

REPORT

Prioritizing Sustainable Development of Ecologically Sensitive Regions

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Under the multiple threats from climate change and human pressures, plateau and alpine regions, super fast-growing cities, and coastal zones/island states are becoming ecologically more fragile. It is extremely difficult to pursue sustainable development goals (SDGs) that enhance human well-being and promote resilient urban economies and societies in such ecologically sensitive regions. Therefore, addressing the threats to ecologically sensitive regions should be prioritized to facilitate the delivery of the global SDGs. To allow this, we need to identify and then prioritize action for the regions that are most sensitive to climatic variability and external perturbations like urbanization, investigate the mechanisms underlying the acute trade-offs between human needs and environmental sustainability, understand social–ecological relationships and socio-economic–environmental interactions in these ecologically sensitive regions, and develop intelligent systems for monitoring and evaluating their sustainability.

2025 marks the 10-year anniversary of the launch of the UN sustainable development goals (SDGs). With only 6 years remaining until the 2030 SDGs target, more than half of the SDGs are thought to be impossible to achieve, and progress remains alarmingly uneven [1]. A “one-size-fits-all” SDG approach may not be workable globally. Therefore, the heads of state and government and senior representatives met at the Summit of the Future at the United Nations Headquarters on 2024 September 22 and 23. They reaffirmed their commitments to the 2030 Agenda for Sustainable Development and their pledge to future generations for furthering the world’s transition from traditional development, which spends down natural capital, to sustainable development, which preserves, restores, grows, and uses natural capital wisely. However, we must recognize that a critical gap exists in current sustainability discourse: i.e., the systemic neglect of region-specific ecological thresholds in SDG implementation frameworks. These leaders emphasized the importance of acknowledging the special challenges faced by urbanizing regions, particularly those that are termed least developed countries, landlocked developing countries, and small island developing states [2], which are mostly located in ecologically sensitive regions. Ecologically sensitive regions—which we suggest include alpine zones, coastal deltas, and resource-depleted areas with rapid urbanization—face compounding crises from climate change and unsustainable development, leading to risks of irreversible ecosystem collapse [3].

Ecologically sensitive regions are typical socio-ecological systems (SES). SES is an integrated system that encompasses ecosystems (ecological part) and human societies (social part)

[4]. The ecological part includes biodiversity, water, soil, atmosphere, and all the processes that connect them, while the social part includes governance, economies, technologies, cultures, and institutions. Its core idea is that these 2 parts are inextricably linked, coevolve, and constantly influence each other. Actions in the social system (e.g., a new intervention policy) create feedback that affects the ecological system (e.g., vegetation coverage). The resulting ecological change (e.g., ecosystem degradation) then creates feedback to the social system (e.g., human health effects). A small change (e.g., a slight temperature rise) can lead to a large, abrupt, and unpredictable “regime shift” or “tipping point” (e.g., ecosystem collapse). These interactions can be reinforcing (driving a system in one direction) or balancing (stabilizing it) to build the system’s resilience and adaptability. SES analysis provides the integrated perspective needed to address the most pressing ecological sensitivity and to steer societies toward a more sustainable and resilient future [5].

Redefining Regions of Ecological Sensitivity

We define ecological sensitivity as a product of climate vulnerability, human pressure index, and ecosystem service value that is vulnerable to climate change and human perturbation with variations in ecosystem service values. Ecologically sensitive regions are those that are highly vulnerable to the impacts of climate change and human activities, most notably industrialization and urbanization [6], while their ecosystem services are low or reduced. Affected by these multiple threats of climate change and human activities, plateau and alpine regions,

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resource-exhausted regions, super fast-growing cities, and coastal zones/island states are becoming ecologically more fragile and increasingly degraded. They are near-irreversible, undesirable state transitions such as desertification, eutrophication dead zones, collapsed fisheries, toxic algal blooms, and more (Fig. 1). They have become the most ecologically sensitive regions on Earth, and it is extremely difficult to pursue coordinated SDGs within them, which enhance human well-being, sustain natural capital stocks, and promote resilient economies and societies [7]. For example, it will be challenging to adhere to the 30X30 target (sustain 30% of nature's services by 2030) of the Kunming–Montreal Global Biodiversity Framework while adhering to the seventeen 2030 SDGs.

