IMPACT OF EXTREME WEATHER EVENTS ON ECOSYSTEM SERVICES

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Abstract. The rise in extreme weather conditions poses a formidable menace to the ecosystem services (ES) bestowed by ecosystems upon humanity. A precise comprehension of the ramifications of extreme weather events on ES is imperative to establish a robust scientific foundation for mitigating the adverse consequences of such phenomena. Despite the extensive corpus of international studies on the impact of extreme weather events on ES, there is a lack of literature reviews and nuanced discussions regarding forthcoming research aims. Therefore, this paper selects to focus on drought, extreme precipitation, heatwaves, and extreme cold—representatives of extreme weather with substantial global ramifications and notable threats. It summarizes the effects of extreme weather events with substantial global on ES, identifies current research issues, and outlines future prospects. Research indicates that the impact of extreme weather events on ES is predominantly negative. Extreme weather affects ecological processes and human needs, subsequently influencing the supply-demand relationship and trade-offs between ES. The diversity of research methods is influenced by differences in research objectives and scales. The interaction of various extreme weather events and the complex coupling with human activities make the mechanisms of extreme weather events impact on ES more intricate. A deficiency exists in the systematic exploration of the dynamic characterization of supply-demand relationships and trade-off dynamics under the sway of extreme weather. Additionally, there is a paucity of research addressing the recovery processes and underlying mechanisms governing ecosystem services (ES) in the aftermath of extreme weather events. Additionally, there is a need for in-depth attention to the spatial scale characteristics of ES under the influence of extreme weather, which is crucial for understanding the mechanism of impacts.
Keywords: *Extreme weather events, ecosystem services, change, impact mechanisms, recovery processes, scale characteristics*

Introduction

Due to its significant impact on human health, ecosystems, socio-economic factors, and industrial and agricultural production, climate change has garnered widespread attention from governments, academic organizations, and various sectors worldwide (Chen et al., 2023; Ge and Lin, 2021; Nowlin, 2022). As reported in the Sixth Assessment by the Intergovernmental Panel on Climate Change (IPCC), the global surface temperature demonstrated a noteworthy increase of ∼1.5°C between 1850–1900 and 2011–2020 (Schenuit, 2023). Along with global warming since the last century, the occurrence of extreme weather events has grown in frequency, expanded in geographical scope, and intensified in severity (Chapman et al., 2023; Zhou et al., 2023). However, due to variations in the regional impacts and magnitudes of global climate change, the characteristics of extreme weather differ across the world (Chaqdid et al., 2023; Shenoy et al., 2022; Yu et al., 2023). The increased frequency and intensity of extreme weather events present substantial challenges and pose grave threats to the ecological environment (Hossain et al., 2023; Rammig and Mahecha, 2015; Tan et al., 2018).

Ecosystem services (ES) are products and services essential for human survival and development rendered by natural ecosystems to humanity. Their pivotal role extends to influencing the sustainable trajectory of human society and ensuring the preservation of ecological environmental quality (Costanza et al., 1997). Existing research confirms that climate change is a significant factor influencing ES (MA, 2005; Runting et al., 2017). Extreme weather constitutes an essential facet of climate change investigation, exerting a profound influence on the structural, compositional, and functional aspects of ecosystems, consequently shaping the dynamics of ES (Dai et al., 2023; Huang et al., 2022). Consequently, scholarly interest in investigating the impacts of extreme weather on ES is on the rise globally, emerging as a focal point within disciplines such as ecology, geography, climatology, and meteorology (Baird et al., 2023; McDonald et al., 2023; Xie et al., 2021).

Despite an increasing body of research evaluating the effects of extreme weather events on ES, there exists a deficiency in exhaustive literature reviews and dialogues concerning prospective research trajectories. Grounded in this foundation, the present study endeavors, through a comprehensive review of pertinent literature, to elucidate the current status of the impact of predominant types of extreme weather on ES. It aims to encapsulate the deficiencies in contemporary research, offering insights into future research directions. Such endeavors hold substantial significance for the scientific governance of ES and the formulation of policies aimed at mitigating the repercussions of extreme weather events.

The impact of extreme weather on ES

The impact of drought on ES

The negative impact of drought on ES

Drought is a widely distributed and extremely severe meteorological disaster globally. Against the backdrop of global climate changes, the occurrence of drought is increasing in both scope and intensity (Kryżak et al., 2023; Walker and Van Loon, 2023). Prior research has established a discernible correlation between drought occurrences and a substantial reduction in the provisioning of essential services, including but not limited to freshwater supply, hydropower production, soil conservation, carbon sequestration, and food production (Al-Qubati et al., 2023; Bai et al., 2021; Han et al., 2019a). The sharp reduction in precipitation under drought conditions directly results in a decrease in freshwater supply and hydropower production (Terrado et al., 2014). Drought exerts a suppressive effect on the primary productivity of ecosystems, significantly weakening the carbon sequestration function of terrestrial ecosystems (Piao et al., 2019). The loss of precipitation in summer and early autumn, as well as soil moisture depletion, severely affects food supply capacity (Li et al., 2017).

The negligible or positive impact of drought on ES

Furthermore, some scholars have found that, under the self-regulating mechanisms of ecosystems (negative feedback), drought does not significantly reduce the supply capacity

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of certain ES. For instance, extreme drought does not alter the above- and below-ground primary productivity of grassland ecosystems. This is because drought events stimulate physiological processes in the ecosystem that regulate productivity (Jentsch et al., 2011). Long-term drought changes the capacity of soil microbial activity and fine root metabolism, thereby reducing soil respiration, which may increase forest soil organic carbon storage (Huang et al., 2018). It is noteworthy that different types of ES exhibit distinct heterogeneity in response to drought. Traditional cultural services such as rain rituals may not be significantly affected by drought (Marambanyika et al., 2021).

