*Biodiversity and climate extremes: known interactions and research gaps*

Article

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**Key Points:**

- Mounting evidence suggests that an ecosystem's capacity to buffer the impacts of climate extremes depends on its biodiversity
- Numerous mechanisms suggest that a reduction in biodiversity could exacerbate climate extremes
- A series of research gaps need to be addressed to understand the full feedback between biodiversity change and climate extremes

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# Biodiversity and Climate Extremes: Known Interactions and Research Gaps

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**Abstract** Climate extremes are on the rise. Impacts of extreme climate and weather events on ecosystem services and ultimately human well-being can be partially attenuated by the organismic, structural, and functional diversity of the affected land surface. However, the ongoing transformation of terrestrial ecosystems through intensified exploitation and management may put this buffering capacity at risk. Here, we summarize the evidence that reductions in biodiversity can destabilize the functioning of ecosystems facing climate extremes. We then explore if impaired ecosystem functioning could, in turn, exacerbate climate extremes. We argue that only a comprehensive approach, incorporating both ecological and hydrometeorological perspectives, enables us to understand and predict the entire feedback system between altered biodiversity and climate extremes. This ambition, however, requires a reformulation of current research priorities to emphasize the bidirectional effects that link ecology and atmospheric processes.

**Plain Language Summary** Climate extremes are increasing and impacting both nature and people. We hypothesize that intact ecosystems, particularly via their biodiversity, can mitigate the impacts of climate extremes. What happens when biodiversity decreases? Could this loss make the effects of climate extremes even worse or change how these events occur? We explore these two questions and summarize the current state of knowledge. We conclude that targeted research efforts at the interface of ecology and atmospheric sciences are needed to answer these questions conclusively.

## 1. Introduction

The transformation of terrestrial ecosystems due to land cover change, land management intensification, and environmental pollution, continues to accelerate globally. These interventions lead to a widespread decline in biodiversity and ecosystem functioning (Bellard et al., 2012; Díaz et al., 2019; IPBES, 2019; Jaureguiberry et al., 2022). At the same time, climate change progresses (IPCC, 2021). Increases in the intensity, frequency and duration of extreme weather and climate events such as droughts, heatwaves, and heavy rainfall, are some of the

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most critical consequences of anthropogenic climate change (Seneviratne et al., 2021). Today, extreme events such as the 2018–2020 multi-year drought in central Europe (Rakovec et al., 2022), the 2022 compound drought-heatwave in most of Europe (van der Woude et al., 2023) and the record shattering 2023 spring heatwave in the western Mediterranean (Lemus-Canovas et al., 2024) are becoming more and more common. Such extreme events impact multiple ecosystem functions and ecological dynamics (Frank et al., 2015; Mahecha et al., 2017; Reichstein et al., 2013), and have the potential to disrupt ecosystem stability (Anderegg et al., 2020; Bastos et al., 2023; Seidl & Turner, 2022). But how will these two global mega-trends—biodiversity decline and the intensification of climate and weather extremes—affect each other? This scientifically challenging question has severe societal implications and needs to be addressed urgently in an integrative research approach (Mahecha et al., 2022).

Extreme weather and climate events are rare events that happen at a specific place and time. For a long time, extreme events have mostly been studied from a univariate perspective. More recently, research on compound events (Zscheischler et al., 2018), the spatio-temporal evolution of extremes (Flach et al., 2018; Zscheischler et al., 2013), and record-shattering extremes (Fischer et al., 2021; Fowler et al., 2024) have gained considerable interest in the research community, mostly because of the relevance of these aspects for impacts (see Figure 1 for an overview of these terms). Variations in atmospheric circulation strongly influence extreme event occurrences (Coumou & Rahmstorf, 2012). For example, atmospheric blocking situations or recurrent atmospheric wave patterns lead to extended and persistent high-pressure systems or stationary lows, which may cause heatwaves or flooding that have severe consequences for ecosystem functioning (Bastos, Ciais, et al., 2020; Desai et al., 2016; Flach et al., 2018; Kornhuber et al., 2019). Ongoing anthropogenic climate change is expected to increase extreme weather around the globe further, and even the underlying circulation patterns are expected to change (Faranda et al., 2020). However, the extent to which such projected circulation changes are robust remains a matter of debate (Huguenin et al., 2020).

To understand the necessity of integrating climate extremes and biodiversity, we initially consider two specific examples. The first involves heavy precipitation events, which can lead to catastrophic outcomes such as flooding, erosion, and landslides, dependent on the water retention capacity of catchments and their geomorphological characteristics (Brunner et al., 2021; Saco et al., 2021; Vári et al., 2022). In these scenarios, the importance of biodiversity is evident as the structure of vegetation, both above and below ground, plays a crucial role in controlling water flows and overall hydrological dynamics. However, the extent to which extreme events impact ecosystems is influenced not only by the type and structure of vegetation but also by its functioning. This can be seen when considering the implications of compounded heat and drought events. Here, reduced moisture availability disrupts the land-surface energy balance, enhancing sensible heat fluxes leading to further increases in air temperatures. This process results in a higher evaporative demand, intensifying the heat/drought episode through what is known as the soil moisture–temperature feedback loop. The variety in plants' physiological responses becomes critical in moderating the severity of this feedback, thereby directly impacting human activities, especially agricultural productivity (Barriopedro et al., 2023; Beugnon et al., 2024; Graf et al., 2020; Miralles et al., 2019).

Ecosystem functioning, particularly under extreme conditions, emerges from the complex interplay among various dimensions of "biodiversity" (De Boeck et al., 2018; Reichstein et al., 2014; Thonicke et al., 2020). These dimensions include (a) genetic diversity, (b) taxonomic diversity, (c) functional diversity, (d) structural diversity within ecosystems, and (e) landscape diversity or heterogeneity (see Figure 2 for an overview and definitions). Typically these dimensions of biodiversity are not independent of each other. Additionally, the specific species present ("plant identities') play a critical role in ecosystem processes. As exemplified above, the imprint of biodiversity on ecosystem functioning is generally relevant because it controls how the land surface responds to atmospheric conditions. Biodiversity controls how ecosystems absorb pollutants, store carbon, or provide numerous natural resources. The regulation of water, gas, and energy fluxes, and the release and absorption of primary emitted particles (Fröhlich-Nowoisky et al., 2016; Sanaei et al., 2023) by functional and structural diversity and landscape heterogeneity, contributes to the regulation of land-surface climate feedbacks and can thereby affect local to global climate (Beugnon et al., 2024; Bonan, 2008; Duveiller et al., 2021; Graf et al., 2020; Miralles et al., 2019; Santanello et al., 2018; Ukkola et al., 2018).

Considering that ecosystems interact with atmospheric conditions, a crucial question arises (Mahecha et al., 2022): Is there a risk that changing biodiversity in ecosystems may not only weaken the resistance of ecosystems to climate extremes, but also exacerbate atmospheric hazards? In other words, may biodiversity

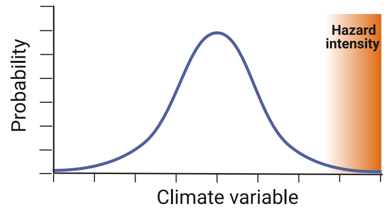
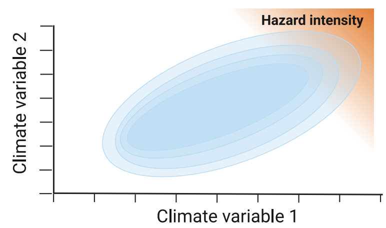
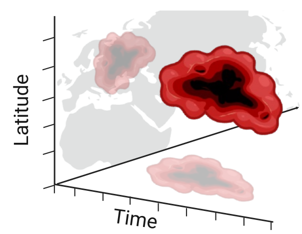
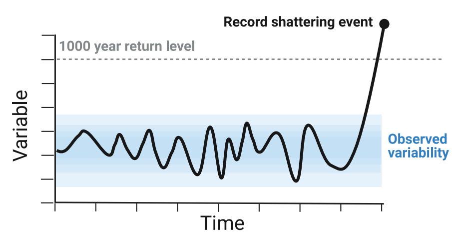
| Extreme | Definition | Illustration |
|---|---|---|
| Univariate | Rarity of an event relative to a statistical probability distribution, either in terms of intensity, frequency, spatio-temporal extent, duration, in one variable of interest. |  |
| Compound | Multivariate indices of extremes, also referred to as 'compound' extreme events, include unusual combinations of climate drivers. |  |
| Spatio-temporal | Considering the spatio-temporal extent of an extreme event leads to additional metrics such as an event's duration, geographical coverage, volume, and integrated magnitude. |  |
| Record-shattering | An event that exceeds previous observed records by a certain margin, typically measured in terms of intensity or the record margin (i.e., exceedance of the previous record), and often improbable without climate change. |  |

**Figure 1.** Extreme weather events are rare occurrences at a specific place and time, while climate extremes are persistent patterns of extreme weather (AR6 WG1 Ch. 11 IPCC, 2021). We consider four relevant empirical descriptions of extremes: univariate, multivariate, spatiotemporal, and record-shattering. These categories describe the intensity, frequency, duration, and extent of events, including compound extremes and multiple meteorological drivers.

changes amplify the risk of weather and climate-related extremes? Pörtner et al. (2023) recently issued a general call for a comprehensive investigation into the intricate relationship between changes in the climate system and biodiversity. Here, we conduct an extensive review of pertinent literature to determine how far we can already give answers to the specific aspect of extremes. We first aim to understand whether higher levels of biodiversity buffer the impact of climate extremes (Section 2), and second, explore amplification processes of weather and climate extreme events dynamics in response to biodiversity (Section 3). Based on the conclusiveness of the literature on these aspects, we identify key research gaps that should be addressed to understand the full feedback between biodiversity change and climate extremes (Section 4).

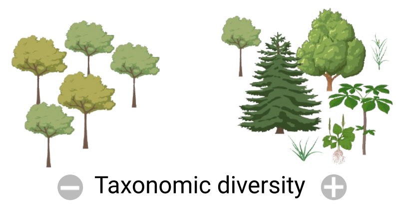
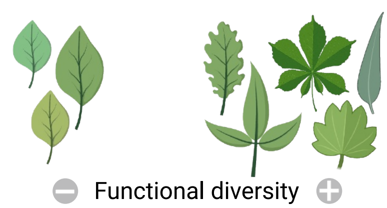
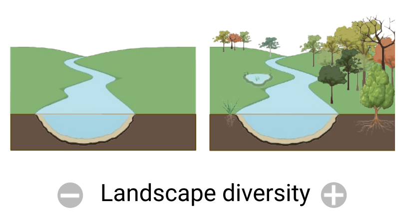
| Dimension | Definition | Illustration |
|---|---|---|
| Genetic | Diversity of genetic properties within and across species. Also contains heritable changes in gene function not involving changes in DNA sequence (i.e., epigenetics). |   |
| Taxonomic | Diversity of species, measured typically as species richness per unit of investigation e.g.in manipulative experiments. In field-based surveys as species richness weighed by relative species abundances. Effects of species interactions are likewise considered |   |
| Functional | "The degree to which species vary in their functional traits" (Weiher et al., 2011). These functional traits include, for example, leaf, stem, and root traits in plants that are analysed in the context of studies relating biodiversity to ecosystem processes. |   |
| Structural | The three-dimensional structural complexity of plant communities including, for example, diversity of plant height, diameter, density, or vertical distribution (Staudhammer & LeMay, 2001). |   |
| Landscape | Diversity and complexity of lateral arrangements of ecosystems within a landscape. Contributes to the overall biodiversity of a region by shaping habitats that support different ecosystems; synonym for landscape heterogeneity. |   |

**Figure 2.** In the seminal definition of the Convention on Biological Diversity (CBD, 1992), biodiversity is "the variability among living organisms from all sources, […]. This includes diversity within species, between species and of ecosystems," pointing to its many facets and scales, which must be distinguished when addressing biophysical and biogeochemical processes (Noss, 1990). The facets in our focus are listed here (Staudhammer & LeMay, 2001; Weiher et al., 2011).