The 4 types of regions are all highly vulnerable to external or internal changes and shocks due to inherent characteristics that make their social and ecological systems fragile and prone to negative feedback loops. They can all be analyzed under the same framework of systemic vulnerability, which typically examines exposure to a significant stressor, sensitivity to being disrupted by that stressor, and adaptive capacity to adjust to or recover from the disruption. Why are these 4 regions of high ecological sensitivity?

Plateau and alpine regions, such as the Tibetan Plateau, Loess Plateau, and Arctic Tundra, are located at high altitudes with cool weather, much ice and snow cover, and scattered vegetation coverage. They are normally “water towers of the world”. Their delicate cryosphere (ice and snow) is extremely sensitive to minor changes in temperature, and melting glacier does not just cause local water issues but threaten the water security for entire river basins downstream (e.g., the Indus, Ganges, Yangtze, and Mekong). Small changes can break the natural balance, leading to desertification, biodiversity loss, and the collapse of pastoral livelihoods. At the same time, for the people who do live there, poverty and poor living standards often coexist with dire environmental degradation and risks

from natural hazards and extreme climate change [8], while their remote nature and often marginalized populations limit their adaptive capacity.

Resource-exhausted regions, such as Pittsburg City in the United States, Taiyuan City and Huaibei City in China, and Baku City in Azerbaijan, had good supplies of minerals, coal, oil, gas, forestry, and other natural resources in the past. They also had good infrastructure and conditions for extracting and processing resources for economic growth, but as resource extraction approached its limits, these regions suffer from an extreme lack of ecosystem restoration and economic resilience, with sensitivity to the ongoing shock of their primary industry's disappearance and post-ecological impacts. They are trapped in a negative feedback loop, becoming economically poor, concurrent with ecological degradation, environmental pollution, and social instability. Breaking this cycle is exceptionally difficult, demonstrating low adaptive capacity.

Super fast-growing cities, such as Surat in India, Sana'a in Yemen, and Shenzhen in China, exhibit concentrated inflows of population, goods, and materials with intensive expansion of built-up areas and land use change. They are highly sensitive to the pressure of population influx and built-up land expansion, leading to disruption in green infrastructure, sanitation systems, and social stability. They operate perpetually at the edge of their capacity. A minor event—a heavy rainstorm in a city with inadequate drainage or a small spike in fuel prices—can trigger major disruptions. The urban surface processes also lead to local climate abnormalities, urban heat island effects, inland flooding, and retreat of natural habitats. Such a system lacks the “slack” to absorb shocks.

Island states and coastal regions are critical zones, with many such areas having high levels of human habitation, city expansion, high resource and environmental pressures, and irrational coastal reclamation. Thus, coastal ecosystems are some of the most impacted and altered worldwide, with a high

