



Re-framing the threat of global warming: an empirical causal loop diagram of climate change, food insecurity and societal collapse

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Abstract

There is increasing concern that climate change poses an existential risk to humanity. Understanding these worst-case scenarios is essential for good risk management. However, our knowledge of the causal pathways through which climate change could cause societal collapse is underdeveloped. This paper aims to identify and structure an empirical evidence base of the climate change, food insecurity and societal collapse pathway. We first review the societal collapse and existential risk literature and define a set of determinants of societal collapse. We 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 in contemporary society and then structure it using a novel-format causal loop diagram (CLD) defined at global scale and national granularity. The resulting evidence base varies in temporal and spatial distribution of study and in the type of data-driven methods used. The resulting CLD documents the spread of the evidence base, using line thickness and colour to depict density and type of data-driven method respectively. It enables exploration of how the effects of climate change may undermine agricultural systems and disrupt food supply, which can lead to economic shocks, socio-political instability as well as starvation, migration and conflict. Suggestions are made for future work that could build on this paper to further develop our qualitative understanding of, and quantitative complex systems modelling capabilities for analysing, the causal pathways between climate change and societal collapse.

Keywords Climate change · Food security · Existential risk · Starvation · Conflict · Migration

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1 Introduction

Despite recent social protests and climate emergency declarations, efforts to mitigate climate change to-date are insufficient (Ripple et al. 2019). Greenhouse gas (GHG) emissions continue to rise and global warming above 3 °C is increasingly likely this century (Raftery et al. 2017). There is emerging evidence of amplifying feedbacks accelerating (Natali 2019) and dampening feedbacks decelerating (Walker et al. 2019). These feedbacks exacerbate the possibility of runaway global warming (Steffen et al. 2018), estimated at 8 °C or greater by 2100 (Schneider et al. 2019). Such temperature increases translate to a range of real dangers (The Center for Climate and Security 2020), shifting the narrow climate niche within which humans have resided for millennia (Xu et al. 2020).

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 (Ord 2020). Understanding these worst-case scenarios is essential for good risk management (Kunreuther et al. 2013). Improving awareness of potential pathways through which climate change poses such a risk can help inform decision-making about interventions (Shepherd et al. 2018). Considering societal impacts that are more tangible for individuals, businesses and governments (Briggs et al. 2015), and better aligned with conventional risk priorities (Wagner and Weitzman 2015), may facilitate more effective action to mitigate climate change (Weber 2006).

A number of pathways through which climate change could cause societal collapse have been identified, one being via food insecurity (Gowdy 2020). Climate change is predicted to undermine agricultural systems and disrupt food supply (FAO, IFAD, UNICEF 2020), which may lead to economic shocks, socio-political instability as well as starvation, migration and conflict at local through to global scale (Rivington et al. 2015). While the climate science underpinning global warming estimates is well established (IPCC 2014), albeit subject to sensitivities, the uncertainties increase significantly when we start to consider these tangible societal impacts given the complex relationships involved (Butzer 2012). 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 (Kemp 2020).

In this paper, 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 (Randers 2000). This paper 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 paper.

2 Literature review

To refine the aim of this paper, 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 paper. Adopting Ord’s (2020) 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. Adopting Kemp’s (2019) definition, societal collapse is an “enduring loss of population, identity [and/or institutional] complexity”; 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. Figure 1 presents a conceptual model of societal collapse, synthesised from the broader literature, to provide further contextual definition.

The rise and fall of civilizations has been documented since the earliest recordings of history and is increasingly studied to inform our understanding of societal collapse (Butzer and Endfield 2012). 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 Menocal (2001) and Weiss and Bradley (2001). For example, Hodell et al. (1995), Haug et al. (2003) and Medina-Elizalde and Rohling (2012) 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 civilization of Mesoamerica in ~eight–tenth century CE. Weiss et al. (1993), Cullen et al. (2000) and Cookson et al. (2019) 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 ~twenty-second century BCE. Similarly, natural climate change has been implicated in the collapse of multiple Late Bronze Age societies around the Mediterranean (Cline 2014), including Mycenaean Kingdoms in ~twelfth century BCE (Finné et al. 2017), the Harappan Civilization of South Asia in ~nineteenth century BCE (Giosan et al. 2012), the Angkor Empire of Southeast Asia in