The impact of extreme precipitation on ES

The negative impact of extreme precipitation on ES

In the present context, influenced by global warming, there is a global increase in both the frequency and intensity of extreme precipitation events (Abbas et al., 2023; Thackeray et al., 2022). The intensity and duration of extreme precipitation exert a direct influence on the supply capacity of ES. Previous research indicates that extreme rainfall, by limiting potential recreational opportunities and increasing the erosive force of precipitation, reduces recreational and soil conservation services (Tomczyk et al., 2016). Floods caused by extreme precipitation damage irrigation facilities, posing a severe threat to agricultural water services (Weerahewa et al., 2023). Extreme precipitation can disrupt the stability of local consumer-crab species interactions, indirectly leading to a reduction in the area and quality of critical coastal habitats (Rocca et al., 2021). Extreme precipitation significantly shapes the spatial and temporal patterns of water yield, water regulation, and flood control services (Dai et al., 2023; Li et al., 2019). Increased precipitation promotes the transition of existing species to deep-rooted woody plants, leading to an increase in ES provided by woody plants (Sala et al., 2015).

The negligible or positive impact of extreme precipitation on ES

Certain studies confirm that the impact of extreme precipitation on some ES is weak or even favorable. As an illustration, the pronounced impact of extreme rainfall resulting from typhoons is conspicuous in altering water yield and soil conservation, yet it exerts a comparatively minor influence on nutrient purification (Chiang et al., 2014). Although extreme precipitation reduces the net primary productivity (NPP) of grasslands, it increases plant species diversity (Knapp et al., 2008). The increased precipitation from extreme rainfall not only does not alter biogeochemical processes but also does not significantly change soil carbon and nitrogen content (Wilcox et al., 2016).

The negligible or positive impact of frequency of wet-dry transitions on ES

Furthermore, the increasing frequency of wet-dry transitions caused by global climate change may also lead to changes in ES. Research suggests that climate changes in extreme wet and dry seasons may inhibit the carbon absorption capacity of sparse tree grasslands (Morales-Rincon et al., 2021). Intense rainfall after drought triggers compensatory growth mechanisms in forests, promoting rapid recovery of forest productivity (Alfaro-Sanchez et al., 2019). Nevertheless, certain investigation has indicated that, owing to prolonged ecological adaptation, transitions between wet and dry climates do not exert a substantial influence on the growth rate of tree species within

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tropical sparse tree grasslands. This adaptation appears to result in minimal negative impact on the overall productivity levels of these ecosystems (Boakye et al., 2023).

The impact of extreme heat on ES

The negative and positive impact of extreme heat on ES

Owing to global climate warming, there is a rapid increase worldwide in both the frequency and severity of extreme heat events, rendering them one of the formidable climate disasters (Röthlisberger and Papritz, 2023; Suarez-Gutierrez et al., 2020). The impact of extreme heat on ES is related to the season, duration, and severity of high-temperature events. Research indicates that elevated spring temperatures lead to a decrease in the population of linnet birds in sparse grasslands, causing widespread occurrence of pests and a decline in pest control services (Wood and Pidgeon, 2015). As the duration of heatwaves increases, the population growth and community structure of marine phytoplankton change, resulting in a reduction in the biomass of certain marine organisms (Chauhan et al., 2023). When heatwaves exceed critical thresholds, soil microbial communities face the threat of death or reorganization, severely affecting the services provided by soil microbes (Bérard et al., 2011). The impact of extreme heat on provisioning services, regulating services, and supporting services is a current focal point of attention. For example, marine heatwaves directly lead to massive deaths of marine organisms such as abalones, sea stars, and sea urchins, causing a significant decline in fisheries production (Rogers-Bennett and Catton, 2019). Under extreme heat stress, plant photosynthesis weakens or stagnates, while respiration intensifies, reducing carbon flux in Eurasian steppe grasslands and decreasing carbon sequestration intensity (Qu et al., 2016). Similar to drought and extreme precipitation, while extreme heat has adverse effects on ES, it may also bring favorable impacts on some ES. For instance, although rising temperatures can lead to a decrease in invertebrate abundance and biodiversity loss in farmlands, it also promotes an increase in soil organic matter turnover (Menezes-Oliveira et al., 2013).

The impact of extreme heat coupled drought on ES

Extreme heat often interacts with drought in ecological processes, thereby influencing ES. Research has found that heatwaves coupled with severe drought significantly reduce soil moisture, causing widespread death of poplar trees and a sharp decline in the ES provided by poplar (Anderegg et al., 2013). Heatwaves coupled with drought result in lower leaf photosynthetic rates, aboveground biomass, and ecosystem CO_2 flux, collectively affecting the carbon sequestration intensity of ecosystems (Li et al., 2021a). Under conditions of high-temperature drought, the size and abundance of bacterial communities significantly decrease (Zaman et al., 2020). High-temperature drought increases global forest mortality, thereby affecting the carbon sequestration capacity of forests (Allen et al., 2010).

The impact of extreme cold on ES

The negative impact of extreme cold on ES

Notwithstanding the diminished frequency and intensity of extreme cold events attributed to global warming, their influence on ecosystems remains a factor that cannot be overlooked (Kuang et al., 2019; Malone et al., 2016). Existing research indicates that

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under the influence of extreme cold, water yield increases while water purification and soil conservation decrease, directly related to the reduced evapotranspiration caused by extreme cold (Han et al., 2019b). The decline in biodiversity, fisheries production, and primary productivity of plants due to extreme cold has become an important focus for scholars. For example, under the influence of low temperatures, the habitat conditions of benthic invertebrate communities in rivers deteriorate, leading to a decrease in species abundance (Shao, 2023b). Extreme cold causes damage to certain walnut species, thereby reducing their productivity levels (Ebrahimi et al., 2020). Extremely low sea temperatures directly result in extensive coral loss, leading to the death of fish that depend on tropical coral reefs and ultimately affecting fisheries production (Leriorato and Nakamura, 2019). Extreme cold damage in high latitudes and subtropical regions poses a severe threat to the primary productivity of plants (Kroll et al., 2022; Liu, 2014). Extreme cold primarily acts on the ES provided by affecting the competition between organisms and the degree of morbidity and mortality. For instance, extreme cold events result in a decline in the stability of biomass within soil mollusk communities, an escalation in the intensity of species competition, and a subsequent diminution in the provisioning of food production and carbon sequestration services to humans (Chen et al., 2021). Unusually cold climates in winter or summer increase the disease and mortality rates of Norway Spruce, resulting in a decline in pest control services provided by Spruce trees (Panayotov et al., 2016).