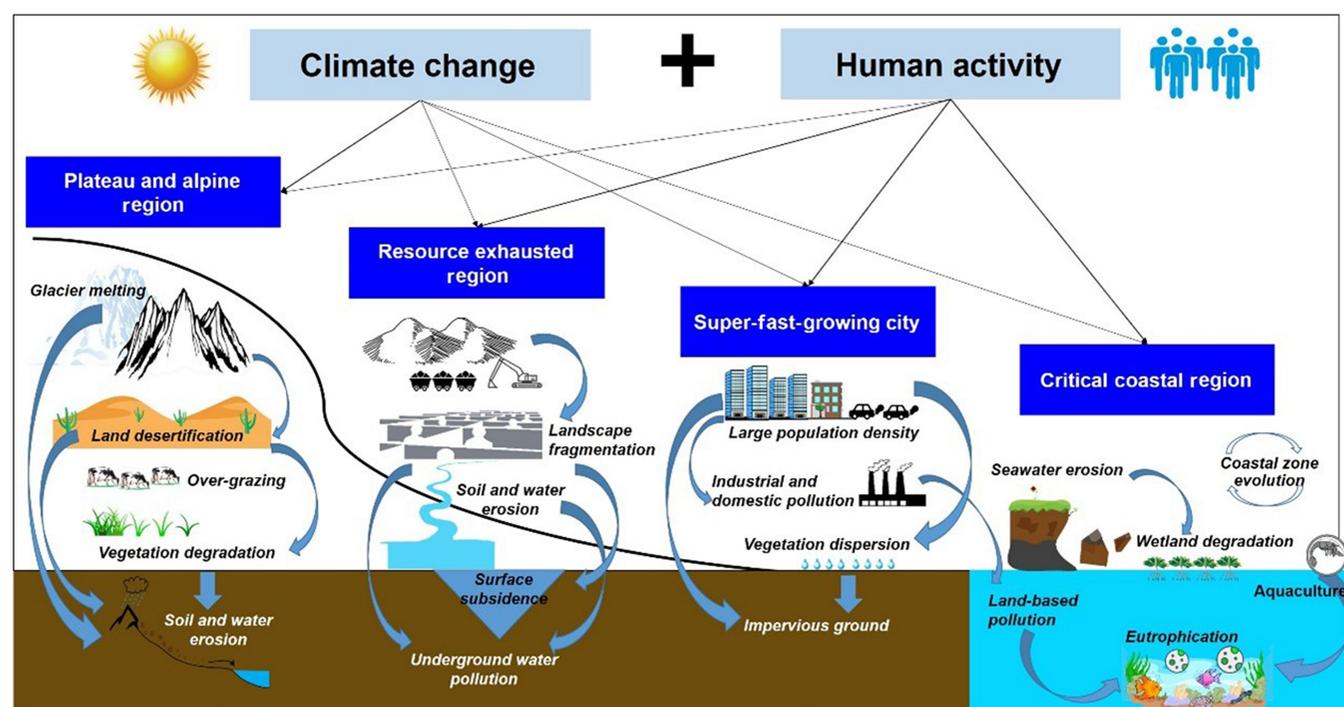


Fig. 1. Major socio-environmental processes in ecologically sensitive regions.

sensitivity to many hazards and risks. They are uniquely sensitive to changes in the global climate system, manifested as sea-level rise and intensified storms. Large-scale, land-based human activities have caused not only the overexploitation of coastal land, energy, and water resources, but also damage to coastal ecosystem services and their environmental quality.

The 4 categories of ecologically sensitive regions represent systems that are highly prone to tipping points and negative cascades. A plateau hits a tipping point when permafrost thaw releases vast amounts of methane. A resource-depleted city hits a tipping point when the last major employer leaves, triggering irreversible decline. A rapidly growing city hits a tipping point when traffic congestion or water scarcity starts strangling economic activity. A coastal area hits a tipping point when seawalls are overtopped, rendering an area uninsurable and uninhabitable. The analytical framework (Fig. 1 and Table 1) allows policymakers and researchers to apply similar principles of risk assessment, resilience planning, and adaptive governance to these critically vulnerable systems, despite the different nature of the stresses they face.

Breaking the Trade-off of Social–Ecological Cycle

Understanding region-specific mechanisms underlying the acute trade-offs between urbanization and environmental sustainability and the socio-ecological interactions that underpin these trade-offs are critical for developing urban sustainability options. This includes the interactions between global and local processes—the global–local nexus—such as learning lessons from national-scale ecological zoning programs to enhance urban ecosystem resilience. Temporal–spatial resilience mapping protocols can help encompass natural capital, social well-being, and economic performance while examining possibilities, opportunities, and challenges associated with attaining ecosystem service provision, nature recovery, poverty alleviation, and human well-being (Fig. 2).

In alpine and plateau regions, priority should be given to ecologically based development and enhancement of social well-being. The first step will be to quantitatively assess the relative response rates of these ecosystems to environmental variability under urbanization and climate change, addressing why some areas are more sensitive than others, and identifying impacts on the resilience of ecosystem service provision and human well-being [9]. How much land and other resources need to be devoted to animal-based agriculture merits critical evaluation and adjustment, as agricultural expansion has had tremendous impacts on habitats, biodiversity, carbon storage, and soil conditions [10]. Land use and land cover change in alpine and plateau regions can magnify the effects of extreme climatic events on ecosystem health; thus, vegetation sensitivity indices might be used to measure air temperature, water availability, cloud cover, and vegetation productivity to support land remediation and rational utilization. Ecosystem restoration based on ecological translocations and relocations continue to be an effective sustainability solution in the poorest and most ecologically degraded areas, but its socio-economic and cultural effects need to be further explored, especially in terms of benefits and disbenefits to local ethnic groups.

