Forecasting Lives Lost to Climate Change: A Precautionary Empirical Framework for Climate-Related Mortality

Short title: Forecasting climate-related mortality

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Abstract

Climate-related mortality remains underdeveloped in climate-risk assessment, despite extensive evidence that climate change affects food security, extreme events, conflict risk, and several health outcomes. This study develops a simplified, precautionary empirical framework to estimate climate-related mortality across selected pathways using historical relationships among population, greenhouse-gas emissions, atmospheric CO_2 concentration, and global mean surface temperature, and introduces a cumulative mortality metric expressed as climate-related deaths per cumulative Mt CO_2-e over 1900--2300. Publicly available datasets were assembled for undernourishment, conflict, disasters, selected health categories, population, emissions, atmospheric CO_2 concentration, and temperature, and mortality was estimated under four stylised emissions pathways: business-as-usual, net zero by 2070, 2060, and 2050 (Paris aligned). Undernourishment and associated conflict emerged as the dominant components of the estimated burden, which also included storm, flood, landslide, and wildfire disaster categories. Air pollution was included although this is arguably an associated rather than climate-implicated cause of mortality. Other pathways were reviewed but excluded from the quantitative totals where globally consistent relationships with climate indicators were presently too weak or conflicting. Across scenarios, business-as-usual emissions are associated with substantially larger climate-related mortality burdens, with harms concentrated disproportionately in lower-income populations. Regional economic capacity, the framework's primary proxy for resilience and adaptive capacity, is the main driver of this unevenness; institutional capacity and population awareness were not modelled separately and instead contribute to the width of the reported uncertainty ranges. In the central estimates, cumulative climate-related deaths over 1900–2300 are roughly 5.8 billion under business-as-usual, compared with around 1.6–2.1 billion under net-zero pathways. Earlier progress toward net zero materially reduces projected mortality within the modelled ranges. Climate risk assessment can be improved by use of the 710 deaths per Mt CO_2-e metric (assuming zero emissions by 2050) in projects that are causing emissions as well as those that save lives by reducing or drawing down emissions. Uncertainty remains substantial, particularly for undernourishment and conflict and for excluded health pathways, so the deaths-per-megatonne estimates are intended as indicative, approximate, and explicitly precautionary rather than as precise forecasts of climate-related mortality. Excluded potential causes and the prospect of accelerating climate change due to compounding feedback loops suggest that these estimates may still be underestimates of true climate mortality.

Keywords: climate-related mortality; deaths per megatonne; undernourishment; conflict; disasters; public health; precautionary risk assessment; emissions pathways; net-zero scenarios; climate risk.

1. Introduction

Climate change is increasingly recognised as a major threat to human health, food security, displacement, and survival, yet systematic estimates of climate-related mortality remain scarce.

Since 1990, the Intergovernmental Panel on Climate Change has assessed the physical science of climate change, adaptation, and mitigation, but it has not provided a comprehensive empirical framework or metric for global climate-related deaths [1]. At the same time, public-health and human-rights scholarship has highlighted the implications of climate change for the right to life, safe living conditions, and sustainable development, underscoring the need for more explicit appraisal of mortality risks alongside economic damages [2-4].

Existing climate-risk assessment has usually focused on economic indicators such as gross domestic product and the social cost of carbon, while the mortality implications of emissions trajectories have been treated more indirectly or in pathway-specific studies [5,6]. Previous work has examined particular climate-sensitive pathways, including undernourishment, extreme events, conflict, heat exposure, vector-borne disease, and air pollution, but few attempts integrate multiple pathways within a single, transparent forecasting framework [7,8]. Given the scale of plausible harms and the uneven distribution of vulnerability, a precautionary public-health perspective calls for indicative estimates that link cumulative emissions to cumulative deaths even where data are incomplete and some pathways remain under-quantified.

This gap is also policy-relevant. Climate governance increasingly invokes precaution, public health, intergenerational equity, and rights-based obligations, yet practical appraisal still rarely expresses emissions choices in terms of potential lives lost or saved [2-4,9]. Climate emergency declarations [10], the growth of climate litigation [11], and broader human-rights framing all point toward a need for metrics that make mortality consequences more explicit, even where uncertainty remains substantial [4,9-11]. Within that context, an approximate and transparent mortality metric may help connect climate science, public-health assessment, and decision-making more directly than economic indicators alone [5,9,10].

This study addresses that gap by developing a simplified, scenario-based empirical framework to estimate climate-related mortality from historical relationships among population, greenhouse-gas emissions, atmospheric CO_2 concentration, and global mean surface temperature. It introduces a cumulative deaths-per-megatonne metric, expressed as cumulative climate-related deaths per cumulative Mt CO_2-e over 1900--2300, to relate emissions choices more directly to human outcomes within a common accounting framework. The aim is not to provide precise forecasts for any particular pathway or region, but to offer a transparent, approximate, and explicitly precautionary first approximation that can be refined as more data arise, as attribution methods and pathway coverage improve.

Scientific concern over the climate emergency has grown steadily, and the broader literature increasingly links climate change to human survival, development, food security, and safe living conditions [9,12,13]. The present study therefore combines a literature review with empirical modelling of selected mortality pathways, with particular emphasis on undernourishment and associated conflict, which emerge as the dominant contributors in the current framework.

The contribution of this study is threefold. First, it integrates several climate-sensitive mortality pathways within a transparent empirical framework that can be scrutinised, revised, and extended. Unlike previous work that focuses on either heuristic rules of thumb or social cost of carbon estimates, this framework combines undernourishment, conflict, disasters, and selected contextual pathways over 1900–2300 within a single empirical structure. Second, rather than applying a single global relationship uniformly, the framework fits climate-driven vulnerability separately across 22 regions and then constrains the resulting estimates using regional economic capacity — the primary proxy for resilience and adaptive capacity used throughout — so that lower-income, less economically protected populations are modelled as carrying a disproportionately larger share of the projected burden (Section 2.4). Third, it expresses the resulting burden in a cumulative deaths-per-megatonne metric that is intended to complement more conventional climate-impact metrics by making the human implications of alternative emissions pathways more explicit.