The positive impact of extreme cold on ES

Although the impact of extreme cold on ES is predominantly negative, it still has favorable effects on a small portion of ES. For example, persistent low temperatures lead to a reduction in the catch of North American species such as Bass, Snook, and Grouper, with a simultaneous increase observed in the catch of Red Drum and Gray Snapper (Santos et al., 2016). Under the influence of extremely low temperatures, urban forests exhibit a stronger warming effect, enhancing the climate regulation service capacity of forests. Forests become refuges for organisms during extreme cold, protecting urban biodiversity (Thompson et al., 2022).

The impact of extreme weather on ES for different ecosystems

The impact of extreme weather on forest ES

Extreme weather events pose significant challenges to the stability of forest ecosystems, primarily manifested as suppressed plant growth, reduced biodiversity, altered biogeochemical cycles, and changes in ecosystem structure and function (Huang et al., 2022). Extensive research has confirmed that extreme weather primarily affects terrestrial carbon balance by altering photosynthesis and ecosystem respiration directly, and indirectly by increasing fire incidence and tree mortality, thus altering forest ecosystem structure and composition, subsequently impacting ecosystem service provision levels (Li et al., 2021b; Kicklighter et al., 2023). The impacts of extreme weather events vary greatly among different forest types (Koelemeijer et al., 2022). Subtropical evergreen broadleaf species, for instance, have not experienced prolonged, high-intensity drought stress throughout their evolutionary history, potentially lacking various drought strategies to enhance their survival capabilities (Shao et al., 2022a). Similarly, mild drought directly triggers extensive mangrove mortality, severely impairing the food supply, climate regulation, and raw material provision capacities of

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tropical mangrove ecosystems (Servino et al., 2018). However, despite exacerbating water stress in trees and hindering their growth, due to long-term adaptation, coniferous forests in semi-arid regions exhibit higher drought resistance compared to deciduous broadleaf forests (Zhao et al., 2024).

The impact of extreme weather on grassland ES

Extreme weather disrupts the stability or equilibrium maintained by grasslands under stable climatic conditions by directly influencing vegetation changes in grassland ecosystems, thereby affecting the stability of grassland ecosystem services. For instance, increased drought frequency alters soil carbon and nutrient cycling in arid and semi-arid grasslands, affecting microbial community composition and structure, consequently reducing microbial diversity and functionality (Ochoa-Hueso et al., 2018). Decreased precipitation, on the other hand, reduces functional diversity of plant communities, possibly linked to differences in resistance to water stress among different plant species in grasslands (Miller et al., 2019). However, research has found that grassland biodiversity mitigates the negative effects of extreme weather by influencing ecosystem resistance and resilience, thereby providing greater ecosystem stability (Xu et al., 2021). Studies have demonstrated that grasslands with higher species biodiversity may exhibit increased resistance and resilience to extreme weather, thereby maintaining ecosystem service provision at higher levels (Cole et al., 2019). Additionally, it is noteworthy that due to different strategies employed by grasslands and forests to cope with extreme weather, the impacts of extreme weather on these two ecosystem types differ (van Dijke et al., 2023).

The impact of extreme weather on farmland ES

Extreme precipitation and drought affect crop physiological ecology, soil microorganisms, and soil temperature and humidity, thereby impacting soil respiration, water cycling, and consequently agricultural productivity. For instance, frequent and severe droughts in mid-latitude regions result in relatively low agricultural productivity in these areas (Wang et al., 2023). Prolonged drought disrupts the balance of pollinator communities, leading to a sharp decline in crop yields (Mukherjee et al., 2019). However, scholars have also confirmed that nitrogen cycling microbial communities in farmland exhibit resistance and resilience to extreme precipitation, resulting in the maintenance of high levels of microbial diversity in farmland (Suolang et al., 2024). Furthermore, extreme high and low temperatures hinder crop growth and development by affecting soil moisture evaporation rates and plant physiology, thus reducing biomass in agricultural ecosystems. Research has found that extreme high temperatures affect soil carbon and nitrogen accumulation mineralization rates and direction, thus affecting the carbon and nitrogen balance and crop yields in agricultural ecosystems (Lazicki et al., 2023). Interestingly, planting perennial crops or adopting diversified cropping systems in farmland can withstand stronger extreme weather and improve the sustainability of grain production (Sanford et al., 2021).

The impact of extreme weather on urban ES

Urban flood regulation, temperature regulation, tree growth and health, and carbon sequestration in green spaces are key concerns regarding the impact of extreme weather on urban ecosystem services. For example, Shen et al. (2019) utilized an ecohydrological

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model to analyze the spatial characteristics and supply-demand relationship of urban flood regulation services under extreme precipitation. The study found that flood regulation services in the city center were significantly lower than in surrounding areas, with the most severe imbalance between supply and demand. Park et al. (2021) quantitatively assessed the cooling capacity and spatial characteristics of different urban ecosystem types under extreme high temperatures using temperature monitoring. The study revealed that water bodies and forests had a significantly higher cooling effect on urban areas compared to other ecosystem types. Zhang et al. (2019a) investigated the effects of drought on the root, stem diameter, leaf parameters, and biomass of urban trees. The research found that reduced soil moisture under drought conditions led to decreased root biomass of trees, reducing the carbon sequestration capacity of urban green spaces. Roetzer et al. (2021) elucidated the impact of drought on urban forest temperature regulation and carbon sequestration. They found significant differences in carbon sequestration capacity and summer temperature regulation ability among different tree species in urban areas due to different adaptation strategies (*Fig. 1*).

