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Climate impact storylines for assessing socio-economic responses to remote events

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ABSTRACT

Quote: "What I hear, I forget. What I see, I remember. What I do, I understand." (Xunzi, ~300 BCE).

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Modelling complex interactions involving climatic features, socio-economic vulnerability or responses, and long impact transmissions is associated with substantial uncertainty. Physical climate storylines are proposed as an approach to explore complex impact transmission pathways and possible alternative unfoldings of event cascades under future climate conditions. These storylines are particularly useful for climate risk assessment for complex domains, including event cascades crossing multiple disciplinary or geographical borders. For an effective role in climate risks assessments, development guidelines are needed to consistently develop and interpret the storyline event analyses.

This paper elaborates on the suitability of physical climate storyline approaches involving climate event induced shocks propagating into societal impacts. It proposes a set of common elements to construct the event storylines. In addition, criteria for their application for climate risk assessment are given, referring to the need for storylines to be physically plausible, relevant for the specific context, and risk-informative.

Apart from an illustrative gallery of storyline examples found in literature, three examples of varying scope and complexity are presented in detail, all involving the potential impact on European socio-economic sectors induced by remote climate change features occurring far outside the geographical domain of the European mainland. The storyline examples illustrate the application of the proposed storyline components and evaluate the suitability of the criteria defined in this paper. It thereby contributes to a rigorous design and application of event-based climate storyline approaches.

1. Introduction

In the modern, highly connected and globalized world, the assessment of impacts of past and projected climate change on nature and society needs to extend beyond the local perspective in which adverse climate features are linked to immediate, localized consequences (Hedlund et al., 2018). Impacts from fast (extreme weather) and slow-onset events (van der Geest and van den Berg, 2021) at any location on the planet can be transmitted to remote areas via various physical and socio-economic pathways (Benzie et al., 2019), including trade (exchange and transportation of goods and services), finance (private and public capital), biophysical transfers (such as spatially extensive hydrological systems), and people's behavioral responses. The societal impacts are not only governed by the physical hazard and the resulting effect cascades but are also strongly linked to the societal risk response (Simpson et al., 2021). The COVID-19 pandemic has contributed to a growing awareness of transboundary implications and considerable complexity of systemic risks (Phillips et al., 2020; Ringsmuth et al., 2022), including climate change (Challinor et al., 2017; Gaupp, 2020; IPCC, 2022).

Assessment of impacts resulting from remote climate change features requires an analysis framework that embraces a "systemic risk" approach (Hochrainer-Stigler et al., 2020) and acknowledges complex interactions between risk attributes (Piontek et al., 2021; Simpson et al., 2021). Globalized, systemic shocks originating from extreme weather or climate conditions have been documented and analyzed for a wide range of events, for instance the 2003 and 2010 breadbasket disruption (Gaupp et al., 2020; Falkendal et al., 2021), global supply chain interruptions (Abe and Ye, 2013; Haraguchi and Lall, 2015) and financial exposure (Woo, 2019; Tesselaar et al., 2020). A systemic risk approach includes the need for a comprehensive definition of the system boundaries, relevant climate features, the risk propagation mechanism, quantitative hazard impact evaluation, and specification of alternative scenarios (Carter et al., 2021). It also requires the development of thorough interdisciplinary analytical and modelling approaches that succeed in making the large complexity and uncertainty of impact chains manageable for societal uptake (Piontek et al., 2021).

However, a generalization of complex cascading events, in order to evaluate societal risk or preparedness, is not trivial (Cutter, 2018, 2021). The topic is complicated by the nearly unlimited spatial extent over which risk transmission can take place, and the numerous pathways, triggers, event cascades and dependencies on boundary conditions. A formal probabilistic assessment of the associated risk is virtually impossible: impacts of climate events propagate through a complex and dynamic network of highly conditional cause-effect chains, and quantitative analysis of signal strength and cascading probabilities is conceptually far from being straightforward (Dessai and Hulme, 2004; Stainforth and Calel, 2020).

Alternatively, the exploration of specific risk-transmission pathways can provide useful information on socio-economic sensitivities to remote and cascading climate events, especially when interactions are very complex and subject to many conditional dependencies, which is a form of deep uncertainty (also framed as "radical uncertainty"; (Kay and King, 2020)). For this, well-designed physical climate storylines triggered by specific climate events (Shepherd et al., 2018; Lloyd and Shepherd, 2020; Sillmann et al., 2021) offer a helpful framework for analyzing how impacts can be diagnosed and resilience to climate change can be enhanced. A description of selected historic events that have been experienced by individuals can give more meaningful insights than a quantitative uncertainty assessment across a complex chain of causes and effect (Shepherd and Lloyd, 2021). Event-oriented physical climate storylines (or in brief: climate event storylines) generate insights that can lead to better preparedness, for instance by developing stress-tests conditioned on plausible and verifiable boundary conditions, or by revealing previously unexplored risk propagation pathways or responses to emerging risks (Baldissera Pacchetti et al.; Albano et al., 2021).

However, similar to probabilistic approaches an effective application of climate event storylines requires a credible and traceable approach to construct them (Stainforth et al., 2007). The number of potential event-chains that could be chosen is infinite, and also the underlying assumptions, tools and metrics require an explicit documentation and justification in order to be useful as a resource for climate risk assessments. Therefore, some standardization of storyline construction and evaluation criteria is desirable.

In this paper we outline a development protocol for climate event storylines that is designed to map impacts of global climate features on selected European socio-economic sectors. We propose a generic structure for the definition, engagement and quantitative analysis of the climate event storylines, and include examples of the use of such a protocol in various contexts. The approach is not free of ethical considerations reflecting stakeholder's perspectives and values as they refer to choices of events, impact transmission pathways and analysis protocol (Baldissera Pacchetti et al.). Stakeholder inputs are addressed here in the scoping of the climate event storylines, but a detailed analysis of the ethical aspects is out of scope of this study. However, to facilitate the societal uptake of this scientific information, a set of criteria ("realistic", "relevant" and "risk-informative") has been formulated and evaluated, broadly similar to those proposed by (Cash et al., 2003) for climate services.

We first outline the criteria and core ingredients of the analysis framework in section 2, and elaborate on storyline ingredients and processing steps in section 3, followed by an illustrative description of a number of storylines (section 4). Methodological concepts including the involved data and modelling approaches, and the role of alternative realizations of the storylines – referred to as "counterfactuals" – are described in section 3 and illustrated on a case-by-case basis in section 4. The storylines are constructed using different types of sources of evidence (e.g., models, data, expert judgment) that can be manipulated (perturbed) such that the result assesses the particular context at hand (i.e. societal risk to climate change). We conclude with a reflection on methodological approaches and application domains (section 5), and finally provide further outlooks to the future development of these and related event-based climate storylines.

2. Criteria for climate event storylines

In order to be a useful source of information supporting the assessment of climate change implications for a specific target domain, the criteria realism, relevance and risk-orientation are used as guidelines. The construction of "realistic" storylines is promoted by using historic event chains that demonstrated the European exposure to worldwide climatic features in practice, or events generated by models with epistemic reliability (Baldissera Pacchetti, 2021). The description of the impact transmission pathway is guided by the use of observations and witness testimonials focusing on key indicators and processes that characterize the storyline. We use or adapt fit-for-purpose modelling concepts that are evaluated for their ability to reproduce the relevant processes and interactions, and set up experiments that allow reproduction, verification and comparison (see (Baldissera Pacchetti, 2021) for a discussion on quality dimensions for forward looking regional climate information). Illustrations of choices and evaluation of modelling concepts are given in the storyline example section below.

The "relevance" (or "salience") of the event storylines is promoted by a number of design principles. First, a storyline scoping and selection process is carried out involving stakeholder insights, documentation of drivers and direct and indirect sectoral impacts of historic events, and screening the relative importance of subjects in the socio-economical domain of interest. To allow analysis of the effect of remote climatic features on European sectors, we compare the outcome of multiple versions of constructed storylines with a reference configuration, and one or more "counterfactuals" with perturbed characteristics derived from predefined climate and socio-economic scenarios. A level of standardization across these scenarios is imposed by making explicit linkages to global warming levels and Shared Socio-economic Pathways (SSPs), matching the boundary conditions used in many national or European-wide climate risk assessments (see e.g. (Talebian et al., 2021)). Finally, the representativity of the storylines for stakeholders can be enriched by adding "micro-stories", illustrating impacts by responses of specific actors related to the stakeholder community.

The climate event storylines are not designed to quantify the probability of the occurrence of impact pathways, which is duly impossible given the complexity of events and their consecutive impact cascade (Sillmann et al., 2021). Rather, the approach focuses on the plausibility (being not demonstrably inconsistent) of the event chains conditioned on specified climatological and socio-economical boundary conditions. They are still designed to be "risk-informative" by revealing or understanding the (sometimes hidden) relationships between climatic hazards and their remote impacts. Also the storylines support the discovery element in exploratory foresight studies designed for informing present day policy making on future implications (Termeer et al., 2017; Wiebe et al., 2018). The assumptions used to select the storyline components need to be documented in order to allow evaluation of the realism of the findings, and reproduction of the storyline in other contexts and by different analysts. In addition, probabilistic context can be added by quantifying the (conditional) occurrence frequency of large-scale climate features giving rise to the hazard event included in the storyline (Shepherd, 2019).