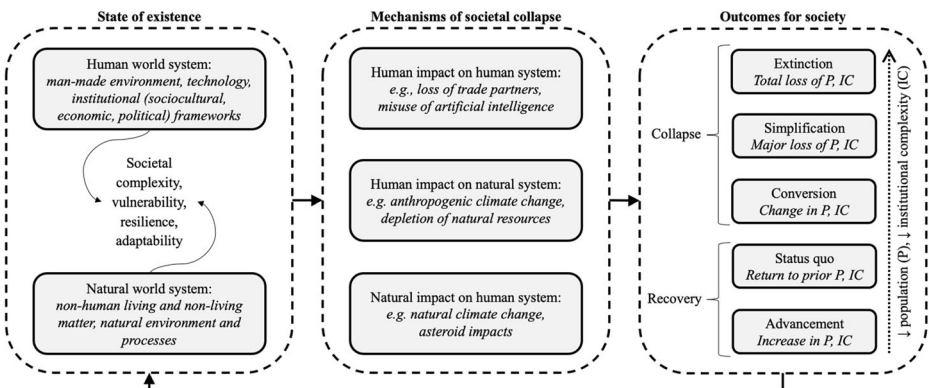


Fig. 1 Conceptual model of the overarching process of societal collapse

~fifteenth century CE (Buckley et al. 2010), multiple Chinese Dynasties (Zhang et al. 2006) and civilizations along the Silk Road (Li et al. 2016) during the previous millennium, the Norse Vikings of Greenland in ~ fifteenth century CE (Kintisch 2016) and the Tiwanaku Empire of Pre-Columbian South America in ~tenth century CE (Ortloff and Kolata 1993), amongst others.

These first type of studies establish 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 (Ehrlich and Ehrlich 2013).

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.

Fagan (2008) and McMichael (2017) focus on natural impact on the human system across multiple civilizations, 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 (Runciman 2001). 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 (1991), Wright (2004) and Diamond (2005) focus on human impact on the natural system across multiple civilizations, 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' (Malthus 1798), 'tragedy of the commons' (Hardin 1968) and 'overshoot-and-collapse' (Catton 1980) theories.

In their 12-volume magnum opus exploring the rise and fall of 28 civilizations, Toynbee (1961) concludes that "great civilizations are not murdered [but rather] they take their own lives" (Kemp 2019). Building on this, Tainter (1988), Acemoglu and Robinson (2012) and Johnson (2017) focus on human impact on the human system across multiple civilizations, 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 (Tainter 1988). This mode

aligns with ‘energy returned on energy invested’ (Murphy and Hall 2010) theory, applied to explore societal collapse by Homer-Dixon (2006).

Diamond (1997), Turchin (2006) and Schwartz and Nichols (2010) examine why some civilizations 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.

These second type of studies highlight that societal collapse involves a complex nexus of factors and dynamically interlinked events. For instance, Gibbon (1789) details how all three of the modes, described in the preceding five paragraphs, contributed to the collapse of the Roman Empire. 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 (Taleb 2007), in different geographic locations and times throughout history. Additionally, a quantitative statistical analysis by Arbesman (2011) shows that societal collapse has occurred randomly and independent of civilization life-spans. 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* (Van Valen 1973).

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 sociocultural norms*, *political structures* or *economic value* accounts for that which notably transforms the identity and institutions of the society.

