempted to maximise the rigour and transparency of our study by first documenting the information in each evidence point with an i-CLD and then consistently applying, and recording, the iterative process of reconciling the variables and links from each i-CLD to construct the f-CLD at the selected global scale and national granularity. In doing so, we sought to enable the reader to be aware of the nuances of the different scales and granularity of information underpinning our CLD, as well as our process of carefully reconciling causality, over 950 variables to 39 variables and 1150 links to 105 links to maximise the information conveyed while balancing readability.

It is also important to note that, due to their qualitative and static nature, CLDs do not enable us to comprehend the dynamics of the system, including nonlinear and emergent behaviour, non-intuitive quantitative results and time delays.¹⁰³ Complex systems models, although with their own challenges and limitations,¹⁰⁴ provide the

opportunity to quantitatively analyse the dynamics of a system and gain insights into the potentially far-reaching impacts of our decisions.¹⁰⁵ However, complex systems models that explicitly examine societal collapse in contemporary society are underdeveloped. The World3 system dynamics model¹⁰⁶ — an evidence point in this study (refer to Supplementary Information D).¹⁰⁷ — is the eminent model of relevance, with only a limited number of studies building on it. World3 examines the potential for “overshoot-and-collapse” given population and industrial growth within the finite carrying capacity of the natural world system, implicitly accounting for climate change and explicitly accounting for food availability.

The information contained in our CLD and empirical evidence base may be useful in identifying and informing opportunities to improve these existing complex systems modelling capabilities for climate change, food insecurity and societal collapse scenarios. For example, our CLD highlights important factors at global scale and national granularity that World3 does not incorporate because it is defined at global scale and granularity.¹⁰⁸ World3 does not distinguish heterogeneous characteristics of nations, such as distribution of *population* or geographic endowment of *natural resources*. It also does not account for international interactions, such as *food trade*, *conflict* and *migration*. Relatedly, World3 evaluates *societal collapse* only by *natural mortality* (defined by *food availability*, age and pollution) and does not include the other two *population loss* secondary determinants, as noted in the previous sentence, nor the three *institutional breakdown* secondary determinants. While our empirical evidence base may provide useful direction to datasets, it is important to note that quantitatively defining these relationships, particularly thresholds as discussed in Section 4.1, remains a key challenge of developing complex systems models. Nonetheless, given that individuals associate with national identity, business governance and policy-making are concentrated at national level, and international interactions underpin the functioning of contemporary society it could be valuable to model societal collapse risk profiles of different nations to inform the prioritisation and development of intervention strategies.

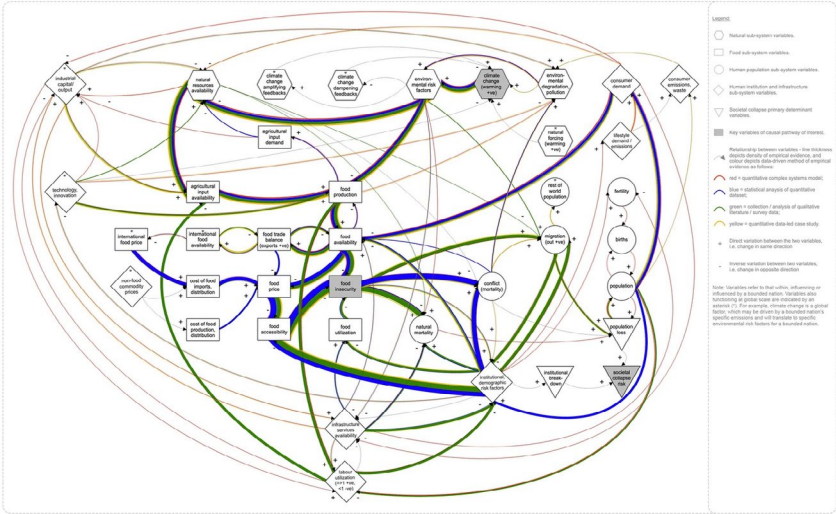


Fig. 5: Causal loop diagram of climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity. Variables are depicted as nodes in five different shapes, indicating different sub-systems. Links between variables are depicted as arrowed lines, indicating the direction of the relationship. Each link has a positive (+) or negative (-) notation, indicating that the two variables change in the same direction or opposite direction, respectively. The density and type of data-driven method of the empirical evidence base, from which the causal loop diagram was constructed, are depicted by line thickness and colour respectively.

5. Conclusions and Future Work

This chapter identified an empirical evidence base of climate change, food insecurity and societal collapse in contemporary society and structured the evidence base using a novel-format CLD defined at global scale and national granularity.

Two types of future work could extend from the results of this chapter. Identification of gaps in the spread of evidence across the CLD may guide future data-driven efforts to examine these causal relationships and define thresholds. The CLD and evidence base may be used to develop quantitative modelling capabilities, particularly by transforming the structure of World3 to account for heterogeneous national characteristics and international interactions. Three types of future work could extend from the methodology and literature

synthesis. The causal pathway examined in this chapter could be further detailed by re-applying the methodology using the *institutional breakdown* set of societal collapse proxies instead of the *population loss* set. The methodology, using either set of societal collapse proxies, could be applied to detail other causal pathways between climate change and societal collapse. The methodology, excluding the contemporary time-period limitation, could be applied to document the information in the historical studies identified in the literature review. Similarly, the methodology could be applied to construct CLDs at different scales and granularities.

It is hoped that this chapter has contributed to developing our understanding of the causal pathways through which climate change poses an existential risk to humanity and facilitates opportunities for future work.

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