3. Construction of event-based climate storylines

We define climate event storylines as "physically self-consistent unfoldings of past events, or of plausible future events or pathways" (Shepherd et al., 2018; Sillmann et al., 2021). In our context, a sequence of events with an underlying causal relationship forms a logical narrative that links climate hazards at a given location in the world with a socio-economic impact materialized in Europe. The storyline is captured in an analysis framework (using models, data or expert judgment) that can be interpreted, perturbed and explained in the context of a societal risk due to global climate change.

The climate event storylines described here connect geographical domains (of climate hazards and (remote) impacts), time scales (for precursors, events, impacts and response actions), process cascades (combining the physical, economic, ecological and social domains) and actors (including those that are directly impacted in the region of climate hazards, contributing to the impact transmission, and experiencing or responding to remote impacts). (Carter et al., 2021) identified similar connecting elements while exploring an analysis framework for remote climate impact chains. In our study, these elements are brought together in the construction of climate event storylines in order to identify a common structure that spans the entire chain between the remote climatic hazards and the final (socio-economic) European impact. The common elements are illustrated for each of the selected storyline examples below. They consist of (see Fig. 1):

A *scoping process:* from the diversity of historic events, societal sectors and physical and socio-economic transmission pathways, a selection of storylines is made that reveal relevant and recognizable impact transmission pathways. This includes an inventory of interested societal stakeholders, analysis of macro-economic global networks and supply/demand chains, inspiration from recent climate events and evidence of shock propagation in the globalized world. Stakeholder feedback by means of interviews and workshops is sought to collect relevant information on impacts, vulnerabilities and non-climatic drivers that are of interest for climate event storylines. This feedback is subsequently analyzed in conjunction with evidence from "top-down" climate and socio-economic scenario information archives (Berkhout et al., 2013; Cairns et al., 2013);

The *remote climate hazard region*: the geographical area where the initial climate triggers are manifested. The selection of hazard regions aims to identify remote regions where climate perturbations have a demonstrable impact on European socio-economic conditions, and is carried out using historical evidence or extractions from model projections. Their description includes their causal drivers, hydrometeorological variables aggregated to an appropriate time and space scale, and an assessment of the level of scientific understanding (LOSU) of the link between climate change and their plausibility of occurrence. Climate hazards of interest usually are common features which are expected to change in intensity/frequency, timing or domain in future climate conditions. Assessment of the likelihood of occurrence in the region is derived from historic observation records, ensembles of model projections, or ensemble techniques exploring alternative event realizations, so-called "downward counterfactuals" (Woo, 2019). However, the hazard occurrence at that location may be unprecedented due to an uncommon hazard pathway, atmospheric circulation pattern or combination of precursors. Multiple hazard regions can emerge simultaneously, for instance by a common large-scale driver such as ENSO or other SST anomaly patterns;

The *impact transmission pathway*: the process chain that links the hazard region to the impact on European stability, growth or resilience. The potential pathways vary widely, and can consist of trade networks, supply/demand chains of food and commodities, financial exposure portfolios (by investors, insurance or liability configurations), or geophysical teleconnections (sea level rise induced by remote ice mass loss, or impacts cascading across transboundary watersheds) (Benzie et al., 2019). Also the potential number of methodological approaches to characterize these pathways is large and varies strongly across applications (Piontek et al., 2021). Inputs can for instance be provided by the stakeholder feedback during the scoping phase, or statistical data on, for instance, historic trade records (Kuhla et al., 2021);

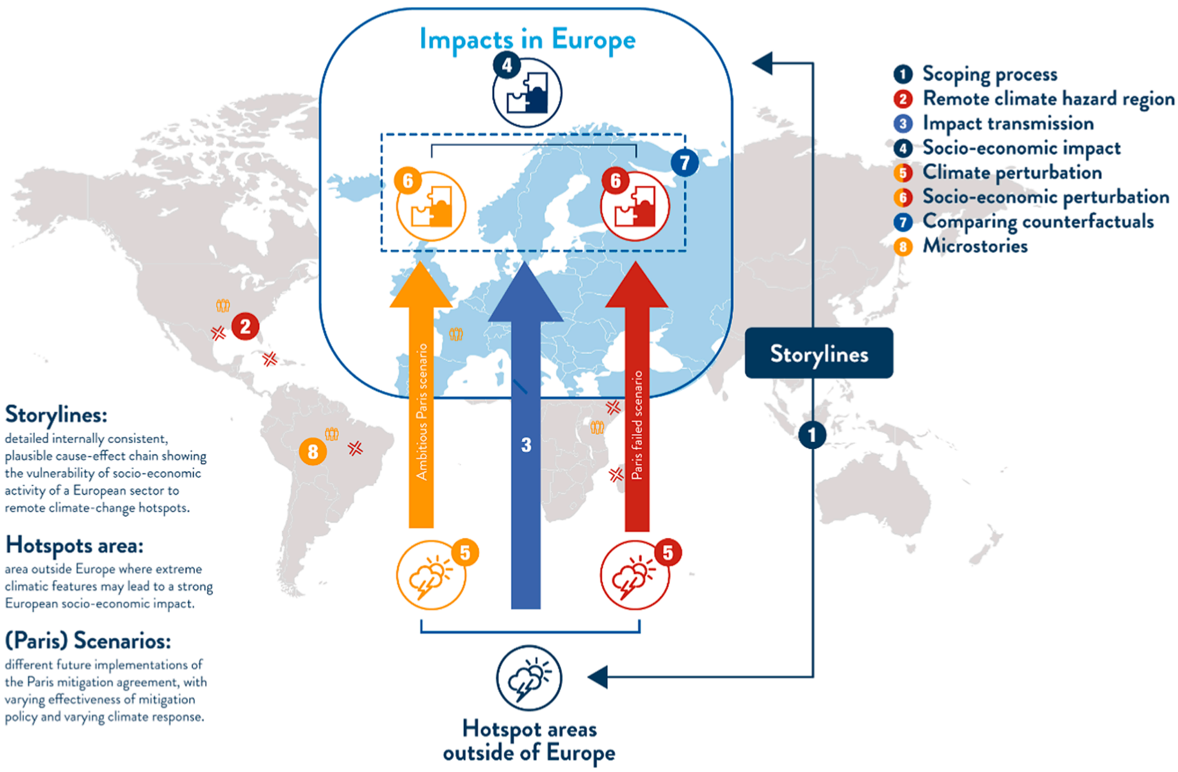

Fig. 1. Design steps for climate event storylines (see text for details).

The *socio-economic impact* of the transmitted disturbances evolving from the remote climate hazard: quantitative measure of consequences for a specified set of societal actors (such as financial damage, anomalies in volume of trade or consumption) are mapped using acknowledged modelling and analysis frameworks. The applied model or data concepts are selected for their ability to define targeted socio-economic metrics for direct or indirect impacts, and to assess dependencies on ancillary conditions (such as different background population, economic structures or financial policies). As for the impact transmission pathway the number of available analysis concepts is large, and selection of these is subject to requirements raised during the scoping phase and stakeholder inputs. Illustrations of model and analysis concepts are provided in the storyline examples below. The combination of the remote climate hazard region, the transmission pathway and the European socio-economic impact metric represents the reference configuration, in which present day (adverse) climate features can be linked to socio-economic impacts;

The *climate perturbation*: the purpose of our climate event storylines is to identify impacts of remote climate change. For this the comparison between different climatic background states is organized, by construction of a so-called *(climate) counterfactual* evolution of the event chain. The construction of perturbed climate event storylines is designed to describe the change of the physical characteristics of the climate feature(s) in the remote hazard region as a plausible response to changing levels of global warming, for which a reasonable LOSU exists (Hazeleger et al., 2015). This can be an observed analogue (for instance in an historic, cooler, climate episode), or a perturbation applied to a modelled representation of the event, for instance by applying a temperature-based scaling (Te Linde et al., 2010), regional modelling (Lenderink et al., 2021), model nudging (Van Garderen et al., 2021), conditional sampling of circulation patterns (Zappa and Shepherd, 2017) or analogue hazards (Hegdahl et al., 2020; Schaller et al., 2020), statistical resampling (Ward et al., 2014; Li et al., 2018) and other techniques. The comparison of different unfoldings of events is inherent to various techniques for climate event attribution (Hannart et al., 2016; van Oldenborgh et al., 2021), including the analysis of the attribution of impacts of these events (see for instance (Mengel et al., 2020));

