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A joint framework for studying compound ecoclimatic events

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Abstract

Weather and climate extremes impact vegetation functioning and trigger disturbances that affect ecosystem dynamics over periods longer than each event's duration. The projected increased frequency or intensity of extreme events might thus amplify ecological impacts and reduce the biosphere's CO_2 mitigation potential, but multiple feedbacks between ecosystems and climate extremes need to be considered in risk assessments.

In this Perspective, we first discuss the strengths and limitations of two broadly used approaches to study the impacts of climate extremes and disturbances on ecosystems: climate risk and disturbance ecology. We propose a unified framework (compound ecoclimatic events) that decomposes events into climatic drivers, stressors, ecological factors, impacts, and their sources of variability, and further incorporates feedbacks between ecosystem processes and stressors. We then illustrate how this framework can be used to develop ecoclimatic storylines to quantify uncertainties associated with internal climate and ecological variability and to quantify the human fingerprint on high-impact ecoclimatic events.

Introduction

Weather and climate extremes (hereafter climate extremes[1], see Glossary) have become the most visible expression of climate change since the 2000s[2]. Record-breaking events such as the hot-dry summers of 2003, 2010 and 2018 in Europe[3] and of 2019/20 in Australia[4], or the prolonged 2020 Siberian heatwave[5] have gathered widespread attention due to their unprecedented impacts on environmental and social systems. It has also been suggested that some forests might be losing their ability to cope with or recover from extreme events [6–9]. For example, in the year following the drought imposed by the strong 2015/16 El Niño, tropical forests in Africa and America showed declining biomass trends rather than signs of recovery[10]. In boreal North America, loss of resilience to more frequent fires was found for some black spruce forests[11]. In central Europe, widespread tree mortality associated with the 2018-2020 extreme summers[8,12,13] highlights how rare[14] consecutive extreme events might trigger unexpected[8] trajectories.

With the increase in frequency, intensity or extent of climate extremes in the coming decades[15], an increasing fraction of global ecosystems is likely to be affected by high-impact events recurring faster than recovery periods, possibly pushing them away from their current states[17–19]. Climate extremes impair plant functioning and growth directly[20,21], but also indirectly by contributing to extreme fires[3,22–24], massive insect outbreaks[25,26], or fungal and pathogen attacks[27–29]. Forests are particularly vulnerable to repeated disruptive events since they can take several years to recover from severe climate extremes or large-scale disturbances[17,30]. Compounding effects between climate extremes and ecosystem disturbances[31] might thus set off cascading impacts such as forest degradation[32,33], large-scale tree mortality events[6,7] and altered composition or structure[19]. These factors all ultimately impact the ecosystems' carbon balance, thus contributing to carbon-climate feedbacks, but both positive and negative effects have been observed[34–36].

Quantifying the anthropogenic fingerprint on high-impact events, referred to as impact attribution, is crucial to better understand the drivers of ongoing ecological changes and to anticipate potential destabilization of ecosystems resulting from the compounding impacts of extreme events and disturbances under anthropogenic change. Attribution of single climate extremes to human-driven climate change is challenging[16,37], but attribution of impacts is further complicated by diverging responses of coupled processes to climatic drivers[20], interactions between disturbances[31], ecological memory [38,39] and past disturbance legacies[32,40]. Moreover, non-climatic anthropogenic drivers such as elevated CO_2, nitrogen deposition, biodiversity loss, air pollution and near-surface ozone, further contribute to increase or decrease forest vulnerability to climate extremes, resulting in diverging feedbacks whose net effect is poorly constrained.

In this Perspective, we first discuss the strengths and limitations of two widely accepted approaches to study high-impact events which reflect distinct ways of perceiving and analysing high-impact ecoclimatic events across scientific domains: climate risk and disturbance ecology. We show that while they provide complementary views on these events, neither can effectively account for the multiple feedbacks between climate, ecosystem dynamics, and disturbances discussed above. We argue that a systemic perspective linking the climate, ecological and human domains is needed for improved process understanding about feedbacks between climate extremes and ecosystems and for attribution of impacts to natural vs. anthropogenic processes.

Building on the climate risk and disturbance ecology approaches, we propose a systemic framework to analyse the causal relationships between climate extremes, disturbance regimes, and ecosystems, and to disentangle natural versus anthropogenic sources of variability, a requirement for formal impact attribution. Finally, we illustrate how the framework can be used to develop ecoclimatic storylines for attribution of high-impact events and for robust projections of climate change risks to ecosystems. This Perspective has a focus on forests and the carbon cycle due to their relevance for carbon-climate feedbacks[20,41], but the framework and overall reasoning about attribution and uncertainties can be extended to a broader range of systems and processes.

Viewpoints on ecoclimatic events

Here, a high-impact ecoclimatic event is defined as a climate and/or human-driven event that results in changes on relevant ecological processes or state variables (such as productivity, biomass, composition, structure) that exceed their normal variability range, which is necessarily system and problem dependent. High-impact ecoclimatic events such as fires, droughts or storms have been referred to interchangeably as climate extremes[20,44,45] or as disturbances[17,40], and studied independently by two broad research fields: climate risk in hydrometeorology and climatology[16,20,46], and by disturbance ecology[17,19,40,47]. We first compare the elements included in each of these two perspectives (Fig. 1), discuss their respective advantages and limitations for process understanding, and provide examples of how relying on a single perspective can result in incomplete or inconsistent conclusions about the underlying drivers and ecological dynamics of a given event.

Climate risk perspective

While the definition of climate extremes is agnostic about impacts, **climate risk** perspectives typically focus on events that have negative impacts [44] (Figure 1). This definition has been later extended to include non-extreme individual climate anomalies that result in typically adverse impacts, when in combination[20,21,32]. Based on this perspective, it has been shown, for instance, that climate extremes drive a large fraction of interannual variability in global gross primary productivity (GPP), with drought and hot temperature extremes being the most relevant drivers of reductions in GPP[20,48].

However, climate extremes or **compound weather and climate events** can be associated with diverging impacts on ecosystem functioning, for example productivity or growth, and some climate extremes might not lead to any measurable impacts[3,49–51]. Focusing only on extreme or detrimental impacts can, however, result in relevant aspects of ecological responses to environmental conditions being overlooked, namely how ecosystem type or biodiversity can modulate responses to climate extremes[52,53]. For example, the heat and drought events in Europe in 2003, 2010 and 2018 were associated with both positive and negative impacts on GPP and net CO_2 uptake, explained by differences in land-cover composition and seasonal legacy effects[54–56].

The categorization of different compound weather and climate event types allows to define clear methodological guidelines that facilitate data analysis and process understanding[57], but ecoclimatic events do not usually fall into single types. In climate risk, climatic variables are considered the top-down drivers of hazards and impacts (Figure 1), but it is known that hazards can be further influenced by ecosystem functioning and/or structure. For example, stomatal responses can modulate drought intensity[55], or impaired tree defence can facilitate the occurrence of insect outbreaks[31].

The study of climate extreme impacts on ecosystems is further complicated by the dominant role of ecological dynamics (mortality, competition, succession), disturbance history and their feedbacks, which are not fully considered in climate risk perspectives[58]. All ecoclimatic events are to some extent multivariate, since ecological processes are influenced by multiple climatic drivers. For example, photosynthesis depends on water, temperature and light availability. Importantly, impacts can also be multivariate, as multiple interacting facets of ecosystem functioning respond differently to the same environmental controls, for example, photosynthesis and respiration, both controlling net ecosystem productivity[20]. Additionally, events are typically preconditioned, given that past environmental conditions affect initial ecosystem structural and physiological conditions, therefore modulating the impacts of a given event[12,40] or the magnitude of the hazards[55]. Legacy effects from past climatic conditions[39] or extremes[30] makes events temporally compounding, especially if multiple events occur during recovery periods. The latter are particularly important for high-impact events[30,33] under transient climate conditions, when recurrence intervals can outpace recovery times[17].

Finally, in climate risk, human influence is typically limited to the effects of climate-change on hazards, vulnerability and impacts[58]. For ecological problems, however, it is important to consider that humans influence a much broader range of ecological processes and states that have the potential to directly or indirectly influence both hazards and impacts of extreme events, through their impacts on landscape structure (deforestation, fragmentation, homogenization, urbanization), ecosystem composition and structure (management), biogeochemical cycling (elevated CO_2, nutrient fertilization, air pollution), and disturbance dynamics (pesticides, fire mitigation). Some of these effects are detrimental, but others can be beneficial. For example, landscape fragmentation associated with human activities has been shown to influence trends in burned area in opposite directions depending on the biome type[36,59], and for certain tree species, stand-thinning can be used to directly mitigate drought conditions or impacts[60,61].

Disturbance ecology perspective

Disturbance types[17,43], sometimes referred to as agents[31] or drivers[40], range from low-intensity to destructive perturbations and include abiotic natural processes such as fires, droughts, hurricanes, floods, volcanic eruptions or biotic agents such as insect outbreaks and pathogens, as well as human activities such as logging, forest clearing, land conversion or wars[17,31,40,43]. Some studies further consider weather extremes, such as minimum temperature extremes, snow and frost events[31,43,45] or even climate variability patterns, such as ENSO[40], as disturbance types or agents. An **extreme climatic event** that triggers adverse ecological impacts, as defined by Smith[44], can therefore be considered a rare and severe disturbance. Several aspects of disturbance ecology that find analogues in climate risk frameworks, but there are also important differences (Figure 1).

Drivers of **ecosystem disturbances** can be climatic, biotic or anthropogenic factors, rather than exclusively climatic as in climate risk perspectives, which can result in ambiguous categorizations and imprecise definitions[40,62]. For example, in ecological studies, drought definitions range from precipitation metrics to qualitative assessments based on the impacts themselves, which results in different event types being studied as "droughts"[62]. In a recent review of ecological drought studies, it has been shown that circa 50% of the events studied were within the normal climatic variability range. Moreover, manipulation experiments, for example of drought, typically focus on one dimensional driver, rather than embracing multivariate approaches as in climate risk, which can result in underestimation of impacts[63].