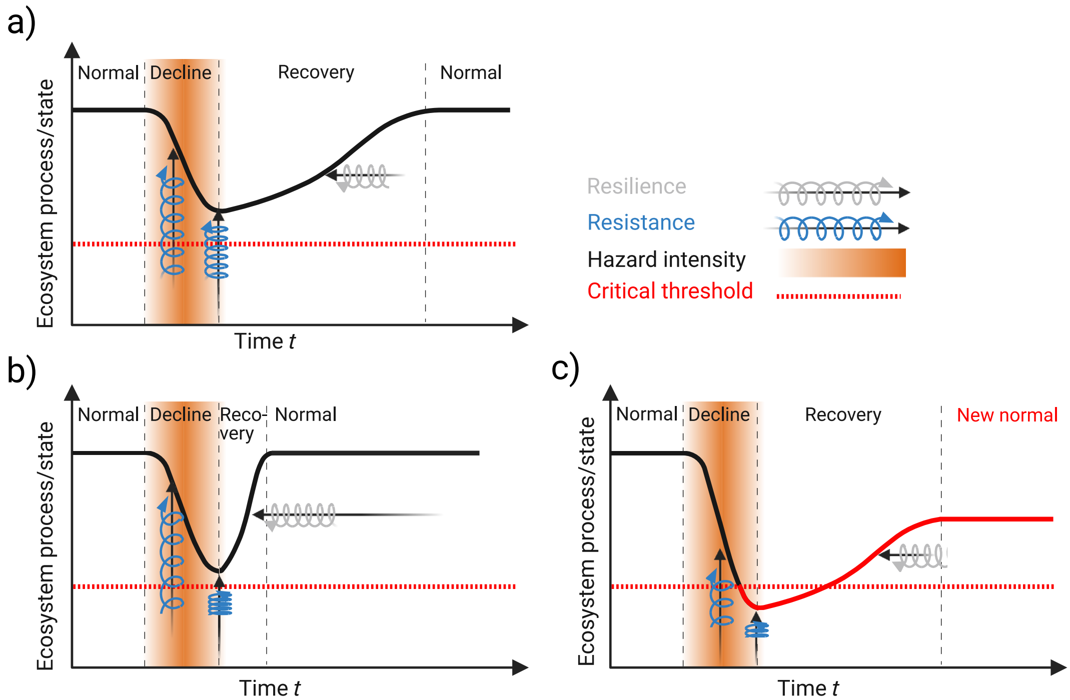



**Figure 3.** Buffering capacity. The ability of an ecosystem to resist or absorb changes in its states and functions over time is defined as "resistance." The capacity to recover to pre-event conditions is termed "resilience." Both resistance and resilience act over time, and jointly constitute the "buffering capacity." In this figure, we exemplify systems with (a) high resistance and low resilience, (b) low resistance, and high resilience, and (c) very low resistance such that the critical threshold is reached and no return to pre-event conditions can be achieved.

## 2. Biodiversity Buffers Against Weather and Climate Extremes

Numerous studies investigate how climate extremes impact ecosystems as a function of their diversity. Two key concepts are frequently used in this context: ecosystem "resistance," which is the capacity to withstand a climate extreme, and ecosystem "resilience," which characterizes how fast and complete a system recovers following an extreme event (sensu Hoover et al., 2014; De Keersmaecker et al., 2016). Together, these concepts help to differentiate and quantify how ecosystems buffer the impact of extreme climatic events (for an illustration, see Figure 3). But given the various dimensions of biodiversity outlined in Figure 2, what knowledge do we have about their role in buffering extremes?

In terms of taxonomic diversity, it appears that a few particular species often resist climate extremes, keeping up ecosystem functioning or preventing community collapse under stress (De Laender et al., 2016; Werner et al., 2021). This phenomenon is classically known as "the insurance effect" (Loreau et al., 2021; Yachi & Loreau, 1999). Figure 4 illustrates how the insurance effect, mediated via functional diversity, could dampen the reduction of net primary production (NPP) and the increase in sensible heat flux during a heat wave in a more diverse forest, compared to a low-diversity forest. Such insights have been mostly inferred from experimental studies (Kayler et al., 2015; Loreau et al., 2021). For example, Isbell et al. (2015) show that grasslands with higher species diversity have higher resistance when exposed to exceptional dry or wet conditions, an effect attributed to the species-specific responses to stress (Craven et al., 2018). Recently, Liu et al. (2022) confirmed a positive effect of species richness on resistance to drought using a global satellite-based indicator of drought resistance and tree species composition data from more than half a million forest plots. Variations in the genetic properties of individuals within species can likewise lead to varying resistance to climate extremes. This was shown for example, by Pfenninger et al. (2021), who analyzed the susceptibility of individual beech trees to the extreme drought in central Europe in 2018 and illustrated the wide range of drought damages within a single species.

Intraspecific (genetic) diversity is one reason why taxonomic diversity alone is insufficient to explain ecosystem responses to extremes. Another reason is that, at the ecosystem level, responses to extremes are also largely

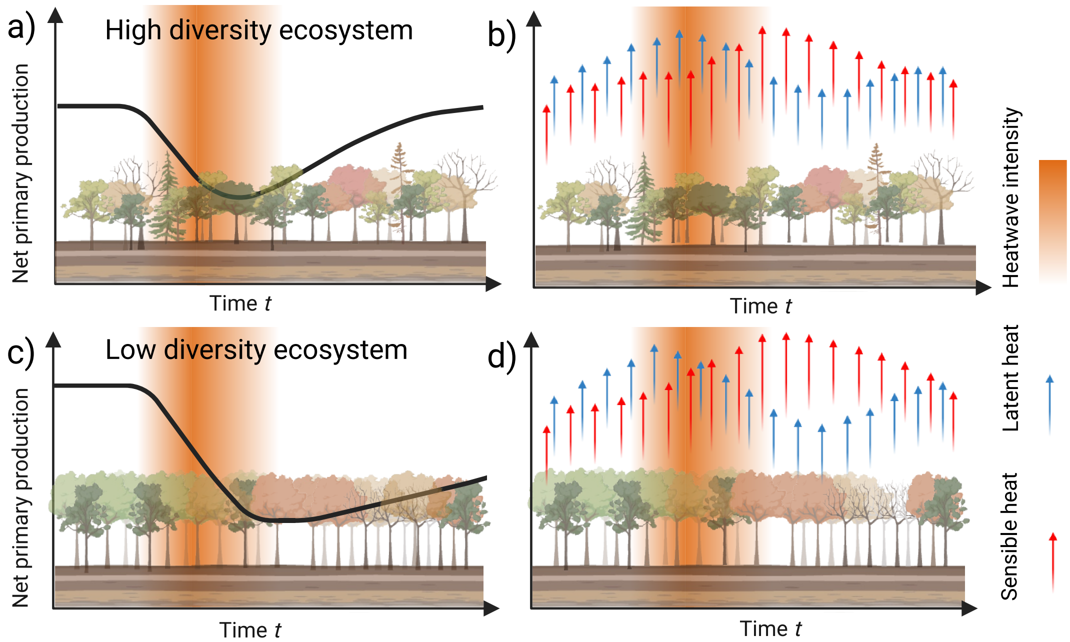



**Figure 4.** Illustration of the insurance effect: Hypothetical response of net primary production (NPP, net $CO_2$ uptake rate) to a heatwave (shown in reddish background colors) in (a) a diverse forest, and (c) a mono-culture. Analogous responses for energy fluxes are shown in (b) and (d). While low-diversity forests might initially have higher NPP, their low resistance might imply higher losses and reduced resilience given the lack of species compensation, that is, a low insurance effect. The same effect can be observed for energy fluxes, where the ratios between latent and sensible heat fluxes change more drastically in low-diversity forests, with consequences for both ecosystems and atmospheric energy budgets.

regulated by the "functional diversity" of ecosystems (see Figure 2). For example, forest responses to droughts largely depend on the diversity of traits associated with the isohydric versus anisohydric behavior of trees (Hartmann et al., 2021; Lübbe et al., 2022). However, it is not only above ground traits that matter. Mursinna et al. (2018) show that functional diversity of root traits can explain the resistance of ecosystems to drought. In general, the diversity of functional traits of organisms regulates how fluxes of energy, water, and nutrients are absorbed, stored, and released given certain environmental conditions (Anderegg et al., 2019; Berendse et al., 2015; Violle et al., 2007). Even organisms coexisting in the same ecosystem (i.e., species that have passed an identical "environmental filter") exhibit a considerable degree of variation in their functional role and, therefore, in their contribution to the resistance of an ecosystem to weather and climate-related extreme events (Felton & Smith, 2017; Reyer et al., 2013), and their ability to recover from such events. The meta-analysis by Craven et al. (2018) emphasizes that functional biodiversity dimensions are determined by the asynchrony of abundances and thus affect the stability of ecosystem functioning.

Structural heterogeneity at the stand level is another dimension of diversity: mixtures of growth forms, plant sizes, and demographic stages induce for example, vertical variability that appears to play an equally important role in the stabilization of ecosystems. Guimarães-Steinicke et al. (2021) report that differences in canopy surface height minimize spatial variation in canopy temperatures. And there is evidence for variations in canopy height to serve as a buffer for heat extremes (Lin et al., 2020). On a broader scale, the composition and heterogeneity of the landscape dictate the extent of land-atmosphere interaction alterations following climate extremes (Bastos, Fu, et al., 2020; Flach et al., 2021). Taken together, in a changing climate with increasing occurrence of extreme weather and climate-related events, all dimensions of diversity may cause some degree of insurance against the shocks induced by climate extremes.

The buffering capacity of biodiversity, as illustrated in Figure 3, is a scale-dependent process. At the landscape scale, diversity encompasses the coexistence and interaction of different ecosystems, for example, through species migration or functional exchanges such as pollination. At regional to continental scales, landscape heterogeneity will determine which response mechanisms jointly dominate how ecosystems react to climate extremes (Bastos, Fu, et al., 2020; Flach et al., 2021; Teuling et al., 2010). Generally, applying insights from experiments and theoretical frameworks to large-scale and real-world contexts is challenging (Grossiord et al., 2019; Kreyling et al., 2008). In this context remote sensing observations are key to overcoming scaling issues (Cavender-Bares et al., 2022; Gonzalez et al., 2020), as they can monitor ecosystem responses, extreme weather and climate events from the ground, as well as from airborne- and space-borne platforms, covering local to global scales (Cavender-Bares et al., 2020; Mahecha et al., 2017; Montero et al., 2023; Peng et al., 2021). For example, De Keersmaecker et al. (2016) studied the resistance and resilience against drought across grasslands in central Europe using optical remote sensing observations. They showed that nutrient-poor and species-rich grasslands are more resistant, but less resilient against drought than fertilized, species-poor grasslands. One explanation could be that nutrient-poor grasslands are likely having multiple resource limitations such that species may have developed more strategies to resist fluctuations in environmental conditions. Given its consistency with local experimental studies, the study is one example of how the emerging and constantly growing body of global remote sensing data improves our capabilities of tracing biodiversity dynamics (Cavender-Bares et al., 2022; Skidmore et al., 2021), ecosystem management (Lange et al., 2022), and multiple land-surface processes (Mahecha et al., 2020). Combined data streams can also be used to quantify how ecosystems buffer impacts of climate extreme events, a task that should be prioritized.