In resource-exhausted regions, priority should be given to industrial transformation and sustainable livelihoods. We need to identify the major areas of resource exhaustion, mining subsidence, and pollution (e.g., by heavy metals), as these areas are sensitive to many hazards and risks, from land subsidence to floods and ill health. It is important to be clear about the factors affecting the development of resource-exploiting cities and the coupled relationship of resources and environment, and to explore the environmental carrying capacity of resource-exploiting cities and the spatial suitability for sustainable restructuring of industry. Landscape redesign could increase vegetation coverage and biodiversity to provide “stepping stones” to enhance ecosystem restoration in the areas of stress and to strengthen the understanding of the linkages between ecosystem recovery and

Table 1. Analytical framework: systematic vulnerability

Category	Primary stressors and exposure	Inherent sensitivity	Low adaptive capacity
Plateau	Climate change, glacial melt, infrastructure development.	Fragile ecology: Slow regeneration, thin soils, unique biodiversity. Water tower role: Changes here affect billions downstream.	Remote, often economically underdeveloped, indigenous cultures with traditional livelihoods that are highly climate-sensitive.
Resource-depleted area	Economic shock from primary industry collapse, price volatility.	Economic monoculture: Entire social and economic fabric is tied to one exhausted resource. Environmental degradation: Pollution, land subsidence.	Lack of economic diversification, “brain drain”, degraded assets, shrinking tax base, legacy pollution.
Fast-growing city	Rapid population influx, massive demand for resources, spatial expansion.	Infrastructure strain: Systems (water, transport, housing, and vegetation) are perpetually overcapacity. Social–ecological friction: Inequality, lack of social cohesion and green space.	Planning lags behind growth, governance is overwhelmed, fiscal pressure is constant, slum formation.
Island and coastal area	Sea-level rise, storm surges, saltwater intrusion, extreme weather.	Physical exposure: Low-lying land is directly in the hazard zone. Economic concentration: Often host major cities, ports, and agriculture.	High population density and fixed infrastructure make retreat or adaptation astronomically expensive. Path dependency.

