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# Mountains magnify mechanisms in climate change biology

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Mountains, with their sharp climatic contrasts, are emblematic of climate-driven species movement and, ultimately, loss. Here, we argue that these same contrasts make mountains powerful natural laboratories for discovering the mechanisms that underlie biological change.

Mountains host exceptional biodiversity and sustain vital ecosystem services[1], yet many mountain regions are warming around 30–50% faster than surrounding lowlands above comparable latitudes and elevations[2]. This rapid change has made them emblematic of climate-driven range shift, often illustrated by the striking but incomplete 'escalator to extinction' narrative of upslope displacement and summit loss[3]. These same systems also expose a deeper and more general challenge in climate change ecology. Species' responses frequently diverge from simple temperature-tracking expectations[4], mirroring the growing mismatch between predicted and observed shifts documented globally. In some cases, species fail to move because they cannot; in others, they persist in place or move idiosyncratically as their realized ranges are shaped by biotic interactions, microhabitat structure and behavioural thermoregulation[4]. These processes generate uneven and difficult-to-predict responses, complicating efforts to project risk and design effective management strategies. Here, we highlight how mountains can magnify this understanding. Their steep climatic gradients, sharp microhabitat contrasts and strong seasonal shifts expose how microclimate, behaviour, physiology and demography interact to shape vulnerability. These natural laboratories reveal when safety margins shrink, why neighbouring populations diverge and where seasonal bottlenecks form, providing early, mechanistic insight into climate impacts that is difficult to obtain in less-variable landscapes. Range-edge maps remain useful, but as a scoreboard for risk they are blunt; mountains show the processes beneath those patterns, offering a clearer view of the mechanisms that matter for persistence. To realize this potential, we must resolve the causal chain linking climate forcing to demographic change.

## The causal chain

Climate impacts are often inferred from broad climate patterns, yet the mechanisms behind them emerge only when traced through the microclimates organisms actually experience[5]. On mountains, steep temperature and moisture gradients push individuals inside or outside their tolerance limits over short distances[6], making the links between microclimate, behaviour, physiology and demography especially clear, because even small spatial shifts can sharply alter exposure, performance and survival[7]. Local conditions shape energy balance, heat stress and water loss. Behaviour mediates exposure through shade-seeking, activity shifts or microhabitat choice. These pressures accumulate into differences in performance, recruitment and survival. Two simple diagnostics — activity windows and safety margins — help to capture these dynamics by indicating when conditions allow safe function and when they impose stress[8]. Because these indicators integrate microclimate with species' traits and behaviour, they offer a more informative picture of exposure and performance than range edges alone[7,9]. In broader climate change research, these mechanistic connections have often been obscured by coarse environmental data and correlative approaches; mountains help to recover them by compressing large climatic gradients into scales that match the way organisms actually experience their environments.

The fine-scale contrasts in aspect, canopy and elevation of mountains turn these landscapes into quasi-experiments, revealing why some populations decline while neighbouring ones persist under the same regional trends. Within metres, neighbouring slopes can differ by several degrees or by orders of magnitude in moisture, creating natural replicates of stress and refuge. Extreme heat or drought amplifies this. When these pulses strike unevenly across mountain landscapes, they generate carry-over costs — reductions in survival and recruitment — that pinpoint when populations cross physiological limits[7]. Such asymmetric impacts reveal causal pathways long before range limits shift, exposing which microhabitats buffer stress and which consistently push organisms beyond tolerance.

## Seasonality as a stress test

Seasonal elevational shifts reveal a critical but underused dimension of climate tracking. Many montane species move downhill in winter and uphill in summer in patterns that mirror seasonal climatic contrasts, redistributing themselves to environments that are typically warmer or cooler at the times they need them[10,11]. Altitudinal migration can briefly widen safe activity periods, but they also create reliance on seasonal habitats whose suitability is rapidly eroding under long-term warming and drying. As these bands warm, dry and lose buffering capacity, the very habitats that once provided seasonal refuge become sites of heightened heat and water stress[7]. This generates a dual vulnerability, as seasonal stress peaks interact with long-term climatic shifts. Yet, species must continue to use deteriorating seasonal habitats at precisely the times when energetic or reproductive demands are greatest. Because most climate impact assessments ignore these seasonal reallocations of space and time, they miss the bottlenecks where reduced activity time, increased water loss or phenological mismatches accumulate into demographic strain. This gap is compounded by the tendency to project impacts using coarse metrics, such as the maximum temperature of the hottest month, which do not capture the interacting pressures created by climate variability and increasing climatic extremes. Mountain systems make these seasonal mechanisms more visible, revealing when and why populations lose the buffer that