Climatic and atmospheric, biotic or anthropogenic factors are typically considered as independent drivers[40], which poses challenges for systemic understanding of disturbance dynamics. It is known that biotic drivers, for example insect outbreaks, are largely influenced by climate themselves (insect development and survival), modulated by ecosystem properties (host distribution, vitality), which can result in interactions among disturbances (wind damage or drought stress)[31]. These links can be included by considering a hierarchy of drivers and typifying events as multivariate, spatially or temporally compounding, as currently done in climate risk.

Naturally occurring disturbances are considered intrinsic components of ecosystem dynamics, influencing landscape dynamics and composition at time-scales from months to centuries[64], and can have either or beneficial effects. For example, fire is a key ecological process shaping global biome distribution[65,66] and, in fire prone regions, controlling reproductive cycles, plant community composition and ecological diversity[67], even if today fire patterns are strongly influenced by human action[36]. Thus, it has been pointed out that the separation between normal variability and disturbance is, to some extent, arbitrary[43] and that the amount of change needed to consider an event as a disturbance is necessarily relative to the spatial and temporal scales of the system studied[47]. This view contrasts with the definition of hazard in climate risk as a necessarily detrimental process. **Disturbance impact** is, consequently, more broadly defined than in climate risk perspectives.

Individual disturbances are typically stochastic and considered unpredictable, but their long-term patterns, constituting the disturbance regime, are expected to be predictable to some extent[17]. The characteristics used to describe disturbances are analogue those used to describe climate-related hazards, for example return times[68], and similarly rely on probabilistic definitions such as the probability of disturbance of a given **intensity**, **severity** or extent to occur[17]. However, the concept of **disturbance regime** in the consideration of hazards is not considered in climate risk (Figure 1). The concept of **post-disturbance recovery**[64,68], included in the disturbance regime, or disturbance history is also not considered in climate risk perspectives.

In disturbance ecology perspectives, it is recognized that human activity not only influences drivers of high-impact events through climate change but also through other environmental changes, for example in atmospheric composition and nutrient cycling, or transport of invasive species and pests. Moreover, several system properties[40] that influence disturbance intensity and/or ecosystem vulnerability (such as tree height, stand density, landscape structure) are influenced by management practices and other human activities. This is not considered in climate risk perspectives that focus on effects of human-driven climate change.

Reframing ecoclimatic events

We have shown that the two viewpoints widely used to study high-impact events on ecological systems – that of climate risk from the hydrometeorology and climate science community, and disturbance ecology, from the biology and ecology communities – share several analogue elements (Figure 1), but with important differences in definitions, terminology and in the processes considered. When considered individually, neither can effectively account for the multiple feedbacks between climate, ecosystem dynamics and disturbances needed to understand high-impact ecoclimatic events. Building on these two perspectives, we propose a systemic framework to analyse the causal relationships between climate extremes, disturbance regimes, and ecosystems. We then discuss how this may allow improving our understanding of impacts of climate extremes and disturbances, their sources of variability, and associated uncertainties.

Compound ecoclimatic events framework

A compound ecoclimatic event is defined here as a relatively time-discrete event, where the combination of multiple drivers and/or stressors alter ecosystem functioning, structure, or composition beyond a given reference state or variability. Given that many disturbances are intrinsic ecosystem components[64], and that a given event can have both beneficial or detrimental outcomes, we propose a value-neutral framework to study compound ecoclimatic events. Analogous to the definition of ecosystem disturbance, we further acknowledge that the separation between normal variability and "high impact" is to some extent arbitrary[47] and likely to be user and/or problem dependent. Finally, we recognize the need to account for the role of ecosystem functioning, structure, composition, and of recovery dynamics, in influencing vulnerability to stressors and/or in modulating the stressors themselves.

Compound ecoclimatic events are conceptually decomposed into climatic drivers, stressors, ecological factors, impacts, and their causal relationships, including potential feedbacks between these components, as internal factors (Figure 2). Human activities are considered as external factors. We further distinguish between two sources of variability of climatic drivers, ecological factors and stressors: climatic and ecological naturally-driven vs. anthropogenically driven variability.

Climatic drivers are, similarly to the climate risk perspective, climate and weather processes, variables and phenomena, that can be multivariate. These include, for example, concurrent high temperatures and low relative humidity. A stressor is defined as a physical, chemical or biological phenomenon that can impose changes in ecosystem functioning or states and has the potential to – but does not necessarily – cause adverse effects. Stressors include phenomena typically considered as ecosystem disturbances such as fire, drought, insect outbreaks or pests, but also a wider range of phenomena. These include direct effects from unusual climate conditions (for example, heat and atmospheric dryness stress) or potentially harmful effects of human activity such as air pollution, ozone, logging[69]. Stressors can be multivariate if they are driven by common climatic drivers, for example, drought and fire, and temporally compounding if their effects compound with those past events. For example damage from wind is known to promote the development of insect populations and subsequent outbreaks[31].

Ecological factors modulate the magnitude of stressors or vulnerability to given stressors (Figure 2). These correspond to a broad range of ecosystem properties (for example, species composition, traits and structure, biodiversity), states (available water, phenological phase), functioning (stomatal regulation), as well as landscape properties (topography, connectivity, aridity). For example, wildfires are strongly controlled by weather but further depend on ecological properties such as fuel load, type and size[70], and plant functional traits have been shown to influence drought intensification[71]. Vulnerability to hot and dry extremes depends on the phenological stage at which they occur[56,72], and forest structure, composition and functional diversity have been shown to modulate forest resistance and resilience to droughts[35,73,74]. Ecological factors are further influenced by legacies resulting from the impacts of past events and recovery dynamics (dashed line in Figure 2). These legacies include damage to tissues and impaired functioning[30] or reduced availability of resources following an event that might increase vulnerability to further stressors[31]. It is worth noting that legacies can also be positive, if the response to a stressor increases resistance to subsequent stressors, that is, acclimation or adaptation at organismic or ecosystem level. Such positive legacies can be due, for example, to changes in water use efficiency, nutrient availability or in species composition, as reported for some grasslands[35,38].

Variability in climatic conditions such as temperature, precipitation and radiation influences ecosystem functioning and carbon cycling[75,76]. Conversely, vegetation activity and composition modulates land-atmosphere interactions[77], thereby influencing atmospheric conditions such as cloud cover[78]. Therefore, potential bidirectional interactions between climatic drivers and ecological factors should be considered when deemed relevant (dashed vertical arrow in Figure 2).

Impacts of compound ecoclimatic events are significant departures of ecosystem functioning or states from a given reference state or variability range, and can be positive or negative. The baseline and the criteria and metrics used to evaluate the significance of departures need to be clearly defined for each study, for example as thresholds based on long-term mean states or variability. Since stressors (for example extreme heat) can impact multiple interacting processes simultaneously (photosynthesis, autotrophic respiration, growth, phenology), impacts can also be multivariate. These depend on the intensity and extent of the stressor(s), but also on ecosystem vulnerability to a given stressor, dependent on ecosystem properties (Figure 2).

In studies of climate risk for ecosystems, human activities are typically considered through climate change[79]. In the framework proposed here, we further consider human activities as external factors that directly or indirectly influence ecological properties and stressors, in turn influencing impacts. For example, anthropogenic CO_2 emissions drive climate change, but elevated CO_2 can also modulate drought responses, alleviating drought stress through changes in water use efficiency[80]. Human activity affects fire in different ways, through direct ignitions or fire suppression (direct arrow to stressors) or indirectly by altering ecological factors, for example by managing fuel load or by altering landscape properties[59,81]. At longer time-scales, species selection and management practices influence forests' composition, structure and biodiversity, and thus resistance and resilience to extremes[53]. Therefore, human activities are considered here under the broader concept of global anthropogenically-driven change, which influences impacts indirectly through direct effects on climate drivers, ecological factors and/or stressors (Figure 2). This aims to facilitate the attribution of impacts to natural vs. anthropogenically driven processes.

While individual events do not necessarily fall into single compound events' typologies[79] as discussed above, methodologies developed for each typology[12,57] can be combined to address specific research questions. For example, the 2018/19 extreme summers in Europe can be seen as two multivariate events, with the impacts of 2019 being further preconditioned on those of summer 2018[12]. It is worth noting that the framework is flexible enough to be applied beyond impact-centered problems, as the analysis can be centered on a given component of interest, for example, on stressors, in order to evaluate the roles of drivers and ecological factors influencing subsequent impacts. For example, to understand differences in vulnerability to drought, one can study gradients of impacts in observations[3], or use counterfactual model simulations to understand differences in impacts, for stressors of similar magnitude[12,55].

Drivers of ecoclimatic variability

The phenomena identified as stressors range from moderate intensity and small-scale to large and destructive events. To understand what makes a given event a high-impact one, it is thus important to understand the sources of variability in drivers, stressors and ecological factors. In the framework proposed here, we distinguish two separate components of ecoclimatic variability – including extremes – influencing ecological factors and stressors: a naturally-driven component (white boxes in Fig. 2) and an anthropogenically-driven component (grey box in Figure 2).

