Forest microclimate in mountains and its impact on plant community: Still a question of shade, but this time it's not coming from the canopy

Recently, microclimate has gained significant momentum[1], as evidenced by the increasing number of studies and the emergence of a dedicated scientific community coordinating research efforts[2]. Several factors underpin this trend, including advances in technology that have made microclimate monitoring[3] and ecological contextualization[4] more accessible, as well as improvements in computational methods that facilitate modeling at unprecedented scales[5]. But the growing emphasis on microclimate is primarily driven by their ecological relevance, as microclimate represent the actual climate conditions experienced by organisms[1]. This makes them more suitable than macroclimate data for understanding and predicting biodiversity responses to climate change[6]. While macroclimate data remain a common tool in ecology, they often represent generalized climatic conditions over large spatial scales. These data are typically derived from statistical models calibrated on observations collected at meteorological stations[7], which are usually located at 2 meters above the ground in open areas and at elevations compatible with human activities. Such characteristics limit the applicability of macroclimate data for understanding biodiversity responses, particularly at finer spatial scales.

This is especially true in forest ecosystems, where microclimate results from the filtering of macroclimate conditions by forest habitats[8]. A simple walk in a forest during summer highlights this filtering, with the cooling effect of canopy shading and tree packing being clearly perceptible. If humans can sense these variations, they likely influence forest biodiversity. In fact, microclimates are crucial for defining the thermal niches of understory plant species[9] and understanding plant community reshuffling in response to climate warming[10]. In mountainous areas, topography adds further complexity to microclimates. The drop in temperature with elevation, known as the elevation-temperature lapse rate, is familiar, but topography also drives fine-scale variations[11]. Solar radiation hitting forest varies with aspect and hillshade, creating localized temperature differences. For example, equator-facing slopes receive more sunlight, while west-facing slopes are sunlit during the warmest part of the day. Consequently, in the northern hemisphere, southwest-facing slopes generally exhibit warmer temperatures, longer growing seasons, and shorter snow cover durations[12]. Thus, both topography and forest canopy shape the understory microclimate experienced by organisms in temperate mountainous forests.

Is biodiversity more influenced by topography- or canopy-induced temperature buffering? While this question may not seem particularly interesting at first glance, understanding the underlying mechanisms of microclimate is crucial for guiding biodiversity conservation decisions in the face of climate change[13]. Poleward-facing slopes, valley bottoms, and dense canopies buffer warm episodes by creating cooler, more humid habitats that can serve as refugia for biodiversity[12]. Both buffering processes are valuable for conservation, but topography-induced buffering is generally more stable over the long term[14]. In contrast, canopy buffering is more vulnerable to human management, disturbances, and the ongoing acceleration of climate change, which is expected to drive tree mortality and lead to canopy opening[15]. Identifying the dominant buffering process in a given area is essential for mapping biodiversity refugia and fully integrating microclimate into conservation strategies. This approach can improve decision-making and actions aimed at promoting biodiversity sustainability in a warming world.

The work of Borderieux and colleagues[16] offers new insights into this question through an innovative approach. They focus on temperate forests in a watershed in the Vosges Mountains, where they monitor understory temperature and inventory forest plant communities in separate samplings. Aiming to disentangle the effects of topography and forest canopy on understory temperature and its impact on plant communities, the authors deployed a network of temperature sensors using stratified sampling, balanced according to topography (elevation, aspect, and slope) and canopy cover. They then correlated mean annual temperatures (daily mean and maximum) with topographic factors and canopy cover, considering their potential interactions in a linear model. The contribution of each microclimate component was computed, and their effects on temperatures were mapped. These predictions were then confronted to floristic inventories to test whether topography- and canopy-induced temperature variations explained plant diversity and assemblages.

First, the authors demonstrated that local topographic variations, which determine the amount of solar radiation reaching forests in mountainous areas, outweigh the contribution of canopy shading to understory temperatures. This result is surprising, as many previous studies have emphasized the importance of canopy buffering in shaping forest microclimate conditions[8]. However, these studies mostly focused on lowland areas or large scales, where terrain roughness has less influence. It is also unexpected because the authors observed that canopy cover varies at a smaller scale than aspect or topographic position in their study area, creating habitat heterogeneity that could reasonably drive local temperature variations. Nevertheless, the authors found that aspect, heat load, and topographic position induced more variation in microclimate than canopy filtering, significantly allowing deviations from the expected elevation-temperature lapse rate. Second, the topographic effect on understory temperature propagated to biodiversity. The authors found that topography-induced temperature offset explained plant diversity and composition, while canopy-induced temperature offset did not. Specifically, cold topoclimates harbored 30% more species than the average species richness across the inventoried plots. This increase in species richness was primarily due to an increase in cold-adapted species, highlighting the role of cold topoclimates as refugia.

It is difficult to assess the extent to which these results are influenced by the specific forest context of the study area chosen by the authors, as there is no clear consensus in previous research regarding the role of topoclimate. For example, Macek et al. (2019)[17] highlighted the predominance of topography in controlling temperature and, consequently, forest community structure in the Czech Republic, while Vandewiele et al. (2023)[18] demonstrated the dominance of canopy control in the German Alps. The forest conditions investigated by Borderieux et al. (2025) were narrow, as they focused mainly on closed forests (more than 80% of the study area and sampling sites exhibiting canopy cover greater than 79%). Given that the canopy buffering effect on temperature increases with canopy cover until plateauing at around 80%[19], this may explain why the authors did not find a strong contribution from the canopy. Nevertheless, the methodology and case presented in their study are both innovative and applicable to other mountainous regions. The work of Borderieux et al. (2025) deserves attention for highlighting a frequently overlooked component of forest microclimate, as canopy filtering is typically regarded as the dominant driver. Topoclimate is a critical factor to consider when protecting cold-adapted forest species in the context of global warming, especially since topographic features are less subject to change than canopy cover. Future research should aim to test this hypothesis across a broader range of forest and topography conditions to identify general patterns, as well as assess the long-term effectiveness of these topographic refugia for biodiversity. It remains unclear whether the cooling effect provided by topoclimate will be sufficient to stabilize climate conditions despite the expected acceleration of climate warming in the coming decades, and whether it will be able to preserve cold-adapted species, which are among the most unique but threatened components of mountain biodiversity.

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