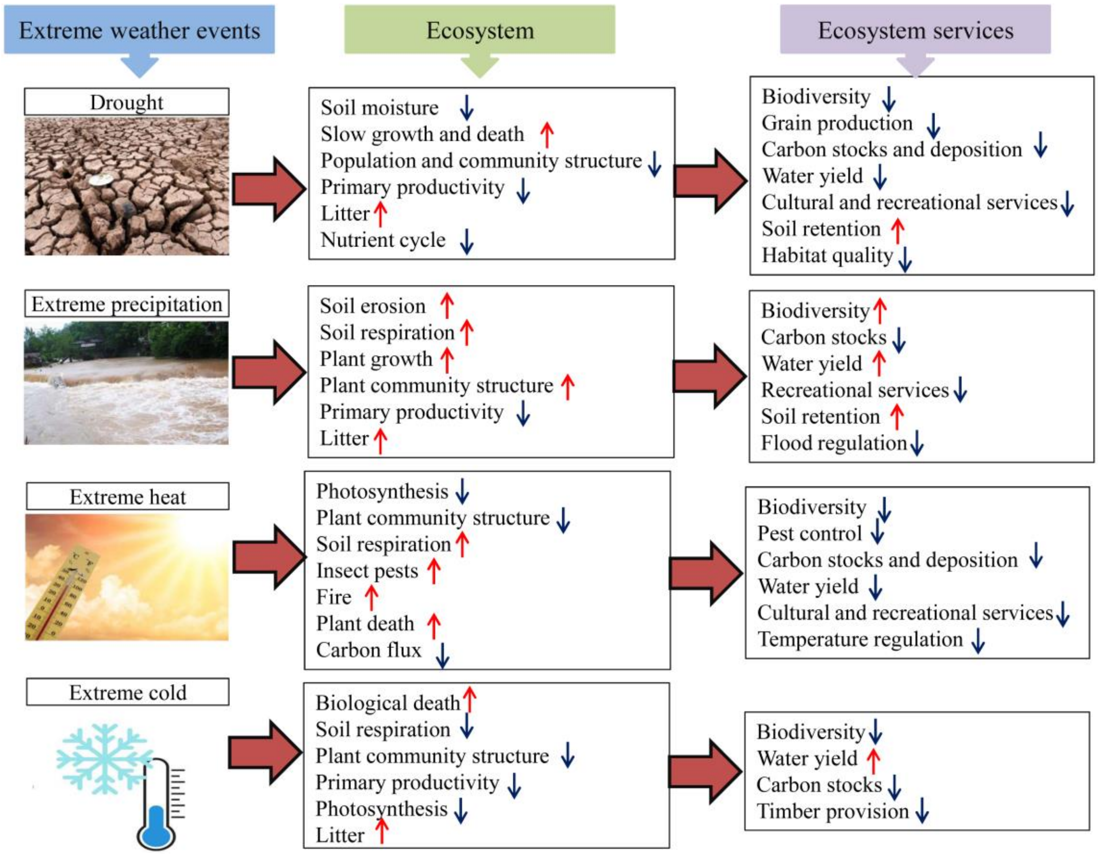

Figure 1. *Cascading impacts of extreme weather events on ecosystems and their services*

The impact of extreme weather on the supply-demand relationship and trade-offs and synergies of ES

The impact of extreme weather on the supply-demand relationship of ES

The supply-demand dynamics of ES encapsulate the dynamic flow process from natural ecosystems to human social systems. Extreme weather phenomena exert a

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substantial impact not only on the provisioning of ES but also play a pivotal role in shaping the demand for and the intricate supply-demand relationship of ES, integral to human social systems. Extreme events contribute to an escalated actual demand for flood regulation services, surpassing their inherent supply capacity (Wübbelmann et al., 2023). Extreme precipitation causes instability in the supply of drinking water and irrigation water sources for residents in the Hindu Kush mountain region, further exacerbating the supply-demand conflict (Mukherji et al., 2015). In the backdrop of extreme weather conditions, a positive correlation is observed between the temperature regulation service rendered by urban vegetation and the summertime cooling demands of residents (Jenerette et al., 2011). Vegetation degradation caused by extreme weather results in a severe decrease in water quality regulation capacity, making drinking water challenging to meet standards, thereby intensifying conflicts in drinking water supply and demand (Beier et al., 2015). The coupling of extreme weather with human activities excessively leads to a decrease in fisheries catch, while the demand for fishery products increases, intensifying the conflict between the supply and demand of fishery products (Gutierrez et al., 2016). In the context of heavy rainfall and flooding, a positive correlation is evident in the spatial distribution of supply and demand for urban eco-hydrological regulation services within the cities of the North China Plain. The matched supply-demand types are predominantly characterized by low supply and low demand configurations. Simultaneously, there are significant spatial clustering characteristics (Jiang et al., 2023). However, scholars have also found that under the influence of extreme rainfall, there is oversupply of flood regulation services in green areas (dominated by ecological spaces), while the demand is not met in areas dominated by human-made structures (industrial, urban, and densely populated areas), highlighting prominent spatial mismatches in supply and demand (Wübbelmann et al., 2022).

The impact of extreme weather on the trade-offs and synergies of ES

Under the influence of extreme weather conditions, diverse ES exhibit variations in their changes, potentially giving rise to either upward or downward trends. This dynamic process engenders a complex interplay of trade-offs and synergies among different ES. Existing research has found that under the impact of extreme rainfall, A synergistic relationship is observed between water yield and soil conservation, while a trade-off relationship exists between water yield and water quality purification, as well as between soil conservation and water quality purification (Han et al., 2021). In the presence of annual-scale drought, a trade-off relationship emerges between water yield and nutrient purification, as well as between soil conservation and nutrient purification. However, under the influence of seasonal drought, a dynamic trade-off or synergies relationship is observed between water yield and nutrient purification, as well as between soil conservation and nutrient purification (Han et al., 2019a). In the context of extreme weather, different planting methods of urban tree species result in a trade-offs relationship between air quality regulation and carbon sequestration as well as between rainwater regulation and carbon sequestration (Wood and Dupras, 2021). Additionally, scholars have also focused on the spatial pattern of trade-offs/synergies relationships of ES under extreme weather conditions. For example, intense rainfall induces noteworthy spatial heterogeneity in the trade-offs and synergies relationships among ES, characterized by synergies in high-value areas and trade-offs in low-value areas (Dai et al., 2023) (*Fig. 2*).