In the absence of human influence (naturally-driven component), weather and climate variations combined with internal ecological processes and feedbacks (ecoclimatic variability) control the occurrence of stress events and impacts[13,20] and can further modulate ecosystem vulnerability[75,76,82,83]. This component is evidenced by the strong degree of synchrony between climate variability and ecosystem functioning at interannual to decadal time scales[82–84] and by the predominant role of climate and weather extremes as drivers of forest disturbances[31,85] and large-scale high impact events[48,86]. Variability in climatic drivers is influenced by stochastic short-term variations in atmospheric circulation and slower semi-stochastic variability due to internal ocean-atmosphere feedbacks (internal climate variability[87]), and by natural climate forcings such as solar variability or volcanic emissions[88,89] (externally forced natural climate variability). The naturally-driven component is, consequently, stochastic or semi-stochastic, including rare extreme weather and climate events. The relationships between climate variability, stressors and impacts are in turn modulated by processes controlling internal ecosystem variability (mortality, gap dynamics, competition, succession) that influence ecosystem vulnerability to stressors[90] and by feedbacks between ecological factors and stressors over years to centuries[17,19]. The combination of naturally-driven climatic and ecological variability should, therefore, exert a key control on the spatiotemporal patterns of disturbance frequency, intensity, and extent in a stationary climate[65,66,70] (temporal variability depicted in Figure 3a).

The anthropogenically-driven component is superimposed onto natural ecoclimatic variability and is controlled by direct or indirect anthropogenic influence on climatic drivers, ecological factors and stressors (Figure 3b, difference between light and dark red lines). This component includes the direct anthropogenic influence on atmospheric greenhouse gas concentrations and aerosols, which affect climate drivers directly and modulate the occurrence of weather and climate extremes[16], which indirectly affect ecological factors such as plant pheonology[91,92] and species distribution[93]. Direct and indirect human impacts on ecosystem function, structure or composition, for example through elevated CO_2, land-use change, management or nitrogen deposition further add to anthropogenic effects on ecological factors. Jointly, human-induced effects can drive changes in the intensity and frequency of high-impact events via changes in the climate drivers or ecological factors influencing stressors, and/or in ecosystem vulnerability through impacts on ecological factors. Effects of repeated stress events driven by climate variability and change, compounded with ecological feedbacks can induce non-linear dynamics and thus threaten ecosystem stability (Figure 3c, difference between red and grey lines).

Embedding the study of compound ecoclimatic events in the context of natural vs. anthropogenically-driven climatic and ecological variability allows for advances in three key domains, namely: improved understanding of the spatiotemporal variability and trends of high-impact events; better characterization of uncertainties associated with the study of high-impact events and; the separation of natural vs. human-driven components, needed for impact attribution. It should be noted, however, that the two components of natural and anthropogenic variability are not fully independent, since dynamic processes controlling natural climate variability and extremes can also be affected by climate change[2].

Ecoclimatic variability and disturbance regimes

Disturbance events are typically considered stochastic and mostly unpredictable, so that they are typically studied in the context of disturbance regimes[17,94,95]. Given the important role of climate variables in driving occurrence of stressors, high-impact events with long return periods are likely to be associated with rare large-scale weather or climate extremes. Even under human influence, and when averaged over sufficiently large spatial and temporal scales, part of the stochastic variability in the occurrence of individual disturbances or stress events should, thus, be explained by the stochastic nature of natural climate variability[96]. Over climatological time-scales, ecosystems should be adapted to variability in the intensity and return times of stressors (Figure 4a). Patterns of natural climate variability (internal variability from coupled ocean-atmosphere dynamics and solar or volcanic forcing) are therefore expected to shape the dynamic equilibrium between ecosystem states, disturbance regimes and landscape composition[65,66,94].

The predominant role of internal climate variability on disturbance regimes is supported by evidence that large-scale atmospheric and ocean-atmosphere circulation patterns drive global ecosystem dynamics at interannual to decadal time-scales, including short-term trends and ecological extremes[97,98]. For example, the El-Niño/Southern Oscillation (ENSO) is known to drive spatiotemporal variability of global fire and drought patterns[36,85,99], thus controlling variability and extremes in the terrestrial carbon cycle at continental and global scales. At continental scale, examples include regional and temporal synchrony in insect outbreaks across the USA linked to the Pacific Decadal Oscillation (PDO)[100]; the modulation of multi-decadal droughts in California by sea-surface temperatures in the Pacific Ocean[101]; the combined influence of ENSO and the Indian Ocean Dipole (IOD) modes in driving mega fire seasons in Australia[4,36]; the role of Atlantic Ocean sea surface temperature variations and shifts in the Intertropical Convergence Zone linked to major non-ENSO related droughts in the Amazon[102,103]; and shifts in drought regimes and associated carbon uptake on the Iberian Peninsula due to phase changes in the Atlantic Multidecadal Oscillation (AMO)[104].

While these modes of internal climate variability are not fully deterministic, some of them are semi-periodic at time-scales that range from a few years (ENSO, IOD) to several decades (PDO, AMO). These slow-modes of internal climate variability can induce long-term variations and extremes in ecosystem functioning, as shown for the carbon cycle[105,97,106], or even shifts in disturbance regimes[104]. Such long term variations or regime shifts might be confounded with climate-change induced trends given the typically short observational records. Therefore, improved understanding about the role of internal climate variability in controlling variations of disturbances and other stressors should allow for better characterization of naturally-driven disturbance regimes, improved understanding of large-scale disturbance regime changes, and even allow for some degree of (limited) predictability of disturbance regimes, even if individual events remain unpredictable.

Uncertainties due to internal climate variability

Climate extremes are driven by both thermodynamic and dynamic processes in the coupled ocean-atmosphere system associated with internal climate variability[15]. Internal climate variability is unpredictable beyond the scale of a few years[87] and constitute an irreducible source of uncertainty in the detection of climate change signals in observations and in future climate projections, especially at regional or smaller scales[46,47]. Moreover, forced changes in dynamical components or weather patterns remain uncertain[108–110], although significant changes in some patterns have been reported, for instance, a weakening of the summer atmospheric circulation in the Northern Hemisphere[111]. Rare events driven by atmospheric dynamics, combined with ecological feedbacks and potentially amplified by climate change, might therefore result in unexpected high-impact events, especially given the short observational records available.

Indeed, many, if not all, high-impact events between 1990 and 2022 were associated with anomalies in atmospheric circulation (Table 1). For example, the heatwave and mega-fires in Russia in summer 2010 was associated with a persistent atmospheric blocking pattern[112] that also caused devastating flooding in Pakistan[113]. Another example is the large-scale forest die-off and bark-beetle outbreaks in California during the 2011-2014 drought which was driven by a persistent atmospheric ridge linked to sea-surface temperature anomalies in the west Pacific[101,114]. For the widespread tree mortality in central Europe due to the 2018/19 extreme hot and dry summers[12,115], the 2018 event was associated with a rare combination of two atmospheric circulation patterns (a positive phase of the North Atlantic Oscillation and a Rossby Wave-7 pattern)[14,116], while the 2019 event was linked to a sequence of two heatwaves driven by sub-tropical ridge patterns[117]. The extreme bushfires of 2019/20 in Australia were promoted by synergistic effects of fire-promoting phases of three modes of climate variability: ENSO, the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM)[4].

In climate risk assessments, uncertainty from internal climate variability is usually addressed by large ensembles of climate model simulations with perturbed initial conditions. Large ensembles depict a broader range of future climates influenced by internal climate variability[107] and thus better represent trajectories or events that are rare, but still physically plausible under given climate change scenarios. Uncertainties are larger at regional (and landscape) scales, and can even result in opposing trends among multiple simulations of the same climate model and future climate scenario. For example, for some regions in the USA including California and the US southwest, both seasonal-scale multi-decadal drying and wetting trends were shown to be plausible under the RCP8.5 radiative forcing scenario in the period 2010-2060[107], based on a 40-member ensemble of a single climate model. For North America and based on a single-model 11-member ensemble, internal climate variability arising from coupled atmosphere-ocean variability was found to be the predominant cause of carbon cycle variability in the historical period[118]. Globally, variability in the land and ocean sinks linked to internal climate variability assessed by a single-model 100-member ensemble[119] led to an uncertainty of 9 PgCyr^{-1} (comparable to the current rates of anthropogenic emissions) in allowable fossil fuel emissions at 2050, for a 3°C warming scenario. Uncertainties related to the choice of model or future scenario can be considerable at regional scales[120] and further add to the uncertainties from internal climate variability.

The strong fingerprint of internal climate variability on climate extremes implies that even if mechanistic understanding of ecological processes would be perfect, inherent uncertainties in the climate system would be propagated to stressors and ecological factors, making individual high-impact events difficult to predict. To anticipate surprising outcomes from low-likelihood high-impact events, projections of climate change risks to ecosystems need to move beyond the projection of mean changes and account for the irreducible uncertainties in future climate scenarios due to internal climate variability[108].

Importantly, on top of the uncertainty due to natural climate variability, uncertainties related to natural ecological variability and human influence need to be considered, since the same climate driver does not necessarily result in the same impact, as discussed above. Projections of high-impact events need, therefore, to explore the full range of possible realizations or plausible scenarios[121], not just in the climate but also in the ecological space. The same applies for attribution of impacts to human activity, discussed in the next section.

Compound ecoclimatic event attribution

The goal of extreme event attribution is to determine whether anthropogenic climate change has altered the frequency or intensity of a particular type of event, for example, a given observed heatwave. The separation of naturally-driven and anthropogenically forced components is therefore a key aspect of attribution of changes in climate variables and individual extreme events to anthropogenic climate change[37], but remains challenging because weather or climate extreme events always represent an interplay of various complex factors.

Probabilistic weather and climate extreme event attribution analyses usually rely on factorial simulations with and without human forcing from ensembles of Earth System Models[37] or on advanced statistical methods[122]. Based on event attribution approaches, of the unexpected high-impact events listed above, the 2011-2014 drought in California has been mainly attributed to natural climate variability[101], while the other three events discussed above (Russian 2010 heatwave, Central Europe dry summers 2018-2020, Australia 2019/20 fire weather) were shown to be amplified by climate change[14,112,117,123]. In the Pacific Northwest region, an unprecedented heatwave exceeded the previous, long-term temperature record by 4.6°C, cumulating at 49.6°C in June 2021, and was followed by large wildfires. Based on statistical analysis, the event had been described as "virtually impossible" without human-caused climate change[124]. However, this heat wave was not, in principle, unforeseeable, as the atmospheric drivers were known in principle, and large climate model ensembles project these types of events as a combination of an unusual realization of internal variability and the forced response[125]. It is thus of high relevance to account for such potentially unseen extreme events when projecting impacts of climate change on ecological systems.