A *socio-economic perturbation:* as indicated in step 4 (socio-economic impacts), changes in the socio-economic background state may strongly affect the European impacts of remote climate hazards. This can include trends in economic structure, population or implementation of adaptation measures. To promote consistency across storylines or benchmarking against widely used global socio-economic projections, local interpretations of Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2014) are carried out. SSPs sketch the global evolution of macro-economic and social indicators (such as GDP, population, industry, land use) following a set of narratives on global cooperation, technology and energy consumption. In many national or regional assessments of future socio-economic developments these SSPs are interpreted for the local context, feeding into projections of spatial developments, employment, mobility, economic structure and other attributes (Frame et al., 2018; Talebian et al., 2021). These downscaled projections usually don't include recursive or planned (adaptation) responses to environmental or socio-economic developments (Andrijevic et al., 2020; Chen et al., 2020). Responses to socio-economic impacts arising from (remote) climate pressures, such as implementing adaptation policies or changing exposure or vulnerability to high-impact shocks may be included in the socio-economic perturbation that is part of the counterfactual event-based storyline, depending on the application scope of the storyline (see subsection on "storyline application domain" below);

Comparison between reference and counterfactual(s): a reference storyline is defined to document the baseline (current) transmission pathway that sets the scope of the analysis. One or multiple counterfactuals allow to explore impacts of perturbed climatological or socio-economic conditions on the baseline impact pathway, leading to a "climate change narrative". Quantitative and qualitative understanding can be derived from following the altered background state through the storyline components: a perturbation of the triggering climate features (an imposed link to global warming) may or may not lead to significant changes in the local impact, downstream transmission, or socio-economic impact, depending on assumptions on specific properties of the causal network chain and its dynamic responses. This requires a careful selection of data and models used, a thorough documentation of conditions and assumptions, and a targeted experimental (model) design to generate the reference and counterfactual storylines;

Accompanying micro-stories: these are complementary narrative elements to enrich the climate event storylines by providing additional detail or context. The event storylines usually contain events, transmissions and impacts whose selection is highly conditional, rendering the storylines adaptable for alternative representations, sensitivities to choices, and diversity in perspectives. "Micro-stories" can be helpful to make occasional excursions from the main storyline narrative, for instance to explore the sensitivity of the processes in the event-cascade to subtle changes in the used assumptions. Also inputs from individuals and stakeholders, for instance "witness reports" from people affected by historic event impacts, or stakeholders involved in the design in impact assessment or adaptation, may be added as micro-stories to the storyline package (see for instance (Jack et al., 2020)).

4. Overview of illustrative storylines

To illustrate the common storyline elements discussed above we describe three storylines in detail:

- Concurrent drivers of disrupted food security in the Horn of Africa;
- Impacts of tropical cyclones on the European Union Solidarity Fund (EUSF);
- Soybean production for European food supply.

The three storylines together encompass a wide range of geographical, climatological and socio-economic contexts. However, the collection of potential scopes of these storylines is virtually unlimited. To provide additional illustration we also describe three additional storylines briefly, providing cross-references to published documentation.

Each storyline describes sector-specific socio-economic impacts of remote climate change features and the insights derived from it.

Approaches, modelling concepts, scenario choices and application domains are outlined following the logic of the protocol steps, and summarized in a dedicated table. Section 5 reflects on methodological approaches and application domains of the event storylines.

Storyline #1: Concurrent drivers of disrupted food security in the Horn of Africa.

Scoping process. Beneath conflict and social instability, many countries in the Horn of Africa are facing frequent drought- or pest-induced domestic harvest failures, which, in combination with relatively small grain reserves (Laio et al., 2016), makes them dependent upon grain imports, or even food aid in crisis situations (ICPAC, and WFP, 2018). Food security and humanitarian wellbeing in African (and other) countries are relevant to a wide range of European policies concerning development aid and humanitarian support (such as the formal partnership agreements with the African, Caribbean and Pacific states, ACP (Hurt 2003)). However, potential impacts of climate change are very strongly intertwined with compounding pressures and responses, and an analysis of the "net" impact of climate change on food security is far from straightforward. Therefore, a storyline is developed that analyzes the local food security crisis during the 2019/2021 locust outbreak in the region, but put in the context of a compounding weather-induced global food price crisis of the year 2007/08 that explores the unfolding of a local food security crisis in a different climatic context. The main short-term driver of the 2007/08 crisis was compounding weather-induced crop failures of the main food crops wheat, maize, and rice in several main producing regions. In response to the resulting production failures, world market prices rose, and market uncertainties increased. In response, many import dependent countries raised unilateral and uncoordinated export restrictions to protect their domestic consumers by insulating them from the price hikes in global markets (Trostle et al., 2011; Challinor et al., 2018). These restrictions further aggravated the crises, especially for import dependent low-income countries in Africa and Asia and pushed an estimated 63 to 80 million people into food insecurity, and sparked food riots around the globe (Tiwari and Zaman, 2010).

We consider two counterfactual storylines, one where the local locust-induced production failures coincide with the global production failures of the 2007/08 crisis, and another where we additionally consider the impact of the escalating export restrictions of the 2007/08 crisis. The scoping process of this storyline was driven by analyses of food security statistics, revealing national and regional cereal import dependencies of countries rendering them vulnerable to global supply failures and associated price hikes at international markets (Fig. 2).

Remote climate hazard region. In the **reference scenario**, we consider the food security risks from locust-induced crop failures in the Greater Horn of Africa region experienced in 2019/21. Desert locusts found ideal breeding conditions on both sides of the Red Sea due to three landfalling tropical cyclones bringing unusual amounts of precipitation. Additionally, response measures were delayed by the COVID-19 pandemic, and large swarms were able to form that spread not only across the Horn of Africa region but also across the Arabian Peninsula and Southeast Asian Countries.

Impact transmission pathway. The impact transmission of the regional food security crises to the EU is governed by historically grown trade dependencies (d'Amour et al., 2016) and development cooperation (Langlois, 2014). Global production of main food crops such as wheat, maize, and rice are concentrated in a few main breadbasket regions such as the EU. The resulting import dependencies of many developing countries of the Global South such as countries in the Greater Horn of Africa, renders these countries vulnerable to remote supply failures and associated price hikes at world markets. Further, many people in these countries strongly depend on international humanitarian aid for their well-being. For instance, in 2020 and 2021 the European Union allocated nearly €200 million for a broad humanitarian-development approach, from which more than €20 million were mobilized to support the United Nations and partner countries in fighting the locust infestation (European Commission).

Socio-economic impact. The socio-economic impact is measured with various metrics: 1) world market price volatility (a potential precursor for insufficient accessibility to food); 2) impaired supply at the national level arising from the harvest failures and export restrictions (which urges countries to tap into their reserves or rely on international markets or humanitarian aid); and 3) the ratio of impaired supply to reserves (an indication for risk to limited food availability at the national level; see Fig. 2).

Climate perturbation. To assess the vulnerability of the Greater Horn of Africa to a (plausible) worst-case combination of local and

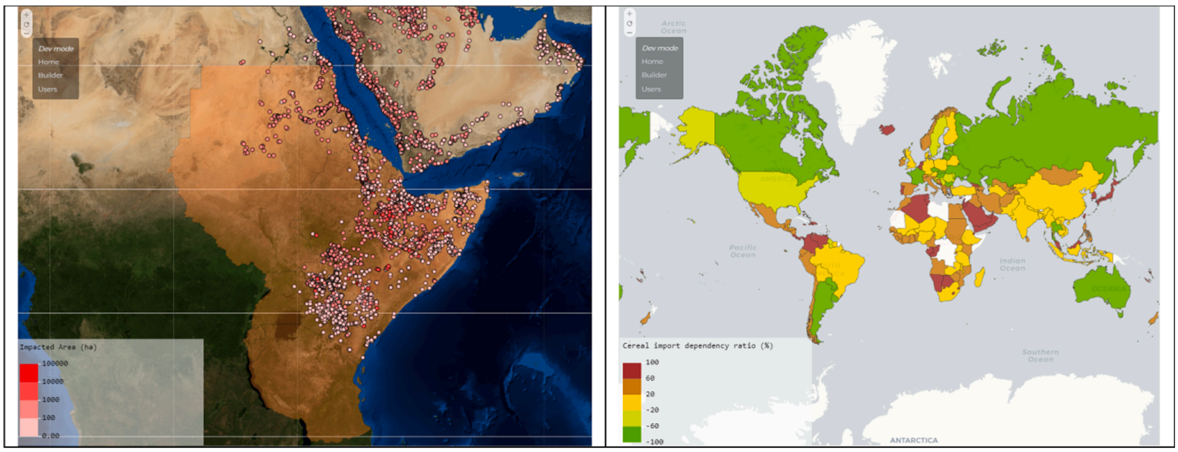

Fig. 2. Source material used for the scoping of the storyline addressing food security crisis in Greater Horn of Africa and Arabic peninsula. Left: area impacted by locust infestation during 2019/21 (source: (FAO, 2021)); Right: global cereal import dependency ratio in 2017 (source: (FAO, 2017)).

global food security crises, we superimpose the global production anomalies of the 2007/08 world food price crisis with the locust-induced production failures for 2019/21. In this way, the climate perturbation is applied by combining the food trade and production conditions in the region where the locust infestation was dominant with the implications of the multi-breadbasket failure experienced during the major global food crisis of 2007/08. This defines a **first counterfactual storyline** for this analysis: what if the 2019/21 locust infestation would have occurred simultaneously with the production failures of 2007/08? (Gaupp et al., 2019) analyzed potential impacts of further global warming to 1.5 or 2 °C on the likelihood of simultaneous crop failures and found that global wheat production failures are particularly sensitive to the degree of global warming. In the current storyline set-up these future warming levels are not explicitly imposed, but the counterfactual combining a factual 2019/21 reference scenario with the 2007/08 global production failure serves as an indication of event cascades impacted by global warming. This climatic counterfactual storyline involving a global food supply failure does not have a single climate hotspot, but is linked to modes of climate variability with the potential to disrupt near-simultaneously cereal production in the major breadbasket regions around the world, specifically El Niño-Southern Oscillation, the Indian Ocean Dipole, Tropical Atlantic Variability, and the North Atlantic Oscillation (Anderson et al., 2019; Gaupp et al., 2020).