Another crucial aspect related to the impact of extremes is occurrence timing (Ma et al., 2015): Both ecosystem responses and their imprints on atmospheric conditions change during the seasonal cycle. Ecosystems comprise individual organisms, each following a characteristic phenological cycle and responding differently to environmental conditions. One could argue that the dominance of, for example, functional traits or structural parameters varies seasonally, making specific dimensions of biodiversity of ecosystems likewise time-dependent (Cinto Mejía & Wetzel, 2023; Ma et al., 2020). This can explain why resistance and resilience at the ecosystem level are determined by an interplay between event-timing and a time-dependent buffering capacity. Carry-over effects are a particular aspect of timing, where resistance and resilience are partly determined from an anomalous preceding period (Cinto Mejía & Wetzel, 2023; Sippel et al., 2018; Wolf et al., 2016). For example, warm spring seasons combined with early water scarcity can result in lower summer resistance to extremes (Flach et al., 2018; Sippel et al., 2018), thus potentially amplifying their impacts in subsequent seasons (see Figure 3). In turn, different land surface characteristics that result from spring weather modulate the evolution of summertime heatwaves (Merrifield et al., 2019). At longer time scales, an ecosystem's specific succession stage leads to different response trajectories (Johnstone et al., 2016). Besides timing, both duration (von Buttlar et al., 2018) and recurrence (Anderegg et al., 2020; Bastos et al., 2021) of extremes are decisive for an ecosystem's resistance and resilience (Frank et al., 2015; Thonicke et al., 2020). Increased disturbance regimes can further influence such feedback loops (Forzieri et al., 2021; Seidl et al., 2017). Recent studies reveal the importance of memory effects from sequential hot drought years on tree growth and stress responses (Bastos, Ciais, et al., 2020; Schnabel et al., 2021). Such events can be considered a particular type of compound event (Figure 1, Zscheischler et al. (2020)), and Figure 5 illustrates how an ecosystem's buffering capacity is weakened by an extreme event over time, such that consecutive droughts may lead to prolonged impacts on vegetation dynamics and functions in subsequent years. This also means that any feedback mechanisms between biodiversity and climate extremes as illustrated in a simplified scheme in Figure 6 must be understood as time-dependent processes.

## 3. Biodiversity Imprints on Atmospheric Processes and Extremes

While extreme weather and climate events are predominantly initiated by atmospheric processes, land-atmosphere interactions can also significantly contribute to their development and occurrence. Given that land-atmosphere interactions are influenced by ecosystem functions, we anticipate an imprint of biodiversity on atmospheric processes. Here, we discuss four examples of such imprints and their relevance to extreme events: surface energy balance, cloud formation, atmospheric chemistry, and fires.

Terrestrial ecosystems are crucial to the surface energy balance through their regulation of hydrological fluxes over land. Globally, evapotranspiration returns 60% of precipitation over land (Trenberth et al., 2011), where 80%–90% occurs via plant transpiration (Jasechko et al., 2013). Transpiration in turn uses 50%–60% of the mean net radiation over land (Wild et al., 2015). Changes in ecosystem composition and their spatial arrangement in the landscape, which may result from land management practices or changes in land use and cover, can modify surface temperatures via changes in albedo, emissivity, surface roughness, evaporative resistance, and heat fluxes (Duveiller et al., 2018; Laguë et al., 2019). The imprint of biodiversity on the land-atmosphere energy balance is expected to become particularly important during extreme events such as heat/drought extreme events. For

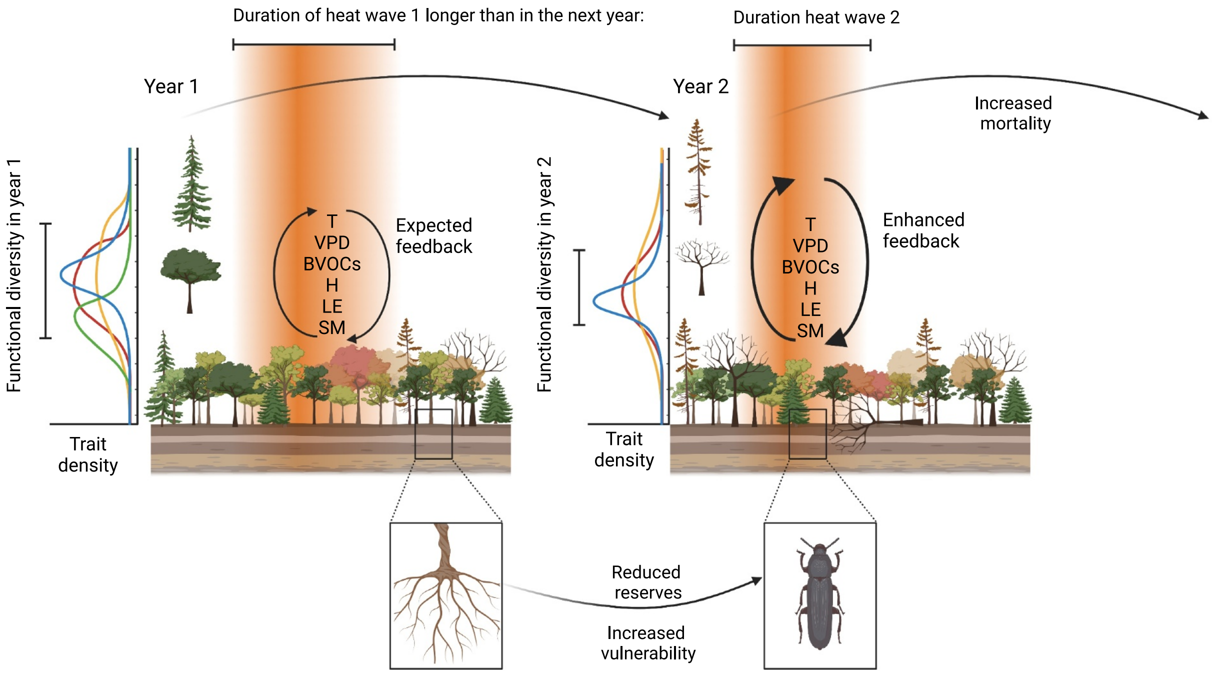



**Figure 5.** Uncommon temporal sequences and carryover effects. Two consecutive years with combined drought and heatwaves can have particularly strong impacts since species-specific defenses can be reduced and lead to higher vulnerabilities to for example, insects. Reduced chemical defenses and generally depleted pools render vegetation more sensitive. The interplay between preconditioning and carryover effects amplifies the impacts of sequential extremes. Abbreviations are: T = temperature, VPD = vapor pressure deficit, BVOCs = biogenic volatile organic compounds, H = sensible heat, LE = latent heat, and SM = soil moisture.

instance, changing surface albedo is known to modulate the intensity of these events through changes in evapotranspiration and vertical energy fluxes, that is, sensible heat, latent heat, and radiative energy fluxes (Miralles et al., 2019; Zhou et al., 2019). Since heat and drought amplification mechanisms depend on the type of ecosystem they affect, it is expected that the ecosystem itself can influence how the land-surface processes propagate to the atmosphere.

In addition to influencing energy and water fluxes, vegetation can serve as a source of atmospheric trace substances such as biogenic volatile organic compounds (BVOCs), pollen, and smoke particles, which may impact cloud formation and the atmospheric radiation budget and processes in complex ways. A prime example of the intricate connections between biodiversity and climate regulation is cloud formation. Clouds are influenced by water in its three thermodynamic phases, energy exchanges (discussed above), as well as BVOCs and aerosol particle fluxes, all of which are affected by vegetation characteristics (Duveiller et al., 2021; Teuling et al., 2017). Furthermore, clouds play a crucial and immediate role in buffering climate extremes: they cool the environment during hot days, buffering heat stress conditions, and keep temperatures warmer during cold nights, buffering against extreme cold. Therefore, biodiversity imprints on cloud formation might contribute to buffer extreme events. For example, BVOCs can initiate the formation of biological secondary organic aerosols (BSOA), altering the cloud condensation nuclei and possibly the ice nucleation properties of particles (Lehtipalo et al., 2018; Riccobono et al., 2014; Riipinen et al., 2011). Primary biogenic particles such as pollen, plant debris, spores and bacteria can additionally foster the heterogeneous freezing of super-cooled cloud droplets by acting as ice-nucleating particles at warmer temperatures than in their absence (Fröhlich-Nowoisky et al., 2016; Kretzschmar et al., 2023; O'Sullivan et al., 2018; Steinke et al., 2020). Since rain is predominantly formed via ice-containing clouds (Mülmenstädt et al., 2015), this implies more frequent rain above pollen-emitting forests (Kretzschmar et al., 2023). Also, such aerosol particles could set off changes in cloud microphysical (droplet size, droplet concentration, and liquid water content) and optical (cloud albedo and transmissivity) properties and, consequently, local precipitation patterns (Jiang et al., 2018; Niinemets, 2010; Sporre et al., 2019; Zhang et al., 2024).

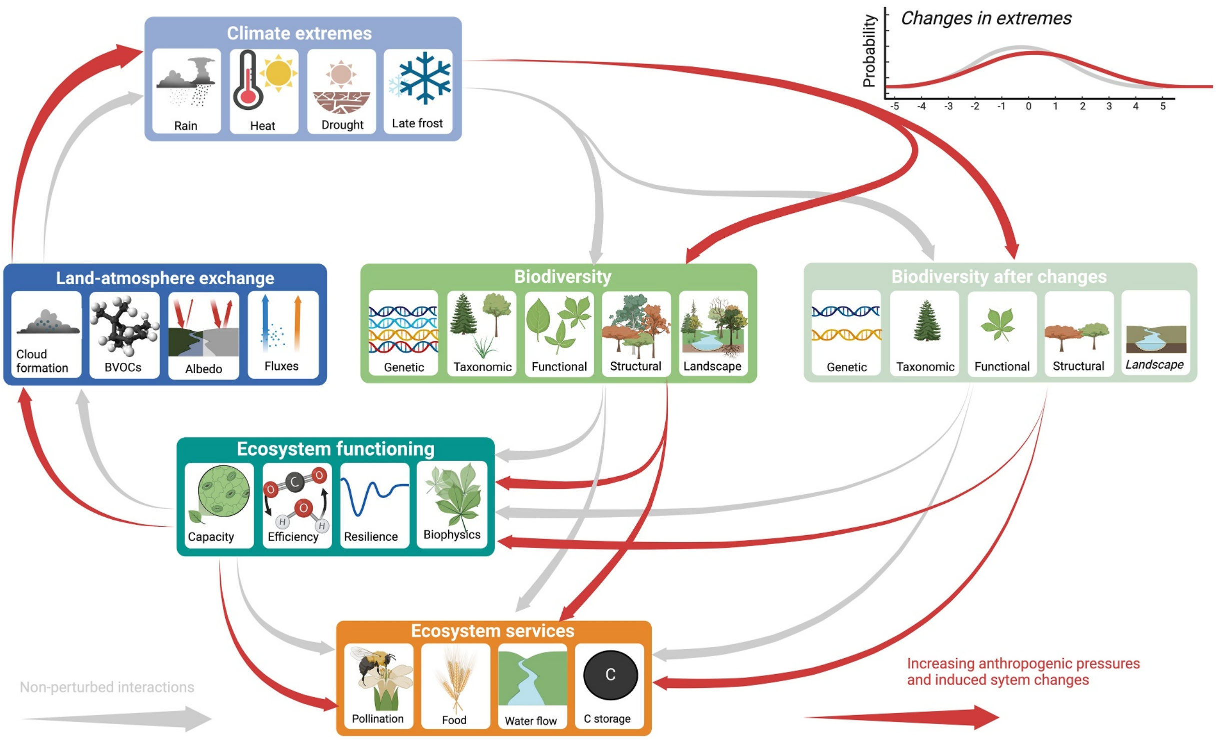



**Figure 6.** Illustration of the general role of biodiversity as a buffer to climate extremes. "Biodiversity" is understood here as a multifaceted term that embraces everything from genetic, via functional traits, to landscape scale heterogeneity, as it is currently the accepted idea in international frameworks (Pereira et al., 2013), and including "geodiversity" (Gray, 2011). All these dimensions of biodiversity constrain ecosystem functioning (Reichstein et al., 2014), effectively translating climate impulses into fluxes and signals that contribute to multiple feedback mechanisms with the atmosphere (Bonan, 2008). Alterations of biodiversity dimensions must therefore feedback to climate extremes (red arrows), which, considering the future intensification of extremes, have the potential to transform biodiversity itself. Ecosystem services are directly affected by biodiversity and ecosystem functions.