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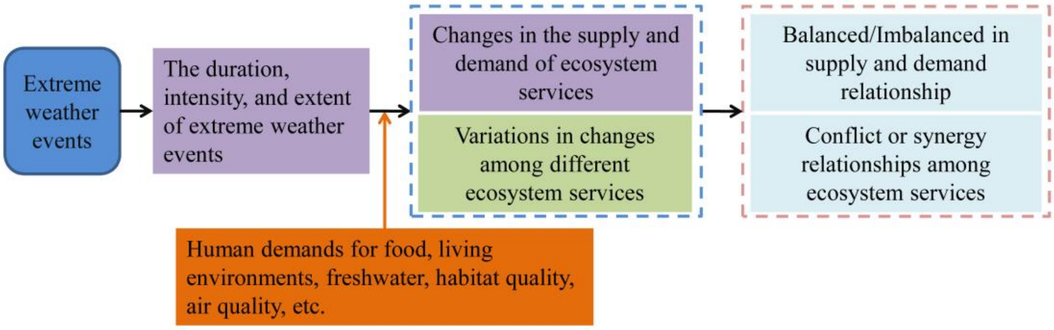

Figure 2. *The process of coupling extreme weather events with human activities, impacting the supply and demand relationship, as well as the trade-off/synergy effects on ecosystem services*

Research methods for assessing the impact of extreme weather on ES

Positioning observation method

Field positioning observation method

Field positioning observation methods based on actual measurement data can provide first-hand fundamental data, facilitating the study of ecological effects during long-term sequences or typical periods of extreme weather. For example, Mason-Romo et al. (2017) conducted an analysis of the repercussions of extreme weather on forest animal diversity, utilizing extensive long-term monitoring data encompassing small mammals and climate observations from six locations spanning a duration of 19 years. Sarà et al. (2021) investigated the effects of multiple extreme events on marine ES by combining observations from ocean temperature data loggers and dissolved oxygen recorders with conventional marine biological sampling methods. Nevertheless, although observational positioning can quantitatively assess the influence of extreme weather on ES at broader temporal and spatial scales, this approach lacks control over the specific attributes of extreme weather (e.g., intensity and frequency) and other covariate factors. This limitation poses a challenge to effectively elucidating the driving mechanisms of multiple contributing factors.

Remote sensing monitoring method

As remote sensing technology progresses, remote sensing imagery finds extensive application in the examination of ecological impacts stemming from extreme events. For instance, Horion et al. (2019) enhanced the evaluation of pressures on land ecosystem change by incorporating NDVI data, land use and land cover data, and climate grid data. This refinement enabled a comprehensive understanding of the interconnected influence of extreme events and land use on ES. Maragno et al. (2018) utilized high-precision remote sensing imagery and census data, considering factors such as high-precision permeable and impermeable spaces, green infrastructure, and population density. They conducted simulations to model the relationship between the supply and demand of urban flood protection services.

Modeling simulation method

Ecological model

Modeling is an effective tool for analyzing the impact of historical and future extreme weather on ES. This method can express spatial patterns and simulate

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different scenarios to reveal the extent of the impact of extreme events on ES. For example, Quagliolo et al. (2021) employed the Integrated Valuation of Ecosystem Services and Trade-offs model to model two distinct extreme rainfall events (50 and 70 mm) and assess the quantitative aspects of urban flood control services. Kicklighter et al. (2023) employed the Terrestrial Ecosystem Model (TEM 4.4) to conduct spatial assessments of services such as carbon sequestration, biomass, and production of paper and wood products under the influence of extreme events. This unveiled disparities in the repercussions of various categories of extreme weather on forest ES. Ecological models have gradually shifted from simple quantitative analysis to spatial expression of a variety of ecosystem services, and more attention has been paid to the development of ecological models based on ecological processes, which directly promotes the exploration of the driving mechanism of the impact of extreme weather on ecosystem services. For example, the InVEST model has been widely applied to the impact of extreme weather on ecosystem services because of its spatial representation and less parameter input. The model can be used to assess the effects of different extreme weather on water yield, soil and water conservation and nutrient purification through different scenarios (Han et al., 2022). Furthermore, the leafood model can evaluate the supply level of urban flood regulation services under heavy precipitation events, and analyze the impact of different landscape types on flood regulation services under the influence of heavy precipitation (Wübbelmann et al., 2022).

Improved ecological model

Some scholars have made improvements to models to enhance the accuracy of ES assessments under the impact of extreme weather. For example, Jenerette et al. (2011) applied an improved simplified surface energy balance model to assess residents' cooling demand under extreme high-temperature conditions (characterized using the required amount of cooling water). They balanced this assessment with an analysis of the urban heat risk landscape, allowing for a high-precision evaluation of the trade-off relationships in cooling ES. Nevertheless, it is crucial to acknowledge that modeling methods often overlook the adaptive mechanisms of ecosystems, potentially introducing deviations in the analytical outcomes from real-world scenarios.

Controlled experiment method

Precipitation control experiment

Conducting controlled experiments to regulate the frequency and timing of extreme events and shorten the time scale at which events that may occur over longer time scales can be effective in analyzing the mechanisms of the impact of extreme weather on ES. For example, Zhang et al. (2019b) explored the impact of extreme precipitation on carbon flux and primary productivity by setting various precipitation gradients representing dry and wet climate conditions. This approach elucidated the sensitivity of net ecosystem exchange to precipitation gradients, unveiling the mechanisms underlying the impact of extreme precipitation. Tredennick et al. (2018) simulated drought and excessive rainfall by respectively increasing and decreasing precipitation by 50%, investigating the effects of extreme precipitation and drought on aboveground plant NPP and species richness.

