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Short Communication

No benefits from warming even for subnival vegetation in the central Himalayas

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Global temperature has been increasing at unprecedented rates during the Anthropocene, impacting both natural and human systems [1]. Alpine biomes, among the most sensitive natural ecosystems to climate warming, show rapid shifts of species distribution ranges and modulations of species interactions [1]. The Himalayas (also known as the "water tower" of Asia and a global biodiversity hot spot) are highly sensitive and vulnerable to global warming as this is one of the fastest-warming regions in the world. Such rapid warming is expected to trigger upward shifts of alpine vegetation, because cold temperature limitations on growth and recruitment are being alleviated [2]. However, increasing drought stress may dampen or even reverse this positive response of alpine ecosystems to warming climate [3,4]. In addition, interactions between alpine plants co-determine the structure and function of subnival vegetation, and thereby stabilize their distribution range [5].

Remote sensing is an important approach to monitor vegetation responses to changing environments at large spatial scales in such inaccessible regions. For example, a study using satellite data inferred expansion of subnival vegetation towards higher elevation from 1993 to 2017 in the Hindu Kush Himalayas [6], which highlighted that vegetation expansion altered the hydrological cycle. However, their study has exposed substantial limitations to retrieve past vegetation changes due to a lack of real field-scale observations and the short time span considered. To date, little is known about whether or not long-term field data support an upward expansion of subnival vegetation in the Himalayas. Resolving this key issue will contribute towards a better understanding of the carbon and hydrological cycles, as well as biodiversity conservation in the Asian water towers.

We aimed to fill this gap by analyzing field data of the recruitment dynamics and spatiotemporal variation in the altitudinal range limit of two juniper species (*Juniperus indica* and *J. squamata*) forming alpine shrublines (4344–5074 m a.s.l.), a clearly visible boundary of subnival vegetation. We also compared our field observations with Landsat satellite images of the investigated shrubline areas for the period between 1989 and 2019. Given the warming trend in recent decades across the upper Himalayas [4], we hypothesized that alpine shrublines will show accelerated recruitment and upslope movement, but that drying conditions might slow down this vegetation ascent.

Eight shrubline plots (30 m × 120 m) were established at three sites on gentle slopes, and far from areas disturbed by landslides or avalanches (Figs. 1d and 2). The bottom left corner of each plot was designated the origin ($(x, y) = (0, 0)$). The long side (y axis) of each plot was set parallel to the elevation gradient, including the

