# Enhancing the resilience of social-ecological systems to heatwave risk through the Prediction-Adaptation-Integration framework

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Under global climate warming, heatwaves have evolved from isolated meteorological events into compound disturbances within social-ecological systems. Current responses, which mainly rely on reactive approaches, cannot effectively address the compound nature of heatwave risks. To address this gap, this study introduces a Prediction-Adaptation-Integration (PAI) framework based on a recursive feedback loop, which reframes heatwave governance as a dynamic system. To put this framework into practice, we outline three design principles: (I) ex-ante risk-informed targeting, (II) in-event risk-proportionate intervention, and (III) ex-post iterative learning. The PAI framework provides a transferable model to strengthen long-term resilience under increasingly severe heatwave conditions.

## HEATWAVES AS A COMPOUND DISTURBANCE IN SOCIAL-ECOLOGICAL SYSTEMS

As global temperatures continue to rise, heatwaves have become one of the most widespread extreme climate events. Their impacts extend across public health, ecosystems, agriculture, and infrastructure, often triggering cascading failures across sectors. These processes have moved beyond the scope of conventional meteorological events, emerging instead as compound disturbances within social-ecological systems.[1] Such disturbances occur over broad spatial and temporal scales, crossing from rural landscapes to urban cores. In cities, accumulated surface and atmospheric heat interacts with dense built environments, creating persistent local temperature anomalies.

From the ecological perspective, extreme heat reduces the cooling capacity of green spaces and water bodies, weakening ecosystem services and eliminating natural temperature regulation. In addition, ecological degradation is difficult to reverse and diminishes the environment's ability to buffer future heatwaves, forming a vicious cycle of "heatwave – ecological degradation – more intense heatwave". From the social perspective, heatwave risks are distributed unequally. Vulnerable groups, such as the elderly, low-income residents, and outdoor workers, often live in substandard housing with limited social protection, leaving them disproportionately exposed to extreme heat.[2]

Critically, within social-ecological systems, the burden of heatwaves arises less from isolated heat exposures than from reinforcing feedbacks between ecological degradation and social vulnerability. In the areas with poor health-care access and weak social protection, the diminished vegetation cooling and depleted soil moisture could highly elevate local heat loads; the resulting stress on health and care systems, in turn, retards ecological recovery. For instance, loss of vegetation cover has been linked to higher land surface temperatures and increased heat-related mortality. A recent study across over 5,000 U.S. cities found that lower tree cover in marginalized neighborhoods led to about 0.2°C higher summer temperatures, causing around 190 additional heat-related deaths per year compared with well-vegetated areas.[3]

## GAPS IN CURRENT HEATWAVE GOVERNANCE

Despite growing impacts, responses to heatwaves are still dominated by reactive approaches. Meteorological agencies mainly issue short-term warnings, and health systems activate emergency responses during extreme heat events. While these actions are necessary, they remain narrow in scope and often disconnected from long-term planning, ecosystem management, and spatial policy.

Siloing across sectors further widens governance gaps. For instance, an analysis of the heat resilience stakeholder network in Los Angeles found a network density of only 0.054, indicating very limited collaboration among agencies.[4] Ecological agencies prioritize area control and vegetation coverage; social policy departments focus on compensation and relief rather than prevention; and spatial planners often lack tools to integrate dynamic risk information. As a result, new green space projects often concentrate in affluent neighborhoods, while ecologically poor and high-risk communities remain underserved, thereby deepening inequalities in resource allocation.[5]

Institutional coordination remains weak. Responsibilities for heatwave governance are divided among meteorological, health, environmental, and planning agencies, with a lack of data sharing, joint planning, and integrated response mechanisms. Policy efforts often emphasize visible and engineered solutions, such as increasing green coverage or building cooling infrastructure, while neglecting underlying risk drivers and the need for anticipatory adaptation. For instance, in Chinese cities, the greening process has been modeled as contributing approximately 54% of the observed disparities in greenspace exposure,[6] indicating that gains in green coverage may unevenly benefit different populations unless allocation principles are adjusted.