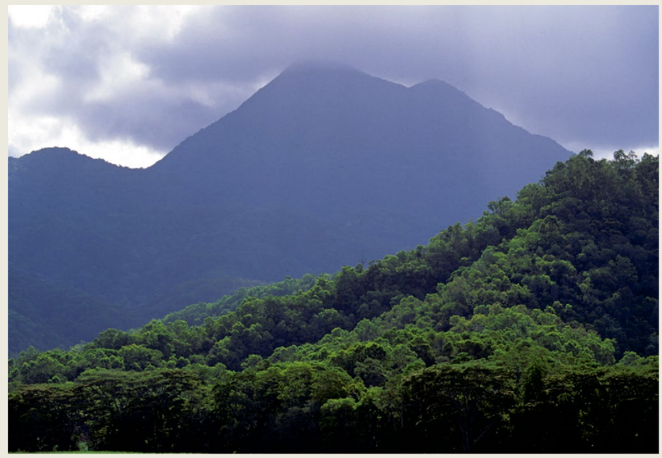
## BOX 1

# Resolving climate-driven decline in a mountain mammal system

A 30-year study of rainforest ringtail possums in the Australian Wet Tropics shows how mountain landscapes can be used to uncover the mechanisms linking climate change to population collapse[7]. Long-term monitoring revealed severe declines — up to approximately 70% in total abundance — across the elevational distributions of two endemic species. Importantly, these losses occurred with little immediate change in geographic range, illustrating how demographic collapse can precede, or occur without, clear spatial redistribution.

Steep elevational gradients provided the leverage needed to resolve why populations declined. Across a few hundred metres, neighbouring sites experienced sharply different thermal and moisture regimes under the same regional warming trend, amplifying climatic signals into strong biological responses. Using this natural laboratory, an integrated mechanistic framework linked microclimate, behaviour, physiology, nutritional constraints and long-term demography within a unified population model. This approach traced how climate forcing progressively reduced activity windows and eroded physiological safety margins, allowing stress to be linked directly to survival and recruitment.

Crucially, the analysis showed that closely related, co-occurring species declined through different physiological pathways. In some populations, intensified heatwaves reduced survival through overheating and dehydration. In others, warming constrained safe foraging time, leading to chronic energy limitation and reduced recruitment. In both cases, short-term heat extremes interacted with long-term warming to create recurring seasonal bottlenecks that governed population trajectories.



**Wet Tropics rainforest mountains, northeast Australia.**

Because mountains compress climatic change into biologically meaningful distances, this system revealed when tolerance limits were crossed, why neighbouring populations diverged and which physiological constraints governed persistence. Framed this way, population decline translated into decision-relevant levers, highlighting narrow seasonal windows — such as the late dry season for ringtails — where targeted management could most effectively mitigate climate impacts.

once kept them within tolerance, and when that loss begins to erode survival and recruitment.

### From mechanisms to decisions

A mechanistic framework turns understanding into application by clarifying what to measure, where to measure it and how those measurements translate into demographic consequences[12]. Mountains make this feasible because their steep gradients allow focused sampling across meaningful contrasts without requiring exhaustive spatiotemporal coverage (Box 1).

Making the transition from correlation to mechanism requires a specific set of measurements. Microclimate observations are needed to validate and refine the models we already use to scale climate to organismal exposure[13]; functional traits translate these conditions into body temperatures, water loss and energetic balance[14]; and behavioural data identify when organisms can buffer stress and when they cannot[8]. Together, these data allow physiologically explicit models to quantify expected changes – such as hours of safe activity gained per degree of local cooling or expected changes in recruitment per hour of recovered foraging. These mechanistic predictions can then be tested against recruitment, survival, or abundance changes in representative populations, providing the demographic validation needed to judge whether interventions are targeting the right bottlenecks. These decision-ready metrics point directly to questions managers can act on. For example, which slopes or microhabitats deliver the required cooling effects, how much canopy or ground cover is needed to recover lost activity time, or when seasonal bottlenecks make interventions most effective.

Progress does not require monitoring every species or every mountain. Strategic effort focused on representative ranges, seasonal bottlenecks and key functional groups can reveal general rules quickly, because biological responses on mountain slopes often emerge in years rather than decades[15]. Model-driven monitoring can further concentrate effort by identifying the sites and seasons where climate forcing is most likely to push populations towards physiological limits. This approach does have limitations. Current applications are biased towards well-studied taxa, accessible sites and particular life stages, and often require assumptions about thermoregulatory behaviour and access to suitable refugia that are difficult to test or validate during extreme events[14]. It also relies on coordinated data collection across microclimate, traits, demography and behaviour – disciplines that do not always intersect in practice – and in some regions or taxa remain difficult to instrument[14]. But when this coordination is achieved, mountains become rapid-learning systems, capable of linking climate forcing to demographic outcomes in ways that make conservation decisions both testable and transferable[7].

## Urgency and opportunity

The need is urgent, and the opportunity is real. Mountains are often portrayed as harbingers of climate-driven loss, yet they also offer some of our strongest tools for understanding and responding to change. They compress discovery time, revealing climate impacts early, sharply and in forms we can act on now. Their steep gradients place future and present climates side-by-side, exposing when safety margins shrink, why neighbouring populations diverge and where seasonal bottlenecks form – insights that can be applied to landscapes where signals emerge more slowly. Coordinated effort across representative ranges and taxa can turn these rapid signals into generalizable rules, moving us from diagnosis to intervention at a pace matched to accelerating change. Mountains are among the strongest lenses available for this task. If we use them to magnify mechanisms, we can move faster from insight to action, and transfer what we learn to other systems facing accelerating change.

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### Competing interests

The authors declare no competing interests.