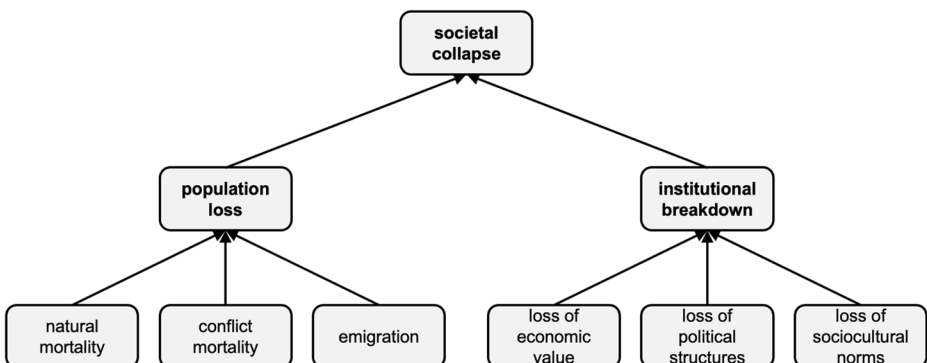


Fig. 2 Primary and secondary determinants of societal collapse for a bounded society

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 (2008), Rees (2018) and Ord (2020) provide eminent scholarly treatment of the field, drawing from the academic literature. WEF (2020) and GCF (2020) 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 Ehrlich (2013) and Häggström (2016) 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 (Rivington et al. 2015). 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 (Morton 2016). In this highly interconnected landscape, 'synchronous' (Homer-Dixon et al. 2015) and 'cascading' (Buldyrev et al. 2010) failures create the potential for mechanisms and outcomes of societal collapse, once contained to a single localised civilization, to rapidly spread across multiple nations and impact humanity on a global scale.

Works by Lynas (2007), Wallace-Wells (2019) and Gowdy (2020) 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. (2017), Hsiang et al. (2013) and Hauer et al. (2020). The feedback between migration and conflict driven by climate change is examined by Abel et al. (2019). Burke et al. (2015), Sofuoğlu and Ay (2020) and Adger et al. (2013), respectively, examine the direct links between climate change and the endpoint impacts of economic loss, political instability and shifts in cultural norms. However, the complex bottom-level links between and surrounding

these endpoints are generally ill understood (Theisen et al. 2013), and the strength of empirical evidence is poorly documented (Gemenne et al. 2014) from a systems science perspective. 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 (Bostrom 2013).

Given the insights from this review, we refine the aim of this paper 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 paper 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 paper. 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 3000 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 (Meadows et al. 2004), 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.

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

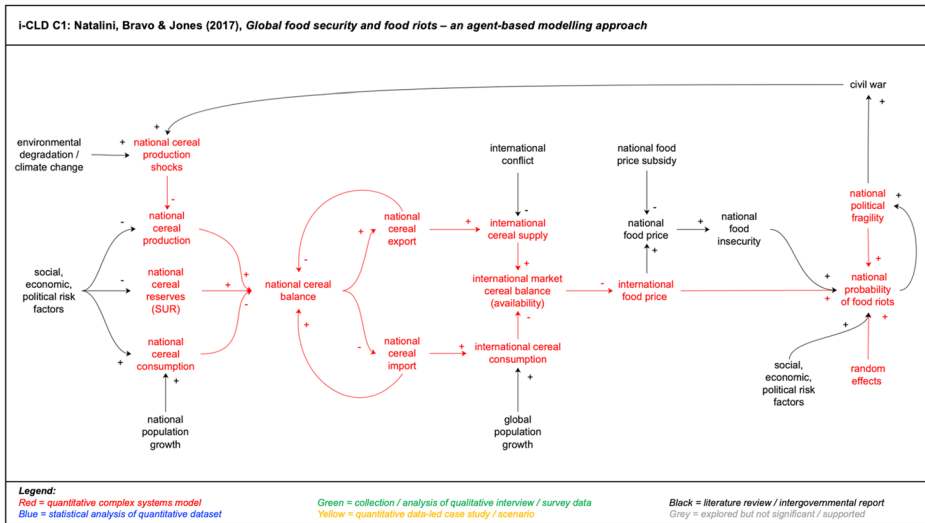


Fig. 3 One of the i-CLDs created for each of the 41 evidence points in the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society

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 2 (e.g. IPCC 2014) 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 un-coloured and un-weighted 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

#	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			Fiedderjohann 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			Koren & Bagozzi, 2016	Global	0.5x0.5 deg.	1991-2008	Yearly
C9			Maysladt 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			Wischmath & 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	Afifi 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			Murali & Afifi, 2014	India	Sub-national	2011	Period
E8			Panter-Brick & Eggeman, 1997	Nepal	Sub-national	1996 (assumed)	Period
E9			Rademacher-Schulz et al, 2014	Northern Ghana	Sub-national	2011	Period
E10			Warner & Afifi, 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

