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EDITORIAL

Human–Earth system interactions under climate change

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1. Introduction

The dynamic interactions between human activities and the components of the Earth system have become a focal point of scientific research, especially as climate change continues to reshape environmental, social, and economic landscapes globally (Lade *et al* 2020). Human activities—including deforestation/afforestation, agricultural expansion, rapid urbanization, and energy generation infrastructure—have fundamentally reshaped the global land surface (Winkler *et al* 2021). These human activities, alongside broader socioeconomic drivers such as agriculture and rising energy demand, interact with natural systems through complex biophysical and biogeochemical pathways operating across various spatial and temporal scales (Morris *et al* 2025).

As human activity adds a new dimension to Earth system interactions, it imposes additional challenges in assessing potential climate tipping points and understanding the future trajectory of the Earth system in the Anthropocene (Steffen *et al* 2018). Addressing these complexities necessitates an integrated approach, fostering synergy across scientific disciplines. Advancing our knowledge in this domain calls for innovative methodologies that integrate diverse perspectives, ranging from survey data and social science frameworks to remote sensing technologies and Earth observation systems, as well as sophisticated process-based and data-driven models. Strengthening these interdisciplinary connections is critical for refining our understanding of human–Earth system feedback and informing effective climate adaptation and mitigation strategies that enhance the resilience of both human societies and natural ecosystems.

This special issue, titled 'Focus on human–Earth system interactions under climate change,' compiles cutting-edge research that deepens our understanding of the complex feedback mechanisms between anthropogenic activities and Earth system processes in the context of a changing climate (figure 1). The featured articles employ a diverse array of methodologies—including field studies, remote sensing, modeling, and socio-ecological analyses—to explore these interconnections. A unifying theme across these contributions is the imperative to bridge disciplinary divides, integrating physical Earth sciences with social sciences to fully capture the spectrum of human-Earth system interactions. Key topics addressed the impacts of human activities on natural systems, encompassing land-use change and water resource management on biogeochemistry, climate dynamics, and feedback on the climate system and socioeconomics from local to global scales under a changing climate.

2. Key contributions and insights

2.1. Anthropogenic forcing, emissions, and global climate dynamics

This set of studies collectively advances our understanding of how anthropogenic forcing and emissions—ranging from energy production to aerosols and greenhouse gases—shape global and regional climate dynamics. At the local and regional scales, Huang *et al* (2024) and Engstrand *et al* (2024) address localized pollution from human activities, showing how high-NO_x ship emissions and repeat artisanal gold mining respectively contribute significantly to environmental degradation. Their findings underscore the need for targeted emissions monitoring

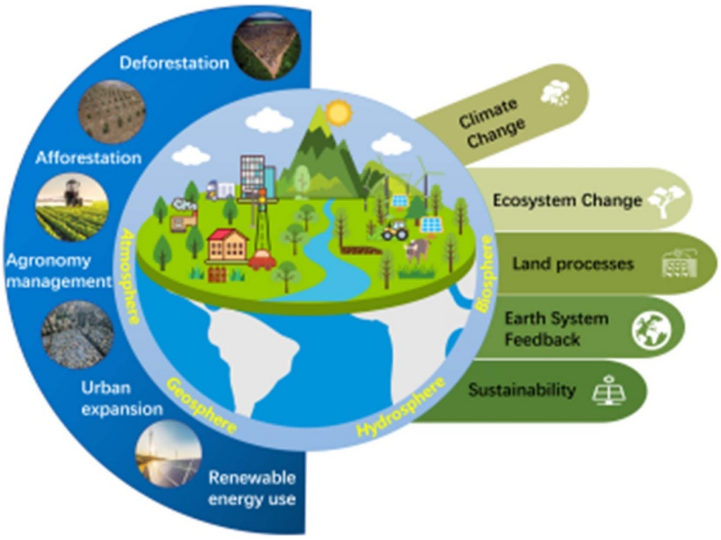

Figure 1. Schematic diagram of human–Earth system interactions under climate change.

and regulatory frameworks, while also highlighting opportunities to incentivize cleaner technologies and alternative fuels in the inland shipping sector. At the global scale, Xie *et al* (2024) and Gu *et al* (2024) demonstrate how reduced aerosols and dust emissions modulate temperature trends and regional precipitation patterns through changes in atmospheric processes. Yu *et al* (2023) further link rising CO_2-driven Indo-Pacific warming to a weakening of the Arctic stratospheric polar vortex, revealing far-reaching climate teleconnections. The emission-climate interactions, however, have a strong link to the socio-political system. As suggested by Perri *et al* (2024) in their study on clean energy transitions, the success of clean energy transitions may depend on the synergy from the socio-political system at multiple levels. A top-down policy approach alone may not be sufficient for effective emission cuts; a multi-level strategy that combines top–down and bottom–up approaches is usually needed. Together, these studies provide regional to global understanding of anthropogenic activities and their feedback on atmospheric systems, offering insights for emission regulation, climate modeling, and adaptation strategies.

2.2. Human impact on ecosystems

Several studies in this special issue investigate the complex interactions between climate change, land use, and ecosystem dynamics across tropical and montane landscapes, highlighting the importance of localized human activities in influencing broader ecosystem and climate dynamics. He *et al* (2025) show that tropical montane forest loss has accelerated significantly in recent decades, with intermediate-sized (1–10 ha) clearings becoming the dominant driver of deforestation, raising alarms for biodiversity, carbon storage, and forest sustainability. Yang *et al* (2024a) provide new evidence that small hydropower reservoirs, often considered low-impact, have collectively caused greater tropical forest loss than large reservoirs, particularly in African regions, underscoring the ecological trade-offs of decentralized hydropower expansion. In contrast, Gao *et al* (2023) document a positive trajectory of forest recovery in Nepal, revealing that community forestry programs for mitigating deforestation and forest degradation at the household level have become the dominant driver of national-scale greening, surpassing the influence of climatic variables in recent decades. Together, these studies highlight both the risks and opportunities presented by human–ecosystem interactions, emphasizing the importance of scale-sensitive governance and nature-based solutions for sustaining forest ecosystems in the face of climate change.