There are indications that BVOC emissions depend on forests taxonomic and functional diversity, resulting in species-specific impacts on the tropospheric gas and particle phase including oxidant as well as BSOA concentration distributions and diurnal cycles (Luttkus et al., 2022, 2024). Intriguingly, a scoping measurement study by Sanaei et al. (2023) found that increased taxonomic biodiversity might result in lower total BVOC emissions compared to the cumulative emissions of individual species. These findings highlight the need for further research, particularly concerning how BVOC oxidation modifies particles through BSOA and the subsequent effects on clouds, precipitation and climate.

A particularly intertwined set of processes linking functional, structural and landscape diversity and extreme events is related to fires (Rosan et al., 2022; Wirth, 2005). In the wake of climate change, fires are also on the rise in many regions, with increased burned area and reduced fire return intervals (Jones et al., 2022). The record-breaking 2019/20 fires in Australia were unprecedented in intensity and extent, leading to enormous emissions of $CO_2$ and soot particles (van der Velde et al., 2021). Given that fire dynamics depend on vegetation traits and the type and amount of available fuel, biodiversity also has an effect on the types of particles emitted (Miller et al., 2012). In a recent review, Jones et al. (2022) describes the complexity of the factors to consider when understanding wildfires. From this review and other studies, the important role of fires on particle injection into the atmosphere and the interaction between lightning and pyroconvection become evident (Altaratz et al., 2010; Dowdy & Pepler, 2018). However, as detailed in Loudermilk et al. (2022) the full extent of fire-vegetation-atmosphere feedback is currently poorly conceived. In a broader context, there is a need to expand the focus from fire frequency and sometimes severity, to address how a broader range of fire regime attributes affect biodiversity (McLauchlan et al., 2020; Miller et al., 2012).

## 4. Biodiversity-Extreme Event Interactions

The examples discussed above suggest that terrestrial vegetation plays an important role in changing, for instance, local atmospheric chemistry or land-atmosphere coupling parameters that may shape the development of extreme events. Considering that biodiversity influences vegetation dynamics, it stands to reason that biodiversity should have a discernible impact on climate extremes, thus potentially influencing their impacts on ecosystems and ecosystem resistance and resilience against extreme weather conditions. For example, some plants respond to drought conditions by reducing stomatal conductance to prevent water loss, which in turn can exacerbate heat anomalies (Sungmin et al., 2022). Severe abiotic (e.g., ozone, heat, drought) and biotic stressors (e.g., herbivore attack and infestation, see also Figure 5), can also induce BVOC emission regulating stress response mechanisms which may lead to extremes both in BVOC and atmospheric aerosol particle emissions (Blande et al., 2014; Grote et al., 2019). More biogenic particles of primary or secondary origin under extreme events are then expected to trigger direct and indirect effects including an enhanced aerosol-radiation interaction, an increase of the fraction of diffuse to direct solar radiation, which in turn has a stimulating effect on vegetation productivity (Rap et al., 2015, 2018). BVOC emissions further impact the tropospheric oxidizing capacity, including oxidizing substances such as ozone being consumed or formed through BVOC chemical degradation processes thereby impacting BSOA formation. In turn, ozone is also an abiotic plant stressor, resulting in complex interactions under extreme events.

Furthermore, all the mentioned processes can substantially alter atmospheric humidity, transport dynamics, and, ultimately, cloud evolution and precipitation at regional and global scales (Avissar & Werth, 2005; Machado et al., 2018). Thus, ecosystem imprints of this kind can also have remote effects. For instance, Schumacher et al. (2019) show that heatwaves can propagate in space through lateral heat transfer (see also Miralles et al., 2019), although the specific role of biodiversity in such lateral processes has not been specifically evaluated. Given the examples above, we expect that by altering the characteristics of a weather or climate extreme itself, ecosystems impacted by an extreme event can impact another ecosystem downstream, leading to the possibility of cascading effects. Considering the significant influence of ecosystems on atmospheric processes, land management practices and land cover change must play a crucial role in affecting atmospheric feedback mechanisms (Duveiller et al., 2018; Lugato et al., 2020). Thus, we hypothesize that management should have an effect on extreme events.

A conceptual diagram of how biodiversity and climate extremes are connected is shown in Figure 6. The figure illustrates how climate extremes of various types influence ecosystem functionality. By ecosystem function, we mean, for instance, the biophysical controls of exchange processes, the capacity of ecosystems to utilize nutrients, efficiencies in assimilating $CO_2$, or their inherent resilience to certain stress (Migliavacca et al., 2021; Musavi et al., 2015; Reichstein et al., 2014). These functional properties are influenced by the different dimensions of biodiversity (as outlined in Figure 2). For example, plant traits affect albedo, thereby providing resistance against extreme events by cooling the local microclimate, that is, by lowering soil temperature and reducing water stress (Iler et al., 2021). An intensification of a specific type of extreme event, such as unprecedented droughts or the compounding of several types of extremes, can modify these intrinsic ecosystem properties. Thus, any change in biodiversity can further alter these pathways. Since ecosystem functioning determines the flow of energy, matter, or particles into the atmosphere, the distribution of subsequent climate extremes may also be affected, closing the feedback loop.

In summary, we presented evidence that ecosystem properties and processes can buffer the impacts of weather and climate-related extremes, with their effectiveness often depending on the state of their biodiversity. Conversely, while it is recognized that biodiversity and land-surface dynamics may influence certain extreme events, the extent of this influence remains inadequately understood. Despite the apparent logical relationship between biodiversity, vegetation attributes, fire-atmosphere dynamics, and their impact on subsequent extreme events, scientific evidence that quantifies these links and their effects on ecosystem resistance and resilience remains sparse. The specific role of biodiversity and the overall magnitude of these effects, from local to global scales, have yet to be quantified. In light of the evidence of this interconnectedness, we need to consider whether deliberately increasing functional diversity, through management or rewilding initiatives (Svenning et al., 2016) should be re-evaluated for its potential to mitigate extreme events, resulting in a win-win situation. Even if shifts in ecosystem characteristics and biodiversity do not substantially alter the frequency of climate extremes, there are multiple processes that have the potential to amplify or dampen a range of weather and climate-related extremes and their impacts. Managing ecosystems to improve their drought resistance and resilience (Balch et al., 2020; Pörtner et al., 2021) could be instrumental in influencing land-atmosphere feedback mechanisms. To leverage this potential, we need a deeper understanding of these feedback mechanisms. The challenge is not necessarily a shortage of scientific hypotheses, but rather the integration of diverse scientific disciplines, their observational methodologies, and modeling approaches.

## 5. Research Gaps

Understanding the connection between climate extremes and biodiversity change is still in its early stage. Despite the array of evidence delineated herein, significant scientific gaps persist. The subsequent points highlight areas that require further scientific study:

- *Considering all dimensions of biodiversity*: Genetic, taxonomic, functional, and landscape diversity all shape buffers and feedback mechanisms between ecosystems and climate extremes in very specific ways. What we miss is a global catalog and understanding of how each of the biodiversity dimensions interacts with the variety of climate extremes. We need to understand the exact role of different dimensions of biodiversity in these interactions. Only by doing so can we clearly formulate ecosystem management priorities and efficient (e.g., remote sensing based) monitoring strategies.
- *Quantifying biodiversity buffers across event types*: For extreme event types other than the well-studied cases of droughts and heatwaves, evidence for the dampening or amplifying processes remains weak. This concerns particularly the rather small-scale events such as spring frost, heavy precipitation events, solar radiation or ozone maxima, and wind storms. Despite their locally important impacts, these events have received less frequent and intense scrutiny in research. Impacts of weather extremes of this kind have been overlooked so far, but may be particularly sensitive to changes in biodiversity.
- *Embracing multiple spatial and temporal scales*: Similar to biodiversity patterns, meteorological drivers are scale-dependent. The occurrence of extremes is linked to micro-meteorological (meters to sub-km), synoptic (up to 1,000 km), and global scales in space. Temporally, atmospheric variability ranges from the weather time scales (hours/days) to the interannual and multidecadal patterns of large-scale circulations. Achieving a comprehensive understanding biodiversity buffers and feedback mechanisms needs to embrace all these different scales which may be achievable by combining remote sensing and modeling approaches. Scale-bridging endeavors are important since ecosystems exhibit characteristic resistances to weather- and climate-related extremes and are part of a dynamic pulse-response mechanism (Harris et al., 2018) that control numerous processes at the land-atmosphere interface across different and interacting spatio-temporal scales.
- *Preconditions are key determinants*: Pre-existing conditions may be induced by ecosystem recovery from earlier disturbances, or from preceding unusual weather and climatic trajectories. For example, winter and spring seasons are warming quickly, which leads to phenological shifts and to potentially enhanced water depletion with associated lower resistance to extremes in summer or in following seasons (see Figure 3). On longer time scales, changes in disturbance regimes and memory effects from hot-dry years can further induce lagged memory effects and reduced resistance. Despite this conceptual basis, however, a key research gap remains in how and which pre-existing conditions mechanistically determine ecosystems' resistance and resilience to weather or climate-related extremes (Figure 5), and how these effects depend on different dimensions of biodiversity.
- *Understanding feedback loops*: Predicting how exactly biodiversity shapes land-atmosphere interactions is not yet possible today. Even less understood are the specific biodiversity features and processes that modulate these interactions and regulate extremes. The involved processes are manifold and range from the emission of biogenic aerosol particles acting as ice-nucleating particles required for heterogeneous ice formation in clouds, and large-scale land-surface-atmosphere interactions. In this broad context, it might be essential to also consider the indirect effects of biodiversity in stabilizing plant communities and vegetation structure. For instance, if biodiversity can prevent a biome shift from tropical forests to grasslands (see e.g. (Sakschewski et al., 2016)), it must have major implications for feedbacks between land and atmosphere. Overall, we find that many research gaps prevent from accurately predicting how changing dimensions of biodiversity are affected and how they, in turn, modulate different types of atmospheric and climatic extremes.
- *From anticipation to sustainable management*: Climate change and the ongoing transformation of terrestrial ecosystems lead to unprecedented constellations of climate extremes and biodiversity. For instance, little is

known about whether extremes exceed historical records by large margins (Fischer et al. (2021), Figure 1). These events are likely to impose disproportionately large effects on ecosystems, potentially exceeding the adaptive capacities. Ecosystems are typically adapted to historical weather and climate conditions, raising questions about their ability to mitigate the impact of such drastic extremes. While such events have been observed recently, their rarity, projected increase in frequency, and the inherent limitations of current models to represent the complex feedback between climate extremes and biodiversity across spatio-temporal scales expose another research gap. Currently, there is no conceptual framework to address this gap. It is unclear what level of process complexity and spatio-temporal scales need to be incorporated into models to generate robust projections, and whether this is computationally feasible. Consequently, the strength and even the direction of the feedback between biodiversity change and various types of climate extremes remain elusive. Effective management strategies for climate adaptation and mitigation require the development of reliable predictive models that adequately represent the nuances of functional diversity, an area that needs further advancement.