2. Methods

This study combines a literature review with an empirical scenario-based modelling framework to estimate climate-related mortality across selected pathways and to express the resulting burden as cumulative deaths per cumulative Mt CO_2-e over 1900--2300. Publicly available global and regional datasets were assembled for population, emissions, atmospheric CO_2 concentration, temperature, undernourishment, conflict, disasters, GDP per capita, and selected health outcomes. The modelling proceeds in four steps: historical empirical relationships are estimated among population, emissions, atmospheric CO_2 concentration, and global mean surface temperature; these relationships are used to construct four future emissions scenarios; mortality pathways are estimated from their observed relationships with climate indicators; and cumulative mortality is related to cumulative emissions to produce a deaths-per-megatonne metric.

2.1 Study design and data sources

The study was designed as a combined literature review and empirical forecasting exercise. The literature review identified the principal pathways through which climate change may contribute to mortality, previous attempts to estimate climate-related deaths, and areas in which evidence remains limited or contested. Publicly available datasets were assembled from FAO, WHO, the World Bank, the United Nations, NASA, EM-DAT, and Our World in Data to support quantitative analysis of undernourishment, conflict, disasters, climate variables, and relevant socioeconomic indicators [14-22].

The framework adopts a precautionary logic in two ways. It combines multiple plausible mortality pathways within one transparent structure rather than restricting analysis to directly attributable heat-related mortality alone, and it treats excluded pathways as unresolved potential additions to burden rather than as evidence of zero effect. FAO undernourishment data and conflict mortality data were used to estimate the dominant combined mortality pathway, EM-DAT data were used to examine disaster classes and mortality patterns, and GDP-per-capita and indicative income-distribution proxies were used to estimate regional economic vulnerability to undernourishment. This economic-capacity measure serves throughout as the framework's primary proxy for regional resilience and adaptive capacity, as distinct from institutional capacity, which is addressed in Section 3.8.

2.2 Scenario framework

Future mortality was estimated under four stylised emissions pathways: business-as-usual, net zero by 2070, net zero by 2060, and net zero by 2050. Business-as-usual represents continued growth in emissions unless reduced indirectly by climate-related population decline, whereas the net-zero pathways represent progressively earlier mitigation with emissions declining along an S-curve toward near-zero by the nominated year.

These pathways are not presented as predictions of actual policy futures. Rather, they function as stylised comparative scenarios that allow the mortality implications of earlier and later mitigation to be assessed. Atmospheric CO_2 concentration was estimated year by year from cumulative emissions net of natural drawdown using a simplified empirical drawdown representation derived from a composite atmospheric half-life of approximately 72 years [23].

2.3 Climate and emissions regressions

Rather than using a full integrated assessment model, the study employs simplified empirical regressions fitted to historical data. These regressions link global population to annual emissions, cumulative CO_2 emissions net of drawdown to atmospheric CO_2 concentration, and atmospheric CO_2 concentration to global mean surface temperature [17,18,19,20]. The resulting relationships provide the scenario-specific trajectories of emissions, atmospheric CO_2 concentration, and warming used in the mortality calculations.

This empirical simplification trades complex climate modelling and scenarios for transparency based on actual historic data. It allows the mortality framework to be evaluated, replicated, and modified more easily, while also making clear that the resulting outputs are indicative estimates rather than high-resolution forecasts.

2.4 Undernourishment and conflict mortality modelling

Undernourishment and conflict were combined because the literature consistently treats them as mutually reinforcing pathways, with food insecurity intensifying displacement, governance stress, and violence, while conflict in turn deepens undernourishment by disrupting production, markets, and humanitarian access [24-26]. The World Food Programme estimate that about 9 million of 740 million undernourished people died in 2021 was used to convert forecast undernourishment into mortality within the model [27]; this case-fatality ratio was applied with a ±2 standard-deviation range around its central estimate to generate the Low, Mean, and High mortality bands reported in Table 1. Within the present framework, undernourishment-related deaths emerge as the dominant component of climate-related mortality.

The combined pathway was modelled using a dual empirical structure: a development-driven decline function representing historical improvements in food security over time, and a climate-driven increase function linked to rising atmospheric CO_2 concentration. These components were separated iteratively to fit the observed combined series of undernourishment and battle deaths, with a fitted crossover around the mid-2010s when the climate-driven component begins to outweigh development-driven improvement. Because to-date, the poorest and most climate compromised regions predominate within the global data, a single global fit would likely overstate future mortality if applied uniformly across all regions. Accordingly, the same iterative method was applied at regional scale where the signal was empirically evident. The resulting climate-fitted exposure was then constrained, region by region, to the minimum of that climate-fitted proportion and an independently estimated economic-vulnerability proportion — the share of the region's population with income below a poverty threshold corresponding to the onset of undernourishment, derived from GDP-per-capita and indicative income-distribution measures [16]. This economic-vulnerability constraint is estimated in parallel with, and independently of, the climate-driven fit; it does not itself determine the region-specific climate response (Section 3.3.2; S3.3 and S3.6 in the Supporting information).

In plain terms, the historical decline in undernourishment and conflict is first fitted as a development-driven trend, the climate-linked increase is fitted separately as atmospheric CO_2

concentration rises, and an iterative procedure then splits the observed combined series into these two components so that they add back up to the total undernourishment and conflict deaths.

2.5 Disaster mortality modelling

The EM-DAT disaster database was analysed to identify disaster classes significantly associated with atmospheric CO_2 concentration [21]. Storms, floods, landslides, and wildfires showed sufficiently robust positive associations to be retained, whereas earthquakes and volcanic events were excluded because their apparent historical increase was not robust after population normalisation and a plausible climate mechanism was not identified. Droughts were excluded from the disaster totals to avoid double counting with undernourishment-related mortality. Total disaster deaths were estimated as the product of modelled disaster frequency and average deaths per disaster. Additional tests assessed whether severity itself increased systematically with climate indicators, but the evidence was stronger for increasing disaster frequency than for systematically increasing deaths per event.

2.6 Other pathways and exclusions

Additional pathways reviewed included heat and cold extremes, diarrhoeal disease, malaria, epidemics, and air-pollution mortality. Several health pathways were not included in the quantitative totals because the available global relationships with atmospheric CO_2 concentration or global mean surface temperature were insufficiently consistent for the present framework, or because the wider evidence base remained conflicting at the aggregate global level [15,28-31]. A broader WHO mortality screening reviewed 751 conditions, of which 88 showed positive and 160 negative correlations with atmospheric CO_2 concentration, but this did not provide a sufficiently consistent basis for inclusion in the aggregate totals. Further work is intended to examine these in more detail.