Since natural climate variability controls variability and multi-decadal trends in ecosystem functioning[106,118], its fingerprint on high-impact events needs to be considered. This is especially important when observational records are too short to encompass multi-decadal scales of low-frequency natural climate variability modes such as the Pacific Decadal Oscillation or the Atlantic Multidecadal Oscillation. Since most ecological observations cover periods of typically only a few decades, caution is needed when attributing high-impact ecoclimatic events or disturbance regime shifts to climate change based on short records[97,126,127].

Furthermore, impacts of climate extremes further depend on interacting physiological and ecological processes and states. For example, photosynthesis and respiration, affecting net carbon exchanges, respond differently to the same climate extreme[20,128,129], and impacts of droughts depend on stand age or biodiversity, and on legacies from past disturbances[31,32,40,130]. These processes are further influenced by internal ecological dynamics, which is likely to increase the noise-to-signal ratio when attributing impacts of climate extremes. Here we discuss these challenges and propose ways forward for high-impact event attribution.

High-impact event attribution

Assuming no change in ecosystem vulnerability or other ecological factors affecting the magnitude of a given stressor, changes in frequency or intensity of climatic drivers due to anthropogenic climate change should result in increased impacts, because ecosystems are in principle adapted to normal climate variability (Figure 4a,b). Attribution of ecological impacts to anthropogenic influence is further complicated by interactions between climate, stressors, and ecological factors and by the broader human influence on ecosystem functioning and structure, which can act to either amplify or offset the effects of climate change[31,34] (Figure 2, 3).

Even if no climate change fingerprint can be found for climate drivers, a given high-impact event can be shaped by anthropogenic influence on relevant environmental processes or states (for example changes to landscape structure or species diversity) that consequently change the ecosystem vulnerability to the climatic drivers or stressors (Figure 4c). As an example, even if the 2011-2014 drought in Northwest USA was attributed to natural variability[101], the widespread tree mortality in 2012-2015 might still have been influenced by increased vulnerability to drought due to warmer background temperatures and atmospheric dryness[7,114], although no formal impact attribution as proposed here has been performed. Furthermore, it should be noted that human fingerprints on drivers and ecological factors can have diverging effects. For example, for some agricultural species, changes in phenology associated with global warming have been shown to increase the risk of frost damage during frost-sensitive periods, even if the total number of frost days decreased due to climate change[131,132].

The disaggregation of compound ecoclimatic events in their relevant components as proposed here (Figure 2) facilitates the attribution of impacts to natural vs. human influence. While all relevant combinations of natural vs. human effects on drivers, stressors and ecological factors should, in principle, be considered, this could easily become very computationally expensive or intractable. One way of facilitating such analysis is to perform the attribution of impacts to human influence in a two-step combination of storylines (Figure 4). First the human fingerprint on the compound (climatic) event is evaluated (Figure 4a,b). Next, the impacts of human activity on ecological factors can be separately evaluated through ecological storylines[55] (Figure 4a,c). Events can be anthropogenically driven if climate change changed the probability of occurrence or intensity of climate drivers (anthropogenically driven through climate, Figure 4b), or if human effects on ecological factors changed the vulnerability of the system or the likelihood of a stressor to occur, given the same climatic drivers (anthropogenically driven, through ecosystems, Figure 4c). Finally, high-impact events can be anthropogenically driven by a combination of both pathways (Figure 4d).

The climate-change fingerprint on compound ecoclimatic events can, in principle, be evaluated based on relatively simple statistical ecological models[12,31] or process-based impact models, following traditional approaches for attribution of extreme climatic events[37], such as single- or multi-model ensembles with perturbed initial conditions to constrain uncertainty due to internal climate variability[133,134]. However, impact attribution requires not only the simulation of natural vs. anthropogenic effects on the climate system, but also appropriate simulation of ecological processes and feedbacks and of human influence on ecosystems that influence stressors and impacts. Uncertainty arising from internal ecological variability should be especially relevant for local and regional scales, while for large-scale impacts uncertainty is more likely to be dominated by uncertainties in the climate space. As the processes driving internal ecological variability are also, to some extent, stochastic, this implies that the projection of impacts needs to incorporate additional probabilistic elements to properly constrain uncertainties.

Current trade-offs in the complexity, number of processes and suitable scales in existing process-based ecological models require the selection of existing impact models depending on the variable and region of interest and the specific question to be addressed. Landscape models simulate the impact of disturbances (fires, storms, insects) on forest productivity[135,136] but lack key biogeochemical processes that are relevant for impact assessment, for example water and nutrient cycling as modulating factors of impacts, and cannot be scaled to the global domain. Although computationally expensive and limited in the processes they can simulate, process-based land-surface and coupled land-atmosphere models are, in principle, more suitable to simulate emerging dynamics resulting from feedbacks between climate drivers, stressors and ecosystem functioning. Still, only few Earth System Models used in large ensembles explicitly simulate fire[133]. Other key disturbances such as storms, insects and pests are usually only implicitly included in background mortality rates in their land surface schemes. Moreover, compound impacts of heat and drought stress are poorly represented[137], and post-stress recovery dynamics, such as functional impairment, irreversible damage, or depletion of non-structural carbon reserves are not represented in most models[30]. All of these are considered crucial to simulate recovery dynamics and legacy effects from extreme events, as demonstrated by Bastos et al.[12] using a reduced version of the framework proposed here.

Ecoclimatic storylines application

Storylines[138] are a particularly powerful tool to account for epistemic uncertainties when evaluating risks from rare and surprising events or scenarios in the future as well as for event attribution. Storylines are defined as qualitative descriptions of plausible future (world) evolutions, describing the characteristics, general logic and developments underlying a particular quantitative set of scenarios[1]. Hence, storylines contain both quantitative and qualitative elements, and can describe plausible past or future events or pathways[121], based on certain physical or ecological assumptions without necessarily requiring a specifically defined occurrence probability.

In climate attribution, storylines are invoked complementary to probabilistic event attribution to assess and isolate the effect of certain factors (such as greenhouse gas induced warming) conditional on a given observed circulation regime[139], thereby allowing to disentangle the better understood thermodynamical effects of warming from the more uncertain dynamically induced changes (see van Garderen et al[140] for a practical application to the European 2003 and Russian 2010 heatwaves). In the context of high-impact ecoclimatic event attribution, storylines could be used to identify individual meteorological drivers contributing to a given event of interest[141], but can also be extended to evaluate the effects of CO_2 fertilization or other natural or human ecological factors, being, therefore, a promising approach in future studies.

Here we illustrate how ecoclimatic storylines could be used to evaluate and attribute variability and extremes on ecosystems, focusing on land carbon cycle variables. We analyze anomalies in climatic drivers and impact variables (carbon fluxes and biomass) in the Mediterranean region, based on two fully coupled atmosphere-ocean climate model simulations with the Community Earth System Model Version 2.1.2 (CESM2[142,143]): one forced with CO_2, climate change, and land-use from historical and near-future (SSP3-7.0) scenarios[144] (forced) and an additional simulation corresponding to pre-industrial conditions (Nudged piControl, with climate, CO_2 and land-use forcings kept constant at 1850 levels, referred to as unforced simulation), in which the horizontal winds are nudged towards the forced run. The two simulations differ in the anthropogenic forcing, but are conditional on very similar variations in large-scale atmospheric circulation. Circulation variability, assumed to represent predominantly natural variability, is therefore controlled for, with the difference between the two simulations allowing to evaluate anthropogenic forcing effects more directly[140]. In the case of ecological systems, this difference also includes potential interactions between natural ecological variability and the anthropogenic forcing. A complete illustration on the implementation of the framework in Figure 2 to develop ecoclimatic storylines and improve the understanding of two selected events is provided in Supplementary Material. In Figure 5, we summarize the results for the climatic drivers and net ecosystem productivity (NEP).

From 1850 until 2040, NEP in the forced simulation increases over time, predominantly due to elevated CO_2, but, importantly, its distribution in the period 2001-2040 broadens substantially with a 1.7-fold increase in standard deviation after mean detrending the forced simulation (Figure 5a, Supplementary Material). By contrast, temperature and relative humidity in the forced simulation show a shift in the mean of the distribution towards warmer conditions (compare mean of distributions in Figure 5b), but no change in variance (compare spread of unforced and detrended forced distributions). This suggests that changes in ecosystem sensitivity to climate associated with interactions between ecological variability and forced anthropogenic effects explain the change in NEP variance, rather than a change of variance in climate drivers. In the period 2001-2040, atmospheric circulation explains 86% of the NEP variability of the forced simulation (Figure 5a; adjusted R^2 between forced and unforced nudged simulations with anthropogenically driven trend removed). This shows that natural climate variability is a key driver of NEP variability and extremes in this region. The remainder 14% correspond, therefore, to natural ecological variability influencing responses to climate (for example, water use efficiency, growth, mortality, fire occurrence), or remaining climate variability that is not captured through the nudging of the horizontal wind fields.