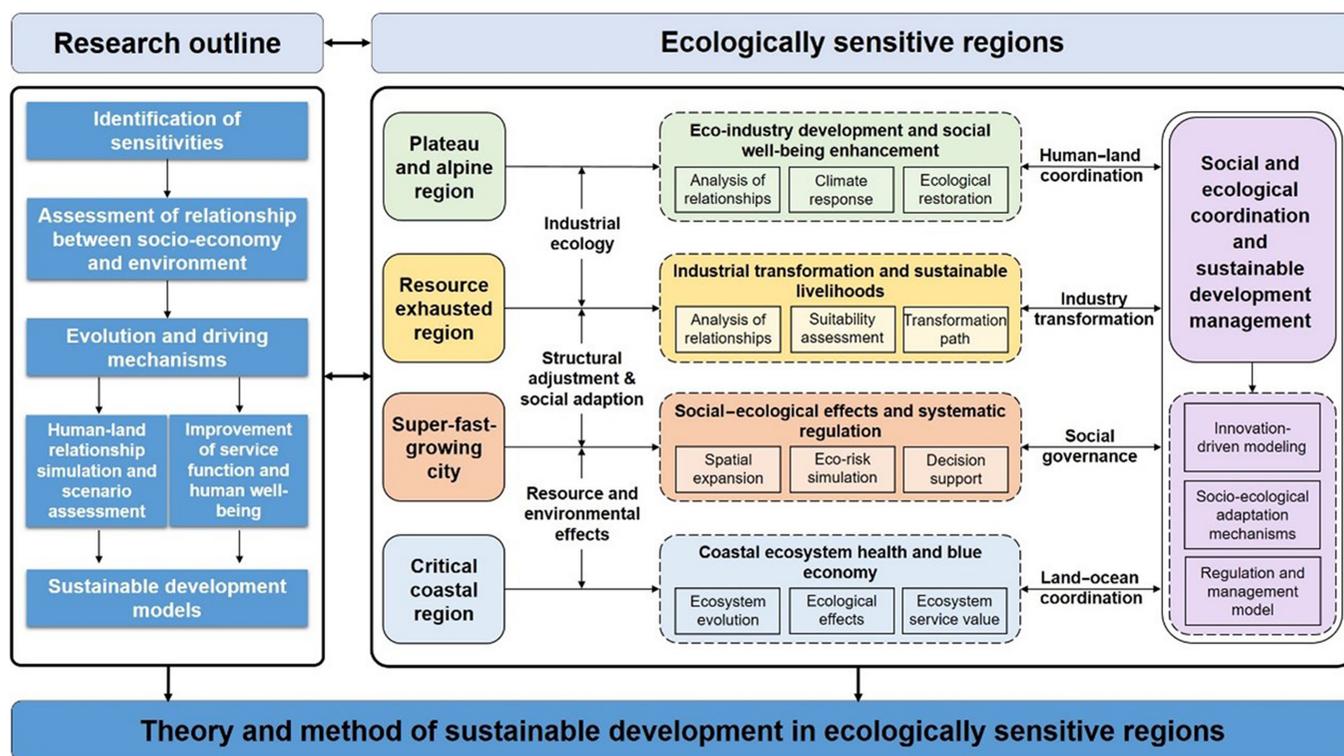


Fig. 2. Diagram of temporal-spatial resilience of ecologically sensitive regions.

human well-being that can help reduce vulnerability and enhance resilience.

In super fast-growing cities and urban agglomerations, priority should be given to urban ecosystem functioning and social governance. It is crucial to identify the major drivers of population increase, industrial expansion, infrastructure construction, and land use change, and their impacts on habitat and species loss, landscape homogenization, agricultural land shrinkage, and resource overuse. As urban population and urban built-up areas grow, vulnerability to heat-related diseases and mortality also increases. Rapid urbanization is increasing the risks of air, water, and soil pollution through industrial emissions, waste disposal, and acid deposition. Water is a necessity for any city, but too much of it can threaten lives and infrastructure; thus, a “sponge city” design could be a cost-effective approach for water recycling and utilization. Renewable energy and waste management is essential for developing sustainable urban ecosystems and minimizing energy consumption and emissions via green design and green technologies. Ecosystem conservation and restoration will be strengthened through protecting urban species, habitats, and ecosystems and creating ecologically valuable green spaces [11]. Ecological and social risks from city expansion need to be scientifically evaluated, diagnosed, and managed by enhancing social interactions and easy access to a variety of ecosystem services. Resilient social-ecological systems and social governance systems should be incorporated and coordinated through diverse mechanisms for living within urban landscapes and responding to unexpected external shocks.

In the critical coastal regions, priority should be given to coastal ecosystem health and sustainable blue economies. Little is known about the impacts of climate extremes on coastal and marine ecosystems in terms of their frequency, intensity, or

duration, primarily owing to the lack of observations [12]. Therefore, it is necessary to make progress on the impacts of coastal development, especially carbon and pollutant emissions from rapid urbanization and industrialization, on offshore biodiversity, blue carbon flux, and wetland ecosystem functioning. Protecting coastal biodiversity in the face of climate change and urbanization is an ongoing mission, which will require a mix of conservation areas that serve as reference points and others to be established to be resilient to climate-related changes [13]. Quantitative assessment of ecological risks and regional distribution patterns is needed to address climate-change impacts on coastal species and ecosystems effectively under the stress of land-based urbanization, especially when considering the extensive effects of climate extremes might have on marine productivity, ecosystem structure and function, ecosystem services, and even the blue economy. Communication, coordination, and collaboration mechanisms across jurisdictions—including state/provincial, national, and international boundaries—are crucial for developing strategic plans for conservation and development, and building capacity for strengthening coastal ecosystem resilience.

Achieving sustainable development in the ecologically sensitive regions requires navigating a complex interplay of social and political factors. Governance, power asymmetries, and environmental justice are crucial for understanding why some regions are more vulnerable and why sustainability actions often fail [14]. Success hinges on integrating community-focused social strategies with robust, adaptive political governance. Actively involving local populations and leveraging their knowledge is a critical success factor. Institutions must be reframed to be more responsive, integrating scientific assessment with institutional change and inclusive decision-making [15].