Air-pollution mortality from fossil fuel combustion was retained for policy context, although it is treated as coincidental rather than strictly climate-driven within the model structure [32,33]. In precautionary terms, excluded pathways are best interpreted as unresolved sources of possible additional burden rather than as evidence that they are unimportant. As such they suggest that these estimates may still be conservative.

2.7 Mortality metric and uncertainty treatment

For each scenario, cumulative climate-related deaths from the included pathways were estimated over 1900–2300 and related to cumulative emissions to produce a deaths-per-megatonne metric. Historical regressions and pathway correlations in the framework are fitted using CO_2 and atmospheric CO_2 concentration, whereas the final summary metric is expressed per cumulative Mt CO_2-e so that alternative greenhouse gases can be represented on a common forcing-equivalent basis. The analysis is subject to substantial uncertainty arising from the limited and heterogeneous undernourishment and conflict data, the simplified empirical structure of the framework, the exclusion of some potentially important mortality pathways, and the stylised nature of the scenario assumptions.

Accordingly, the resulting estimates are interpreted as indicative, approximate, and precautionary rather than as precise forecasts of climate-related mortality. The purpose of the metric is therefore not to establish a final mortality account, but to provide a transparent first-order basis for comparing emissions pathways in public-health terms.

3. Results and Discussion

3.1 Mortality pathways identified in the literature

The literature identifies undernourishment, conflict, disasters, thermal stress, infectious disease, and air pollution as major pathways through which climate change may contribute to mortality [2,15,29,34-43]. However, these pathways are unevenly developed in the literature, and integrated assessment across them remains limited [7,8].

Undernourishment is a particularly important pathway because food insecurity reflects interacting effects on crop yields, water stress, poverty, and political instability, and famine mortality can rise sharply when these pressures coincide [24,36-39]. The conflict literature similarly suggests that climate is rarely a sole cause of violence, but often acts as a risk multiplier through resource scarcity, migration, governance stress, and displacement, creating both direct and indirect mortality burdens [25,26,40-43].

Research on storms, floods, wildfires, and other extreme events provides stronger evidence for changing hazard patterns and improving event attribution, but translating those signals into globally consistent forward mortality totals remains difficult because exposure, preparedness, reporting quality, and adaptation also change over time [21,35,44,45]. Health impacts such as heat mortality, diarrhoeal disease, malaria, and broader climate-sensitive morbidity are also well recognised in public-health research, yet they remain difficult to include consistently in an aggregate empirical framework at global scale with the presently assembled data [2,3,15,28-31].

Taken together, the literature supports a precautionary synthesis approach: selected pathways can be integrated now, while excluded pathways should be treated as unresolved components of possible additional burden rather than as evidence of no effect. This review supports the decision to prioritise undernourishment and associated conflict within the present framework while also preserving a broader climate-health perspective for future model development.

3.2 Climate and emissions relationships

This simplified empirical modelling allows climate-related mortality to feed back into the population driving emissions, so that in the most extreme business-as-usual pathway emissions eventually stabilise as global population declines.

3.3 Undernourishment and conflict mortality

Prior to about 2010, global undernourishment declined substantially, broadly consistent with reductions in infant mortality and development gains in many low-income regions [46,47]. From around 2010, corresponding to atmospheric CO_2 levels of roughly 405 ppm, that trend reversed in vulnerable regions despite continued improvements in infant survival [46,47]. This divergence is interpreted in the present framework as evidence that climate impacts on food security have begun to outweigh development-driven improvements, as illustrated in S7 Fig.

Conflict incidence has also risen beyond earlier ranges. Although conflict-related deaths do not show a clear aggregate trend because of large variability in fatalities per event [22], in aggregate they do show a similar trend to undernourishment mortality. Given the strong interlinkages between food insecurity, famine, and violence, undernourishment and battle deaths were combined for modelling purposes, though the estimates remain dominated by undernourishment-related mortality. For precautionary interpretation, this divergence matters because it suggests that a mortality signal may already be emerging in vulnerable regions before complete attribution is possible.

3.3.1 Global modelling

The combined undernourishment and conflict world mortality data were separated into a development-driven decline function and a climate-driven increase function. The resulting global fit yields large future mortality under business-as-usual, but this estimate is likely to overstate global climate-related undernourishment because the current global data are dominated by already vulnerable and relatively poor regions. The modelled annual trajectory for this dominant combined pathway is shown in Fig 1.

Fig 1. Undernourishment and conflict deaths: global modelling

3.3.2 Regional modelling

The same methodology was therefore applied at regional scale, taking account of economic factors — the model's proxy for regional resilience and adaptive capacity — affecting the proportion of populations economically vulnerable to undernourishment. Undernourishment and conflict data were available for 22 regions covering most of the global population, and direct climate-driven coefficients were fitted where the signal was empirically evident. For more economically protected regions — eight of the 22 regions considered — undernourishment remained low and comparatively stable to date, leaving no empirical basis for a direct climate-driven fit at current warming levels. Accordingly, these regions were assigned the average climate-driven correlation factors derived from regions with a direct fit, on the assumption that if and when they become more economically vulnerable they would experience a broadly similar average climate sensitivity; this necessarily carries wider uncertainty than the directly-fitted regions. This fitting therefore assigns materially different vulnerability to different regions rather than treating them uniformly: the fitted atmospheric CO_2 concentration corresponding to 50% undernourishment — a direct measure of how readily a region's combined undernourishment-and-conflict burden deteriorates under climate stress — ranges from approximately 604 ppm in Western Asia and 629 ppm in Southern Africa up to as much as 3644 ppm in Central America, suggesting up to a roughly six-fold difference in the fitted climate response itself; this upper bound is drawn from a comparatively weakly-constrained regional fit (S2 Table) and is best read as indicative of substantial regional variation in historical climate-and-conflict sensitivity rather than as a precisely determined ratio. This climate-fitted range is independent of, and separate from, the region's economic-vulnerability constraint (Section 2.4): C50% is estimated purely from each region's climate-and-conflict history and is not itself a function of economic development. These C50% values are fitted logistic-curve midpoints — the concentration at which the climate-driven component alone would reach 50% — rather than concentrations that any region is projected to approach; atmospheric CO_2 concentration under every modelled emissions pathway in this study, including business-as-usual to 2300, remains far below even the lowest regional C50% value, so these figures should be read as a relative index of regional sensitivity rather than as a forecast of approaching 50% undernourishment in any region. Full regional factors and fitted parameters are summarised in S2 Table.