Based on the climate drivers, we then select two case studies: the wettest and the driest events in the forced simulation, E1 and E2 respectively, and assess their corresponding impacts in the two simulations. The event pairs in the forced and unforced nudged simulations differ mostly in that the temperatures increased (Figure 5b), resulting in higher vapor pressure deficit, with minor changes in relative humidity. These events are associated with strong positive NEP departures from the 40-yr mean for wet conditions (E1) and with below average NEP for atmospheric dryness (E2). The absolute difference between the forced and unforced simulations, shown in Figure 5c, includes anthropogenic effects through climate change, elevated CO_2 and land-use change as well as a naturally-driven term resulting from ecological variability and potential feedbacks between ecological variability and anthropogenically-driven change (for example long-term changes in water-use efficiency, or increased water stress through higher evaporative demand). These different anthropogenic effects can have amplifying or offsetting effects on the impacts of E1 and E2, and would require additional simulations to control for each individual factor. Therefore, we analyse the aggregated anthropogenically-driven component and the naturally-driven component (Figure 5c, more details in Supplementary Material).

For both events, the absolute difference between the forced and unforced is predominantly positive, driven by a strong increase in NEP due to anthropogenic effects, likely to be mostly explained by elevated CO_2[83]. The naturally-driven component shows a widespread increase in NEP over most of the Mediterranean basin for E1 (Figure 5c), mostly dominated by increased gross primary productivity (GPP) in response to higher water availability. For E2, the decrease in NEP (Figure 5c) is explained by decrease in GPP in most regions, except Turkey where increase Total Ecosystem Respiration (TER) dominates. Some regions in Northern Africa show a naturally-driven increase in GPP and NEP along with an increase in water availability. This is likely explained by lower aboveground biomass from anthropogenic effects resulting in lower evapotranspiration losses during the dry event (Supplementary Figure 2). A more detailed analysis can be found in Supplementary Material.

This example is based on a single model and specific setup, model uncertainties and potential errors need to be acknowledged. Nevertheless, this example shows how anthropogenic effects (here combined thermodynamic changes, land use change and elevated CO_2 effects) can be evaluated and attributed via ecoclimatic storyline approaches using the compound ecoclimatic events' framework (Figure 2). This approach can further be extended to disentangle individual anthropogenic effects and to assess epistemic uncertainties in specific driving factors of relevant ecoclimatic events, such as the effects of elevated CO_2, land-use and management, or uncertainties related to future atmospheric circulation.

Summary and future perspectives

Here we discuss the need to embrace the complex interactions between climate drivers and disturbance dynamics, ecological processes and human factors to improve understanding of ecological variability and, specifically, high-impact ecoclimatic events. We propose a unified framework to analyze compound ecoclimatic events building on the climate risk and disturbance ecology perspectives. We discuss how impact attribution needs to consider not only the human influence on climate variables, but more generally environmental changes that influence stressors, ecosystem vulnerability and impacts. We finally illustrate how our framework can be implemented for impact attribution using ecoclimatic storylines based on simulations of an Earth System Model. However, we recognize that the tools to robustly quantify the human fingerprint on high-impact events and disturbance regimes are still in their infancy. This is due to limitations in impact modelling capabilities, which in turn result from observational gaps and incomplete process understanding.

Quantifying relationships between the different elements of compound ecoclimatic events based on observations is still limited by the amount and type of relevant data available. Most ecosystem monitoring networks and remote-sensing platforms cover only a few decades starting at the end of the 20th century, when most of the global biosphere has been influenced by anthropogenic activities[145–147], and, additionally, multi-decadal trends in observations must be expected to contain substantial internal variability[106]. While carbon and water fluxes have been intensively measured and studied[20,148], other relevant ecological and landscape variables (root-zone soil-moisture, root dynamics, mortality rates, …) are more difficult, if not impossible, to observe at large scales. These limitations are expected to be partly overcome by ongoing efforts in collecting, harmonizing and providing relevant ecosystem monitoring data openly[7,149], but more integration and harmonization of the information compiled by different networks is needed. Second, knowledge about past disturbance occurrence and impacts is, in many regions, limited[150]. Attribution of disturbed areas to natural disturbances beyond wildfires and drought[151–153], is needed to evaluate spatiotemporal patterns and identify potential changes in interactions between disturbances[31]. Recently available high-resolution and very high resolution satellite data, combined with the use of artificial intelligence and fuelled by increasing computing power allow mapping individual trees and tree density[154,155], which can lead to a step change in disturbance mapping. It should be noted that the long-term and high-resolution records of Landsat and MODIS, even if having limited spatiotemporal resolution and spectral information, are still highly valuable since they can provide information of disturbance dynamics[13,152,156,157] at the longer time-scales needed to separate natural vs. forced variability[106].

Impact attribution requires models that can realistically simulate the causal relationships between climate drivers, stressors and impacts. Statistical approaches are useful to infer potential changes in future disturbance dynamics and impacts on forest stability[7,158], but these typically consider only a limited range of processes, do not include feedbacks between stressors and ecosystem dynamics, and cannot anticipate responses to conditions far beyond the training sample, as expected in the coming decades. Ecosystem dynamics and carbon uptake potential also depend on other factors such as the effects of elevated CO_2 or nutrient limitations[145,159,160]. A mechanistic representation of the processes driving ecosystem dynamics, disturbances and their feedbacks in global Land Surface Models is therefore needed when projecting future changes. Efforts to improve the representation of forest responses to climate stressors[161–163] and tree mortality[164–166], of functional diversity[167] and of management activities[168], and to prognostically simulate disturbances beyond fire in Land Surface Models[169] are currently ongoing. These efforts hold great promise to improve the attribution of high-impact ecoclimatic events and, when implemented in Earth System Models, to quantify feedbacks between climate extremes, forest disturbances, and the carbon cycle, but are still challenged by the lack of data needed to develop underlying theory.

Advances in observational and modelling capabilities are thus critically needed for better understanding the extent to which high-impact events result from ongoing climate change and other human effects, or might be rare events, unseen in the relatively short ecological records. Ecoclimatic storylines can be a powerful tool to improve understanding about recent high-impact ecoclimatic events, diagnose their sources of variability and trends, and to account for epistemic uncertainty in future projections. This knowledge is in turn key to assess the stability of the world's forests and quantify potential carbon-climate feedbacks arising from more frequent extreme events.

Glossary

WEATHER AND CLIMATE EXTREME is an unusual event at a given place and time of year, usually defined by the occurrence of a value of a weather or climate variable, or combination of variables, above (or below) a threshold value near the upper (or lower) ends of the observed distribution of the variable over a reference time-frame[16,170]. Both extreme weather events and extreme climate events are usually referred to collectively as climate extremes[1].

CLIMATE RISK is defined as "the potential for [climate change related] adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems"[46]. Risk is a function of **hazard**, **vulnerability** and **exposure**. Climate risk refers strictly to negative consequences of climate change, while positive consequences are referred to as opportunities or potential benefits. Reisinger et al.[46] acknowledge, however, that other fields treat risk as a value-neutral concept, and that the value of a given consequence might depend on the point of view.

HAZARD is the "potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources"[170]. Hazard relies on the assessment of potential consequences of a given climate-related event or trend, not on the change of the climate variable itself. According to the climate risk perspective, climate extremes might not be hazardous if they do not result in negative consequences and, conversely, non-extreme events might be hazardous if they potentially result in negative consequences.

VULNERABILITY corresponds the propensity or predisposition to be adversely affected, encompassing a variety of concepts that include sensitivity or susceptibility to harm and lack of capacity to cope and adapt[170].

EXPOSURE describes the presence of people; livelihoods; species or ecosystems; environmental functions, services, resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected. [170]

COMPOUND WEATHER AND CLIMATE EVENTS refer to "the combination of multiple drivers and/or hazards contributes to societal or environmental risk"[58,79]. Drivers encompass variables and processes in the climate domain and hazards correspond to physical precursors of typically negative impacts[58]. Events such as droughts, heatwaves, flooding and fires are typically referred to as hazards in climate risk literature[79]. Compound events have been categorized into four main types: (i) multivariate, where multiple drivers and/or hazards result in a given impact; (ii) preconditioned, where a climate-driven precondition amplifies the impact; (iii) temporally and (iv) spatially compounding, where hazards connected in time or space result in aggregated impacts[79].

ECOSYSTEM DISTURBANCE The most widely used definition of ecosystem disturbance is that by White and Picket[171], that described disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment". More specific definitions have been proposed, for example by Grime[172], who defined disturbance as "a relatively discrete event in time that specifically results in biomass removal". Disturbances are characterized by type, frequency, return interval, size, intensity, severity, impact and recovery time.

EXTREME CLIMATIC EVENT is defined as an event "[…] in which a statistically rare or unusual climatic period alters ecosystem structure and/or function well outside the bounds of what is considered typical or normal variability.

DISTURBANCE IMPACT corresponds to the specific effects on ecosystem properties triggered by a given disturbance: loss of organic matter by fires, removal or damage of organisms by hurricanes or logging, or mortality induced by droughts, floods or frost events, for example.

DISTURBANCE SEVERITY corresponds to the magnitude of the impacts[17,43], and depends on ecosystem sensitivity to the disturbance intensity, that is, ecosystem vulnerability.

POST-DISTURBANCE RECOVERY corresponds to the return of a disturbed system to a previous "undisturbed" or "quasi-equilibrium"[40,64] state or to a new state[19]. The time required to reach this state since the occurrence of disturbance corresponds to the recovery time.

Figures and Tables

Table 1 | Examples of high-impact events globally since the 1990s. For each event, the climatic drivers, reported stressors, ecological factors modulating vulnerability and/or stressors and impacts on the carbon cycle are described. The influence of patterns of natural climate variability, if relevant to explain the events, is included and anthropogenic influence in climatic drivers or vulnerability is reported if formal attribution has been performed. "No evidence" indicates that formal attribution has been performed an no evidence for human influence on climatic drivers has been found. "Not reported" indicates that no formal attribution has been made. "Uncertain" refers to cases where a potential role of climate change has been noted, but with inconclusive results, or where conflicting studies exist. Arrows indicate direction of changes (↑increase, ↓ decrease, ↑↓ both). GPP corresponds to Gross Primary Productivity, TER to Total Ecosystem Respiration, LAI to Leaf Area Index, NBP to Net Biome Productivity.