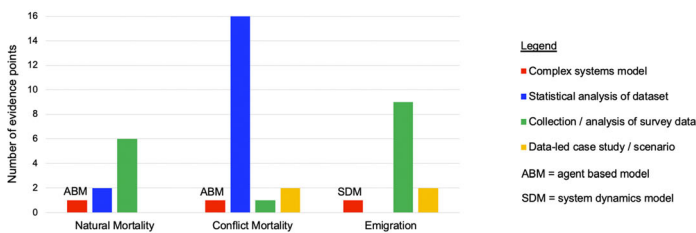


Fig. 4 Summary and custom colour-coded typology of the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society. A full reference list is contained in Supplementary Information (E)

human survival is well established (FAO 2004); 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 (2019), 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 IOM GMDAC (2019). 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’ (Kintigh et al. 2014).

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 paper 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

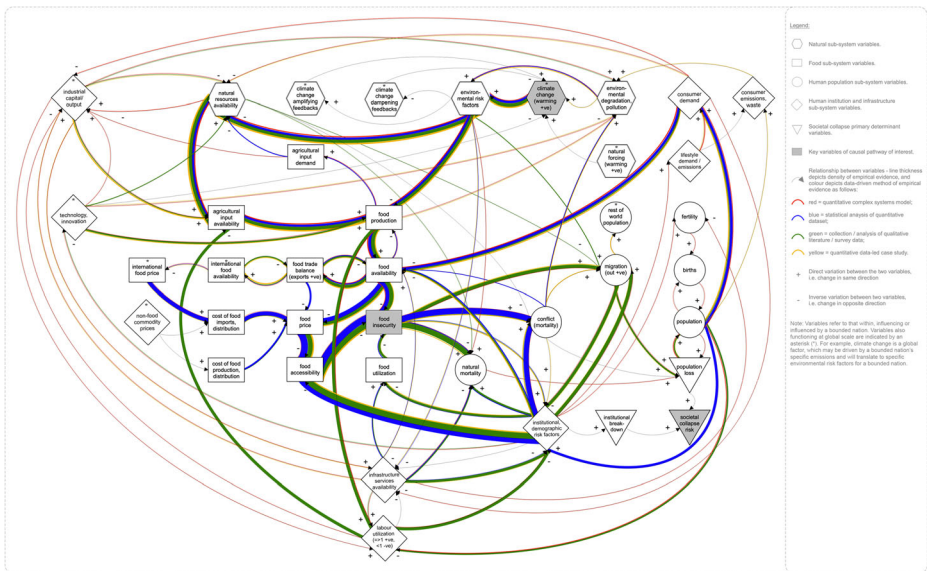


Fig. 5 Causal loop diagram of climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity. Variables are depicted as nodes in five different shapes, indicating different sub-systems. Links between variables are depicted as arrowed lines, indicating 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

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 (Beard et al. 2020).

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 (Sterman 2011). Our CLD visually depicts a system of 39 variables, 105 links and 32,000 feedback loops,¹ integrating information from different fields including climate science, food security, conflict, migration and health research.

¹ Calculated using Vensim® PLE software, Ventana Systems Inc.

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 utilization* 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 utilization*. 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 (Kemp 2020), with serious consequences for humanity's 'existential security' (Sears 2020).

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 (Sterman 2011). 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 (Hinkel et al. 2020).

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 (Cernev and Fenner 2020). 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 (Sterman 2011). Complex systems models, although with their own challenges and limitations (Sterman 2002), provide the opportunity to quantitatively analyse the dynamics of a system and gain insights into the potentially far-reaching impacts of our decisions (Sterman 2000). However, complex systems models that explicitly examine societal collapse in contemporary society are underdeveloped. The World3 system dynamics model (Meadows et al. 2004) — an evidence point in this study (refer Supplementary Information D. for respective i-CLD) — is the eminent model of relevance, with only a limited number of studies building on it (e.g. Ansell and Cayzer 2018). 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 (Meadows et al. 2004). World3 does not distinguish heterogenous 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 policymaking 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.