- *Societal dimensions and systemic risk*: Looking forward, we argue that empirical and modeling research need to adopt more integrated approaches that encompass biodiversity, multiple ecosystem services, and socio-ecological dynamics (Thonicke et al., 2020). Such an approach is essential to comprehensively address feedback loops leading to systemic risks associated with climate extremes (Reichstein et al., 2021). Achieving this necessitates collaboration across different disciplines, such as ecology, atmospheric sciences and climatology, psychology, and social sciences. Understanding the interactions between climate extremes, biodiversity, ecosystem services, and long-term societal demands can also inform policy-making and management strategies to reduce greenhouse gas emissions and mitigate the impacts of climate change without sacrificing other ecosystem services. For example, policies that prioritize the protection of critical ecosystems and biodiversity can enhance the resilience of ecosystems to climate extremes and support carbon sequestration, which can help mitigate the impacts of climate change through a no-regret strategy (Erb et al., 2022).

The overarching and unresolved question we identify here is: Under which conditions do we expect dampening or amplifications due to interactions between biodiversity and climate extremes? Only by answering this question, taking into account all the different dimensions of biodiversity and types and dynamics of extremes, can we effectively manage ecosystems to maximize their resistance and resilience against future climate conditions, particularly amidst more frequent extremes. More research is required to understand and quantify such feedback mechanisms and their spatial and temporal dependencies. Local-scale studies are particularly important to quantify changes in biodiversity-related drivers of the climate system. A pivotal issue that remains unresolved is how to quantify the imprints of local and small-scale biodiversity patterns on large-scale synoptic or global circulation patterns. An additional complication is how to identify the remote influence of biodiversity linked to atmospheric teleconnections.

## 6. Conclusions

The scientific gaps identified in this paper call for the formulation of an ambitious interdisciplinary research agenda. We need to explore the multiple relationships between biodiversity and climate extremes across spatial scales and extensive environmental gradients. One cornerstone is observations. In situ and remote sensing observations that can simultaneously quantify multiple dimensions of taxonomic, structural, functional, and landscape diversity and composition need to be harmonized with the monitoring of atmospheric thermodynamics and composition. There are fundamental advances in satellite-based Earth observations for both climate and ecosystem monitoring (Montero et al., 2023; Skidmore et al., 2021) that are increasingly integrated with in situ observations of biodiversity (Dornelas et al., 2018), global observatories of ecosystem-atmosphere exchanges such as FLUXNET (Baldocchi, 2020), or specific processes such as tree mortality (Hartmann et al., 2018). Machine learning plays a key role in achieving this much-needed data integration (Bodesheim et al., 2022) and is increasingly empowered by deep learning (Reichstein et al., 2019).

In addition to high-quality observations, we need powerful models. We must understand how terrestrial ecosystem dynamics feed back into atmospheric variability and how biodiversity modulates these relationships. For this, we need a new generation of predictive models, which are capable of capturing the complex interactions between atmospheric processes, biodiversity patterns, and ecosystems. Crucially, these models should facilitate adequate testing of hypotheses concerning feedback mechanisms. Although functional digital twins of the climate system are now in reach, soon providing climate simulations at the kilometer-scale resolutions (Bauer et al., 2021;

Slingo et al., 2022), it is unlikely that high-resolution simulations alone can fully encapsulate the coupling and feedback loops between climate and biodiversity. The digital twin concept for ecosystems is still in a conceptual phase (Buonocore et al., 2022), substantial research is imperative to realistically represent biodiversity in land-surface models (Bendix et al., 2021; Scheiter et al., 2013). Today, several prototypes of a Digital Twin for biodiversity are currently being developed (de Koning et al., 2023), but these will not be able to fully predict the feedback loops described here and thus must be used in concert with fully dynamic modeling schemes.

Today, there is a growing awareness of the intricate interplay between biodiversity decline and climate change, as shown in a recent collaborative report jointly published by IPCC and IPBES (Pörtner et al., 2021, 2023) and in a series of policy directives. For instance, the new European Union (EU) Forest Strategy for 2030 and policy initiatives by the European Commission have recognized the value of the multi-functionality of forests, including their regulatory role in atmospheric processes. However, the observational and modeling frameworks are still rather weak to support policy decisions. Elsewhere, the lack of research on the feedback loop linking biodiversity changes and climate extremes is also evident in policy, which sometimes pays insufficient attention to both aspects. New policy tools (e.g., the Carbon Removal Certification Proposal by the European Union) and nature-based climate solutions, including climate-smart forestry, aim to address this issue by implementing management actions that improve biodiversity. Simultaneously, there is a shortage of scientific studies on the interactions between changes in biodiversity, climate extremes, and biophysical feedbacks. By addressing these critical research gaps, we can significantly enhance our understanding of biodiversity's buffering capacities and better support policy decisions. In doing so, we strengthen the ability to mitigate the impacts of climate extremes and enhance ecosystem resilience, thereby safeguarding our planet's ecological integrity.

## Data Availability Statement

This paper is based on a literature review; no original data have been used. All figures were generated based on conceptual considerations using the biorender.com software.

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## References

Altaratz, O., Koren, I., Yair, Y., & Price, C. (2010). Lightning response to smoke from Amazonian fires. *Geophysical Research Letters*, *37*(7), L07801. https://doi.org/10.1029/2010gl042679

Anderegg, W. R. L., Trugman, A. T., Badgley, G., Konings, A. G., & Shaw, J. (2020). Divergent forest sensitivity to repeated extreme droughts. *Nature Climate Change*, *10*(12), 1091–1095. https://doi.org/10.1038/s41558-020-00919-1

Anderegg, W. R. L., Trugman, A. T., Bowling, D. R., Salvucci, G., & Tuttle, S. E. (2019). Plant functional traits and climate influence drought intensification and land-atmosphere feedbacks. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(28), 14071–14076. https://doi.org/10.1073/pnas.1904747116

Avissar, R., & Werth, D. (2005). Global hydroclimatological teleconnections resulting from tropical deforestation. *Journal of Hydrometeorology*, *6*(2), 134–145. https://doi.org/10.1175/JHM406.1

Balch, J. K., Iglesias, V., Braswell, A. E., Rossi, M. W., Joseph, M. B., Mahood, A. L., et al. (2020). Social-environmental extremes: Rethinking extraordinary events as outcomes of interacting biophysical and social systems. *Earth's Future*, *8*(7), e2019EF001319. https://doi.org/10.1029/2019EF001319

Baldocchi, D. D. (2020). How eddy covariance flux measurements have contributed to our understanding of global change biology. *Global Change Biology*, *26*(1), 242–260. https://doi.org/10.1111/gcb.14807

Barriopedro, D., García-Herrera, R., Ordóñez, C., Miralles, D. G., & Salcedo-Sanz, S. (2023). Heat waves: Physical understanding and scientific challenges. *Reviews of Geophysics*, *61*(2), e2022RG000780. https://doi.org/10.1029/2022RG000780

Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., et al. (2020). Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity. *Science Advances*, *6*(24), eaba2724. https://doi.org/10.1126/sciadv.aba2724

Bastos, A., Fu, Z., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., et al. (2020). Impacts of extreme summers on European ecosystems: A comparative analysis of 2003, 2010 and 2018. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1810), 20190507. https://doi.org/10.1098/rstb.2019.0507

Bastos, A., Orth, R., Reichstein, M., Ciais, P., Viovy, N., Zaehle, S., et al. (2021). Increased vulnerability of European ecosystems to two compound dry and hot summers in 2018 and 2019. *Earth System Dynamics Discussions*, 1–32. https://doi.org/10.5194/esd-2021-19

Bastos, A., Sippel, S., Frank, D., Mahecha, M. D., Zaehle, S., Zscheischler, J., & Reichstein, M. (2023). A joint framework for studying compound ecoclimatic events. *Nature Reviews Earth & Environment*, *4*(5), 333–350. https://doi.org/10.1038/s43017-023-00410-3

Bauer, P., Dueben, P. D., Hoefler, T., Quintino, T., Schulthess, T. C., & Wedi, N. P. (2021). The digital revolution of earth-system science. *Nature Computational Science*, *1*(2), 104–113. https://doi.org/10.1038/s43588-021-00023-0

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, *15*(4), 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Bendix, J., Aguire, N., Beck, E., Bräuning, A., Brandl, R., Breuer, L., et al. (2021). A research framework for projecting ecosystem change in highly diverse tropical mountain ecosystems. *Oecologia*, *195*(3), 589–600. https://doi.org/10.1007/s00442-021-04852-8

Berendse, F., van Ruijven, J., Jongejans, E., & Keesstra, S. (2015). Loss of plant species diversity reduces soil erosion resistance. *Ecosystems*, *18*(5), 881–888. https://doi.org/10.1007/s10021-015-9869-6

Beugnon, R., Le Guyader, N., Milcu, A., Lenoir, J., Puissant, J., Morin, X., & Hättenschwiler, S. (2024). Microclimate modulation: An overlooked mechanism influencing the impact of plant diversity on ecosystem functioning. *Global Change Biology*, *30*(3), e17214. https://doi.org/10.1111/gcb.17214

Blande, J. D., Holopainen, J. K., & Niinemets, l. (2014). Plant volatiles in polluted atmospheres: Stress responses and signal degradation. *Plant, Cell and Environment*, *37*(8), 1892–1904. https://doi.org/10.1111/pce.12352

Bodesheim, P., Babst, F., Frank, D. C., Hartl, C., Zang, C. S., Jung, M., et al. (2022). Predicting spatiotemporal variability in radial tree growth at the continental scale with machine learning. *Environmental Data Science*, *1*, e9. https://doi.org/10.1017/eds.2022.8

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Brunner, M. I., Slater, L., Tallaksen, L. M., & Clark, M. (2021). Challenges in modeling and predicting floods and droughts: A review. *WIREs Water*, *8*(3), e1520. https://doi.org/10.1002/wat2.1520

Buonocore, L., Yates, J., & Valentini, R. (2022). A proposal for a forest digital twin framework and its perspectives. *Forests*, *13*(4), 498. https://doi.org/10.3390/f13040498

Cavender-Bares, J., Gamon, J., & Townsend, P. (Eds.) (2020)., *Remote sensing of plant biodiversity*. Springer International Publishing. https://doi.org/10.1007/978-3-030-33157-3

Cavender-Bares, J., Schneider, F. D., Santos, M. J., Armstrong, A., Carnaval, A., Dahlin, K. M., et al. (2022). Integrating remote sensing with ecology and evolution to advance biodiversity conservation. *Nature Ecology & Evolution*, *6*(5), 506–519. https://doi.org/10.1038/s41559-022-01702-5

CBD. (1992). *Convention on biological diversity: Text and annex*. United Nations Environment Programme. Retrieved from http://www.cbd.int/doc/legal/cbd-en.pdf

Cinto Mejía, E., & Wetzel, W. C. (2023). The ecological consequences of the timing of extreme climate events. *Ecology and Evolution*, *13*(1), e9661. https://doi.org/10.1002/ece3.9661

Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature Climate Change*, *2*(7), 491–496. https://doi.org/10.1038/nclimate1452