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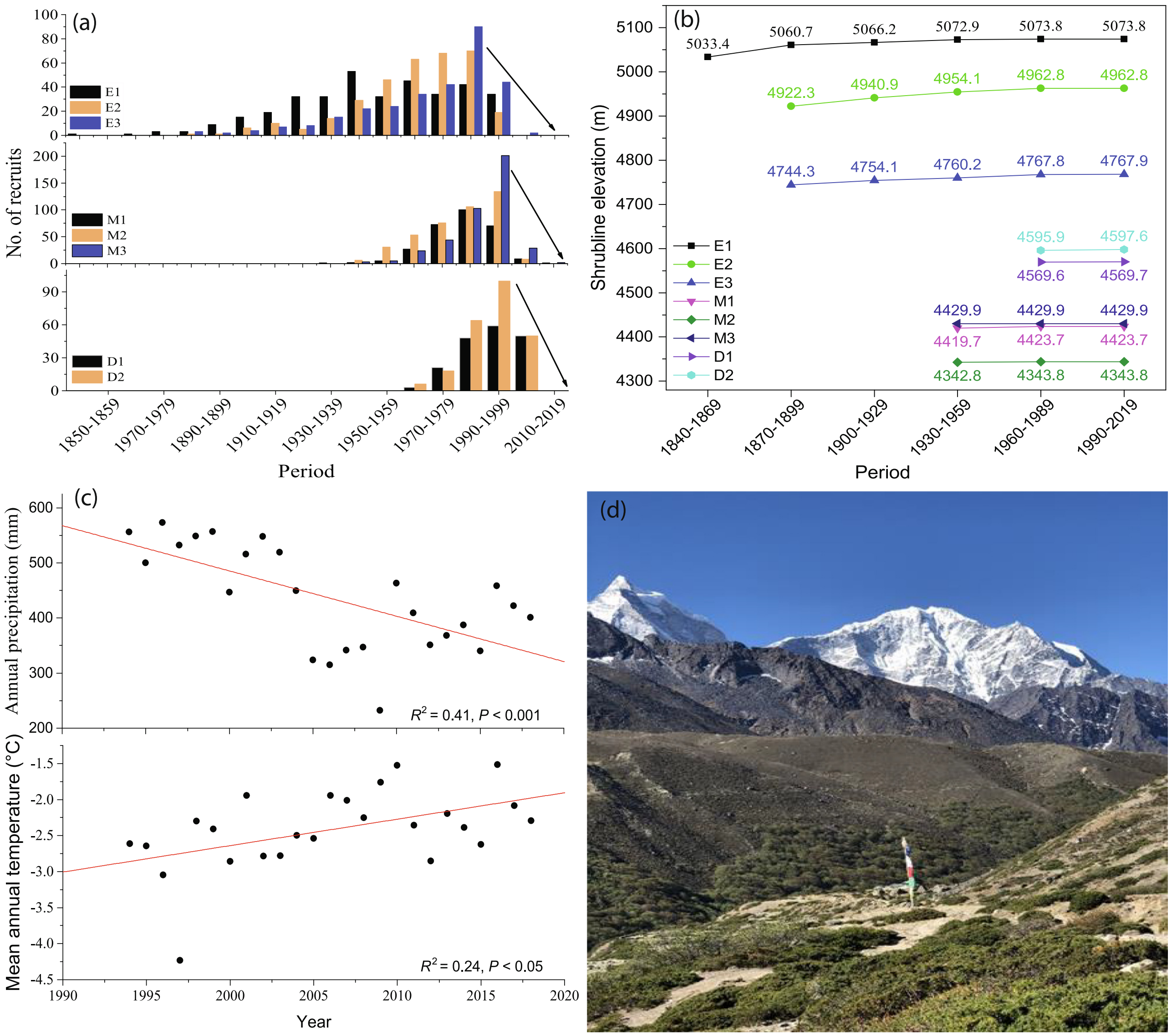

Fig. 1. Overview of shrubline sites, temporal variation in climate, shrub recruitment and shrubline positions in the central Himalayas. (a) Number of recruits on a decadal scale at the studied Himalayan juniper shrublines since the mid-19th century (3 sites, 8 plots; arrows show the decline in recruitment after 2000). (b) Long-term changes in shrubline elevation reconstructed since the mid-19th century at the eight study plots (E1–E3, M1–M3 and D1–D2 represent the locations of shrubline plots in the Everest, Manang and Dolpa valleys, respectively). (c) Variation of mean annual precipitation and temperature at the Pyramid meteorological station (5050 m a.s.l.), Everest region, from 1994 to 2018. (d) Landscape view of a juniper shrubline site in the Everest region (taken from 4770 m a.s.l.).

uppermost limit of juniper shrubs. The juniper shrubs are generally distributed in patches with single main stem. We identified and measured the main stem in each patch [7]. We recorded the diameter at ground level, height, canopy area and location of each shrub individual within the plots, and we also collected 25–40 wood cross-sections from each plot (representing different shrub sizes) to reconstruct age structure. After crossdating (mean inter series correlation: R_{BAR} = 0.25) following standard dendrochronological methods [8], we established age-diameter relationships (Fig. S1 online) to estimate the germination age of each individual within the studied plots and reconstructed recruitment dynamics and spatiotemporal variations in shrubline positions [2,7]. Temperature and precipitation data from the Pyramid meteorological station (5050 m a.s.l., Everest region, 1994–2018 period) were used (Fig. 1c) [4]. We also retrieved temperature and scPDSI data from the Climate Research Unit (CRU) TS4.02 database from the 0.5° grids encompassing the shrubline sites and correlated them with shrub recruitment trends (5-year average) over the past 60 years. Despite noticeable variability (with averages ± 1 standard deviations of 436.1 ± 92.1, −2.41 ± 0.54, 1086.7 ± 180.4, and 1.46 ± 0.42 for local precipitation, local temperature, CRU precipitation and CRU temperature, respectively) between observed and CRU gridded data, they are highly synchronized with the local meteorological data from the Pyramid station (temperature r = 0.96, $P < 0.001$, n = 300 months; precipitation r = 0.88, $P < 0.001$, n = 300 months) as reported in the previous study [9]. Thus, we assumed that CRU gridded datasets represent well climatic conditions in the central Himalayas. Landsat satellite images were retrieved to analyze temporal changes in subnival vegetation greenness/brownness between 1989 and 2019, particularly at the three studied shrubline sites. After pre-processing of the satellite images, including radiometric and geometric corrections, we used the normalized difference vegetation index (NDVI) with a lower threshold of 0.1 to map vegetation status [6].