	Region	Period	Climatic drivers	Stressors	Ecological factors	Natural climate variability influence	Impacts	Anthropogenic influence	Refs.
Asia	Siberia	2020	Persistent high temperature	Extreme heat, fires	Phenological stage	Strong and persistent AO+	GPP↑ and NBP ↑↓	Intensity of heatwaves ↑	5,173–175
	SE Asia	2015/16	Prolonged precipitation deficit, high temperature	Extreme heat and drought, fires	Land cover and biome type	El Niño	NBP ↓, Biomass ↑↓ Fire emissions ↑	No evidence	10,176–178176–179
	Indonesia	1997/1998	Prolonged precipitation deficit	Drought, extreme fires	Land use and management	El Niño	Net CO_2 uptake ↓, Fire emissions ↑	No evidence	176,180–182
Africa	Tropical Africa	2015/16	Low precipitation, high temperature	Extreme heat and drought	Land cover and biome type	El Niño	TER↑, NBP ↑↓, Biomass ↑↓	No evidence	177–179
	Southern Africa	1991/92	Prolonged precipitation deficit	Extreme drought	Not reported	Co-ocurrence El Niño and +SLP anomalies over Darwin	Crop yield ↓ Tree mortality ↑	Not reported	6,183–185
	East Africa	2019	Persistent high precipitation	Floods, landslides, locust outbreaks	Not reported	IOD+ and MJO	Crop yield ↓	Not reported	186–188
	South Africa	2014-16	Prolonged precipitation deficit	Multi-year drought	Species, woody vegetation height, topography	Poleward shift of southern jet stream and SAM+	Tree mortality ↑	Not reported	189,190
Europe	Central and Northern Europe	2018-20	Spring and summer heatwaves, spring precipitation deficit, land-atmosphere feedbacks	Extreme hot and dry summers, bark beetle outbreaks	Land-cover composition, precondition from spring ET ↑ Precondition from 2018	2018: Wave 7 pattern and NAO+ 2019: Saharan air mass intrusion and land-atmosphere feedbacks	GPP and NBP ↑↓ Crop yield ↑↓ Tree mortality ↑	Magnitude and probability of heatwaves ↑	8,13,14,14,26,55,191–193
	Western Europe	2003	Low spring precipitation, high temperatures	Extreme hot and dry summer, bark beetle outbreaks	Not reported	Wave7 pattern, atmopsheric blocking	GPP and NBP ↓ Tree mortality ↑	Magnitude and probability of heatwaves ↑	3,6,116,194–197
	Western Europe	2022	Persistent heatwaves	Extreme heat, fires	Not yet evaluated	Increased persistence of double jets	Not yet evaluated	Not reported	198
Oceania	Australia	1997-2009	Prolonged precipitation deficit	Multi-year drought	Soil type, topography, local climate	Lack of La Niña and of IOD-events	GPP and NBP ↓ Tree mortality ↑	Uncertain	6,8,199
		2011	Prolonged high precipitation	Floods, extreme rainfall	Mean aridity	La Niña	GPP and NBP↑, LAI ↑	No evidence	105,200–202

		Since 2017	Prolonged precipitation deficit, high temperature	Multi-year drought, extreme fires	Land cover composition	ENSO+, IOD+, SAM-	Tree mortality ↑ Biomass ↓ NBP ↓ Fire emissions ↑	Fire danger ↑	4,23,199,203,204
Americas	Northwest USA	2011-2014	Precipitation deficit over three consecutive winters	Multi-year drought, bark beetle outbreaks	Precondition from warm 2012 spring and from past canopy expansion and ET ↑	La Niña 2011/12 and warm tropical west Pacific SST anomaly 2013/14	GPP and NBP ↓ Tree mortality ↑	No evidence	101,114,205
	Southwest North America	2000–2021	Prolonged precipitation deficit, high temperature	Multi-year drought, fires	Land cover	Decadal variability in tropical Pacific SSST	Crop yield ↓ GPP and TER ↓ NBP ↑↓	Uncertain	206–208
	Central Chile	2010–2019	Prolonged precipitation deficit, reduced snowpack	Multi-year drought	Land cover	Persistent atmospheric dipole over the south Pacific and positive phase of the Southern Annular Mode	GPP ↓, Tree growth ↓	Intensity and longevity of multi-year drought event ↑	209,210
	Northwest USA and Canada	2021	Dry warm season, heatwaves, strong winds	Fires	Earlier snowmelt	Heat dome over western North America associated with Rossby wave train	Timber ↓	Magnitude and probability of June heatwave ↑	124,211,212
	Amazon	2015/16	Low precipitation, high temperature	Extreme heat and drought	Land cover and biome type	El Niño	GPP and NBP ↑↓ Tree mortality ↑ Delayed recovery	No evidence	8,10,22,177,213,214
	Amazon	2005 and 2010	Low precipitation, prolonged dry season	Extreme drought, fires	Not reported	Warm SST in North Atlantic and northward diplacement of ITCZ	GPP and NBP ↓ Tree mortality ↑	Not reported	7,102,103,215,216

Figure legends

Figure 1. Comparison of elements in climate risk and ecosystem disturbance perspectives. The main elements of each perspective are included in the boxes: the left column for climate risk as defined by the IPCC and the right column for the most commonly used elements in disturbance ecology. The lines show conceptual links between elements across perspectives: bold line for elements considered similarly in both, dashed line for elements that are analogue but only partly considered in each perspective, and dotted line indicates elements missing in one perspective. The text below the boxes indicates the relevant aspects that are similar or distinct across perspectives. Because there is not a 1:1 match in most cases, a given element in one perspective might be connected to several elements in the other.

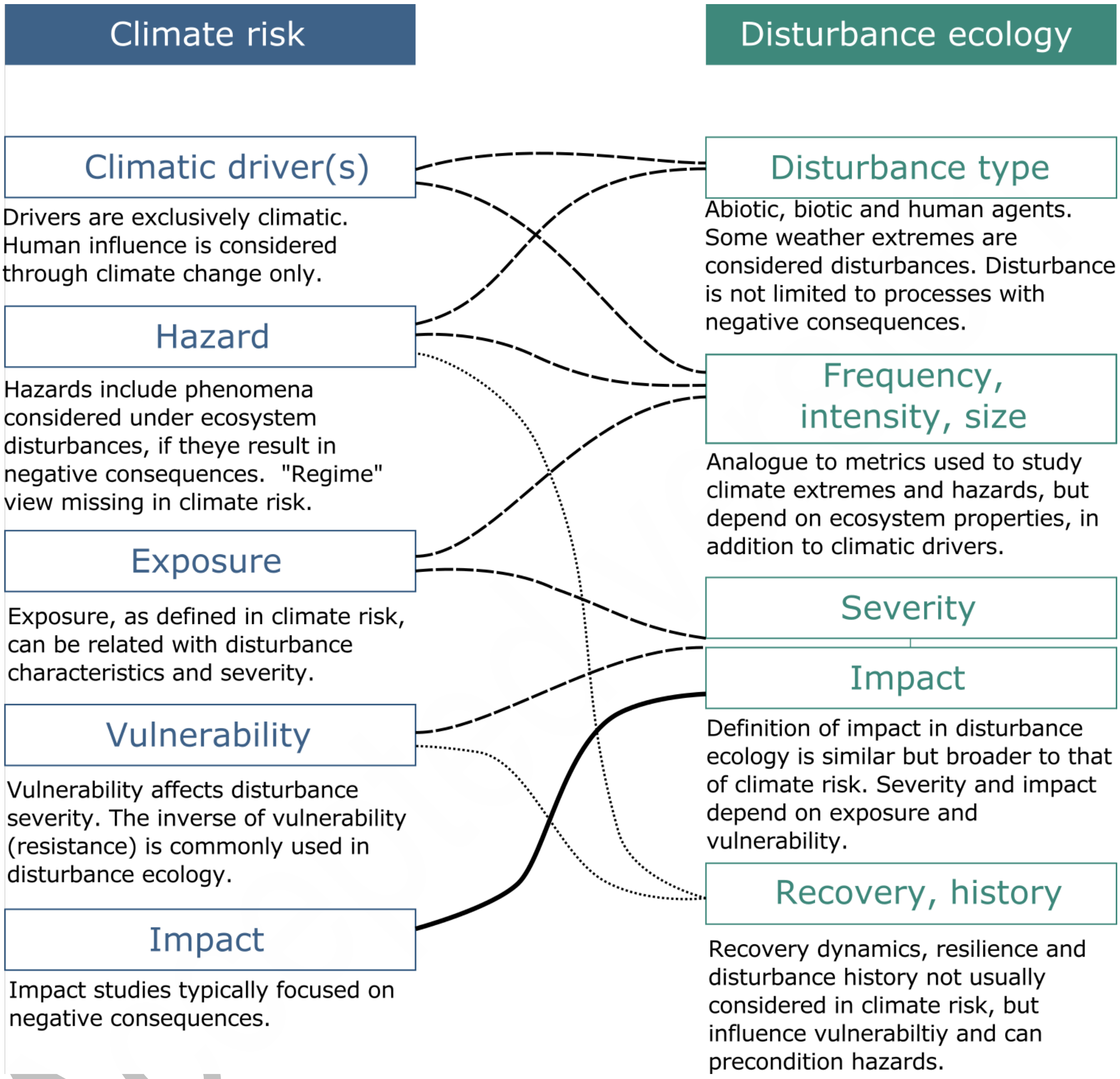
Figure 2. Conceptual framework of ecoclimatic events. Building on both the climate risk and ecosystem disturbance perspectives, compound ecoclimatic events (elements within the grey shaded area) are conceptually decomposed into climatic drivers (blue boxes), ecological factors (yellow), stressors (red), and impacts (green), and their causal relationships, including potential feedbacks between these components as internal factors, and human activities as external factors. Human activity (grey boxes) is included as an external modulator of climatic drivers through climate change, of ecological factors through management and broader changes in the environment or direct influence on stressors, for example by pollution or ignition of fires. Ecological factors can influence stressors directly and modulate impacts by influencing ecosystem vulnerability to stressors. Feedbacks due to land-atmosphere interactions and legacy effects from previous events (succession dynamics, composition and/or structural changes) are shown in dashed lines.