3.4 Disaster-related mortality

Consistent with the modelling approach in Section 2.5, disaster mortality is driven primarily by rising frequency of storms, floods, landslides, and wildfires rather than by systematically increasing deaths per event, and total disaster mortality is estimated from modelled frequency multiplied by average deaths per disaster, with class-specific coefficients reported in the Supporting information.

3.5 Other pathways

Other health-related pathways reviewed — heat and cold extremes, diarrhoeal disease, malaria, and broader WHO mortality categories — were excluded from the quantitative totals on the same consistency grounds set out in Section 2.6. Air-pollution mortality was retained for policy context, since fossil-fuel reduction would lower both greenhouse-gas emissions and air-pollution deaths, even though it is not categorised here as strictly climate-driven. Screening criteria and excluded pathways are detailed in the Supporting information (Section S4.2).

3.6 Total climate-related deaths and deaths per megatonne

The final aggregate results are summarised in Table 1 and Figs 2 and 3. Across the modelled scenarios, higher cumulative emissions are associated with substantially larger climate-related mortality burdens over 1900–2300. In the central estimates, cumulative climate-related deaths are about 5.8 billion under business-as-usual compared with approximately 2.1 billion, 1.8 billion, and 1.6 billion under net zero by 2070, 2060, and 2050 respectively. Peak annual deaths in the net-zero scenarios range from about 16 million to over 40 million per year depending on parameter choices, whereas peak values under business-as-usual are too uncertain to report as precise numbers because of the strong feedback between mortality, population, and emissions in that pathway. Expressed as cumulative deaths per cumulative Mt CO_2-e, the central estimates are around 810 deaths/Mt CO_2-e under BAU and 790, 750, and about 710 deaths/Mt CO_2-e under net zero by 2070, 2060, and 2050 respectively, with low and high cases spanning roughly 440–960 deaths/Mt across the scenario set. These values indicate that earlier net-zero trajectories are associated with materially lower cumulative climate-related mortality than business-as-usual, even though the deaths-per-megatonne ratios themselves remain within a broadly similar order of magnitude across the principal model variants.

Table 1. Aggregate summary results

Metric		Scenarios: BAU	Zero Emissions by: 2070	2060	2050
Peak Climate Caused Deaths (Millions / year)	Low (yr)	Too Uncertain	9.2 (2058)	7.5 (2096)	6.2 (2095)
	Mean (yr)	Too Uncertain	16.0 (2042)	14.7 (2042)	13.3 (2032)
	High (yr)	Too Uncertain	41 (2049)	35 (2045)	29 (2041)
Cumulative Climate Deaths (Millions) 1900-2300	Low (yr)	5950	1340	1160	1010
	Mean (yr)	5770	2050	1830	1630
	High (yr)	6060	3020	2720	2430
Cumulative CO2 Emissions (Pt) 1900-2300	Low (yr)	9142	2602	2456	2311
	Mean (yr)	9144	2604	2458	2313
	High (yr)	9146	2606	2460	2315
Cum. Climate Deaths per Cum. Mt of CO2 emissions	Low (yr)	820	510	470	440
	Mean (yr)	810	790	750	710
	High (yr)	960	1160	1110	1050

The estimated summary values reported in the manuscript show that earlier net-zero trajectories are associated with materially lower cumulative climate-related mortality than business-as-usual within the modelled ranges. The results further suggest that the consequences of continued emissions are likely to be distributed unevenly. Lower-income populations appear more exposed in the modelled pathways, both because climatic impacts on food security are more severe and because economic protection against undernourishment is more limited. This distributional asymmetry strengthens the relevance of the analysis to climate justice, public health, and adopting the precautionary policy.

Fig 2. Graphical presentation of summary results for climate

Fig 3. Graphical presentation of summary results for mortality

3.7 Positioning within the emerging mortality--emissions literature

Several recent studies have begun to relate greenhouse-gas emissions to human mortality, but they differ substantially in pathway coverage, time horizons, and methodological assumptions. Parncutt's 1,000-tonne rule offers an order-of-magnitude ethical heuristic suggesting roughly one future death per 1,000 tonnes of fossil carbon burned, which converts stoichiometrically to approximately 273 deaths per megatonne of CO_2-e, whereas Bressler's mortality cost of carbon embeds mortality within a broader social-cost-of-carbon framework and is not directly comparable to a multi-pathway mortality accounting. The present framework differs by combining undernourishment, conflict, disasters, and selected contextual pathways within a unified empirical structure over 1900–2300 and by expressing the results in a deaths-per-megatonne metric explicitly tied to empirical undernourishment/conflict and disaster data.

Taken together, these results suggest that climate-related mortality is not well captured by conventional climate-impact framing that prioritises economic damages while treating mortality mainly in pathway-specific or marginal terms. In this framework, higher cumulative emissions are associated with larger aggregate mortality burdens, dominated by undernourishment and associated conflict, with additional contributions from selected disaster pathways and with disproportionate exposure among lower-income populations. At the same time, the analysis remains constrained by substantial uncertainty in the dominant pathways, by the need to extrapolate beyond currently observed regional relationships in some settings, and by the exclusion of several plausible mortality channels from the quantitative totals.

Several important confounders remain unresolved, including changes in disaster reporting, population exposure, healthcare, agricultural technology, humanitarian aid, adaptation, and governance [16,21,24]. Some of these factors could inflate apparent relationships, but others, such as improved preparedness, medical care, food trade, and adaptive capacity, act in ways that may suppress observed mortality relative to underlying climate pressure [24,35,44]. For that reason, uncertainty in the present framework should not be interpreted only as a source of possible overestimation; in several pathways it may also mean that historically observed mortality understates the longer-run burden associated with continued warming. A related concern is that, because atmospheric CO_2 concentration and calendar time are highly correlated across the industrial-era record used here, the fitted undernourishment-and-conflict relationship could in principle reflect a generic secular time trend rather than a genuine climate mechanism. Extending the timeframe under consideration, including over paleoclimatic timescales, shows no consistent correlation between atmospheric CO_2 concentration and time [48], which supports treating the industrial-era CO_2-mortality relationship identified here as a genuine association rather than an artefact of a shared time trend.