All investigated shrubline sites have shown increasing recruitment until the 1990s, and a decreasing trend thereafter (Fig. 1a).

We found few shrubs that established in the 2010s, despite our very careful inventory of all shrub recruits located within each sampled plot. However, the peak recruitment periods slightly varied across sampling sites (the 1980s in Everest, and the 1990s in Manang and Dolpa). No dead shrubs were found in the investigated plots and above their shrublines, indicating that the sampled shrubs were first generation established during at least the last six decades. In addition, recruitment showed negative relationships ($P < 0.05$) with both spring and summer temperature, and a positive relationship with scPDSI ($P < 0.05$) (Fig. S2 online). All studied shrublines showed stable elevations over the past 60 years (Figs. 1b and S3 online). Furthermore, analysis of multi-temporal Landsat images did not show an increase of vegetation greenness between 1989 and 2019, and even some reduction (2%–6%) of the total vegetation greenness was observed near the shrubline areas in the Everest and Manang valleys (Fig. 2). The analysis of Landsat images also showed no evidence for vegetation greening in the Dolpa valley, although estimation of vegetation changes is associated with uncertainty at this location due to the topographic complexity and shadowed images.

Warmer spring and summer conditions can ameliorate seed germination and increase the survival of juniper seedlings, thus affecting recruitment patterns [10]. However, rising temperature and decreasing precipitation exacerbate moisture stress. Higher evapotranspiration rates during recent decades [2] could also increase seedling mortality and reduce the establishment of juniper shrubs by exacerbating soil moisture stress. This is supported by evidence for moisture-limited shrub growth at alpine shrublines, tree growth and treeline shifts in the central Himalayas [2,3,8], and declining trends of alpine shrub recruitment with warming temperature in the nearby Tibetan Plateau [7]. The variations in the peak recruitment periods might be due to variability in micro-site conditions such as topography, elevation, edaphic composition and interactions between co-existing species [7]. Accordingly, such conditions likely also influence shrub recruitment and elevational shifts of shrublines, as revealed by our results (Fig. 1b). The stationarity of shrublines may be due to negative feedbacks of warming temperature on subnival vegetation, which is likely to cause a decline of vegetated areas with predicted future warming [11]. Such a negative impact would be driven by the warming and drying trend across the high Himalayas (Fig. 1c) and an associated decrease in the duration and depth of snowpack [4]. In addition, decreasing subnival vegetation greenness in the shrubline sites is in agreement with our field data (Figs. 2 and S4 online), which indicates either shrinkage of vegetated area or abnormal vegetation growth. Negative responses of shrub recruit-