5 Conclusions and future work

This paper 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 paper. 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 heterogenous national characteristics and international interactions. Three types of future work could

extend from the methodology and literature synthesis. The causal pathway examined in this paper 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 paper 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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Data availability Not applicable. All relevant information is contained in the Manuscript or Electronic Supplementary Material.

Compliance with ethical standards

Conflict of interest The authors declare that they have no known conflict of interest, including competing affiliations, funding sources, financial or personal relationships that could be perceived, either directly or indirectly, as potential sources of bias with respect to this paper.

Code availability Not applicable.

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References

- Abel GJ, Brottrager M, Cuaresma JC, Muttarak R (2019) Climate, conflict and forced migration. *Glob Environ Chang* 54:239–249. <https://doi.org/10.1016/j.gloenvcha.2018.12.003>
- Acemoglu D, Robinson JA (2012) *Why nations fail: the origins of power, prosperity, and poverty*. Crown Publishers, New York

- Adger WN, Barnett J, Brown K et al (2013) Cultural dimensions of climate change impacts and adaptation. *Nat Clim Chang* 3:112–117. <https://doi.org/10.1038/nclimate1666>
- Ansell T, Cayzer S (2018) Limits to growth redux: a system dynamics model for assessing energy and climate change constraints to global growth. *Energy Policy*:514–525. <https://doi.org/10.1016/j.enpol.2018.05.053>
- Arbesman S (2011) The life-spans of empires. *Hist Methods A J Quant Interdiscip Hist* 44:127–129. <https://doi.org/10.1080/01615440.2011.577733>
- Beard S, Rowe T, Fox J (2020) An analysis and evaluation of methods currently used to quantify the likelihood of existential hazards. *Futures* 115:102469. <https://doi.org/10.1016/j.futures.2019.102469>
- Bostrom N (2013) Existential risk prevention as global priority. *Glob Policy* 4:15–31. <https://doi.org/10.1111/1758-5899.12002>
- Bostrom N, Čirković MM (2008) *Global catastrophic risks*. Oxford University Press, Oxford
- Briggs S, Kennel CF, Victor DG (2015) Planetary vital signs. *Nat Clim Chang* 5:969–970. <https://doi.org/10.1038/nclimate2828>
- Buckley BM, Anchukaitis KJ, Penny D et al (2010) Climate as a contributing factor in the demise of Angkor, Cambodia. *Proc Natl Acad Sci U S A* 107:6748–6752. <https://doi.org/10.1073/pnas.0910827107>
- Buldryev SV, Parshani R, Paul G et al (2010) Catastrophic cascade of failures in interdependent networks. *Nature* 464:1025–1028. <https://doi.org/10.1038/nature08932>
- Burke M, Hsiang SM, Miguel E (2015) Global non-linear effect of temperature on economic production. *Nature* 527:235–239. <https://doi.org/10.1038/nature15725>
- Butzer KW (2012) Collapse, environment and society. *Proc Natl Acad Sci U S A* 109:3628–3631. <https://doi.org/10.1073/pnas.1114845109>