Socio-economic perturbation. There was no strong and coordinated response of the international community to the 2007/08 world food crisis. Many exporting countries wanted to make sure that they protected domestic consumers from high world market prices, so they overreacted by raising export taxes and imposing severe export restrictions. This further reduced the grain availability at world markets, drove the prices high, and had unintended consequences of exacerbated hunger in the Greater Horn of Africa. A socio-economic perturbation is therefore addressed in a **second counterfactual storyline**: what if the 2019/21 locust infestation would have occurred simultaneously with the production failures of 2007/08 and the uncoordinated export restrictions?

Comparison between reference and counterfactual(s): The comparison of counterfactuals allows the evaluation of the effectiveness of regulating the unilateral policy responses on the food security indicators. The analysis of the local locust infestation of 2019/21 shows that the locust infestation had severe impacts on food security at the Greater Horn of Africa, which however remained limited to this region. From the two counterfactuals, we see that the compounding impact of local and global food security crises can be devastating. Grain supply for many import-dependent middle- and low-income countries in Africa and Asia would be reduced by one-third. Food security consequences would be especially severe for countries in the Greater Horn of Africa being struck in parallel by locust-induced production declines. Many import-dependent countries would not be able to buffer the failures with their own reserves and may not be able to buy grain at world markets due to prices reaching the level of the 2007/08 crisis. This highlights the importance for the international community to ensure food deliveries and aid for vulnerable populations in import-dependent developing countries.

Micro-stories allow assessing food security implications at the sub-national level using the INFORM Severity Index framework (Poljanšek et al., 2020). This framework also allows analyzing the impact of compounding crisis situations such as the ongoing conflict in Ethiopia as well as the efficacy of different humanitarian response options.

Implications and application: The analysis reveals that the global food security implications of the 2007/08 multi-breadbasket failures would be strongly exacerbated by the escalating export restrictions. Already the export restrictions of a few key middle-

Table 1
Overview of modelling options and data sources of information for the Africa food security storyline.

Storyline development step	Modelling approach	Data sources
1. Scope	Risk indices (INFORM), stakeholder input	Statistics on food security and trade are released by FAOSTAT (FAOSTAT, 2021), World Bank (Worldbank, 2021), and USDA's PSD database (USDA, 2021)
2.Remote climate hazard regions	Local and global crises in the Greater Horn of Africa*Local crisis*: The 2019/21 locust infestation*Global crisis*: The 2007/08 world food crisis	Statistics on food security and trade are released by FAOSTAT (FAOSTAT, 2021), World Bank (Worldbank, 2021) and USDA's PSD database (USDA, 2021)
3. Impact transmission	The Greater Horn of Africa region is highly vulnerable during global food crises, and the EU is one of the main providers of humanitarian aid to the region.	Data on bi-lateral aid flows are provided by the Financial Tracking Service of the United Nations' Office for the Coordination of International Affairs (UN-OCHA, 2023)
4. Socio-economic impacts	Three impact metrics:1) World market price volatility;2) National level impaired supply arising from the harvest failures and export restrictions; and3) The ratio of impaired supply to reserves.	A global model for world market prices of staple crops accounting for trade policies and storage (Schewe et al., 2017) and a food supply network model (Falkendal et al., 2021)
5. Climate perturbations	In 2007/08, drought conditions in several breadbasket regions reduced grain production globally. Such multi-breadbasket failures are projected to become more frequent under global warming.	FAOSTAT (FAOSTAT, 2021) and USDA's PSD database (USDA, 2021)
6. Socio-economic perturbations	In response to the multi-breadbasket failures of 2007/08 many exporting countries restricted exports aiming to ensure food security domestically. This dramatically reduced grain availability at world markets leading to price spikes and had unintended consequences of exacerbated hunger in the Greater Horn of Africa.	The Agricultural Market Information System (OECD, 2023) provides information on export restrictions during the 2007/08 world food price crisis
7. Comparison reference/ counterfactual	*Reference* – The factual locust infestation of 2019/21*Counterfactual #1* – what if the 2019/21 locust infestation occurred simultaneously with ONLY the production failures of 2007/08*Counterfactual #2* – what if the 2019/21 events occurred simultaneously with the production failures AND the export restrictions of 2007/08	

income exporters such as Argentina, Russia, and Ukraine are enough to jeopardize food security, globally. This highlights the importance for the international community to provide targeted help to these vulnerable key exporters. There needs to be a global coordinated effort to reduce market uncertainties and keep markets open in times of crisis. The analyses show that substantial mitigation potential exists in better coordinating policy responses in times of global food crises (Falkendal et al., 2021).

Integration and dissemination of the information in this storyline via the INFORM Severity Index framework ensures its propagation to a range of INFORM partner organisations. The INFORM platform is operated by the European Commission Joint Research Centre, and coordinated by the United Nations Office for the Coordination of Humanitarian Aid (UN-OCHA, 2023).

A summary of methodological approaches for this storyline is given in Table 1.

Storyline #2: Impacts of tropical cyclones on the European Union Solidarity Fund (EUSF).

Scoping process. An extraordinarily active Atlantic hurricane season in 2017 (Klotzbach et al., 2018) directly affected the European Union's outermost regions in the Caribbean. Particularly the island of St Martin (French overseas collectivity) and Guadeloupe were strongly hit by hurricanes Irma and Maria, with severe damage to human life, property and mangrove ecosystems (Walcker et al., 2019). The events in the Caribbean and mainland Europe are connected to the European Union (EU) via the European Union Solidarity Fund (EUSF) (Hochrainer-Stigler et al., 2017) which arranges payouts to member states (including their overseas territories) in response to disasters due to extreme natural hazards such as floods, forest fires, earthquakes, storms and droughts. In 2017 payouts due to disasters in the Caribbean and (particularly) the earthquakes in central Italy led to a potential negative EUSF capital position, which was avoided by using capital originally allocated for 2016 and 2018. This occasion triggered the question whether alternative, unprecedented yet plausible, realizations of past hurricane events could have compromised the EUSF. If so, this may reveal weak spots in the system impact causal chains and serve as guidance for further stress-testing under climate and socio-economic changes. This question is not readily answered by following generic probabilistic climate attribution approaches (Frame et al., 2020), but acknowledges the highly conditional problem statement required for this particular context. During the scoping process of this storyline, procedures for the assessment of risk of the EUSF capital being compromised were explored. Possible situations were investigated in which the EUSF would not be able to fund recovery and emergency operations efforts; the identification of such scenarios can be helpful to prevent the depletion of the fund. To this aim, alternative hurricane trajectories (or "downward counterfactuals", (Woo, 2019)), generated with natural catastrophe assessment models, were used to develop storylines of spatial and temporal compound events (Ciullo et al., 2021).

Remote climate hazard region. The remote climate hotspots for this storyline are the hurricane-prone territories of the Eastern Atlantic (Canary Islands, Azores, Madeira), Western Atlantic (Saint Martin, Guadeloupe, Martinique and French Guiana) and the West Indian Ocean. In 2017, the hurricane season was active with 17 storms, including Irma and Maria; EUSF contributed €48.9 million to recovery efforts. However, other tropical cyclones almost led to damages in the EU overseas territories in the Eastern Atlantic and the West Indian ocean. The annual number of hurricanes in these areas varies considerably (Knapp et al., 2010), and overall there is no clear trend in the observed frequency of hurricane development. However, an increasing trend in intensity with global warming is becoming apparent (IPCC, 2021).

Impact transmission pathway. The impact transmission of the intense hurricane season in the EU overseas territories reaches the European continent via (among others) the payout scheme of the EUSF.

Socio-economic impact. For this storyline, the main impact indicator is the capital availability of the EUSF fund, particularly the possibility of the fund not having enough capacity to cope with requested payouts. The amount that EUSF pays is based on recorded damages and the GDP of the affected region. If pay-outs are higher than the funds available, the EUSF can no longer fulfill its function. This scenario may become reality if multiple disasters coincide and/or persist over consecutive years.