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Temperature control experiment

Similarly, scholars have conducted controlled experiments on temperature gradients to study the effects of extreme high and low temperatures on ES. For instance, Mancuso et al. (2023) simulated short-term extreme temperatures using three 100-watt infrared lamps, exploring the impact of short-term extreme high temperatures on biodiversity and ES in intertidal communities. Menezes-Oliveira et al. (2013) designed four temperature gradients and three high-temperature exposure periods to simulate the annual average of extreme events in Southern Europe, examining the impact of the severity and duration of extreme high temperatures on species diversity and soil ES. However, although controlled experiments can explain the impact of a specific climatic factor, they may not effectively eliminate the influence of changes in other simultaneous climatic factors on ES.

Interdisciplinary integration method

Applied to the impact of extreme weather on ES supply

The examination of the influence of extreme weather on ES encompasses not only natural sciences such as meteorology, ecology, geography, and biology but also social sciences, including sociology, economics, and management. Employing interdisciplinary methodologies in the investigation of the impact of extreme weather on ES facilitates the disclosure of cascading effects among extreme events, ES, and human well-being. This contributes to the mitigation of the adverse consequences of extreme weather on both ecosystems and human socio-economic systems. For example, Kabisch et al. (2021) employed environmental monitoring methodologies rooted in the natural sciences, alongside social science approaches like visitor observations and questionnaire surveys, to assess the regulatory and recreational services provided by urban parks during hot and arid conditions. Through the identification of vegetation and infrastructure characteristics in urban parks to enhance their regulatory function, this methodology contributed to the improvement of visitor well-being. Boogaard et al. (2017) combined 3D virtual technology with elevation models, buildings, and aerial photos to build a 3D model of urban floods for risk assessment and optimization of urban flood control services.

Applied to the impact of extreme weather on the supply-demand relationship and trade-offs and synergies of ES

The focus of applying interdisciplinary integration methods is on studying the supply and demand relationships, as well as the trade-offs/synergies relationships of ES under the influence of extreme weather. For example, Xiong and Wang (2022) evaluated the supply and demand dynamics of water flow regulation services during extreme rainfall conditions, utilizing data encompassing annual precipitation, annual evapotranspiration, and annual soil moisture grids, alongside population data. This study linked macro-scale water flow regulation supply and demand assessments with micro-scale assessments of urban construction environments, contributing to improving flood protection well-being for urban residents. However, the interdisciplinary character of cross-disciplinary methods introduces potential constraints on the application of such approaches due to challenges related to the availability and reliability of diverse datasets, as well as the suitability of varied assessment methodologies (*Fig. 3*).

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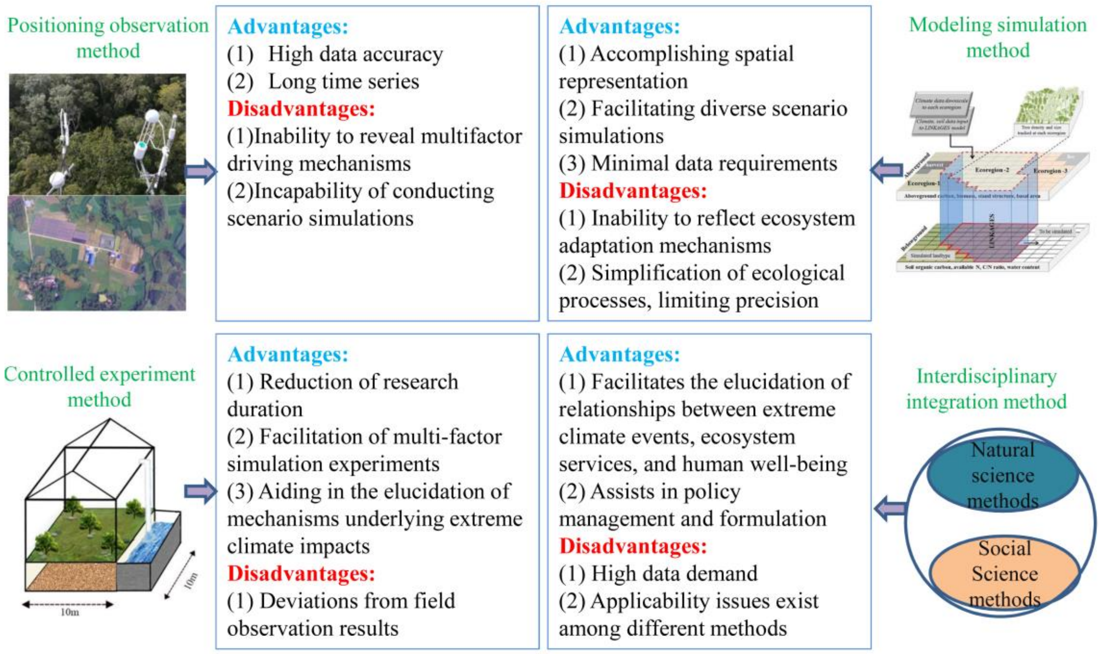

Figure 3. *Advantages and disadvantages of different research methods*

Future research prospects

In summary, extreme events exert a substantial and incontrovertible influence on ES. The scholarly community has undertaken extensive investigations into the repercussions of extreme events on ES, leveraging diverse data sources and employing a range of methodologies, resulting in a relatively comprehensive body of research findings. However, there are still several inadequacies in the current understanding of this complex scientific problem, primarily reflected in the following aspects: (1) The intricate mechanisms governing the influence of extreme weather on ES remain inadequately elucidated; (2) Existing research on the dynamic characterization of supply-demand relationships and trade-off dynamics of ES under the sway of extreme weather is constrained; (3) Insights into the recovery processes and dynamic mechanisms governing ES under the impact of extreme weather are currently limited; (4) A comprehensive exploration of the scale characteristics defining the impact of extreme weather on ES is yet to be thoroughly addressed.

Mechanisms of the impact of extreme weather on ES

The impact of extreme weather on ES results from the interactions among climate factors, ecological factors related to extreme weather, and human activities (Filazzola et al., 2021; Megía-Palma et al., 2020; Truchy et al., 2020). For a precise quantification of this impact, it is imperative that scientists attain a comprehensive understanding of the dynamic mechanisms through which extreme weather influences ES.