The distributional pattern implied by the model is also important. Climate-related mortality is not projected as an evenly shared burden, but as one concentrated more heavily among populations with less economic capacity to buffer food insecurity, displacement, and other climate stresses [2,3,14,16]. This gives the framework relevance not only to mitigation policy in aggregate, but also to climate justice and health equity, because the pathways contributing most strongly to the estimated burden are those most sensitive to poverty and institutional vulnerability [2-4,39]. A mortality framing therefore helps clarify that cumulative emissions are linked not only to total harm, but also to the unequal distribution of that harm.

The deaths-per-megatonne metric may also have practical value beyond scenario comparison alone. If refined and used cautiously, it could support ex ante appraisal of projects, infrastructure strategies, mitigation pathways, or broader policy portfolios by expressing climate consequences in public-health terms rather than only in monetary or emissions terms [5,9,10]. In that sense, the metric may complement existing climate-risk tools, climate-health assessments, and emerging accountability frameworks, including those concerned with equity, intergenerational harm, and institutional precaution [2-4,11]. Even without claiming precise quantification, the framework indicates that cumulative emissions can be interpreted as carrying potentially large and uneven human mortality consequences, and that this underdeveloped dimension of climate risk warrants more explicit integration into climate-health assessment, mitigation policy, and future empirical research.

3.8 Resilience, adaptive capacity, and unmodelled sources of variance

A further consideration raised by this framing is regional resilience and adaptive capacity — the extent to which populations and institutions can absorb, buffer, or recover from climate-related stress rather than experiencing it as direct mortality. Economic capacity, measured through GDP-per-capita and indicative income-distribution proxies (Section 2.1), is the framework's principal proxy for this resilience, but it operates as an independent constraint rather than as the source of the region-specific climate response reported in Section 3.3.2. The up-to-six-fold range in fitted C50% values across regions — from around 604–629 ppm in the most climate-sensitive regions (Western Asia and Southern Africa) up to as much as 3644 ppm in Central America — reflects each region's own historical climate-and-conflict sensitivity, not its economic development; as noted in Section 3.3.2, these are fitted curve parameters rather than concentrations any modelled pathway approaches, and, because the Central America fit is comparatively weakly constrained (S2 Table), this range is intended only as an indicative illustration of relative regional climate sensitivity rather than a precisely determined ratio. Economic capacity instead differentiates mortality risk through a separate, parallel mechanism (Section 2.4; S3.3 and S3.6 in the Supporting information): the modelled proportion of a region's population suffering undernourishment-related mortality is taken as the minimum of its climate-fitted exposure and an independently estimated economic-vulnerability proportion — the share of the population with income below a poverty threshold corresponding to the onset of undernourishment, estimated from regional income distributions using an income-threshold (Z-statistic) method (S3.6). Lower economic capacity means a larger share of the population falls below that threshold, so the economic constraint binds less tightly and a larger fraction of the climate-fitted exposure is realised as modelled mortality; this is the mechanism by which lower economic capacity is associated with weaker buffering against food insecurity, displacement, and disaster impacts, and with correspondingly larger modelled mortality responses to the same climate signal.

Institutional capacity — governance quality, early-warning systems, health-system strength, and disaster-response effectiveness — and population awareness — risk perception, disaster-preparedness behaviour, and the practical reach of early-warning and public-health information — are not separately parameterised in the present framework. Because both vary across countries independently of the regional groupings used here, their effects are expected to appear as unexplained variance around the regional and aggregate estimates rather than as distinct modelled terms, consistent with the wide low-to-high ranges reported in Table 1, where central estimates necessarily average over this within-region heterogeneity. This omission would only threaten the validity of the reported CO_2–mortality relationship if either factor varied systematically with atmospheric CO_2 concentration itself, independent of economic development, and there is no established basis for such a direct relationship. Institutional capacity is instead understood in the governance and development literature primarily as a correlate of economic development [35], which is already the framework's explicit resilience proxy, rather than as a variable that tracks atmospheric CO_2 concentration directly. Population awareness depends substantially on literacy, educational attainment, and access to media and communications infrastructure — themselves well-documented correlates of economic development [35] — and so is already partly reflected, indirectly, in the same economic-capacity proxy. Both factors are therefore treated as sources of additional, largely random regional variance captured within the reported uncertainty ranges, rather than as systematic confounders of the central emissions–mortality relationship. Future work using country-level governance, literacy, and media-access indicators could test this assumption directly and potentially narrow the reported uncertainty ranges.

4. Conclusions

This study develops a simplified empirical framework for estimating climate-related mortality and relating that mortality to cumulative greenhouse-gas emissions across alternative emissions pathways. By combining selected mortality pathways within a common scenario-based structure and expressing the resulting burden as cumulative deaths per cumulative Mt CO_2-e over 1900--2300, the analysis offers a transparent way to relate emissions choices to human consequences. In keeping with a precautionary climate-health perspective, the framework is intended as an approximate and policy-relevant first estimate rather than as a definitive forecast of future deaths.

Across the modelled scenarios, higher cumulative emissions are associated with substantially larger climate-related mortality burdens, while earlier progress toward net zero materially reduces projected mortality within the modelled ranges. Within the present framework, the aggregate burden is dominated by undernourishment and associated conflict, with smaller but still material contributions from selected disaster pathways including storms, floods, landslides, and wildfires. The analysis also suggests that climate-related mortality burdens are likely to be distributed unevenly, with greater exposure among populations that have less economic capacity to buffer food insecurity and related climate stresses. This unevenness reflects differences in regional economic capacity, the framework's proxy for resilience and adaptive capacity; institutional capacity and population awareness were not modelled separately and are instead reflected in the width of the reported uncertainty ranges (Section 3.8).