Climate perturbation. The historic damages recorded for the tropical cyclones Irma and Maria were nearly €2 billion, and the EUSF sent nearly €50 million in aid. Meanwhile, efforts to recover from the major earthquakes in Central Italy received €1.2 billion from

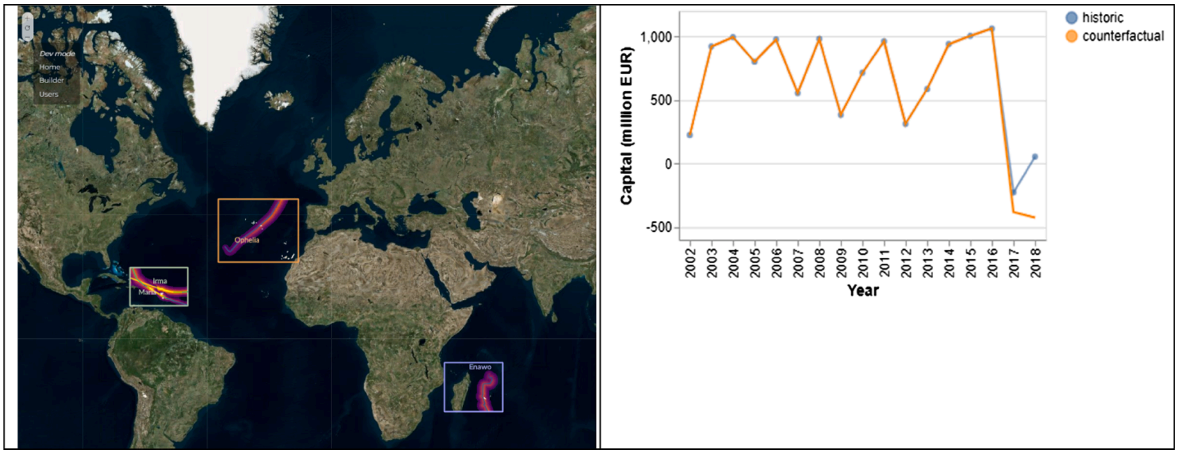

Fig. 3. Left: remote climate hazard regions for the EUSF storyline with historic and reconstructed cyclone pathways; right: development of historic and counterfactual capital level of the EUSF fund (Ciullo et al., 2021).

EUSF. Fig. 3 shows that in 2017 the funds dipped below €0. The EUSF coped with this by exceptionally anticipating funding allocated to 2018. With only €294 million in funds available for disaster relief this was left without major consequences as there were minimal payouts in 2018.

The storyline explores what could have happened if large payouts due to the 2017 earthquakes in Italy coincided with even more tropical cyclone damages abroad in 2017/18. The plausibility of this counterfactual scenario is illustrated by some near-misses in the 2017/18 season. Three hurricanes occurred in the Eastern Atlantic (Ophelia, 2017) and in the West Indian Ocean (Enawo, 2017, and Berguitta, 2018). Luckily, these hurricanes did not make landfall on EU outermost regions. The construction of downward counterfactuals showed that they could have reached these territories, and could have been disastrous enough to require EUSF aid. In that case the fund would not have been able to help. Due to the costly earthquakes in Italy, the EUSF's capital was depleted in 2017. Had the large payouts due to the 2017 earthquakes in Italy coincided with even more tropical cyclone damages abroad in 2017/18 this would have resulted in nearly €500 million in deficit (orange line in Fig. 3).

Climate perturbations are used to simulate such "alternative past" tropical cyclones. The perturbations are applied in two steps. First, interesting cyclone tracks are selected from a catalog of historic events and their alternative trajectories. The selection is made based on the maximum damage the alternative trajectories may cause in one of the target regions. The second step addresses global warming. With 2 °C global surface warming, the intensity of tropical cyclones may increase by up to 10 % (Knutson et al., 2021). This general range of intensity increases was used to simulate various tropical cyclones. The level of scientific understanding of the relationship between ambient atmospheric and oceanic temperatures and hurricane intensity justifies the exploration of intensified hurricanes and their potential damage via an adopted hurricane intensity range setting up a range of climate counterfactuals.

Socio-economic perturbations are applied by adopting different levels of (future) GDP to the overseas target regions, which affects the value of exposed objects to extreme events and the calculated EUSF payouts. Average GDP in the EU has increased by about 20 % since the EUSF was established in 2002. A range of increases in GDP of 0 % up to 20 % was used to simulate future socio-economic changes. In addition, policy changes are explored by changing the capitalization of the EUSF. The available EUSF capital depends on the amount contributed to it by EU member states. Currently, the EU annually contributes €500 million. Future increases between 0 % and 150 % were analyzed.

Direct economic damages from tropical cyclones were estimated using the CLIMADA impact model (Aznar-Siguan and Bresch, 2019). Direct damages were assessed as a function of weather-related hazards, exposure of people and goods to such hazards, and vulnerability of the exposed entities. The exposed economic value was calculated by downscaling regional GDP using nighttime lights data.

Table 2

Overview of modelling approaches and data sources of information for the European Solidarity Fund storyline.

Storyline development step	Modelling approach	Data sources
1. Scope	Recent Atlantic hurricane season in 2017 and related EUSF payouts	Historic payouts from the European Union Solidarity Fund (European Commission, 2023)
2. Remote climate hazard regions		Hazard data about historic tropical cyclone tracks are retrieved from the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al., 2010). Hazard data on counterfactual tropical cyclones are simulated by using forecast data retrieved by the THORPEX Interactive Grand Global Ensemble (TIGGE) program (Swinbank et al., 2016).
3. Impact transmission	Natural catastrophe assessment model CLIMADA (Aznar-Siguan and Bresch, 2019)	Nightlight data from the the DMSP-OLS Nighttime Lights Time Series (Lloyd, 2016) provided by NOAA until 2013 and the NASA's Black Marble data (Román, 2019) after 2013. Vulnerability functions are provided by (Eberenz et al., 2021)
4. Socio-economic impacts	Capital availability of the EUSF fund are simulated, based on the fund's payouts and capitalization rules.	
5. Climate perturbations	Tropical cyclones' intensity increases	Tropical cyclone intensity can increase between 1 % and 10 % in a 2-degrees warmer world based on expert knowledge (Knutson et al., 2020).
6. Socio-economic perturbations	*Socio-economic*: derived from GDP projections*Policy*: increase in the fund's annual capitalization	*Socio-economic:* Increase up to 20 %, based on the average GDP increase registered in Europe since the establishment of the fund (i.e., 2002) assessed using regional GDP data taken from (EUROSTAT, 2023) *Policy:* Annual capitalization increase up to 150 %, based on the pre-2014 reform capitalization levels
7. Comparison reference/ counterfactual	*Reference*: combination of historic tropical cyclones (Ciullo et al., 2021) ● *Counterfactuals*: simulated scenarios with ranges of combinations for: ● exposure increases due to potential increases in tropical cyclone intensity of 0 % up to 10 % ● GDP increases of 0 % up to 20 % ● EUSF annual capital increases of 0 % up to 150 %	

Comparison between reference and counterfactual(s): The comparison of counterfactuals allows mapping the boundaries of the tolerable operating space of the EUSF. The counterfactuals incorporate a range of increased hurricane intensity levels (0 % up to 10 %), GDP increases of 0 % up to 20 % and annual EUSF capital increases of 0 % up to 150 %. Critical EUSF capital conditions will occur when in subsequent years rare (and high-damage) events are combined.

The analysis of the occurrence of the historic storms Irma and Maria together with the "alternative past" tropical cyclones Enawo, Ophelia and Berguitta, reveals that the European Union Solidarity Fund (EUSF) capital may undergo severe stress unless the fund is recapitalized. When the fund is not additionally capitalized, the EUSF may be in deficit by up to €1 billion. A 50 % increase in EUSF capital may result in either a surplus or a deficit in the availability of funds, depending on the considered counterfactual. The capital level in 2017 is sufficient for all scenarios when the funds are increased by 150 % per year in capital. However, there are trade-offs underlying the policy negotiations for this level of capitalization increase.

Potential *micro-stories* can relate to the longer-term impact on these small islands of such worst-case events and focus on the long-term sustainability of these regions.

Implication and application: Payouts due to tropical cyclones can deplete the EUSF fund if large payouts abroad occur concurrently with disasters in mainland Europe. In a 2 °C warmer world in which cyclones are more frequent and more intense, it is wise to anticipate fund depletion. In 2021, the tasks of EUSF tasks have been transferred to the Solidarity and Emergency Aid Reserve (SEAR). The results of this storyline can inform how SEAR can cope with maintaining sufficient funds given the increasing climate risks. This storyline shows that the EU should increase disaster funds by at least 50 %.

A summary of data and modelling concepts is given in Table 2.

Storyline #3: Soybean production for European food supply.

Scoping process. The vast majority of all soybean consumed and processed in Europe is produced in areas concentrated in the Midwest US, Brazil and Argentina, together accounting for over 90 % of the total global soybean export (Wellesley et al., 2017). These main soybean production areas are exposed to varying patterns of climate variability and trends, having pronounced impacts on regional production volume and world trade volumes (Anderson et al., 2017; Torreggiani et al., 2018).

In addition, various societal responses to climate and environmental change affect the sector strongly. Rainforest conservation policies in importing countries impose additional criteria on the spatial extent of soybean exploitation and are considered to constrain options of producers to expand or transfer production regions (Gibbs et al., 2015; Heilmayr et al., 2020; Bager et al., 2021). Also changes in dietary preferences in importing countries may affect demand and hence trade volumes and prices (Willett et al., 2019; Ortiz et al., 2021).