The impact of extreme weather itself and the feedback of ecosystem

The intensity and duration of extreme events constitute pivotal factors influencing ES (Dai et al., 2023; Dodd et al., 2023). Generally, as the intensity of extreme events increases or their duration lengthens, the changes in ES become more pronounced

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(Caurla and Lobianco, 2020; Zhang et al., 2018). Extreme weather often influences ES supply levels by affecting ecological structure and composition, as well as key ecological processes (Kuang et al., 2019; Li et al., 2021b). For example, previous research has found that extreme events impact forest productivity and carbon sequestration capacity by influencing the composition and structure of above-ground and below-ground biological communities, as well as ecological hydrological processes and carbon cycling (Li et al., 2021a; Sánchez et al., 2021). However, within these impact processes, ecosystems can manifest adaptability and resilience to extreme weather by triggering feedback mechanisms, thereby alleviating the adverse effects of extreme weather (Bogati and Walczak, 2022). While scholars have generally focused on the influence of individual extreme events on ES (Al-Qubati et al., 2023; Dai et al., 2023; Wang et al., 2019), research on how multiple extreme weather factors simultaneously affect ES is relatively lacking. Additionally, the current research methods on the impact of extreme weather on ES are diverse, with differences in their applicability. Different research methods have their own strengths and weaknesses in revealing the mechanisms of extreme weather impacts, leading to significant variations in research conclusions based on different methods. How to choose appropriate methods to explore these impact mechanisms is a current research gap.

The impact of human activities

Human activities may exacerbate or alleviate the impact of extreme weather on ES, depending largely on the effectiveness of human management measures (Su et al., 2022). For instance, research affirms that urban green infrastructure has the potential to alleviate the detrimental effects of extreme weather on urban ES. Conversely, the occupation of green spaces may exacerbate the adverse impacts of extreme weather. (Kraemer and Kabisch, 2022; Song et al., 2021). While scholars are gradually paying attention to the role of human activities in the influence of extreme weather on ES, such as afforestation and reforestation efforts (Han et al., 2022; Vecchiato et al., 2023), a notable gap persists in conducting comprehensive research on the merits, drawbacks, and applicability of various measures undertaken as part of human activities in the context of extreme weather impact on ES.

Future prospect

Based on the foregoing analysis, future research endeavors should prioritize the following areas: (1) Investigating the intricate mechanisms governing the impact of diverse extreme events on ES, with a particular focus on elucidating how concurrent occurrences of various extreme events contribute to changes in ES, supply-demand dynamics, and trade-off relationships; (2) Exploring the inherent mechanisms of ecosystem resilience to extreme events, aiming to uncover how ecological feedback mechanisms counteract the adverse effects of extreme weather on ES through physiological and ecological processes, as well as plant functional regulation; (3) Selecting appropriate methodologies and integrating theoretical models to scrutinize the mechanisms underlying the impact of extreme weather on ES, and delineating the disparities among various research methods in unveiling impact mechanisms; (4) Investigating the interplay of human activities with ES in the context of extreme weather, and unraveling the merits, drawbacks, and applicability of diverse measures associated with human activities.

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Dynamic characterization of supply-demand relationships and trade-off relationships of ES under the impact of extreme weather

Dynamic characterization of supply-demand relationships ES under the impact of extreme weather

The entire process of extreme events, from occurrence to conclusion, exhibits either short or long-term temporal characteristics (Li et al., 2022; Naderi, 2020). Over the course of this temporal progression, extreme events exert a profound impact not only on pivotal ecological processes such as water cycling, nutrient cycling, and energy flow but also on the trajectory of human demand for ES (Arenas-Wong et al., 2023; Mejía and Wetzel, 2023; Sharafatmandrad and Mashizi, 2021; Wollheim et al., 2015). In the concurrent sway of ecological processes and human demand dynamics, the supply-demand relationships of ES exhibit dynamic characteristics (Chhetri, 2011). Although scholars have analyzed the dynamic evolution of ES supply under the impact of extreme weather through indoor experiments (such as setting drought gradients) (Mancuso et al., 2023; Van Sundert et al., 2021; Zhan et al., 2022), the dynamic study of ES demand, as well as the supply-demand relationships, under the impact of extreme weather is still relatively scarce due to the difficulty in accurately quantifying ES demand during the entire process from the occurrence to the conclusion of extreme events.

Dynamic characterization of trade-off relationships of ES under the impact of extreme weather

Similarly, under the influence of extreme weather, the processes of change for various ES differ, leading to dynamic changes in trade-off relationships among ES over time. Although scholars have concentrated on investigating the influence of extreme weather severity, including variations in drought intensities, on trade-off relationships among ES (Che et al., 2023; Han et al., 2019a), there is a notable absence of reported studies examining the dynamic characterization of trade-off relationships among ES throughout the duration of extreme weather.

Future prospect

We propose that future research should enhance the dynamic characterization of supply-demand relationships of ES under extreme weather conditions, with a specific focus on delineating the manifestations of supply-demand relationships across diverse spatiotemporal scales and providing a dynamic portrayal of supply-demand elasticity. Additionally, it is suggested to focus on determining the types of trade-off relationships between ES, quantifying their nonlinear characteristics, and expressing them in both spatial and temporal dimensions during the entire process from the occurrence to the conclusion of extreme events. These prospective research directions will establish a scientific foundation for optimizing and planning practices related to supply-demand relationships and trade-off dynamics of ES.