These findings should be interpreted cautiously. The estimates remain subject to substantial uncertainty arising from the limited and heterogeneous undernourishment and conflict data, the simplified empirical structure of the model, the need to extend some regional parameters beyond directly fitted observations, and the exclusion of several potentially important mortality pathways from the quantitative totals. For that reason, the deaths-per-megatonne values should be read as indicative, approximate, and explicitly precautionary estimates that help clarify the possible scale and direction of climate-related mortality under contrasting emissions trajectories.

Even with these limitations, the framework helps make a currently underdeveloped dimension of climate risk more explicit. By linking mortality outcomes to cumulative emissions, it provides a basis for integrating human survival more directly into climate-risk assessment and for refining future estimates as attribution methods, regional mortality datasets, and pathway coverage improve. The main contribution is therefore not a claim of precise quantification, but a transparent and testable framework for precautionary assessment of climate-related mortality across multiple pathways.

From a policy perspective, the results support treating climate mitigation not only as an environmental or economic objective but also as a public-health and equity intervention. If higher cumulative emissions are associated with larger and more uneven mortality burdens, then earlier emissions reduction, stronger food-system resilience, and protection of economically vulnerable populations become precautionary measures for reducing avoidable loss of life. In this sense, the framework may help governments, health agencies, and other decision-makers evaluate climate actions in terms of lives potentially lost or saved, while recognising that uncertainty itself strengthens rather than weakens the case for precautionary risk reduction.

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CRediT authorship contribution statement

Nigel Howard: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing -- original draft, Project administration, Funding acquisition. Peter Newman: Conceptualization, Supervision, Writing -- review and editing.

Availability of data and materials

All data and materials used in this study are publicly available from the sources cited in the manuscript references.

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Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Generative AI statement

During the preparation of this work, the authors used Perplexity AI to assist with editorial review of the manuscript and supplementary information, including alignment with journal formatting and submission requirements. The authors reviewed and edited the output as needed and take full responsibility for the content of the publication.

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Supporting information

S1 Fig. Global mean surface temperature anomaly relative to the 1850–1900 baseline.

S2 Fig. Global CO_2 emissions growth since 1900.

S3 Fig. Historical and projected global population growth.

S4 Fig. Global CO_2 emissions versus global population.

S5 Fig. Atmospheric CO_2 concentration versus cumulative CO_2 emissions net of drawdown.

S6 Fig. GMST anomaly versus cumulative CO_2 emissions net of natural drawdown.

S7 Fig. Divergence between undernourishment and child mortality trends in the world and selected regions.

S8 Fig. Undernourishment versus GDP per capita.

S9 Fig. Undernourishment versus GDP per capita, histogram.

S10 Fig. Median and 10% poorest daily incomes.

S11 Fig. Estimated standard deviation of incomes.

S12 Fig. Income level at which the proportion poorer corresponds to the proportion undernourished.

S13 Fig. Proportion of population with income low enough for undernourishment exposure.

S16 Fig. Deaths per million population versus atmospheric CO_2 concentration, excluding outliers.

Equation S1. Population to emissions regression.

Equation S2. Emissions S-curve decline function.

Equation S3. Scenario S-curve factor expression.

Equation S4. CO_2 drawdown.

Equation S5. CO_2 emitted net of drawdown per year.

Equation S6. Cumulative CO_2 emitted net of drawdown since 1900.

Equation S7. Atmospheric CO_2 concentration.

Equation S8. GMST anomaly versus cumulative CO_2 emissions net of drawdown.

Equation S9. Development-driven decline function for undernourishment and conflict.

Equation S10. Climate-driven increase function for undernourishment and conflict.

Equations S11–S12. Iterative separation methodology.

Equation S13. Estimation of standard deviation of daily incomes.

Equation S14. Threshold income ($/day) for undernourishment.

Equation S15. Z Statistic for proportion of population undernourished.

Equation S16. Climate-driven disaster numbers.

Equation S17. Disaster mortality estimate.

S1 Table. S-curve factors for scenario CO_2 emissions decline to near zero.

S2 Table. Factors used with Equations S9 and S10.

S3 Table. GDP per capita growth rates and income thresholds for undernourishment.

S4 Table. Correlation factors for use with Equation S16.

S5 Table. Deaths per disaster for use with Equation S17.