This climate event storyline explores the potential climate change impact on temporary production declines in major soybean producing areas in the US and South America. It reconstructs a number of weather-induced soybean losses that occurred in 2012 and their impacts on global and European prices, trade and consumption patterns, and explores how these events could unfold in a future warmer world. In addition, counterfactual storylines also account for impacts of diet changes towards less meat consumption and forest conservation policies. The scoping process was guided by a consultation with NGOs representing local soybean producers, shaping the analysis of local climate impacts and the various counterfactuals.

Remote climate hazard region. A survey of global climate hotspots for agricultural drought in major food production areas (Ercin et al., 2019) contributed to the selection of the remote target regions and identification of climatic drivers of yield losses in South America and US. Weather events in Brazil, Argentina and the US affect the EU through soy transmission links, as was seen in the 2012 drought and the correlated trade responses. The storyline focuses on the 2011/2012 growing season which displayed an unprecedented loss in soybean yields that resulted from a combination of low precipitation and high summertime temperature in the US

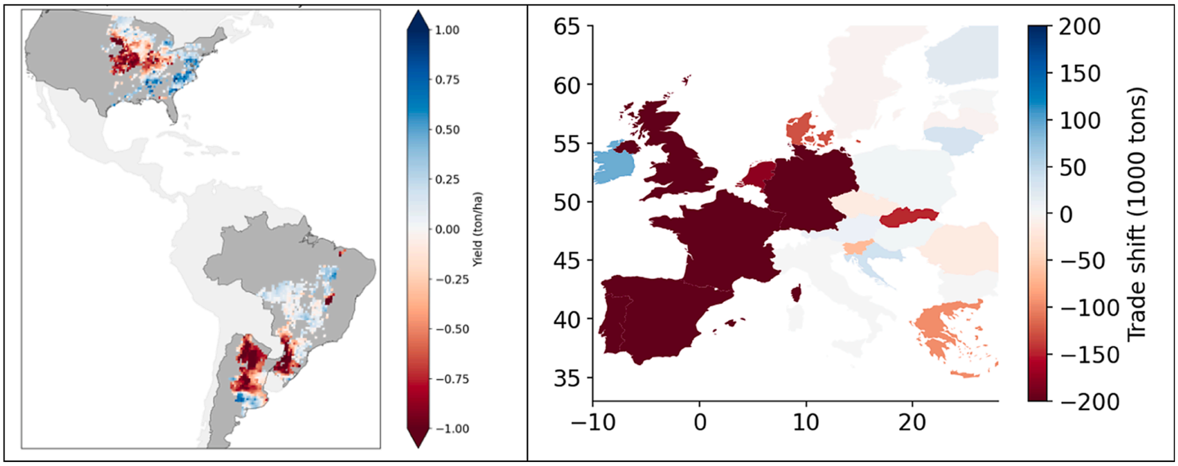

Fig. 4. Left: 2012 production shock of soybean in major producing areas relative to the 2000/15 mean (source: (Goulart et al., 2023)); Right: Changes in imported soybeans by European country in 2013 compared to the average of the 2011/15 period. Source: BACI bilateral trade data (Gaulier and Zignago, 2010).

(Goulart et al., 2021; Hamed et al., 2021) (see Fig. 4).

Impact transmission pathway. The dramatic increase in global demand for soybeans has led to a surge in supply from Brazil and Argentina. Large shares of agricultural land in both countries produce this crop, often at the expense of highly biodiverse areas. The concentrated production to these regions makes soybeans vulnerable to large shocks related to weather and crop disease. Consequently, the entire supply chain is vulnerable to disturbances in the local production sides. The EU is highly dependent on soybean as a livestock feed, for biofuels and in the food industry. Each year, the EU imports 14 million tons of soy, making it the second biggest importer worldwide and thereby highly vulnerable to global shortages.

Socio-economic impact. Soybean shortages lead to different socio-economic impacts, including shocks and anomalies on commodity prices, trade, imports and exports, consumption, and food security risk around the world. These socio-economic impact metrics are assessed with the global biosphere management model GLOBIOM (Havlík et al., 2014; Soterroni et al., 2018; Jägermeyr et al., 2021), and here include changes in bilateral trade flows, prices and value added, and changes in the consumption of soy for food, feed and other products (see Fig. 4 for an illustration).

Climate perturbation. A simulation of yield loss for future weather anomalies similar to 2012 was carried out for different global warming scenarios. From scenario simulations of the UKESM1-0-LL model (Sellar et al., 2019) under two Representative Concentration Pathways (RCP2.6 and 8.5), 30-year time slices were selected around the mid-century (2035–2065) and the late century (2066–2096). These climate simulations were used to simulate yield anomalies using the crop model EPIC-IIASA (Balkovič et al., 2014). Climate counterfactuals are created by selecting extreme events defined as seasons with equivalently large yield losses from the selected time slices for selected global warming levels (2.5 °C and 3 °C relative to the pre-industrial mean global temperature).

Socio-economic perturbation. A number of socio-economic counterfactuals were designed to explore the impact of implementation of alternative policies: i) a "diet-oriented policy", where EU citizens change to a more plant-based diet to reduce their livestock consumption by 50 % as of 2030 (reducing the dependency on soy imports), and ii) "no deforestation perspective", which enforces producer countries to prohibit conversion of primary forests to cropland (as of 2030 in the US, Argentina and Brazil). Socio-economic calculations were carried out using the GLOBIOM model forced with a SSP2 emission scenario (Havlík et al., 2014).

Comparison between reference and counterfactual(s). The different climate and societal alternatives reveal several relevant impacts. In the 2011/2012 reference scenario, European imports of soybeans decreased by 11 % compared to the year 2010. At the same time, producer prices in Europe increased by 21 %. Under the warmer climate counterfactuals larger soybean production losses are generated, cascading into larger market distortions. A "diet-oriented policy" reduces the European dependency on soybean consumption for its own markets. A "no deforestation policy" will modify the geographical distribution of local production regions. A reduced market sensitivity to climate impacts can be a result of protecting drought prone regions which currently contribute significantly to the trade volume to the EU.

Micro-stories can be used to describe specific implications for one of the many actors in this sector, for instance addressing conflicts on water use in soybean production areas with other sectors under sustained drying (Flach et al., 2020), shifts in employment in the agri-food business both in production areas and within Europe, drought impacts on domestic transportation (Marengo et al., 2021), risk of depreciated investments (Chain Reaction Research, 2018), trends in predictability of climatic and technological impacts on yields, the interactions between regional deforestation and increased magnitude and frequency of soybean losses (Flach et al., 2021) and the role of carbon pricing to reduce deforestation pressures.

Implication and application: a climate-induced reduction in soybean supply to the EU leads to an increase in prices of both meat and

Table 3
Overview of modelling approaches and data sources of information for the soybean production storyline.

Storyline development step	Modelling approach	Data sources and references
1. Scope	Trade statistics. BACCI bilateral trade data (Gaulier and Zignago, 2010) were used to calibrate the GLOBIOM model to the historical reference event.	FAOSTAT statistics (FAOSTAT, 2019) were used to assess import dependency
2. Remote climate hazard regions	Climate reanalysis archives and hydrological water resource modelling are used to generate spatial distributions of soybean production areas, water footprints (water use intensity) and agricultural drought.	Ercin et al. (2019). SPAM data (SPAM, 2019) and subnational statistics were used to identify harvested areas.
3. Impact transmission	The weather to crop yield variability transmission was done with a hybrid data/forecast model, combining machine learning and outputs from the global gridded crop model EPIC-IIASA.The impact transmission of socio-economic dynamics was simulated with the GLOBIOM model.	(Balkovič et al., 2014; Havlík et al., 2014; Goulart et al., 2021)
4. Socio-economic impacts	Socio-economic impacts were simulated using the global biosphere management model GLOBIOM	(Havlík et al., 2014; Soterroni et al., 2018; Jägermeyr et al., 2021).
5. Climate perturbations	Simulated soybean yields are generated by EPIC-IIASA, with climatological forcing from UKESM1-0-LL model under RCP 2.6 and 8.5 for mid 21st century.	CMIP6/ISIMIP3B model ensemble, UKESM1-0-LL (Sellar et al., 2019)
6. Socio-economic perturbations	Alternative socio-economic scenarios are imposed by driving the GLOBIOM model with SSP2	(Havlík et al., 2014)
7. Comparison reference/ counterfactual	*Reference* – the anomaly of the 2011/2012 season relative to a 30-yr time series of selected metrics.*Physical counterfactuals* – anomaly of 2011/2012 combined with the expected mean yield at a 2.5 °C and 3 °C warming relative to pre-industrial.*Socio-economic counterfactuals* –"diet-oriented policy" / "no deforestation policy"	

soybeans and therefore lead to a decrease in consumption. The “no deforestation policy” helps mitigate negative environmental impacts in the production areas from soybean trade. If successful policies and adaptation measures are adopted the future impacts of extreme events will be considerably reduced.

Table 3 shows an overview of model and concepts used for this storyline.

Short descriptions of other storylines involving complex impact cascades.