The recovery process and dynamic mechanisms of ES under the impact of extreme weather

The recovery process of ES under the impact of extreme weather

Extreme weather exerts a robust influence on the exchange of energy and matter within the vegetation-soil system and the natural environment. This influence

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precipitates alterations in the structure and function of both the vegetation and soil systems, consequently impacting the resilience of ES (Behboudian et al., 2023; Dodd et al., 2023). For example, drought affects the NPP of terrestrial ecosystems through the photosynthetic rate of plants and soil respiration. When it exceeds the recovery threshold, the level of primary productivity may be challenging to recover in the short term (Machado-Silva et al., 2021). A comprehensive comprehension of the recovery process of ES following the impact of extreme weather facilitates the formulation of ecological restoration strategies and the selection of socio-ecological coordination paths (Degani et al., 2019; Tomczyk et al., 2016). From a temporal perspective, ES undergo essential processes such as formation, maintenance, and self-recovery (Cortés-Calderón et al., 2021; Yang et al., 2015). Assessing the long-term impact of extreme weather on ES includes not only the processes of formation and maintenance but also the self-recovery process of ES. Although the influence of diverse extreme weather events on the formation and maintenance processes of ES has garnered considerable attention (Arnone et al., 2011; Hernández et al., 2023; Yin et al., 2022), there remains a deficiency in a comprehensive understanding of the self-recovery process of ES following the conclusion of extreme events.

The dynamic mechanisms of ES under the impact of extreme weather

The resilience strength of ES is intricately linked not only to the attributes of extreme weather and ecosystems but also potentially influenced by the intensity of human activities (Kendrick et al., 2019; Nowicki et al., 2017; Walcker et al., 2019). Alterations in extreme weather and human activities have the potential to induce shifts in the recovery thresholds and recovery potentials of ES (Brotherton and Joyce, 2015). Although research has confirmed that the recovery capacity of ES is influenced by multiple factors (Brisson et al., 2014; Guo et al., 2022; Meli et al., 2014), the dynamic mechanisms governing the recovery of ES under the impact of extreme weather remain unclear. This is crucial for mitigating the long-term impact of extreme weather on ES. Moreover, the matter of scale constitutes a pivotal dimension within ecological restoration theory (Bullock et al., 2022; Callicott, 2002). However, a void persists in current research concerning the dynamic mechanisms governing the recovery of ES under the influence of extreme weather across various scales.

Future prospect

We propose that future research endeavors should enhance the following dimensions: (1) develop an evaluative index system for the resilience of ES under the influence of extreme weather and gauge recovery levels across various temporal stages; (2) quantify the temporal evolution of ES recovery under extreme weather impact, elucidate nonlinear patterns in recovery time variation, and ascertain the presence of recovery change thresholds; (3) quantify the interplay between extreme weather and human activities and its repercussions on the resilience of ES recovery. Define the pivotal factors influencing this impact and delineate the interrelationships among these factors. Investigate the dynamic mechanisms by which extreme weather, in synergy with other factors, influences the resilience of ES recovery at diverse spatial scales; (4) advocate for the application of the concept of ES resilience in practical measures addressing extreme weather, land resource management, ecological restoration, and related domains.

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The scale characteristics of ES under the impact of extreme weather

Scale dependence

The formation of ES hinges upon the structural configuration and processes of the ecological system at specific temporal and spatial scales (Faber et al., 2021). Owing to the pronounced spatiotemporal heterogeneity, intricate elemental complexity, and systemic attributes inherent in the frequency and extent of extreme weather events, distinctive scale characteristics emerge in the impact of extreme weather on ES. A comprehensive comprehension of these scale characteristics facilitates enhanced recognition of impact mechanisms and furnishes a scientific foundation for decision-making and management across diverse spatial scales.

Scale characteristics

Although scholars have observed that the influence of extreme weather on ES demonstrates specific scale characteristics (Korell et al., 2021; Luna et al., 2023), and researchers both domestically and internationally have conducted some case studies at different spatial scales (global, regional, and local scales) (Al-Qubati et al., 2023; Lunyolo et al., 2021; Yang et al., 2023), the scale characteristics of the processes, modes, and mechanisms of extreme weather impact on ES have not been clearly elucidated. At the same time, the scale attributes of extreme weather impact on ES are not only manifested at a single scale but also in the spatial correlations between different scales. Focusing solely on a single scale may overlook the information of the interactions between different scales, resulting in one-sidedness in the revealed impact mechanisms. Unfortunately, current research still lacks studies comparing multiple scales and examining scale correlations. In addition, scientifically effective scale analysis methods are crucial for identifying spatial scale characteristics and clarifying the key factors in scale correlations (Zhang et al., 2020). Analytical results based on different scale research methods are bound to differ (Reyer et al., 2015). However, due to the differences in data characteristics and research methods at different scales, the applicability of different scale methods is affected, thereby influencing the accuracy of the analytical results. There is currently a lack of in-depth research on this issue.

Future prospect

Subsequent investigations into the scale characteristics of extreme weather impact on ES should concentrate on the following dimensions: (1) delineating the scale attributes governing the processes and mechanisms of extreme weather impact on ES; (2) discerning scale differentials in the collective influence of extreme weather, intertwined with other natural and anthropogenic factors, on ES; (3) exploring the supply-demand relationships and trade-off dynamics of ES amidst the influence of extreme weather across varied scales; (4) conducting cross-scale analyses of the impact of extreme weather on ES, encompassing multi-scale correlations.

Conclusion

Our comprehensive review systematically concludes that extreme weather poses a widespread and severe threat to ES. The supply capacity of the majority of ES is notably perturbed by extreme weather, resulting in imbalances within the supply-

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demand relationships and trade-offs/synergies associations of ES. The scholarly focus is particularly directed towards aquatic ecosystem services (ES) and terrestrial ES, encompassing areas such as carbon sequestration, primary productivity, climate regulation, and biodiversity. The applicability of research methods varies under different research objectives and scales, resulting in heterogeneity in research results based on different methods.

Future research endeavors should intensify their examination of the intricate processes and mechanisms governing the compound effects of diverse extreme weather on ecosystem services (ES), particularly under the influence of human activities. This emphasis should include a focus on the dynamic characterization of the supply-demand relationships and trade-offs relationships of ES under extreme weather, as well as research on the recovery processes and dynamic mechanisms of ES. Additionally, it is imperative to prioritize future research efforts that delve into the scale characteristics dictating the impact of extreme weather on ES.

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