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Extreme heat and the limits of tree and forest resilience

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The 2021 Pacific Northwest heat dome shows how acute thermal stress challenges prevailing assumptions about ecological resilience and adaptation. Extreme heat events are revealing physiological limits in forests that are not captured by conventional climate risk frameworks.

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In late June 2021, the US Pacific Northwest and western Canada experienced an extreme heat event without historical precedent. Air temperatures exceeded 45 °C across Oregon, Washington and British Columbia, causing hundreds of human fatalities and infrastructure failures. In the weeks that followed, a less visible but consequential impact emerged: extensive browning of evergreen forest canopies across the region[1,2]. To our knowledge, no previous foliar scorching event of this spatial magnitude has been documented.

The phenomenon can be understood as a terrestrial analogue of coral bleaching: a rapid, heat-driven collapse of physiological function revealing limits long assumed to be distant. The comparison matters because bleaching is no longer viewed as an anomaly, but as a signal that systems are approaching critical limits. These findings suggest that extreme heat should be treated not only as a driver of drought but also as an independent disturbance regime with distinct ecological dynamics.

At first glance, this damage resembled familiar symptoms of drought stress. Evergreen forests in the Pacific Northwest have been shaped by summer dryness and droughts, and changes in canopy conditions are often interpreted through that lens. Yet recent research shows that this assumption can be incorrect in ways that reshape climate risk. The dominant driver of canopy damage was not drought, but extreme heat directly damaging leaf tissues. Heat also intensified soil water limitation by driving increased transpiration and evaporative demand[1,2]. The heat dome exposed a critical gap between how ecological vulnerability is often conceptualized and how climate change is increasingly experienced: as acute, threshold-crossing events rather than gradual change.

Here we suggest that extreme heat events require rethinking resilience frameworks in climate science and adaptation policy. These events are not merely amplifications of existing stressors, but a distinct class of disturbance with unique ecological mechanisms and ethical implications. As such events become more frequent under climate change, the assumptions guiding ecological research and environmental decision-making warrant closer scrutiny.

Extreme heat as a stressor

Recent studies have examined the causes of widespread foliar damage following the 2021 heat dome using field observations, physiological thresholds and satellite-based analyses[2,3]. Emerging evidence from other recent heatwaves similarly indicates that short-duration thermal extremes can damage plants, even in the absence of soil drought[4,5]. The conclusion is consistent: direct thermal injury, rather than drought alone, can drive canopy damage. Foliar browning developed rapidly in 2021, even in stands with adequate soil moisture. Leaf temperatures exceeded thresholds for cellular integrity and photosynthetic function, causing tissue necrosis, with damage concentrated on south- and west-facing slopes under high radiation loads.

This finding challenges a long-standing tendency to treat heat primarily as a driver of drought, or to conflate heat and drought[6,7]. While drought remains a dominant driver of tree mortality, the heat dome revealed that short-duration thermal extremes can independently overwhelm organismal tolerance. Trees that have persisted for centuries under variable precipitation and temperature regimes were nonetheless vulnerable to temperatures only a few degrees beyond their historical range.

The implications extend beyond the Pacific Northwest. As climate warming increases the probability of extreme heat events, ecosystems adapted to moderate climates may face risks poorly captured by theories and models focused on chronic stress, mean conditions or gradual change. Extreme heat thus functions as a test of poorly understood limits and thresholds.

From trends to events

The heat dome lasted four days in most locations, yet its ecological effects unfolded too rapidly for acclimation, with effects on canopy development and stem growth that persist in the longer term. Such events compress ecological change into moments of crisis, revealing thresholds that remain invisible in trend-based analyses. What lies on the other side is not always the world we expected to return to.

From a scientific perspective, this challenges assumptions embedded in resilience theory, which often emphasizes gradual recovery from disturbance and the capacity of systems to absorb change without fundamental reorganization[8,9]. From a societal perspective, it complicates adaptation planning that prioritizes incremental adjustment over low-probability, high-impact events. In forest management, this may require anticipating abrupt canopy damage, thermal thresholds and rapid functional loss. Extreme events shift attention from averages to exposure – from what ecosystems can tolerate in general to what they cannot withstand even briefly. A climate increasingly defined by such extremes demands frameworks capable of capturing abrupt, nonlinear and potentially irreversible changes.

A regional reckoning

For those who live and work in the Pacific Northwest, forests are not abstract systems. They are cultural identity, ecological imagination and moral orientation. Evergreen canopies have long symbolized continuity – an assurance that some aspects of the landscape endure beyond human timescales.

In late summer 2021, these meanings shifted. Walking beneath Douglas fir and western hemlock in western Oregon revealed browning needles and a landscape newly marked by visible stress. Forests that had seemed insulated were, in fact, exposed. Satellite imagery revealed that canopy damage from the heat dome extended across an area the size of Rhode Island, scorching almost 5% of forested lands in western Oregon and Washington in 2021[2]. This was regional in scale, rapid in onset and unprecedented in the observational record for these forests.

This realization carries ethical weight. Conservation and adaptation strategies frequently rely on historical baselines and assumptions of persistence that may no longer hold under increasingly volatile climate regimes. Care for ecosystems cannot mean preservation alone – it must also involve preparedness for loss, recognition of limits, and difficult decisions about where intervention is possible, justified or effective. An ethic adequate for a world of extremes must grapple with responsibility under uncertainty, acknowledging that not all losses can be prevented while resisting the normalization of avoidable harm. Such an ethic does not abandon resilience but reframes it as the capacity to respond wisely to disruption rather than to maintain stability at all costs.

Trees, heat and exposure

Extreme heat events also expose inequalities – both ecological and social. In forests, leaf damage tracks microclimate, landscape orientation, species-specific thermal tolerances and canopy position. In human communities, exposure to extreme heat is likewise mediated by vegetation, but is also known to disproportionally impact certain groups of people. Farmworkers, unhoused residents, the elderly and those living in poorly insulated housing faced elevated risk[10]. Extreme events thus function as diagnostic moments, revealing how vulnerability is distributed across ecosystems and societies, and future warming promises substantially more harm to human societies[11].

This convergence matters for interdisciplinary climate research and governance. Ecological and social vulnerability are often analysed separately, yet extreme heat makes their interdependence visible. Ethical considerations are not external to climate impacts; they are embedded in how exposure, harm and recovery are structured[12]. Responsibility cannot be reduced to attribution alone; it must also address preparedness, protection and the uneven capacity to respond.

Living with extremes

The 2021 Pacific Northwest heat dome was not an isolated anomaly. Events of comparable magnitude are becoming more likely as global temperatures rise and heatwaves intensify under climate change[13,14]. The forests affected by this event offer an early warning of how ecosystems – and the human values attached to them – may be reshaped by a climate defined less by gradual change than by episodic extremes.

Understanding these transformations requires collaboration. Physiological research is essential for identifying vulnerabilities and thresholds. Ethical reflection is necessary for interpreting what these findings mean for responsibility, adaptation and care in a world where surprise is increasingly normal. It also requires academics to work directly with affected communities.

Extreme heat events force clarity. They reveal the limits of existing frameworks and demand new ways of thinking about resilience, risk and the futures societies are preparing for. The scorched canopies of 2021 remind us that climate change is not only a matter of degrees and trends but also of moments that compel both science and ethics to confront where their assumptions fail.

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Competing interests

The authors declare no competing interests.