Apart from the collection of illustrative storylines described above, an increasing number of storyline studies appear in the scientific literature. Below a small sub-selection is presented without the elaborate description of each of the storyline ingredients.

Impact of TC landfalls in the US on European consumption and trade. Major tropical cyclones making landfall – besides causing devastating local damages and economic losses (the direct impact) – can result in macro-economic trade shocks and ripples through trade loss propagation (indirect impact). (Middelanis et al., 2021) analyzed the potential indirect impact on global (final) consumption by the New York/New Jersey landfall of hurricane Sandy (2012), showing that both downstream and upstream interactions can result in losses or gains of consumption in other parts of the world that are not directly affected. (Middelanis et al., 2022) focused on shock propagation in the trade network induced by the direct effects from the landfall of tropical cyclone Harvey (2017) and its global indirect economic repercussions, including impacts onto the European economy. These studies make include an impact assessment of climate change due to the response of intensity and size of tropical cyclones to global warming. Propagation and cumulative economic shocks by tropical cyclones are specific to many attributes of the event cascade. An event storyline built using a trade network modelling framework supports the mapping and quantification of climate changes footprints on specific steps in the impact cascades.

Flood-induced displacement caused by Tropical Cyclone Idai. (IPCC, 2022) concluded with high confidence that climate and weather extremes in all world regions are increasingly determining human displacement and contributing to humanitarian crises where hazards overlap with high vulnerability. Beyond financial considerations, the EU’s responsibility to protect people from vital threats also requires that displacement risk, and the means to reduce it, is factored into EU policymaking. Displacement can lead to a cascade of mutually reinforcing effects, increasing urbanization stress and fueling internal or transboundary conflicts (Desai et al., 2021). A tool to assess different drivers of humanitarian risk is the INFORM Risk Severity Index (Poljanšek et al., 2020). An analysis of the 2019 landfall of tropical cyclone Idai in Mozambique triggered national and international disaster relief funding and interventions of NGOs including the International Red Cross Red Crescent Movement. Apart from COVID19 and various reasons for blocking the access to humanitarian relief resources, the effect of climate change features on the specific INFORM risk assessment were analyzed using dedicated event storylines by (Mester et al., 2023). A set of historical counterfactuals is created by removing the effects of anthropogenic climate change on storm intensity and sea level, which are main drivers of coastal flooding and its consequences.

Impacts of Storm Xaver on infrastructure damage in German Bight. Global warming and sea level rise will continue to increase the frequency and severity of flood hazards across European coastal regions. Together with continued development of the coastal floodplains, coastal risk is projected to grow by a factor of two by 2050 (Jongman et al., 2014). Storm Xaver made landfall in the German Bight on 6 December 2013. The coinciding surge and tide created “record breaking water levels for large parts of the southwestern German North Sea coastline” (Dangendorf et al., 2016), which boosted the estimate of the water level with a 1:200 year probability exceedance by 40 cm. Although the storm led to large direct damage in United Kingdom (UK), Netherlands, Germany and Denmark (Wadey et al., 2015; Rucińska, 2019), the considerable improvements in coastal protection and disaster risk reduction management significantly reduced the total damage and number of people affected compared to a similar storm in 1953 (Spencer et al., 2015; Wadey et al., 2015). Both the large anomaly of the storm and the complex cascade of impacts (particularly relating to the macroeconomic losses from long-term business interruption, damage to transportation networks and other critical infrastructure) create deep uncertainty that is difficult to assess using probabilistic approaches. A storyline analysis by (Koks et al., 2023) quantified the local direct physical damages to critical infrastructure and the (indirect) macroeconomic losses due to infrastructure failure for different sea level scenarios, developments of the spatial extent of risk prone assets and adaptation strategies.

5. Reflection on methodological approaches and application domains of event-based storylines

This gallery of climate event storylines illustrates the wide diversity of impact-pathways of climate change features. The pathways connect locations separated by long distances via complex physical and socio-economic cause-effect chains propagating over multiple time scales. Diagnosing the impact of climate change on the impact cascades involves a methodological approach that generally involves synthetic model outcomes, and makes the (inevitably) subjective choices on assumed boundary conditions, uncertainty estimates and analysis tools explicit.

To make the construction of the storylines and its climate analyses transparent and reproducible, we have introduced a methodological protocol that distinguishes a set of predefined storyline development steps, and have applied this protocol to three examples. The purpose of this inventory is to illustrate the practical implementation of the physical climate event storylines (Shepherd et al., 2018; Sillmann et al., 2021), and discuss concrete choices made to include stakeholder views, select analysis tools, interpret findings, represent uncertainty and provide useful information to societal actors.

For each of the storylines several criteria were evaluated assessing their potential to facilitate societal uptake (Table 4). All three storylines are built on historic events, and have used impact mapping tools that have either been shown to give realistic results in earlier applications, or show good correspondence with observed impacts. The counterfactuals are rooted in historic climate trends or apply well-documented climate projections or physical scaling protocols, which provides *realism* to the storylines. Apart from a broad societal interest in the topic of analysis most storylines have gained *relevance* by concrete contributions by stakeholders. An explicit analysis of potential adaptation strategies is included in a few storylines, and standard risk reporting tools are used to support *risk-*

Table 4
Evaluation of the criteria for societal uptake of the climate event storylines.

Criterion	Africa food security	European Solidarity Fund	Soybean production
Realism	Evidence of plausible joint occurrence of multiple drivers of local food security	Historic event selection; evidence of consecutive active hurricane seasons	Historic event and subsequent impacts; stakeholder reports; physically based climate projections; documented agronomy models
Relevance	Broad concern of food security and societal instability and displacement	Stakeholder participated in storyline development	Societal attention for environmental impacts, land allocation and forest conservation
Risk-informativeness	Exploration of future resilience and mitigation strategies	Explore different GDP and climate conditions	Visualization of illustrative metrics on soy consumption, trade and prices

assessments. Risk-oriented information is derived from the exploration of expected future climate and/or socio-economic conditions.

The storylines explored in this paper are intended to map risks to the European socio-economy that emerge from an immensely complex cascading set of event-impact chains (triggered by remote climate features), which cannot be analysed without a very stringent set of constraints imposed on available projection outputs from climate and impact assessment models. The concept does not rely on a standardized climate modelling toolset such as CMIP6 (Touzé-Peiffer et al., 2020), but instead combines stakeholder evidence, historic events and a mix of data analysis and model experiment techniques to arrive at evidence based narratives of "unfoldings of events and their hypothetical future counterfactuals" (Shepherd et al., 2018). As such it combines quantitative and qualitative elements (Shepherd and Lloyd, 2021), where the quantitative information gives a meaningful contribution to the risk assessment from complex climate change processes, and the qualitative elements provide insights in relevant pathways of risk transmission. By exploring a range of present-day or future counterfactual conditions in most storylines, crucial climatic elements in the storylines are complemented with a quantification of the underlying uncertainty. However, given that the event cascades and a large number of compounding boundary conditions or contextual settings are prescribed, any probabilistic statement on the outcome of the storylines is highly conditioned on these assumptions, and thus heavily constrained. Storylines like these may serve as a stress-test for particular critical societal functions, or contribute to exploratory foresight analyses of future societal developments (Wiebe et al., 2018). However, a review of storyline applications in the climate change domain is out of scope of this paper (Baldissera Pacchetti et al.).

The prime purpose of this paper is to document a methodological protocol to construct storylines that can contribute to the exploration of potential implications of climate change for a collection of societal topics. The steps in the protocol are organized around a central narrative of the chosen storyline, which is segmented into more or less standard scripting building blocks. Surrounding this central narrative the communicative power of the storylines can be promoted by a carefully designed visual and textual language (Jack et al., 2020), application of story maps (Vollstedt et al., 2021), enhancing personal context by use of personas or actors (Moezzi et al., 2017), and other attributes. However, a standardization of the storyline approach has to appreciate the sheer variety of approaches and analysis needs within a specific storyline, emerging from the inherent complexity of the topic of analysis. Even with a structured outline of the storylines, methodological approaches to assess scope, remote hazard regions, impact metrics, perturbations and comparison of counterfactuals show variability as a result of significant variability of the nature of the considered impact pathways and application domains. A standardization of storyline ingredients is a necessary basis to canalize efforts and connect different impact domains and stakeholder groups.

The synthesis of a collection of storylines does allow extraction of generic principles, calibration of crucial parameters in for instance macro-economic supply–demand interaction models (Robinson and Roland-Holst, 1988; Partridge and Rickman, 2010; Otto et al., 2017), or to build conceptual system dynamics or Bayesian network models (Bala et al., 2017) exploring key dynamics,

Table 5
Key elements contributing to the storyline application criteria described in section 2.