2.3. Human disturbance on biogeochemical dynamics

This group of studies illustrates how anthropogenic activities intersect with climate and landscape processes to alter biogeochemical dynamics across terrestrial and aquatic systems. Rahman *et al* (2024) demonstrate how historical phosphorus loading from urbanized river catchments in Osaka Bay shaped long-term phosphorus speciation in coastal sediments, with calcium-bound phosphorus forming a key immobile sink. Shao *et al* (2024) present a high-resolution remote sensing framework to assess surface water pollution susceptibility in urban areas, linking fine-scale land use characteristics to pollution risks and offering new tools for urban water quality monitoring. Chien *et al* (2024) reveal a negative association between human population density and mangrove soil carbon stocks, although climate-adjusted models suggest that urban mangroves can still retain significant blue carbon value under proper conservation.

Guo *et al* (2023) review emerging insights into how climate change influences soil organic carbon dynamics, emphasizing the complex interplay between biological communities, abiotic regulation, and environmental drivers that shape carbon stabilization and decomposition. Yang *et al* (2024b) find that microbial communities in degrading permafrost zones maintain distinct biogeographic patterns, but exhibit differential vulnerability to environmental tipping points, raising concerns about microbial ecosystem stability in a warming world. Collectively, these studies highlight the need for integrated monitoring and management of biogeochemical functions in ecosystems increasingly shaped by human disturbance and climate stressors.

2.4. Urban climate, heat exposure, and adaptation

Several studies in this special issue advance our understanding of urban climate impacts through a diverse set of studies that focus on extreme heat hazards and exposure, urban microclimate dynamics, and associated behavioral and infrastructural responses. For example, Li *et al* (2024) map human heat stress across 14 US cities at ultra-fine resolution using the Universal Thermal Climate Index, revealing consistent links between lower income levels and greater thermal vulnerability. Zhao *et al* (2024) develop a novel clustering approach to characterize intra-city thermal heterogeneity during heatwaves in Paris, Montreal, and Zurich, uncovering complex land–atmosphere feedbacks. Wang *et al* (2023) distinguish the differential effects of urbanization on land surface and air temperature during heatwave and non-heatwave conditions across China, emphasizing the role of wind and precipitation in modulating urban–rural temperature differences. Yan *et al* (2024) evaluate how seasonal climatic changes affect multifunctionality in urban parks, documenting shifts in ecological and recreational services between summer and winter. Finally, Li *et al* (2023) link three decades of increased space cooling demand across five global cities to the combined influence of climate warming and urban heat islands, highlighting both the energy implications and potential mitigation through behavioral adaptation and regulatory intervention. Collectively, these studies reveal the multidimensional nature of urban heat and underscore the urgent need for spatially targeted, socially informed climate adaptation strategies.

2.5. Climate-induced drought, feedback, and societal consequences

Several studies reveal the multifaceted consequences of climate-induced droughts, spanning ecological feedbacks, hydrological shifts, and human vulnerabilities. Russo *et al* (2025) demonstrate that a 0.5 °C increase in global warming—from 1.5 °C to 2.0 °C—substantially intensifies drought conditions in the Iberian Peninsula, reinforcing the urgency of limiting warming through emissions mitigation. Goswami *et al* (2024) develop global water-budget-based evapotranspiration estimates that capture both anthropogenic and climatic signals, improving our ability to detect and monitor drought variability, especially in irrigated regions. Vahedifard *et al* (2024) propose an overlooked feedback loop in which drought-induced soil desiccation cracking enhances CO_2 emissions from deeper soil layers, potentially accelerating atmospheric warming and threatening both soil health and infrastructure stability. Shyrokaya *et al* (2024) uncover robust correlations between multiple drought indicators and sector-specific impacts during the 2018–2019 drought in Germany, providing a scalable framework for linking hydrometeorological data with socioeconomic losses. Finally, Eklund *et al* (2024) analyze cropland abandonment in northeast Syria, finding that while drought played a role, long-term mismanagement, economic restructuring, and migration patterns were key drivers—highlighting the intertwined effects of environmental stress and structural socio-political change. Together, these studies highlight the need for integrated climate-risk governance that accounts for biophysical feedbacks, water stress, and socio-political contexts in drought-prone regions.

3. Implications for policy and future research

The findings from this special issue support the urgent need for policy frameworks that are spatially explicit, socially responsive, and grounded in a process-level understanding of Earth system dynamics. As climate change accelerates and interacts with land-use pressures, water scarcity, urbanization, and socio-political factors, policies must move beyond generic mitigation targets to incorporate localized risk profiles, feedback mechanisms, and cumulative impacts. Future research should prioritize the integration of fine-scale observational data with models that capture coupled human–environment interactions, enabling more accurate forecasting and place-based decision-making. This includes advancing tools for high-resolution monitoring of urban heat, drought vulnerability, forest loss, and biogeochemical shifts, alongside robust governance strategies that account for social heterogeneity and behavioral dynamics. The complex, cross-scale nature of human–Earth system interactions demands a new generation of interdisciplinary science that is co-produced with stakeholders and aligned with both planetary boundaries and justice-oriented adaptation goals.

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