Craven, D., Eisenhauer, N., Pearse, W. D., Hautier, Y., Isbell, F., Roscher, C., et al. (2018). Multiple facets of biodiversity drive the diversity-stability relationship. *Nature Ecology & Evolution*, *2*(10), 1579–1587. https://doi.org/10.1038/s41559-018-0647-7

De Boeck, H. J., Bloor, J. M. G., Kreyling, J., Ransijn, J. C. G., Nijs, I., Jentsch, A., & Zeiter, M. (2018). Patterns and drivers of biodiversity–stability relationships under climate extremes. *Journal of Ecology*, *106*(3), 890–902. https://doi.org/10.1111/1365-2745.12897

De Keersmaecker, W., van Rooijen, N., Lhermitte, S., Tits, L., Schaminée, J., Coppin, P., et al. (2016). Species-rich semi-natural grasslands have a higher resistance but a lower resilience than intensively managed agricultural grasslands in response to climate anomalies. *Journal of Applied Ecology*, *53*(2), 430–439. https://doi.org/10.1111/1365-2664.12595

de Koning, K., Broekhuijsen, J., Kühn, I., Ovaskainen, O., Taubert, F., Endresen, D., et al. (2023). Digital twins: Dynamic model-data fusion for ecology. *Trends in Ecology & Evolution*, *38*(10), 916–926. https://doi.org/10.1016/j.tree.2023.04.010

De Laender, F., Rohr, J. R., Ashauer, R., Baird, D. J., Berger, U., Eisenhauer, N., et al. (2016). Reintroducing environmental change drivers in biodiversity-ecosystem functioning research. *Trends in Ecology & Evolution*, *31*(12), 905–915. https://doi.org/10.1016/j.tree.2016.09.007

Desai, A. R., Wohlfahrt, G., Zeeman, M. J., Katata, G., Eugster, W., Montagnani, L., et al. (2016). Montane ecosystem productivity responds more to global circulation patterns than climatic trends. *Environmental Research Letters*, *11*(2), 024013. https://doi.org/10.1088/1748-9326/11/2/024013

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., et al. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, *366*(6471), eaax3100. https://doi.org/10.1126/science.aax3100

Dornelas, M., Antao, L. H., Moyes, F., Bates, A. E., Magurran, A. E., Adam, D., et al. (2018). Biotime: A database of biodiversity time series for the anthropocene. *Global Ecology and Biogeography*, *27*(7), 760–786. https://doi.org/10.1111/geb.12729

Dowdy, A. J., & Pepler, A. (2018). Pyroconvection risk in Australia: Climatological changes in atmospheric stability and surface fire weather conditions. *Geophysical Research Letters*, *45*(4), 2005–2013. https://doi.org/10.1002/2017gl076654

Duveiller, G., Filipponi, F., Ceglar, A., Bojanowski, J., Alkama, R., & Cescatti, A. (2021). Revealing the widespread potential of forests to increase low level cloud cover. *Nature Communications*, *12*(1), 4337. https://doi.org/10.1038/s41467-021-24551-5

Duveiller, G., Hooker, J., & Cescatti, A. (2018). The mark of vegetation change on earth's surface energy balance. *Nature Communications*, *9*(1), 679. https://doi.org/10.1038/s41467-017-02810-8

Erb, K.-H., Haberl, H., Le Noë, J., Tappeiner, U., Tasser, E., & Gingrich, S. (2022). Changes in perspective needed to forge 'no-regret' forest-based climate change mitigation strategies. *GCB Bioenergy*, *14*(3), 246–257. https://doi.org/10.1111/gcbb.12921

Faranda, D., Vrac, M., Yiou, P., Jézéquel, A., & Thao, S. (2020). Changes in future synoptic circulation patterns: Consequences for extreme event attribution. *Geophysical Research Letters*, *47*(15), e2020GL088002. https://doi.org/10.1029/2020gl088002

Felton, A. J., & Smith, M. D. (2017). Integrating plant ecological responses to climate extremes from individual to ecosystem levels. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1723), 20160142. https://doi.org/10.1098/rstb.2016.0142

Fischer, E., Sippel, S., & Knutti, R. (2021). Increasing probability of record-shattering climate extremes. *Nature Climate Change*, *11*(8), 689–695. https://doi.org/10.1038/s41558-021-01092-9

Flach, M., Brenning, A., Gans, F., Reichstein, M., Sippel, S., & Mahecha, M. D. (2021). Vegetation modulates the impact of climate extremes on gross primary production. *Biogeosciences*, *18*(1), 39–53. https://doi.org/10.5194/bg-18-39-2021

Flach, M., Sippel, S., Gans, F., Bastos, A., Brenning, A., Reichstein, M., & Mahecha, M. D. (2018). Contrasting biosphere responses to hydrometeorological extremes: Revisiting the 2010 western Russian heatwave. *Biogeosciences*, *15*(20), 6067–6085. https://doi.org/10.5194/bg-15-6067-2018

Forzieri, G., Girardello, M., Ceccherini, G., Spinoni, J., Feyen, L., Hartmann, H., et al. (2021). Emergent vulnerability to climate-driven disturbances in European forests. *Nature Communications*, *12*(1), 1081. https://doi.org/10.1038/s41467-021-21399-7

Fowler, H. J., Blenkinsop, S., Green, A., & Davies, P. A. (2024). Precipitation extremes in 2023. *Nature Reviews Earth & Environment*, *5*(4), 1–3. https://doi.org/10.1038/s43017-024-00547-9

Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank, D., Mahecha, M. D., et al. (2015). Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. *Global Change Biology*, *21*(8), 2861–2880. https://doi.org/10.1111/gcb.12916

Fröhlich-Nowoisky, J., Kampf, C. J., Weber, B., Huffman, J. A., Pöhlker, C., Andreae, M. O., et al. (2016). Bioaerosols in the Earth system: Climate, health, and ecosystem interactions. *Atmospheric Research*, *182*, 346–376. https://doi.org/10.1016/j.atmosres.2016.07.018

Gonzalez, A., Germain, R. M., Srivastava, D. S., Filotas, E., Dee, L. E., Gravel, D., et al. (2020). Scaling-up biodiversity-ecosystem functioning research. *Ecology Letters*, *23*(4), 757–776. https://doi.org/10.1111/ele.13456

Graf, A., Klosterhalfen, A., Arriga, N., Bernhofer, C., Bogena, H., Bornet, F., et al. (2020). Altered energy partitioning across terrestrial ecosystems in the European drought year 2018. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1810), 20190524. https://doi.org/10.1098/rstb.2019.0524

Gray, M. (2011). Other nature: Geodiversity and geosystem services. *Environmental Conservation*, *38*(3), 271–274. https://doi.org/10.1017/S0376892911000117

Grossiord, C., Sevanto, S., Bonal, D., Borrego, I., Dawson, T. E., Ryan, M., et al. (2019). Prolonged warming and drought modify belowground interactions for water among coexisting plants. *Tree Physiology*, *39*(1), 55–63. https://doi.org/10.1093/treephys/tpy080

Grote, R., Sharma, M., Ghirardo, A., & Schnitzler, J.-P. (2019). A new modeling approach for estimating abiotic and biotic stress-Induced de novo emissions of biogenic volatile organic compounds from plants. *Frontiers in Forests and Global Change*, *2*, 26. https://doi.org/10.3389/ffgc.2019.00026

Guimarães-Steinicke, C., Weigelt, A., Proulx, R., Lanners, T., Eisenhauer, N., Duque-Lazo, J., et al. (2021). Biodiversity facets affect community surface temperature via 3D canopy structure in grassland communities. *Journal of Ecology*, *109*(5), 1969–1985. https://doi.org/10.1111/1365-2745.13631

Harris, R. M. B., Beaumont, L. J., Vance, T. R., Tozer, C. R., Remenyi, T. A., Perkins-Kirkpatrick, S. E., et al. (2018). Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, *8*(7), 579–587. https://doi.org/10.1038/s41558-018-0187-9

Hartmann, H., Link, R. M., & Schuldt, B. (2021). A whole-plant perspective of isohydry: Stem-level support for leaf-level plant water regulation. *Tree Physiology*, *41*(6), 901–905. https://doi.org/10.1093/treephys/tpab011

Hartmann, H., Moura, C. F., Anderegg, W. R. L., Ruehr, N. K., Salmon, Y., Allen, C. D., et al. (2018). Research frontiers for improving our understanding of drought-induced tree and forest mortality. *New Phytologist*, *218*(1), 15–28. https://doi.org/10.1111/nph.15048

Hoover, D. L., Knapp, A. K., & Smith, M. D. (2014). Resistance and resilience of a grassland ecosystem to climate extremes. *Ecology*, *95*(9), 2646–2656. https://doi.org/10.1890/13-2186.1

Huguenin, M. F., Fischer, E. M., Kotlarski, S., Scherrer, S. C., Schwierz, C., & Knutti, R. (2020). Lack of change in the projected frequency and persistence of atmospheric circulation types over central europe. *Geophysical Research Letters*, *47*(9), e2019GL086132. https://doi.org/10.1029/2019gl086132

Iler, A. M., Walwema, A. S., Steltzer, H., & Blázquez-Castro, A. (2021). Can flowers affect land surface albedo and soil microclimates? *International Journal of Biometeorology*, *65*(12), 2011–2023. https://doi.org/10.1007/s00484-021-02159-0

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services (Tech. Rep.)*. IPBES secretariat. https://doi.org/10.5281/zenodo.3831673

IPCC. (2021). In V. Masson-Delmotte, et al. (Eds.), *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., et al. (2015). Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, *526*(7574), 574–577. https://doi.org/10.1038/nature15374

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., & Fawcett, P. J. (2013). Terrestrial water fluxes dominated by transpiration. *Nature*, *496*(7445), 347–350. https://doi.org/10.1038/nature11983

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D. E., Coscieme, L., Golden, A. S., et al. (2022). The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances*, *8*(45), eabm9982. https://doi.org/10.1126/sciadv.abm9982

Jiang, X., Guenther, A., Potosnak, M., Geron, C., Seco, R., Karl, T., et al. (2018). Isoprene emission response to drought and the impact on global atmospheric chemistry. *Atmospheric Environment*, *183*, 69–83. https://doi.org/10.1016/j.atmosenv.2018.01.026

Johnstone, J. F., Allen, C. D., Franklin, J. F., Frelich, L. E., Harvey, B. J., Higuera, P. E., et al. (2016). Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, *14*(7), 369–378. https://doi.org/10.1002/fee.1311

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., et al. (2022). Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, *60*(3), e2020RG000726. https://doi.org/10.1029/2020rg000726

Kayler, Z. E., De Boeck, H. J., Fatichi, S., Grünzweig, J. M., Merbold, L., Beier, C., et al. (2015). Experiments to confront the environmental extremes of climate change. *Frontiers in Ecology and the Environment*, *13*(4), 219–225. https://doi.org/10.1890/140174

Kornhuber, K., Osprey, S., Coumou, D., Petri, S., Petoukhov, V., Rahmstorf, S., & Gray, L. (2019). Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern. *Environmental Research Letters*, *14*(5), 054002. https://doi.org/10.1088/1748-9326/ab13bf

Kretzschmar, J., Pöhlker, M., Stratmann, F., Wex, H., Wirth, C., & Quaas, J. (2023). From trees to rain: Enhancement of cloud glaciation and precipitation by pollen. *arXiv*. https://doi.org/10.48550/ARXIV.2305.06758

Kreyling, J., Wenigmann, M., Beierkuhnlein, C., & Jentsch, A. (2008). Effects of extreme weather events on plant productivity and tissue die-back are modified by community composition. *Ecosystems*, *11*(5), 752–763. https://doi.org/10.1007/s10021-008-9157-9