## PAI FRAMEWORK AS A GOVERNANCE RESPONSE TO HEATWAVE RISK

To address these limitations, we propose the Prediction-Adaptation-Integration (PAI) framework, which reframes heatwave governance as a dynamic system (Figure 1). Instead of viewing prediction, adaptation, and integration as separate tasks, the framework connects them through a recursive feedback loop.

*Prediction* extends beyond meteorological indicators to establish cross-scale and cross-sector predictive risk sensing. This includes high-temperature alerts derived from remote sensing and ground-based observations, along with the integration of social-exposure indicators (e.g., housing quality, health status, income), ecological-exposure indicators (e.g., land surface temperature, green space deficits), and historical response data to create detailed heatwave risk maps. These maps can support automatic policy activation and targeted warnings issued about 24 hours in advance. In practice, community-facing platforms such as Bangladesh's Heatwave Alert localize national forecasts to the ward and upazila levels, offering up to five-day early-warning maps.[7] Their main value lies in improving risk targeting and early mobilization, linking forecast triggers to pre-identified high-exposure groups.

*Adaptation* aligns ecological and social sides into function-oriented interventions. On the ecological side, it requires moving beyond simple area expansion to focus on cooling performance and resilience, such as creating ecological buffers where high social exposure overlaps with ecological deficits. On the social side, it involves linking risk assessment with social protection delivery to support populations facing multiple vulnerabilities. Governance systems should empower community-based organizations to identify local needs, coordinate resources, and facilitate communication. In practice, targeted greening in resource-poor neighborhoods should be monitored using impact indicators (e.g., service accessibility). The San Salvador

