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The state and fate of soil organic matter in alpine ecosystems of the Indian Himalayas

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The Himalayas and the recipients of its natural resources are both under threat from recent climate change, leading to accelerated glacier loss, extended growing seasons, and increased occurrence of extreme rainfall events. Microbial degradation of soil organic matter due to climate warming further converts long-stored organic carbon (OC) into greenhouse gases (GHGs) that can influence the regional carbon budget and future climate feedback. However, soil carbon dynamics in these high-altitude Indian Himalayan ecosystems remain poorly understood. This study investigates soil CO_2 fluxes and biogeochemical characteristics of soil substrates from two distinct climatic regions of the Indian Himalayas across elevations: the cold, arid Ladakh and the warmer, wetter Central Himalayas. Soil CO_2 flux measurements revealed nearly twice the emissions in the Central Himalaya compared to the Ladakh Himalaya, driven by a warmer, wetter climate and denser vegetation cover. The CO_2 fluxes are comparable to those reported from other high-elevation forest and grassland ecosystems. Central Himalayan soils exhibited significantly higher total organic carbon (TOC) content, with deep peat layers indicating substantial carbon storage susceptible to decomposition under continued warming. In contrast, Ladakh soils contain relatively low organic carbon, consistent with limited biomass input and stronger decomposition. Geochemical and biomarker proxies (C/N, CPI, OEP, ACL, bulk $\delta^{13}C$, and nC_{29}-$\delta^{13}C$) suggest that soil organic matter (OM) in both regions is predominantly derived from C3 higher terrestrial plants; however, the Central Himalayas retain less degraded OM and show evidence of vegetation shifts from woody to herbaceous inputs. The carbon isotopic composition of soil-respired CO_2 ($\delta^{13}C$-CO_2) was enriched in ^{13}C relative to the bulk OM, likely driven by microbial metabolic processes and partial contributions from older, deeper carbon sources. Radiocarbon dating indicates mid-to-late Holocene ages for subsurface OM, demonstrating long-term carbon accumulation under historically cooler and wetter conditions. Hydrogen isotope (δ^2H) profiles of n-alkanes reveal a transition toward warmer and/or drier conditions in the late Holocene, consistent with regional paleoclimate records. Together, these findings highlight the vulnerability of deep-seated old carbon mobilization in Himalayan alpine ecosystems to climate warming, with implications for increased GHG emissions from high-mountain landscapes in the future.