Laguë, M. M., Bonan, G. B., & Swann, A. L. (2019). Separating the impact of individual land surface properties on the terrestrial surface energy budget in both the coupled and uncoupled land–atmosphere system. *Journal of Climate*, *32*(18), 5725–5744. https://doi.org/10.1175/jcli-d-18-0812.1

Lange, M., Feilhauer, H., Kühn, I., & Doktor, D. (2022). Mapping land-use intensity of grasslands in Germany with machine learning and sentinel-2 time series. *Remote Sensing of Environment*, *277*, 112888. https://doi.org/10.1016/j.rse.2022.112888

Lehtipalo, K., Yan, C., Dada, L., Bianchi, F., Xiao, M., Wagner, R., et al. (2018). Multicomponent new particle formation from sulfuric acid, ammonia, and biogenic vapors. *Science Advances*, *4*(12), eaau5363. https://doi.org/10.1126/sciadv.aau5363

Lemus-Canovas, M., Insua-Costa, D., Trigo, R. M., & Miralles, D. G. (2024). Record-shattering 2023 spring heatwave in western mediterranean amplified by long-term drought. *npj Climate and Atmospheric Science*, *7*(1), 25. https://doi.org/10.1038/s41612-024-00569-6

Lin, H., Tu, C., Fang, J., Gioli, B., Loubet, B., Gruening, C., et al. (2020). Forests buffer thermal fluctuation better than non-forests. *Agricultural and Forest Meteorology*, *288–289*, 107994. https://doi.org/10.1016/j.agrformet.2020.107994

Liu, D., Wang, T., Peñuelas, J., & Piao, S. (2022). Drought resistance enhanced by tree species diversity in global forests. *Nature Geoscience*, *15*(10), 800–804. https://doi.org/10.1038/s41561-022-01026-w

Loreau, M., Barbier, M., Filotas, E., Gravel, D., Isbell, F., Miller, S. J., et al. (2021). Biodiversity as insurance: From concept to measurement and application. *Biological Reviews*, *96*(5), 2333–2354. https://doi.org/10.1111/brv.12756

Loudermilk, E. L., O'Brien, J. J., Goodrick, S. L., Linn, R. R., Skowronski, N. S., & Hiers, J. K. (2022). Vegetation's influence on fire behavior goes beyond just being fuel. *Fire Ecology*, *18*(1), 9. https://doi.org/10.1186/s42408-022-00132-9

Lübbe, T., Lamarque, L. J., Delzon, S., Torres Ruiz, J. M., Burlett, R., Leuschner, C., & Schuldt, B. (2022). High variation in hydraulic efficiency but not xylem safety between roots and branches in four temperate broad-leaved tree species. *Functional Ecology*, *36*(3), 699–712. https://doi.org/10.1111/1365-2435.13975

Lugato, E., Cescatti, A., Jones, A., Ceccherini, G., & Duveiller, G. (2020). Maximising climate mitigation potential by carbon and radiative agricultural land management with cover crops. *Environmental Research Letters*, *15*(9), 094075. https://doi.org/10.1088/1748-9326/aba137

Luttkus, M. L., Hoffmann, E. H., Poulain, L., Tilgner, A., & Wolke, R. (2022). The effect of land use classification on the gas-phase and particle composition of the troposphere: Tree species versus forest type information. *Journal of Geophysical Research: Atmospheres*, *127*(7). https://doi.org/10.1029/2021JD035305

Luttkus, M. L., Hoffmann, E. H., Tilgner, A., Wolke, R., Herrmann, H., & Tegen, I. (2024). Urban and remote chemistry modelling with the new chemical mechanism URMELL: Part I gas-phase mechanism development. *Environmental Sciences: Atmosphere*, *4*(2), 164–189. https://doi.org/10.1039/D3EA00094J

Ma, X., Huete, A., Moran, S., Ponce-Campos, G., & Eamus, D. (2015). Abrupt shifts in phenology and vegetation productivity under climate extremes. *Journal of Geophysical Research: Biogeosciences*, *120*(10), 2036–2052. https://doi.org/10.1002/2015jg003144

Ma, X., Migliavacca, M., Wirth, C., Bohn, F. J., Huth, A., Richter, R., & Mahecha, M. D. (2020). Monitoring plant functional diversity using the reflectance and echo from space. *Remote Sensing*, *12*(8), 1248. https://doi.org/10.3390/rs12081248

Machado, L. A. T., Calheiros, A. J. P., Biscaro, T., Giangrande, S., Silva Dias, M. A. F., Cecchini, M. A., et al. (2018). Overview: Precipitation characteristics and sensitivities to environmental conditions during GoAmazon2014/5 and ACRIDICON-CHUVA. *Atmospheric Chemistry and Physics*, *18*(9), 6461–6482. https://doi.org/10.5194/acp-18-6461-2018

Mahecha, M. D., Bastos, A., Bohn, F. J., Eisenhauer, N., Feilhauer, H., Hartmann, H., et al. (2022). Biodiversity loss and climate extremes – Study the feedbacks. *Nature*, *621*(7938), 30–32. https://doi.org/10.1038/d41586-022-04152-y

Mahecha, M. D., Gans, F., Brandt, G., Christiansen, R., Cornell, S. E., Fomferra, N., et al. (2020). Earth system data cubes unravel global multivariate dynamics. *Earth System Dynamics*, *11*(1), 201–234. https://doi.org/10.5194/esd-11-201-2020

Mahecha, M. D., Gans, F., Sippel, S., Donges, J. F., Kaminski, T., Metzger, S., et al. (2017). Detecting impacts of extreme events with ecological in situ monitoring networks. *Biogeosciences*, *14*(18), 4255–4277. https://doi.org/10.5194/bg-14-4255-2017

McLauchlan, K. K., Higuera, P. E., Miesel, J., Rogers, B. M., Schweitzer, J., Shuman, J. K., et al. (2020). Fire as a fundamental ecological process: Research advances and frontiers. *Journal of Ecology*, *108*(5), 2047–2069. https://doi.org/10.1111/1365-2745.13403

Merrifield, A. L., Simpson, I. R., McKinnon, K. A., Sippel, S., Xie, S.-P., & Deser, C. (2019). Local and nonlocal land surface influence in european heatwave initial condition ensembles. *Geophysical Research Letters*, *46*(23), 14082–14092. https://doi.org/10.1029/2019gl083945

Migliavacca, M., Musavi, T., Mahecha, M. D., Nelson, J. A., Knauer, J., Baldocchi, D. D., et al. (2021). The three major axes of terrestrial ecosystem function. *Nature*, *598*(7881), 468–472. https://doi.org/10.1038/s41586-021-03939-9

Miller, J. D., Skinner, C. N., Safford, H. D., Knapp, E. E., & Ramirez, C. M. (2012). Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecological Applications*, *22*(1), 184–203. https://doi.org/10.1890/10-2108.1

Miralles, D. G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land–atmospheric feedbacks during droughts and heatwaves: State of the science and current challenges. *Annals of the New York Academy of Sciences*, *1436*(1), 19–35. https://doi.org/10.1111/nyas.13912

Montero, D., Aybar, C., Mahecha, M. D., Martinuzzi, F., Söchting, M., & Wieneke, S. (2023). A standardized catalogue of spectral indices to advance the use of remote sensing in Earth system research. *Scientific Data*, *10*(1), 1–20. https://doi.org/10.1038/s41597-023-02096-0

Mülmenstädt, J., Sourdeval, O., Delanoë, J., & Quaas, J. (2015). Frequency of occurrence of rain from liquid-mixed-and ice-phase clouds derived from a-train satellite retrievals. *Geophysical Research Letters*, *42*(15), 6502–6509. https://doi.org/10.1002/2015GL064604

Mursinna, A. R., McCormick, E., Van Horn, K., Sartin, L., & Matheny, A. M. (2018). Plant hydraulic trait covariation: A global meta-analysis to reduce degrees of freedom in trait-based hydrologic models. *Forests*, *9*(8), 446. https://doi.org/10.3390/f9080446

Musavi, T., Mahecha, M. D., Migliavacca, M., Reichstein, M., van de Weg, M. J., van Bodegom, P. M., et al. (2015). The imprint of plants on ecosystem functioning: A data-driven approach. *International Journal of Applied Earth Observation and Geoinformation*, *43*, 119–131. https://doi.org/10.1016/j.jag.2015.05.009

Niinemets, Ü. (2010). Mild versus severe stress and BVOCs: Thresholds, priming and consequences. *Trends in Plant Science*, *15*(3), 145–153. https://doi.org/10.1016/j.tplants.2009.11.008

Noss, R. F. (1990). Indicators for monitoring biodiversity: A hierarchical approach. *Conservation Biology*, *4*(4), 355–364. https://doi.org/10.1111/j.1523-1739.1990.tb00309.x

O'Sullivan, D., Adams, M. P., Tarn, M. D., Harrison, A. D., Vergara-Temprado, J., Porter, G. C. E., et al. (2018). Contributions of biogenic material to the atmospheric ice-nucleating particle population in North Western Europe. *Scientific Reports*, *8*(1), 13821. https://doi.org/10.1038/s41598-018-31981-7

Peng, J., Albergel, C., Balenzano, A., Brocca, L., Cartus, O., Cosh, M. H., et al. (2021). A roadmap for high-resolution satellite soil moisture applications – Confronting product characteristics with user requirements. *Remote Sensing of Environment*, *252*, 112162. https://doi.org/10.1016/j.rse.2020.112162

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science*, *339*(6117), 277–278. https://doi.org/10.1126/science.1229931

Pfenninger, M., Reuss, F., Kiebler, A., Schönnenbeck, P., Caliendo, C., Gerber, S., et al. (2021). Genomic basis for drought resistance in European beech forests threatened by climate change. *Elife*, *10*, e65532. https://doi.org/10.7554/elife.65532

Pörtner, H., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., et al. (2021). IPBES-IPCC co-sponsored workshop report on biodiversity and climate change. Bonn, Germany: Intergovernmental science-policy platform on biodiversity and ecosystem services (IPBES) and intergovernmental panel on climate change (IPCC). https://doi.org/10.5281/zenodo.4659158

Pörtner, H.-O., Scholes, R., Arneth, A., Barnes, D., Burrows, M. T., Diamond, S., et al. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642), eabl4881. https://doi.org/10.1126/science.abl4881

Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., et al. (2022). The 2018–2020 multi-year drought sets a new benchmark in europe. *Earth's Future*, *10*(3). https://doi.org/10.1029/2021EF002394

Rap, A., Scott, C. E., Reddington, C. L., Mercado, L., Ellis, R. J., Garraway, S., et al. (2018). Enhanced global primary production by biogenic aerosol via diffuse radiation fertilization. *Nature Geoscience*, *11*(9), 640–644. https://doi.org/10.1038/s41561-018-0208-3

Rap, A., Spracklen, D. V., Mercado, L., Reddington, C. L., Haywood, J. M., Ellis, R. J., et al. (2015). Fires increase amazon forest productivity through increases in diffuse radiation. *Geophysical Research Letters*, *42*(11), 4654–4662. https://doi.org/10.1002/2015gl063719

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., et al. (2013). Climate extremes and the carbon cycle. *Nature*, *500*(7462), 287–295. https://doi.org/10.1038/nature12350

Reichstein, M., Bahn, M., Mahecha, M. D., Kattge, J., & Baldocchi, D. D. (2014). Linking plant and ecosystem functional biogeography. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(38), 13697–13702. https://doi.org/10.1073/pnas.1216065111

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., & Prabhat (2019). Deep learning and process understanding for data-driven Earth system science. *Nature*, *566*(7743), 195–204. https://doi.org/10.1038/s41586-019-0912-1