- Butzer KW, Endfield GH (2012) Critical perspectives on historical collapse. *Proc Natl Acad Sci U S A* 109:3628–3631. <https://doi.org/10.1073/pnas.1114772109>
- Catton WR (1980) *Overshoot: the ecological basis of revolutionary change*. Board of Trustees of the University of Illinois
- Cernev T, Fenner R (2020) The importance of achieving foundational sustainable development goals in reducing global risk. *Futures* 115:102492. <https://doi.org/10.1016/j.futures.2019.102492>
- Cline EH (2014) *1177 BC: the year civilization collapsed*. Princeton, USA
- Cookson E, Hill DJ, Lawrence D (2019) Impacts of long term climate change during the collapse of the Akkadian empire. *J Archaeol Sci* 106:1–9. <https://doi.org/10.1016/j.jas.2019.03.009>
- Cullen HM, deMenocal PB, Hemming S et al (2000) Climate change and the collapse of the Akkadian empire: evidence from the deep sea. *Geology* 28. [https://doi.org/10.1130/0091-7613\(2000\)28<379:CCATCO>2.0.CO;2](https://doi.org/10.1130/0091-7613(2000)28<379:CCATCO>2.0.CO;2)
- de Menocal PB (2001) Cultural responses to climate change during the late holocene. *Science* (80-) 292:667–673. <https://doi.org/10.1126/science.1059827>
- Diamond J (1997) *Guns, germs and steel: a short history of everybody for the last 13,000 years*. Vintage, London
- Diamond J (2005) *Collapse: how societies choose to fail or succeed*. Penguin Group, London
- Ehrlich P, Ehrlich A (2013) Can a collapse of global civilization be avoided? *Proc R Soc B* 280. <https://doi.org/10.1098/rspb.2012.2845>
- Fagan BM (2008) *The great warming: climate change and the rise and fall of civilizations*. Bloomsbury Press, New York
- FAO (2004) *Human energy requirements*. Report of a Joint FAO/WHO/UNU Expert Consultation, Rome
- FAO, IFAD, UNICEF, et al (2020) *The state of food security and nutrition in the world 2020: transforming food systems for affordable healthy diets*. Rome
- Finné M, Holmgren K, Shen C-C et al (2017) Late bronze age climate change and the destruction of the Mycenaean palace of Nestor at Pylos. *PLoS One* 12. <https://doi.org/10.1371/journal.pone.0189447>
- GCF (2020) *Global catastrophic risks 2020*. Global Challenges Foundation
- Gemenne F, Barnett J, Adger WN, Dabelko GD (2014) Climate and security: evidence, emerging risks, and a new agenda. *Clim Chang* 123:1–9. <https://doi.org/10.1007/s10584-014-1074-7>
- Gibbon E (1789) *The history of the decline and fall of the Roman empire* (Vol I - VI). Strahan & Caddell, London
- Giosan L, Clift PD, Macklin MG et al (2012) Fluvial landscapes of the Harappan civilization. *Proc Natl Acad Sci U S A* 109:E1688–E1694. <https://doi.org/10.1073/pnas.1112743109>
- Gowdy J (2020) Our hunter-gatherer future: climate change, agriculture and uncivilization. *Futures* 115:102488. <https://doi.org/10.1016/j.futures.2019.102488>
- Hägström O (2016) *Here be dragons: science, technology and the future of humanity*. Oxford University Press, Oxford
- Hardin G (1968) The tragedy of the commons. *Science* (80-) 162:1243–1248. <https://doi.org/10.1126/science.162.3859.1243>
- Hauer ME, Fussell E, Mueller V et al (2020) Sea-level rise and human migration. *Nat Rev Earth Environ* 1:28–39. <https://doi.org/10.1038/s43017-019-0002-9>