AI-Enhanced Monitoring and Evaluation of Ecological Sensitivity

In response to the major challenges faced in the ecologically sensitive regions, there is a need to leverage science, technology, innovation, and strategic foresight to develop and implement sustainable practices and institutional reforms. Artificial intelligence (AI)-enhanced monitoring and early warning frameworks that integrate satellite data, IoT (Internet of Things) sensors, and indigenous knowledge represent a transformative approach to ecological sensitivity identification, disaster management, environmental monitoring, and public health. By synthesizing cutting-edge technologies with traditional wisdom, these systems enhance predictive accuracy, reduce response times, and foster community resilience [16].

Satellite-based remote sensing can provide real-time information on land use and vegetation dynamics to measure ecosystem changes, and to underpin the development of scenarios for ecologically sensitive regions. Satellite imagery is pivotal for large-scale ecological surveillance. AI algorithms, such as deep learning models, process raw satellite data to detect anomalies like droughts, deforestation, wildfires, or floods in near real time. Deep learning frameworks like hybrid convolutional prediction models are employed for space situational awareness in satellite IoT networks, tracking objects and environmental changes with high precision. IoT devices act as critical data sources, collecting localized ecological metrics (e.g., hydrology, temperature, humidity, and vegetation) and transmitting them to central systems via satellite or terrestrial networks. This decentralized approach ensures coverage in remote areas where satellite links are the only viable communication medium.

Indigenous knowledge can complement technological systems by providing context-specific historical data and localized indicators for social–ecological synergies and governance. For the enhancement of social–ecological processes and resilience, it is critical to explore the evolution and driving mechanisms of the coupled relationship between economic growth and ecological degradation, the impacts of different types and intensities of human activities on urban ecologies and their interactions, and the supporting functioning of biodiversity for sustainable economic and social development. Such work will need to assess the dynamic trends in different types of social–ecological systems and develop representative indices of natural capital, social capital, and energy and carbon use intensities under different future development scenarios. Thus, the fusion of satellite data, IoT networks, AI, and indigenous knowledge is essential to monitor, simulate, and evaluate the progress of SDGs in different ecologically sensitive regions. For so doing, we need to address such potential challenges as power imbalances in knowledge coproduction, data sovereignty, or epistemic conflicts between scientific and traditional systems.

The ethical implementation of AI-enhanced monitoring requires a careful balance between technological potential and core human values. Key considerations include ensuring fairness, protecting autonomy, and building participatory frameworks that give stakeholders a genuine voice. Adopting participatory methodologies is a practical pathway to address these ethical concerns. Thus, clear policies are needed on data ownership, access, and the right to contest AI-driven decisions; priority should be given to the use of AI models and tools that make the reasons behind predictions understandable to humans; and context-specific ethical approaches should be taken to address the ethical risks under different social–ecological settings.

In the future, a Global Sensitivity Observatory Network could be established for the purpose of unifying, processing, and verifying data [16]. Future research should aim to systematically explore the rules governing human–nature interactions in ecologically sensitive regions, understand mechanisms underlying the coupled relationship between human activities and local environmental processes, and thereby provide sensitivity-weighted SDG funding allocation mechanisms to promote the sustainable development of ecologically sensitive regions in the world.

To prioritize sustainable development in ecologically sensitive regions, a fundamental shift in governance is essential. Thus, we make the following key recommendations:

- Empower local communities: Place local and indigenous communities at the center of decision-making, recognizing their knowledge and ensuring they receive equitable benefits from conservation and development efforts.
- Foster adaptive governance: Implement flexible, multi-level governance systems that can integrate ecological science with social needs, coordinate across sectors, and adapt to changing conditions.
- Resolve policy conflicts: Actively align economic and environmental policies to avoid undermining sustainability goals, moving beyond purely market-based approaches to include community-driven models.
- Secure long-term commitment: Ensure durable political will and dedicated funding at local, national, and international levels to support robust enforcement and long-term program sustainability.

Ultimately, success depends on intertwining social equity with political resolve, ensuring that both people and ecosystems can thrive together.

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Competing interests: The authors declare that they have no competing interests.

Data Availability

The data are freely available upon request.

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