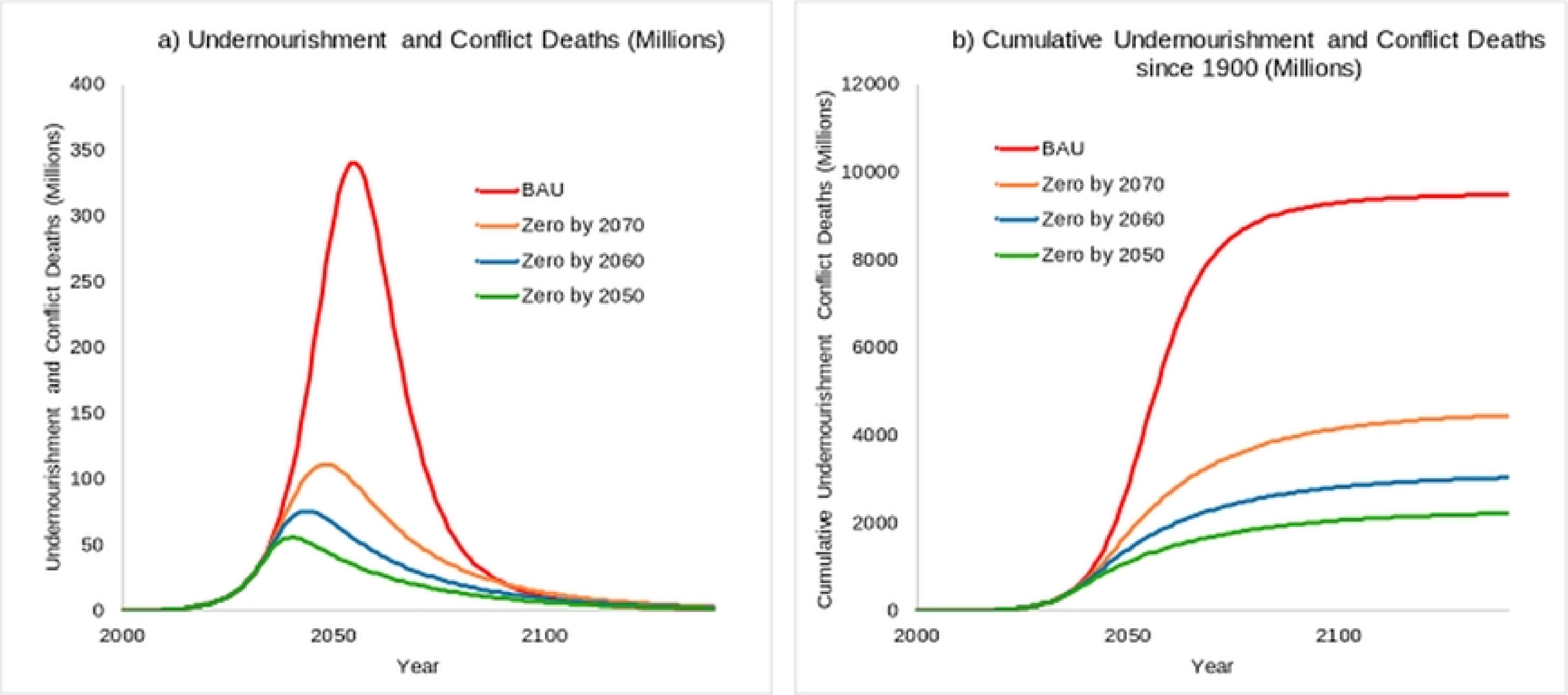
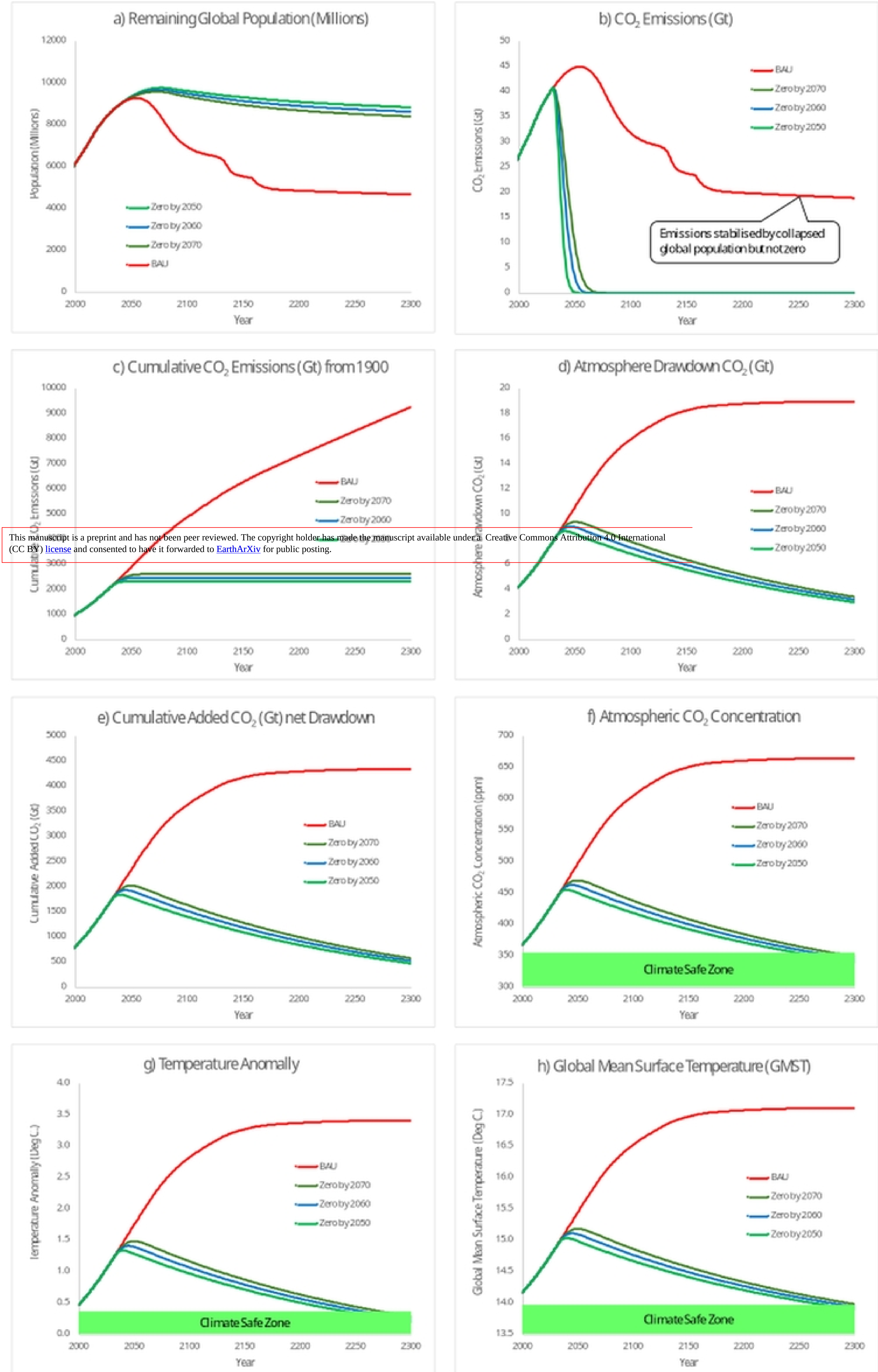

a) Undernourishment and Conflict Deaths (Millions)
Undernourishment and Conflict Deaths (Millions)
400
350
300
250
200
150
100
50
0
2000
2050
2100
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
b) Cumulative Undernourishment and Conflict Deaths since 1900 (Millions)
Cumulative Undernourishment Conflict Deaths (Millions)
12000
10000
8000
6000
4000
2000
0
2000
2050
2100
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050