- Haug GH, Günther D, Peterson LC et al (2003) Climate and the collapse of Maya civilization. *Science* (80-) 299: 1731–1735. <https://doi.org/10.1126/science.1080444>
- Hinkel J, Mangalagu D, Bisaro A, Tàbara JD (2020) Transformative narratives for climate action. *Clim Chang* 160:495–506. <https://doi.org/10.1007/s10584-020-02761-y>
- Hodell D, Curtis JH, Brenner M (1995) Possible role of climate in the collapse of classic Maya civilization. *Nature* 375:391–394. <https://doi.org/10.1038/375391a0>
- Homer-Dixon T (2006) *The upside of down: catastrophe, creativity, and the renewal of civilization*. Random House of Canada, Canada
- Homer-Dixon T, Walker B, Biggs R et al (2015) Synchronous failure: the emerging causal architecture of global crisis. *Ecol Soc* 20:6. <https://doi.org/10.5751/ES-07681-200306>
- Hsiang SM, Burke M, Miguel E (2013) Quantifying the influence of climate on human conflict. *Science* (80-) 496. <https://doi.org/10.1126/science.1235367>
- IOM GMDAC (2019) Migration Data Portal: The Bigger Picture. <https://migrationdataportal.org>
- IPCC (2014) Climate change 2014: synthesis report. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva
- Johnson SAJ (2017) *Why did ancient societies fail?* Routledge, New York
- Kemp L (2019) Are we on the road to civilization collapse? BBC Futur
- Kemp L (2020) Climate endgame: understanding worst-case warming. In: Riede F, Evans M, Harrington L (eds) *Learning from the past working group webinar*. Future Earth's Knowledge Action Network on Emergent Risks and Extreme Events, Online
- Kintigh KW, Altschul JH, Beaudry MC et al (2014) Grand challenges for archaeology. *Proc Natl Acad Sci* 111: 879–880. <https://doi.org/10.7183/0002-7316.79.1.5>
- Kintisch E (2016) Why did Greenland's Vikings disappear? *Science* (80-)
- Kunreuther H, Heal G, Allen M et al (2013) Risk management and climate change. *Nat Clim Chang* 2:447–450. <https://doi.org/10.1038/NCLIMATE1740>
- Li Z, Chen Y, Wang Y, Weihong L (2016) Drought promoted the disappearance of civilization along the ancient Silk Road. *Environ Earth Sci*:75. <https://doi.org/10.1007/s12665-016-5925-6>
- Lynas M (2007) *Six degrees: our future on a hotter planet*. Fourth Estate, London
- Malthus TR (1798) *An essay on the principle of population*. London
- McMichael AJ (2017) *Climate change and the health of nations: famines, fevers and the fate of populations*. Oxford University Press, Oxford
- Meadows DH, Meadows DL, Randers J (2004) *The limits to growth: the 30-year update*. Chelsea Green Publishing Company, Vermont
- Medina-Elizalde M, Rohlhing EJ (2012) Collapse of classic maya civilization related to modest reduction in precipitation. *Science* (80-) 335:956–959. <https://doi.org/10.1126/science.1216629>
- Mora C, Dousset B, Caldwell IR et al (2017) Global risk of deadly heat. *Nat Clim Chang* 7:501–506. <https://doi.org/10.1038/nclimate3322>
- Morton O (2016) *The planet remade: how geoengineering could change the world*. Princeton University Press, Princeton
- Murphy DJ, Hall CAS (2010) Year in review—EROI or energy return on (energy) invested. *Ann N Y Acad Sci* 1185:102–118. <https://doi.org/10.1111/j.1749-6632.2009.05282.x>
- Natali SM (2019) Large loss of CO₂ in winter observed across the northern permafrost region. *Nat Clim Chang* 9:852–857. <https://doi.org/10.1038/s41558-019-0592-8>
- Ord T (2020) *The precipice: existential risk and the future of humanity*. Bloomsbury Publishing, London
- Ortloff CR, Kolata AL (1993) Climate and collapse: agro-ecological perspectives on the decline of the Tiwanaku state. *J Archaeol Sci* 20:195–221. <https://doi.org/10.1006/jasc.1993.1014>
- Ponting C (1991) *A new green history of the world: the environment and the collapse of great civilizations*. Vintage, London
- Raftery AE, Zimmer A, Frierson DMW et al (2017) Less than 2 °C warming by 2100 unlikely. *Nat Clim Chang* 7:637–641. <https://doi.org/10.1038/nclimate3352>
- Randers J (2000) From limits to growth to sustainable development or SD (sustainable development) in a SD (system dynamics) perspective. *Syst Dyn Rev* 16:213–224. [https://doi.org/10.1002/1099-1727\(200023\)16:3<213::AID-Rees M \(2018\) On the future: prospects for humanity. Princeton University Press, Princeton](https://doi.org/10.1002/1099-1727(200023)16:3<213::AID-Rees M (2018) On the future: prospects for humanity. Princeton University Press, Princeton)
- Ripple WJ, Wolf C, Newsome TM et al (2019) World scientists' warning of a climate emergency. *Bioscience* 70: 8–12. <https://doi.org/10.1093/biosci/biz088>
- Rivington M, Bailey R, Benton T, et al (2015) Extreme weather and resilience of the global food system - synthesis report
- Runciman WG (2001) The origin of human social institutions. *Proc Br Acad* 110
- Schneider T, Kaul CM, Pressel KG (2019) Possible climate transitions from breakup of stratocumulus decks under greenhouse warming. *Nat Geosci* 12:163–167. <https://doi.org/10.1038/s41561-019-0310-1>