Criterion	Storyline development elements contributing to criteria
Realism	● use historic event and impact-chains as a starting point; this provides a realistic reference to plausible situations ● anticipate divergent levels of understanding and intrinsic interests by different categories of stakeholders ● invest in efforts to create bridges of confidence and trust, to make complexity of remote climate risks tangible and manageable by day-to-day business of stakeholders ● an iterative storyline development enhances stakeholder involvement; mutual learning can be promoted by testing prototype storylines with stakeholders
Relevance	● careful documentation of drivers, boundary conditions and impact metrics of historic events using stakeholder experience as input ● improve reference to broadly accepted scenario frameworks by making explicit linkages to global warming levels and Shared Socio-economic Pathways (SSPs) ● use observations and witness testimonials from stakeholders in a "micro-stories" format; they stimulate empathy and consideration of multiple perspectives, contributing to awareness raising and appreciation of the multiple dimensions of climate risks
Risk-orientation	● demonstrate the plausibility of the event chains conditioned on specified climatological and socio-economical boundary conditions ● consider including risk mitigation options as counterfactuals in the event storylines, to illustrate the impacts of taking risk reduction measures

vulnerabilities and adaptation options under specific sets of assumptions. Also integrated or cross-sectoral climate change assessments carried out by these approaches rely on explicit or implicit choices on scope, boundary conditions and interactions between drivers and impacts. As such, a storyline structure as described above can also be applied to this cross-sectoral climate impact assessment.

Practical guidelines to meet application criteria.

Adopting a generic structure for the development of climate event storylines allows to identify a number of practical guidelines to support future applications of the storyline concept for the understanding of complex climate risks.

The selection and design process of complex event-impact chains is usually triggered by historic events and the presence of a societal stakeholder group that is particularly exposed to such type of event cascades. This introduces a subjective element in the chosen transmission pathways, boundary conditions and impact metrics. Making these assumptions explicit provides a powerful tool to enhance awareness of conditional dependence, compounding drivers and sources of uncertainty. To utilize this tool due attention needs to be paid to the robust documentation of assumptions, reasoning, and methodology (Sillmann et al., 2021).

The reference storylines are based on historical events linked to remote climate impacts on a European socio-economic sector. Possible impacts of climate change are estimated by perturbing the reference storylines in multiple ways: climate change can affect intensity or frequency of climatic drivers, the transmission pathways and the societal response. Ideally, stakeholders are central to the selection of storylines, to ensure the relevance of the analysis and promote the uptake of results. However, for some storylines illustrated above, it is not immediately obvious what societal actor should be considered to be the prime "stakeholder" invited to respond to the analysis findings. Socio-economic impacts may affect a very broad range of societal actors, or lead to unclear or even divergent optimal responses by different stakeholder groups. In practice an iterative approach with long-term engagement with stakeholder groups is usually necessary and simultaneously challenging. Most of the storylines illustrated in section 4 followed a staged iterative approach consisting of showcasing initial science-based storylines compiled by the researchers, and subsequent finetuning of boundary conditions and impact metrics based on stakeholder experience. While this is a good baseline for storyline co-creation, the approach is rather stakeholder-informed than stakeholder-driven.

During the development of the storylines illustrated here several key elements were experienced to contribute particularly to the criteria that should be met to be a useful source of information supporting the assessment of climate change implications for a specific target domain (see section 2). These elements are presented in Table 5.

The standardization of storyline characteristics and criteria also proved to support the (usually required) interdisciplinarity of the research teams. The protocol contributed to mutual understanding and adjustment of disciplinary science output to create the comprehensive interdisciplinary storylines aligning the multiple elements (remote climate hazard regions, impact transmission, socio-economic responses). Selected insights from the storyline development teams may further inform practical guidelines for storyline development, and are shared in Table 6.

Storyline visualization.

The storylines illustrated in Section 4 are supported by a storyline visualizer platform, which was structured according to the protocol described in section 3 (RECEIPT project team, 2023). The visualizer greatly supported the standardization and harmonization

Table 6
Practical insights from the storyline development teams.

Main topic	Practical insights
Why or when can a storyline approach be helpful?	Storylines… ● can help to connect previously disconnected variables (e.g. crop yield and price); ● allow to focus on 'unseen' extreme events that may be relevant to society; ● allow exploration of climate change impacts on complex event-impact chains that are otherwise difficult to resolve; ● allow unpacking 'black-box' interactions for stakeholders, illustrating cause and effect rather than risks and uncertainties; ● enable formulation of a wide range of societal stress-tests using extreme – yet plausible – events which can be visualized, communicated and connected to history, experience and memory of the affected parties; ● offer the possibility to explore both worst-case and optimal response scenarios in a transparent, realistic and consistent manner.
Main difficulties or obstacles	● Storylines are highly context-specific, giving the risk of narrowing the perspective on climate change features (e.g. by focusing on worst-case scenarios); ● Reaching out to potential stakeholders can prove difficult when limited data is available; ● Trade-offs need to be made between rich qualitative event descriptions and quantitative modeling limitations; ● Difficulty in finding selection criteria for representative events from large data ensembles; ● Risk of making arbitrary assumptions on the magnitudes, geographical locations, or event-impact chains; ● Occasionally not straightforward to scale the magnitude of the impact with level of global warming. ● Balancing detailed versus simplistic assumptions on combined and cascading uncertainties across all storyline elements; ● Difficult to manage expectations and/or requirements of stakeholders.

of the storyline approach across different disciplines and application domains, and structured the adjustment process of the interdisciplinary storyline production teams by the application of a coherent and well-defined narrative and its supporting elements. This has facilitated the explicit formulation and justification of storyline assumptions and structure. The documentation of subjective assumptions does enable the storyline approach to reduce complexity by selecting representative scenarios that are relevant for specific societal applications.

Application domains.

Climate risk assessments are supporting a numerous number of societal applications and sectors. The climate event storylines described in this study generally serve the assessment of complex risks emerging from transboundary transmission of climate hazards to socio-economic impacts, that can materialize in many different manners (Carter et al., 2021). A coherent description of potential application domains is not straightforward, so again we use the gallery of storyline illustrations to provide a selective overview.

The storyline on the Greater Horn of Africa provides information on cascading food security triggers, including the potential implications of major climate-induced global cereal production declines. The World Food Program enriches their subnational food shock impact assessments with global drivers of these impacts. The INFORM risk framework is used by the European Commission to prioritize humanitarian and emergency assistance and anticipate, prevent and prepare for famines and food crisis, including through development agreements such as the new EU-OACPS (Organisation of African, Caribbean and Pacific States (OACPS) Partnership Agreement). Evidence on trends in risk for humanitarian crises can support policy formulation on risk management building on enhanced climate attribution of hazards and impacts (see (IPCC, 2021, 2022)), and initiatives to protect people displaced across borders in the context of disasters and climate change, such as the Platform on Disaster Displacement (PDD). Causal event pathways similar to the one explored here can serve as a blueprint for mapping impacts of geopolitical disruptions like the Russian-Ukraine 2022 war on African food security, as illustrated by (Gbadamosi, 2022).

The EUSF storyline is used to stress-test the EUSF, which is to be merged with a newly formed European emergency aid fund, the European Support Instrument. It provides support to choices regarding the fund capitalization and pay-out protocols. However, major hurricane event cascades have the potential to affect other European policies and regulations, including financial disclosure schemes, national catastrophe financial protection and solvency (e.g. stress and sensitivity tests performed by the European Insurance and Occupational Pension Authority (EIOPA, 2021)), and identification of remote climate risks in national and European climate risk assessments and adaptation strategies.

The soy market has many actors, including soybean producers, traders, food processing companies, but also consumers, policy makers, financing industry and NGOs addressing environmental or social wellbeing aspects. The relevance of the storyline is supported by the large economic value, the contribution to food supply in Europe, evidenced exposure to climatic pressures, and societal attention to efficient land allocation and environmental impacts of soybean production and consumption. The illustration of the impact of changing characteristics of climate extremes and socio-economic interventions in well-constrained climate event storylines are used in policy simulations to support for instance development of international policies on land management or food security (van Meijl et al., 2020). It also serves as a stress-test in activities aimed at preparing for global shocks in one or more major food sectors, both for public and private company responses. And it can assist in shaping the communication and intervention policies of NGOs active in the field.

6. Conclusions

A methodological protocol is proposed to construct climate event climate storylines, designed to analyze and document complex cascading event-impact chains contributing to societal climate risk. The protocol distinguishes a number of standardized steps in the narrative, connecting a (remote) climate hotspot region to a particular socio-economic impact to be explored for a baseline and one of more alternative realizations of the storyline. It includes stakeholder input to define the scope, allows for the exploration of alternative response options, and mixes qualitative and quantitative components to construct the storyline.

Baseline versions of the storyline are usually rooted in historic events where documented hazards and consecutive impacts are captured in data analysis and modelling tools that are able to represent essential dynamics of the event evolution. Climate change perturbations and alternative societal configurations are derived from plausible projections and scenarios, and resulting impacts are mapped for one or multiple counterfactual realizations of the storyline.

A set of criteria is defined to promote the societal relevance and uptake of the storylines. They should be expected to be realistic, relevant and risk-informative. A list of three example storylines is described and explored in this paper, to illustrate the protocol and the application of the criteria.

The protocol and criteria checklist are shown to enable covering a wide range of storylines for a diverse set of sectoral applications, and help to standardize the design and application of climate event climate storylines.

Declaration of Competing Interest

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.

Data availability

Data will be made available on request.

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