Fig 1



a) Remaining Global Population (Millions)
Population (Millions)
Year
Zero by 2050
Zero by 2060
Zero by 2070
BAU
b) CO_2 Emissions (Gt)
CO_2 Emissions (Gt)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Emissions stabilised by collapsed global population but not zero
c) Cumulative CO_2 Emissions (Gt) from 1900
Cumulative CO_2 Emissions (Gt)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
d) Atmosphere Drawdown CO_2 (Gt)
Atmosphere Drawdown CO_2 (Gt)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
e) Cumulative Added CO_2 (Gt) net Drawdown
Cumulative Added CO_2 (Gt)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
f) Atmospheric CO_2 Concentration
Atmospheric CO_2 Concentration (ppm)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Climate Safe Zone
g) Temperature Anomally
Temperature Anomally (Deg C.)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Climate Safe Zone
h) Global Mean Surface Temperature (GMST)
Global Mean Surface Temperature (Deg C.)
Year
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Climate Safe Zone

Fig 2

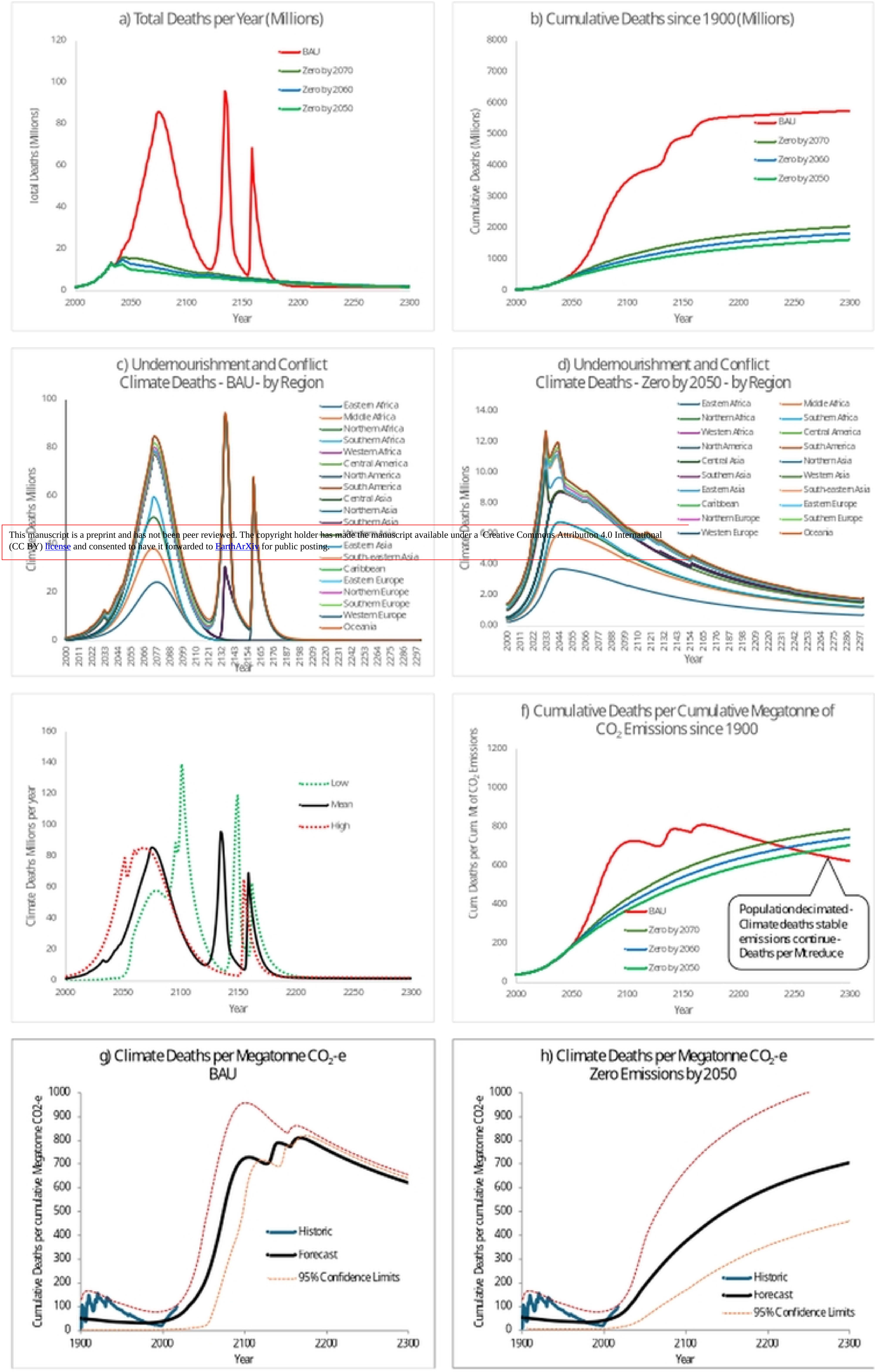

a) Total Deaths per Year (Millions)
Total Deaths (Millions)
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Year
b) Cumulative Deaths since 1900 (Millions)
Cumulative Deaths (Millions)
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Year
c) Undernourishment and Conflict
Climate Deaths - BAU - by Region
Climate Deaths Millions
Eastern Africa
Middle Africa
Northern Africa
Southern Africa
Western Africa
Central America
North America
South America
Central Asia
Northern Asia
Southern Asia
Eastern Asia
South-eastern Asia
Caribbean
Eastern Europe
Northern Europe
Southern Europe
Western Europe
Oceania
Year
d) Undernourishment and Conflict
Climate Deaths - Zero by 2050 - by Region
Climate Deaths Millions
Eastern Africa
Middle Africa
Northern Africa
Southern Africa
Western Africa
Central America
North America
South America
Central Asia
Northern Asia
Southern Asia
Western Asia
Eastern Asia
South-eastern Asia
Caribbean
Eastern Europe
Northern Europe
Southern Europe
Western Europe
Oceania
Year
Climate Deaths Millions per year
Low
Mean
High
Year
f) Cumulative Deaths per Cumulative Megatonne of
CO2 Emissions since 1900
Cum. Deaths per Cum. Mt of CO2 Emissions
BAU
Zero by 2070
Zero by 2060
Zero by 2050
Population decimated - Climate deaths stable emissions continue - Deaths per Mt reduce
Year
g) Climate Deaths per Megatonne CO2-e
BAU
Cumulative Deaths per cumulative Megatonne CO2-e
Historic
Forecast
95% Confidence Limits
Year
h) Climate Deaths per Megatonne CO2-e
Zero Emissions by 2050
Cumulative Deaths per cumulative Megatonne CO2-e
Historic
Forecast
95% Confidence Limits
Year

Fig 3