- Schwartz GM, Nichols JJ (2010) *After collapse: the regeneration of complex societies*. University of Arizona Press, Tucson
- Sears NA (2020) Existential security: towards a security framework for the survival of humanity. *Glob Policy* 11: 255–266. <https://doi.org/10.1111/1758-5899.12800>
- Shepherd TG, Boyd E, Calel RA et al (2018) Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Clim Chang* 151:555–571. <https://doi.org/10.1007/s10584-018-2317-9>
- Sofuoğlu E, Ay A (2020) The relationship between climate change and political instability: the case of MENA countries (1985:01–2016:12). *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-020-07937-8>
- Steffen W, Rockström J, Richardson K et al (2018) Trajectories of the earth system in the Anthropocene. *Proc Natl Acad Sci U S A* 115:8252–8259. <https://doi.org/10.1073/pnas.1810141115>
- Sterman JD (2000) *Business dynamics: systems thinking and modeling for a complex world*. McGraw-Hill Higher Education, USA
- Sterman JD (2002) All models are wrong: reflections on becoming a systems scientist. *Syst Dyn Rev* 18:501–531. <https://doi.org/10.1002/sdr.261>
- Sterman JD (2011) Communicating climate change risks in a skeptical world. *Clim Chang* 108:811. <https://doi.org/10.1007/s10584-011-0189-3>
- Tainter JA (1988) *The collapse of complex societies*. Cambridge University Press, Cambridge
- Taleb NN (2007) *The black swan: the impact of the highly improbable*. The Random House publishing group, New York City
- The Center for Climate & Security (2020) *A security threat assessment of global climate change: how likely warming scenarios indicate a catastrophic security future*. The National Security, Military and Intelligence Panel on Climate Change, The Center for Climate and Security
- Theisen OM, Gleditsch NP, Buhaug H (2013) Is climate change a driver of armed conflict? *Clim Chang* 117: 613–625. <https://doi.org/10.1007/s10584-012-0649-4>
- Toynbee AJ (1961) *A study of history (Vol I - IX)*. Oxford University Press, Oxford
- Turchin P (2006) *War and peace and war: the rise and fall of empires*. Penguin Group, New York
- UCDP/PRIO (2019) *Uppsala Conflict Data Program*. <https://ucdp.uu.se/>
- Van Valen L (1973) A new evolutionary law. *Evol Theory* 1:1–30
- Wagner G, Weitzman ML (2015) *Climate shock: the economic consequences of a hotter planet*. Princeton University Press, Princeton
- Walker XJ, Baltzer JL, Cumming SG et al (2019) Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* 572:520–523. <https://doi.org/10.1038/s41586-019-1474-y>
- Wallace-Wells D (2019) *The uninhabitable earth: a story of the future*. Crown Publishing Group, New York City
- Weber EU (2006) Evidence-based and description-based perceptions of long-term risk: why global warming does not scare us (yet). *Clim Chang* 77:103–120. <https://doi.org/10.1007/s10584-006-9060-3>
- WEF (2020) *The global risks report 2020*. Switzerland, Geneva
- Weiss H, Bradley RS (2001) What drives societal collapse? *Science* (80-) 291:609–610
- Weiss H, Courty M-A, Wetterstrom W et al (1993) The genesis and collapse of third millennium north Mesopotamian civilization. *Science* (80-) 261:995–1004. <https://doi.org/10.1126/science.261.5124.995>
- Wright R (2004) *A short history of progress*. House of Anansi Press Inc., Toronto
- Xu C, Kohler TA, Lenton TM et al (2020) Future of the human climate niche. *Proc Natl Acad Sci U S A* 117: 11350–11355. <https://doi.org/10.1073/pnas.1910114117>
- Zhang DD, Jim C, Lin G-S et al (2006) Climatic change, wars and dynastic cycles in China over the last millennium. *Clim Chang* 76:459–477. <https://doi.org/10.1007/s10584-005-9024-z>

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