Figure 3. Conceptual representation of the influence of natural vs. human-driven climate variability in ecological variability and high-impact events. (a) Scenario under stationary climate (no anthropogenic influence). In this scenario, a given carbon-cycle related state variable or process, for example biomass carbon (light red line) varies around a long-term reference state in a dynamic equilibrium being exposed to stress of variable intensities. This long-term variability can be described by a statistical distribution (right panel), whose tails correspond to high-impact ecoclimatic events occurring relatively seldom (horizontal dashed line in the right panel). (b) Shifts in the distribution of climatic drivers under climate change can lead to a shift in the distribution of the variable (dark red line) and result in more frequent and/or intense stress events. (c) Compounding effects of stress events and recovery dynamics can induce declining trajectories and result in non-linear impacts, threatening forest stability (dark grey line). We note, however, that other environmental changes occurring along changes in climate, such as elevated CO_2 for example, can result in positive and offsetting effects. This is the case of the example in Figure 5 and Supplementary Material.

Figure 4. Factorial approach for the attribution of compound ecoclimatic events to human versus natural effects. The white lines show different distributions of climate forcing and the color gradient represents ecosystem vulnerability to climate, from low vulnerability in purple to high vulnerability in yellow. Different events are represented by vertical dashed lines. In a baseline scenario (a), variability in the climate forcing and vulnerability to related stressors should be in quasi-equilibrium, so that normal climate conditions would induce "normal" responses by ecosystems adapted to more frequent conditions (peak of the forcing distribution associated with low vulnerability), and rare climate extremes would lead to extreme impacts (higher vulnerability for less frequent climate conditions). Changes in the distribution of the climate drivers driven by anthropogenic climate change can lead to more frequent high-impact events (b, shift in the forcing distribution towards higher ecosystem vulnerability). Human activities can change the vulnerability of ecosystems to stressors, represented by the expansion of the higher vulnerability domain (red and yellow) in panel c). Changes in vulnerability can thereby increase the frequency of high-impact events, even under the same distribution of climate drivers (shift in ecosystem vulnerability without changes in the forcing distribution). Finally, these effects b) and c) can be combined, leading to amplified impacts due to anthropogenic activity (d).

Figure 5. Illustration of climate-ecosystem-carbon cycle storylines for attributing ecosystem variability and extremes. (a) time-series of annual Net Ecosystem Productivity (NEP) in the Mediterranean region simulated in a forced (historical and SSP3-7.0) CESM2 simulation (red line) compared to an unforced "nudged circulation" simulation in which the large-scale simulation is nudged to the transient run, but with pre-industrial forcing (blue line). The difference between the two simulations (grey line) reflects anthropogenic influence and its interactions with ecological variability. The detrended forced simulation corresponds to a component only influenced by ecological variability since natural climate variability is controlled for by keeping atmospheric circulation fixed. (b) climatic drivers of summer (JJA) NEP anomaly: temperature and relative humidity anomalies relative to the period 2001-2040. The grey dotted lines connect events with the same circulation in the forced and the unforced nudged simulation and the size of the points is proportional to the JJA NEP value (detrended for the transient simulation). The two case-study events correspond to the wettest (E1) and driest (E2) summers in the forced simulation during the period 2001-2040. (c) Spatial patterns corresponding to the forced simulation and its decomposition into the anthropogenically- and naturally-driven components for the two case-study events. The naturally-driven component here includes only ecological variability since atmospheric circulation is fixed.

Figures



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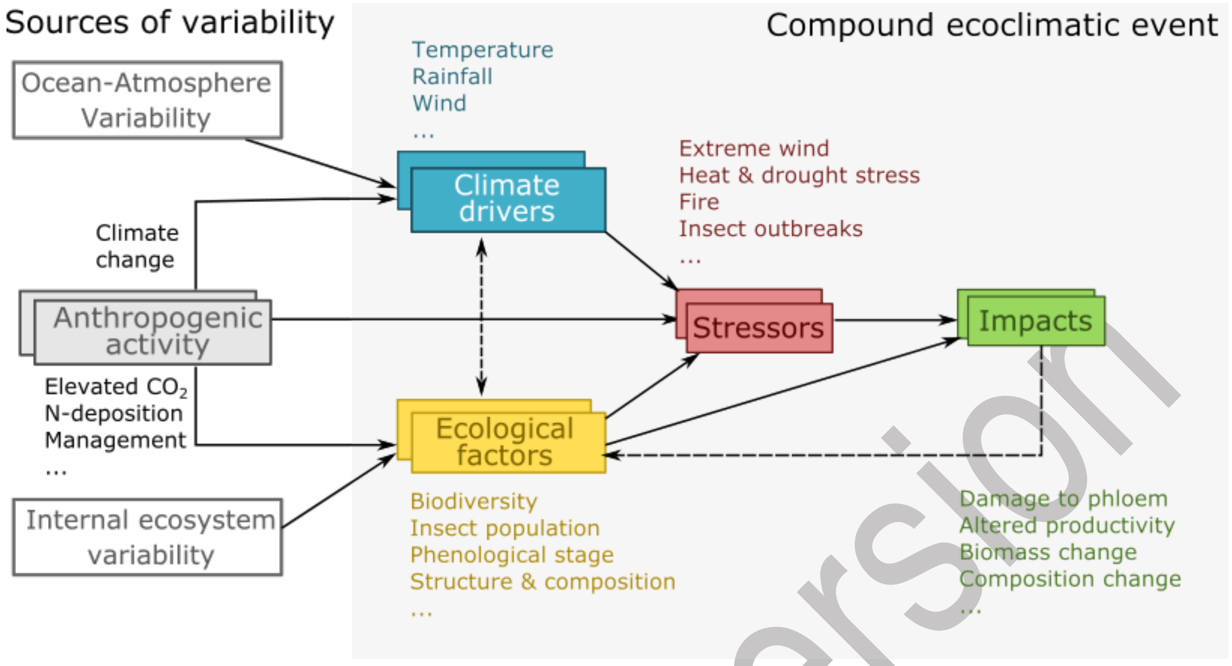

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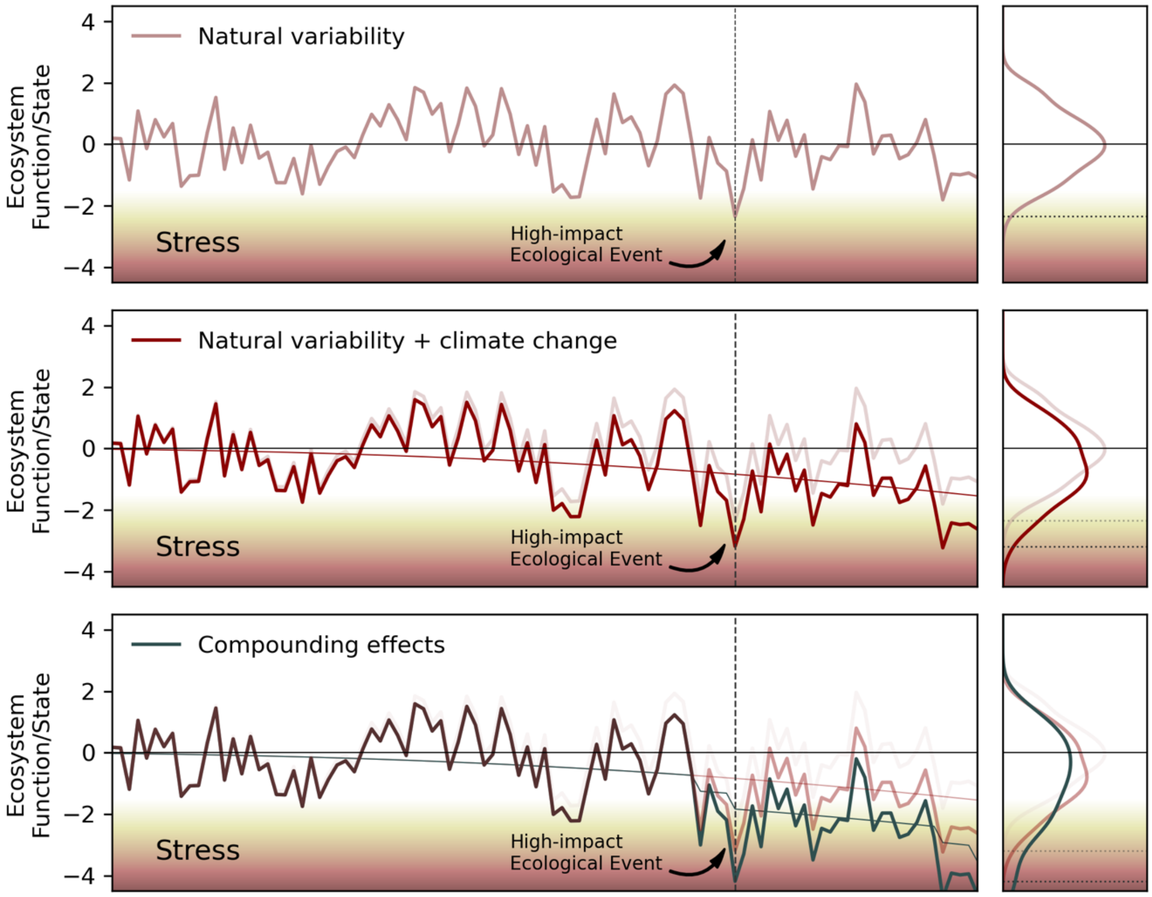

Figure 3. Conceptual representation of the influence of natural vs. human-driven climate variability in ecological variability and high-impact events. (a) Scenario under stationary climate (no anthropogenic influence). In this scenario, a given carbon-cycle related state variable or process, for example biomass carbon (light red line) varies around a long-term reference state in a dynamic equilibrium being exposed to stress of variable intensities. This long-term variability can be described by a statistical distribution (right panel), whose tails correspond to high-impact ecoclimatic events occurring relatively seldom (horizontal dashed line in the right panel). (b) Shifts in the distribution of climatic drivers under climate change can lead to a shift in the distribution of the variable (dark red line) and result in more frequent and/or intense stress events. (c) Compounding effects of stress events and recovery dynamics can induce declining trajectories and result in non-linear impacts, threatening forest stability (dark grey line). We note, however, that other environmental changes occurring along changes in climate, such as elevated CO_2 for example, can result in positive and offsetting effects. This is the case of the example in Figure 5 and Supplementary Material.