Reichstein, M., Riede, F., & Frank, D. (2021). More floods, fires and cyclones—Plan for domino effects on sustainability goals. *Nature*, *592*(7854), 347–349. https://doi.org/10.1038/d41586-021-00927-x
Reyer, C. P., Leuzinger, S., Rammig, A., Wolf, A., Bartholomeus, R. P., Bonfante, A., et al. (2013). A plant's perspective of extremes: Terrestrial plant responses to changing climatic variability. *Global Change Biology*, *19*(1), 75–89. https://doi.org/10.1111/gcb.12023
Riccobono, F., Schobesberger, S., Scott, C. E., Dommen, J., Ortega, I. K., Rondo, L., et al. (2014). Oxidation products of biogenic emissions contribute to nucleation of atmospheric particles. *Science*, *344*(6185), 717–721. https://doi.org/10.1126/science.1243527
Riipinen, I., Pierce, J. R., Yli-Juuti, T., Nieminen, T., Häkkinen, S., Ehn, M., et al. (2011). Organic condensation: A vital link connecting aerosol formation to cloud condensation nuclei (CCN) concentrations. *Atmospheric Chemistry and Physics*, *11*(8), 3865–3878. https://doi.org/10.5194/acp-11-3865-2011
Rosan, T. M., Sitch, S., Mercado, L. M., Heinrich, V., Friedlingstein, P., & Aragão, L. E. (2022). Fragmentation-driven divergent trends in burned area in amazonia and cerrado. *Frontiers in Forests and Global Change*, *5*, 801408. https://doi.org/10.3389/ffgc.2022.801408
Saco, P., McDonough, K., Rodriguez, J., Rivera-Zayas, J., & Sandi, S. (2021). The role of soils in the regulation of hazards and extreme events. *Philosophical Transactions of the Royal Society B*, *376*(1834), 20200178. https://doi.org/10.1098/rstb.2020.0178
Sakschewski, B., von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., et al. (2016). Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, *6*(11), 1032–1036. https://doi.org/10.1038/nclimate3109
Sanaei, A., Herrmann, H., Alshaabi, L., Beck, J., Ferlian, O., Fomba, K. W., et al. (2023). Changes in biodiversity impact atmospheric chemistry and climate through plant volatiles and particles. *Communications Earth & Environment*, *4*(1), 1–12. https://doi.org/10.1038/s43247-023-01113-9
Santanello, J. A., Dirmeyer, P. A., Ferguson, C. R., Findell, K. L., Tawfik, A. B., Berg, A., et al. (2018). Land–atmosphere interactions: The LoCo perspective. *Bulletin of the American Meteorological Society*, *99*(6), 1253–1272. https://doi.org/10.1175/BAMS-D-17-0001.1
Scheiter, S., Langan, L., & Higgins, S. I. (2013). Next-generation dynamic global vegetation models: Learning from community ecology. *New Phytologist*, *198*(3), 957–969. https://doi.org/10.1111/nph.12210
Schnabel, F., Purrucker, S., Schmitt, L., Engelmann, R. A., Kahl, A., Richter, R., et al. (2021). Cumulative growth and stress responses to the 2018–2019 drought in a European floodplain forest. *Global Change Biology*, *28*(5), 1870–1883. https://doi.org/10.1111/gcb.16028
Schumacher, D. L., Keune, J., van Heerwaarden, C. C., Vilà-Guerau de Arellano, J., Teuling, A. J., & Miralles, D. G. (2019). Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. *Nature Geoscience*, *12*(9), 712–717. https://doi.org/10.1038/s41561-019-0431-6
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., et al. (2017). Forest disturbances under climate change. *Nature Climate Change*, *7*(6), 395–402. https://doi.org/10.1038/nclimate3303
Seidl, R., & Turner, M. G. (2022). Post-disturbance reorganization of forest ecosystems in a changing world. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(28), e2202190119. https://doi.org/10.1073/pnas.2202190119
Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., et al. (2021). Weather and climate extreme events in a changing climate. In: *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. In (pp. 1513–1766). Cambridge University Press. https://doi.org/10.1017/9781009157896.013
Sippel, S., Reichstein, M., Ma, X., Mahecha, M. D., Lange, H., Flach, M., & Frank, D. (2018). Drought, heat, and the carbon cycle: A review. *Current Climate Change Reports*, *4*(3), 266–286. https://doi.org/10.1007/s40641-018-0103-4
Skidmore, A. K., Coops, N. C., Neinavaz, E., Ali, A., Schaepman, M. E., Paganini, M., et al. (2021). Priority list of biodiversity metrics to observe from space. *Nature Ecology and Evolution*, *5*(7), 896–906. https://doi.org/10.1038/s41559-021-01451-x
Slingo, J., Bates, P., Bauer, P., Belcher, S., Palmer, T., Stephens, G., et al. (2022). Ambitious partnership needed for reliable climate prediction. *Nature Climate Change*, *12*(6), 499–503. https://doi.org/10.1038/s41558-022-01384-8
Sporre, M. K., Blichner, S. M., Karset, I. H. H., Makkonen, R., & Berntsen, T. K. (2019). BVOC–aerosol–climate feedbacks investigated using NorESM. *Atmospheric Chemistry and Physics*, *19*(7), 4763–4782. https://doi.org/10.5194/acp-19-4763-2019
Staudhammer, C. L., & LeMay, V. M. (2001). Introduction and evaluation of possible indices of stand structural diversity. *Canadian Journal of Forest Research*, *31*(7), 1105–1115. https://doi.org/10.1139/x01-033
Steinke, I., Hiranuma, N., Funk, R., Höhler, K., Tüllmann, N., Umo, N. S., et al. (2020). Complex plant-derived organic aerosol as ice-nucleating particles – More than the sums of their parts? *Atmospheric Chemistry and Physics*, *20*(19), 11387–11397. https://doi.org/10.5194/acp-20-11387-2020
Sungmin, O., Bastos, A., Reichstein, M., Li, W., Denissen, J., Graefen, H., & Orth, R. (2022). The role of climate and vegetation in regulating drought–heat extremes. *Journal of Climate*, *35*(17), 5677–5685. https://doi.org/10.1175/jcli-d-21-0675.1
Svenning, J.-C., Pedersen, P. B. M., Donlan, C. J., Ejrnæs, R., Faurby, S., Galetti, M., et al. (2016). Science for a wilder Anthropocene: Synthesis and future directions for trophic rewilding research. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(4), 898–906. https://doi.org/10.1073/pnas.1502556112
Teuling, A. J., Seneviratne, S. I., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., et al. (2010). Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geoscience*, *3*(10), 722–727. https://doi.org/10.1038/ngeo950
Teuling, A. J., Taylor, C. M., Meirink, J. F., Melsen, L. A., Miralles, D. G., Heerwaarden, C. C. V., et al. (2017). Observational evidence for cloud cover enhancement over western European forests. *Nature Communications*, *8*(1), 14065. https://doi.org/10.1038/ncomms14065
Thonicke, K., Bahn, M., Lavorel, S., Bardgett, R. D., Erb, K., Giamberini, M., et al. (2020). Advancing the understanding of adaptive capacity of social-ecological systems to absorb climate extremes. *Earth's Future*, *8*(2), e2019EF001221. https://doi.org/10.1029/2019ef001221
Trenberth, K. E., Fasullo, J. T., & Mackaro, J. (2011). Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *Journal of Climate*, *24*(18), 4907–4924. https://doi.org/10.1175/2011jcli4171.1
Ukkola, A. M., Pitman, A. J., Donat, M. G., De Kauwe, M. G., & Angélil, O. (2018). Evaluating the contribution of land-atmosphere coupling to heat extremes in CMIP5 models. *Geophysical Research Letters*, *45*(17), 9003–9012. https://doi.org/10.1029/2018GL079102
van der Velde, I. R., van der Werf, G. R., Houweling, S., Maasakkers, J. D., Borsdorff, T., Landgraf, J., et al. (2021). Vast co2 release from Australian fires in 2019–2020 constrained by satellite. *Nature*, *597*(7876), 366–369. https://doi.org/10.1038/s41586-021-03712-y
van der Woude, A. M., Peters, W., Joetzjer, E., Lafont, S., Koren, G., Ciais, P., et al. (2023). Temperature extremes of 2022 reduced carbon uptake by forests in Europe. *Nature Communications*, *14*(1), 6218. https://doi.org/10.1038/s41467-023-41851-0
Vári, Á., Kozma, Z., Pataki, B., Jolánkai, Z., Kardos, M., Decsi, B., et al. (2022). Disentangling the ecosystem service 'flood regulation': Mechanisms and relevant ecosystem condition characteristics. *Ambio*, *51*(8), 1855–1870. https://doi.org/10.1007/s13280-022-01708-0
Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., & Garnier, E. (2007). Let the concept of trait be functional. *Oikos*, *116*(5), 882–892. https://doi.org/10.1111/j.2007.0030-1299.15559.x

von Buttlar, J., Zscheischler, J., Rammig, A., Sippel, S., Reichstein, M., Knohl, A., et al. (2018). Impacts of droughts and extreme-temperature events on gross primary production and ecosystem respiration: A systematic assessment across ecosystems and climate zones. *Biogeosciences*, *15*(5), 1293–1318. https://doi.org/10.5194/bg-15-1293-2018

Weiher, E., Freund, D., Bunton, T., Stefanski, A., Lee, T., & Bentivenga, S. (2011). Advances, challenges and a developing synthesis of ecological community assembly theory. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *366*(1576), 2403–2413. https://doi.org/10.1098/rstb.2011.0056

Werner, C., Meredith, L. K., Ladd, S. N., Ingrisch, J., Kübert, A., Haren, J. V., et al. (2021). Ecosystem fluxes during drought and recovery in an experimental forest. *Science*, *374*(6574), 1514–1518. https://doi.org/10.1126/science.abj6789

Wild, M., Folini, D., Hakuba, M. Z., Schär, C., Seneviratne, S. I., Kato, S., et al. (2015). The energy balance over land and oceans: An assessment based on direct observations and CMIP5 climate models. *Climate Dynamics*, *44*(11–12), 3393–3429. https://doi.org/10.1007/s00382-014-2430-z

Wirth, C. (2005). Fire regime and tree diversity in boreal forests: Implications for the carbon cycle. In *Forest diversity and function: Temperate and boreal systems* (pp. 309–344). Springer.

Wolf, S., Keenan, T. F., Fisher, J. B., Baldocchi, D. D., Desai, A. R., Richardson, A. D., et al. (2016). Warm spring reduced carbon cycle impact of the 2012 US summer drought. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(21), 5880–5885. https://doi.org/10.1073/pnas.1519620113

Yachi, S., & Loreau, M. (1999). Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(4), 1463–1468. https://doi.org/10.1073/pnas.96.4.1463

Zhang, Y., Subba, T., Matthews, B. H., Pettersen, C., Brooks, S. D., & Steiner, A. L. (2024). Effects of pollen on hydrometeors and precipitation in a convective system. *Journal of Geophysical Research: Atmospheres*, *129*(6), e2023JD039891. https://doi.org/10.1029/2023JD039891

Zhou, S., Williams, A. P., Berg, A. M., Cook, B. I., Zhang, Y., Hagemann, S., et al. (2019). Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(38), 18848–18853. https://doi.org/10.1073/pnas.1904955116

Zscheischler, J., Mahecha, M. D., Harmeling, S., & Reichstein, M. (2013). Detection and attribution of large spatiotemporal extreme events in Earth observation data. *Ecological Informatics*, *15*, 66–73. https://doi.org/10.1016/j.ecoinf.2013.03.004

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., et al. (2020). A typology of compound weather and climate events. *Nature Reviews Earth & Environment*, *1*(7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., et al. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3