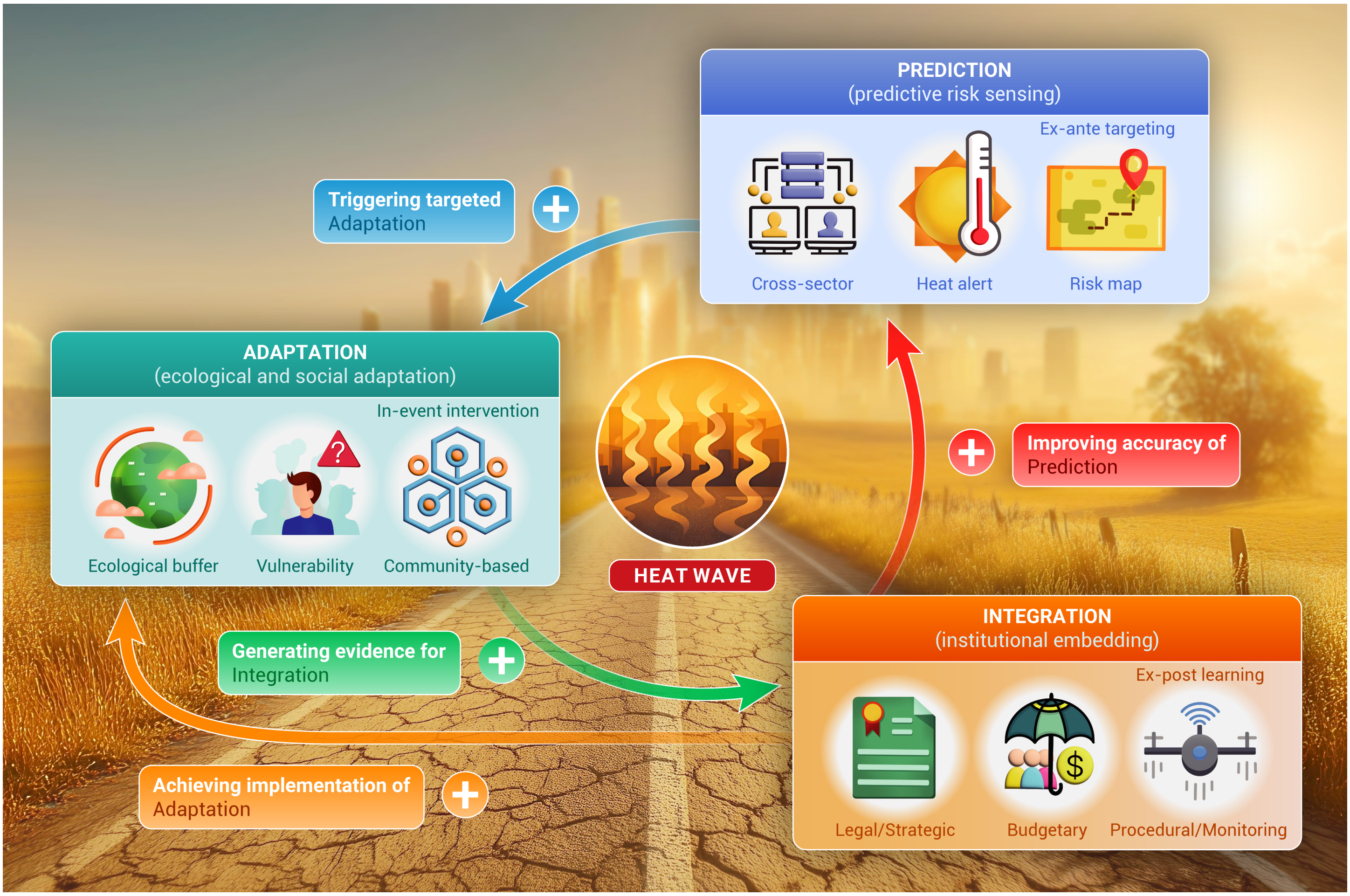


**Figure 1. The Prediction–Adaptation–Integration (PAI) framework** *Prediction* extends beyond meteorological indicators to establish cross-scale and cross-sector predictive risk sensing, triggering targeted *Adaptation* (+); *Adaptation* aligns ecological and social sides into function-oriented interventions, generating evidence for *Integration* (+); and *Integration* embeds heatwave governance within institutional structures, improving the accuracy of *Prediction* (+) and achieving the implementation of *Adaptation* (+). The background image is AI-generated and included for visual design only.

pilot project, implemented in low-income and heat-vulnerable municipalities, demonstrated clear benefits, showing 7-11°C temperature differences between shaded and unshaded areas.[8] These results align with recent research on targeted non-climatic interventions that enhance urban tree cooling.[9]

*Integration* embeds heatwave governance within institutional structures. It operates through three main mechanisms: (I) Legal and strategic: require heatwave risk assessments in master plans and incorporate thermal safeguards into land-use and zoning regulations; (II) Budgetary: allocate cross-agency budget lines for heat adaptation that connect forecast triggers with pre-approved actions; (III) Procedural and monitoring: establish inter-departmental platforms with data-sharing protocols and post-event evaluations. In the Netherlands, the National Institute for Public Health and the Environment (RIVM) manages the National Heatwave Plan, working with national health and care organizations as well as local agencies.[10] When activated, RIVM issues alerts to about 70 partner organizations, ensuring coordinated response across sectors.

The PAI framework operates as a recursive feedback loop: *Prediction* guides *Adaptation*; *Adaptation* enables *Integration*; and *Integration* strengthens both *Prediction* and *Adaptation* through institutional learning. To translate this framework from concept to practice, we propose three design principles for embedding the PAI framework into real-world policy systems: (I) Ex-ante risk-informed targeting: require heatwave risk assessments in urban and environmental planning that combine ecological and social indicators to identify priority areas for intervention; (II) In-event risk-proportionate intervention: during heat events, focus on performance-based actions (e.g., ecological buffers, targeted greening) that deliver effective cooling and protection in high-risk zones; (III) Ex-post iterative learning: establish post-event evaluations to update risk models and refine early-warning thresholds.

## CONCLUSION

Heatwaves have evolved beyond meteorological events to become a threat to the stability of social-ecological systems. Conventional governance, driven by reactive approaches, is insufficient to address the compounding and interconnected effects of heatwave risks. The PAI framework offers a transferable model for restructuring governance toward long-term resilience. By emphasizing a recursive feedback loop, predictive risk sensing, ecological and social adaptation, and institutional embedding, the PAI framework reshapes the end-to-end pathway from risk detection to coordinated action. Although its implementation requires political commitment and cross-sectoral collaboration, the PAI framework provides a practical foundation for transforming reactive governance into a proactive and adaptive system.

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## AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

## DECLARATION OF INTERESTS

The authors declare no competing interests.