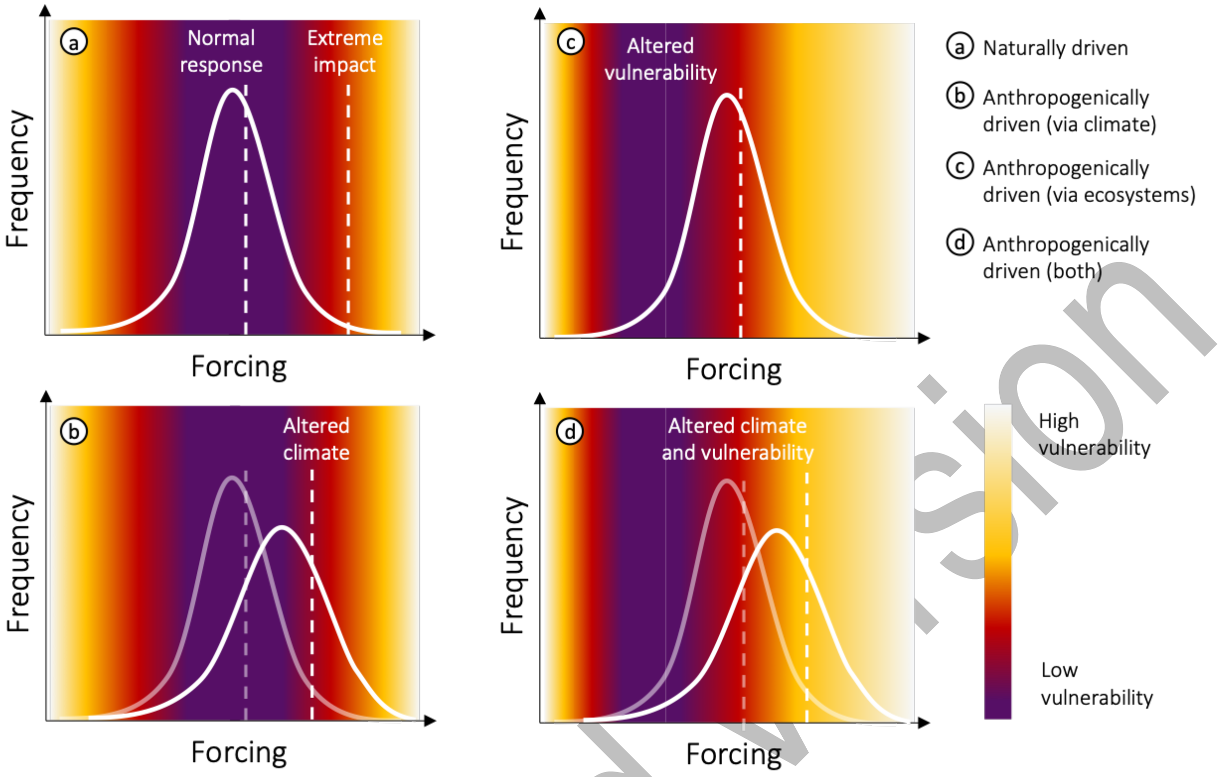

Figure 4. Factorial approach for the attribution of compound ecoclimatic events to human versus natural effects. The white lines show different distributions of climate forcing and the color gradient represents ecosystem vulnerability to climate, from low vulnerability in purple to high vulnerability in yellow. Different events are represented by vertical dashed lines. In a baseline scenario (a), variability in the climate forcing and vulnerability to related stressors should be in quasi-equilibrium, so that normal climate conditions would induce "normal" responses by ecosystems adapted to more frequent conditions (peak of the forcing distribution associated with low vulnerability), and rare climate extremes would lead to extreme impacts (higher vulnerability for less frequent climate conditions). Changes in the distribution of the climate drivers driven by anthropogenic climate change can lead to more frequent high-impact events (b, shift in the forcing distribution towards higher ecosystem vulnerability). Human activities can change the vulnerability of ecosystems to stressors, represented by the expansion of the higher vulnerability domain (red and yellow) in panel c). Changes in vulnerability can thereby increase the frequency of high-impact events, even under the same distribution of climate drivers (shift in ecosystem vulnerability without changes in the forcing distribution). Finally, these effects b) and c) can be combined, leading to amplified impacts due to anthropogenic activity (d).

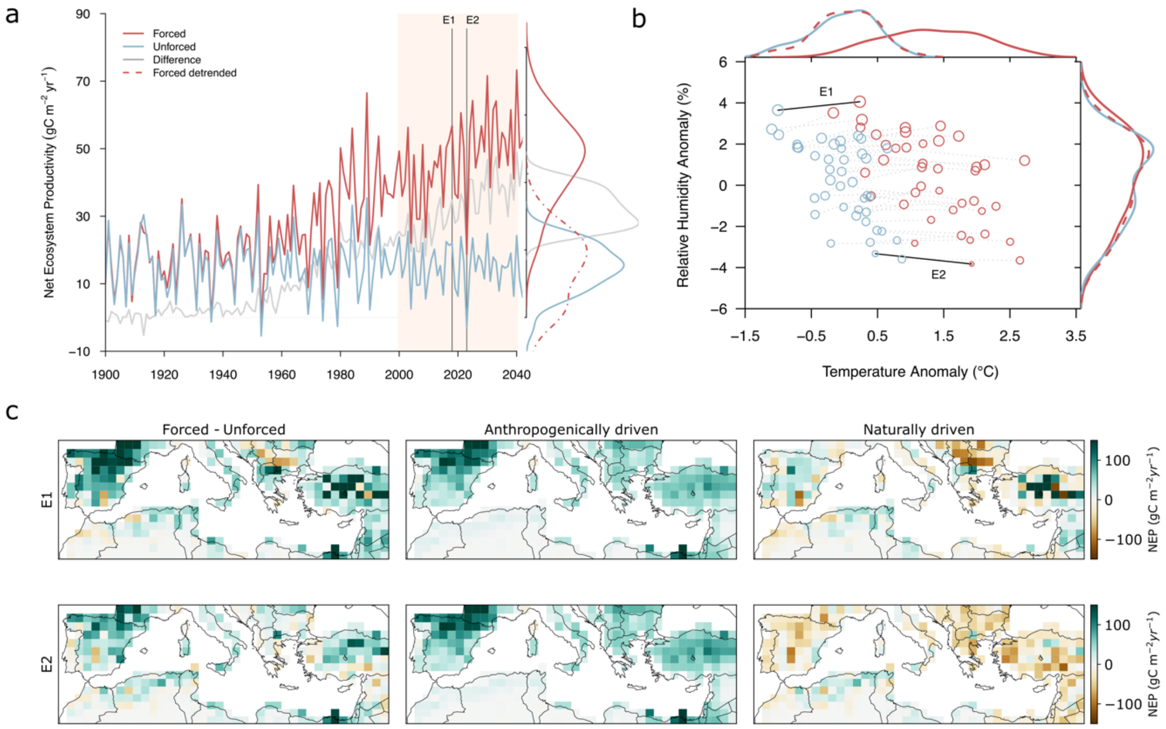

Figure 5. Illustration of climate-ecosystem-carbon cycle storylines for attributing ecosystem variability and extremes. (a) time-series of annual Net Ecosystem Productivity (NEP) in the Mediterranean region simulated in a forced (historical and SSP3-7.0) CESM2 simulation (red line) compared to an unforced "nudged circulation" simulation in which the large-scale simulation is nudged to the transient run, but with pre-industrial forcing (blue line). The difference between the two simulations (grey line) reflects anthropogenic influence and its interactions with ecological variability. The detrended forced simulation corresponds to a component only influenced by ecological variability since natural climate variability is controlled for by keeping atmospheric circulation fixed. (b) climatic drivers of summer (JJA) NEP anomaly: temperature and relative humidity anomalies relative to the period 2001-2040. The grey dotted lines connect events with the same circulation in the forced and the unforced nudged simulation and the size of the points is proportional to the JJA NEP value (detrended for the transient simulation). The two case-study events correspond to the wettest (E1) and driest (E2) summers in the forced simulation during the period 2001-2040. (c) Spatial patterns corresponding to the forced simulation and its decomposition into the anthropogenically- and naturally-driven components for the two case-study events. The naturally-driven component here includes only ecological variability since atmospheric circulation is fixed.

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Competing interests

The authors declare they have no competing interests.

Author contributions

A. Bastos conceptualized the study and wrote the first draft. A.B., M.R., D.F and S.S. prepared the figures. S.S. analysed the CESM outputs. D.F., M.D.M., S.Z., S.S., M.R. and J.Z. contributed to the development of the study through extensive discussions and feedback on initial stages of the manuscript. All authors contributed to revisions of the manuscript.