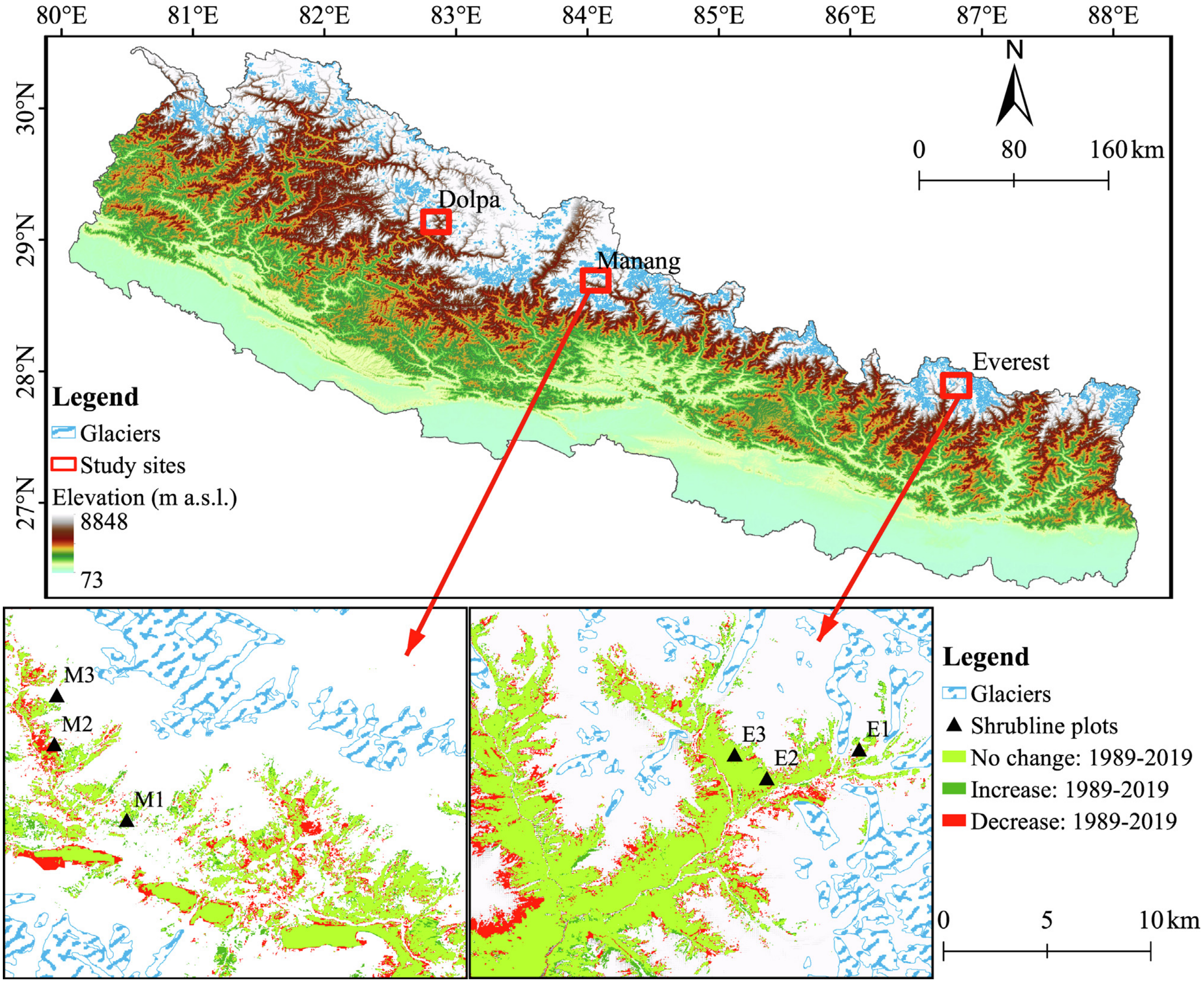

Fig. 2. Changes in vegetation greenness between 1989 and 2019 in two valleys that include the studied shrubline sites in the central Himalayas. The light green color represents the unchanged vegetation greenness between 1989 and 2019, the dark green color represents the vegetation greenness gains between 1989 and 2019, and the red color represents the vegetation greenness losses between 1989 and 2019. Black triangles with plot abbreviations E1–E3 and M1–M3 represent the locations of shrubline plots in the Everest and Manang valleys, respectively. Vegetation greenness changes in Dolpa valley are not calculated due to the topographic complexity and shadowed images.

ment to climate warming and scPDSI, along with stationary shrublines (Figs. S2 and S3 online) suggest that shrubs were not contributing to the subnival vegetation expansion inferred from satellite data as reported by earlier studies [6]. Additionally, photographs and satellite images do not allow disentangling local ecological processes in remote regions with complex topography, such as the Himalayan Mountains. Furthermore, satellite-based vegetation expansion trends may also be due to artifacts from topography shading, cloud cover, variations in color bands between different sensors, or a mismatch between the timing of images taken [6], which is likely in light of the heterogeneous Himalayan topography (Fig. 1d). Thus, our findings highlight the importance of ground-truthing remote-sensing studies by *in-situ* data to minimize or correct uncertainties and biases [12].

Decreasing precipitation and increasing temperature (Fig. 1c) are clearly reflected by the retreat of Himalayan glaciers in response to a warming climate [4], posing severe threats to alpine vegetation and water supply. Due to harsh climatic conditions experienced, alpine plants are likely to colonize and establish through facilitation, which could weaken the response of alpine plant communities to climate warming and control their range shift [5,13]. Juniper shrubs can live more than 400 years [7]. Hence, it is difficult to compute a recruitment threshold, as the sampled shrub community may not have reached a maximum age. Moreover, an advancement of vegetation phenology and greening would thus be expected under a warming climate, but moisture stress negatively impacts plant growth, seedling survival and likely causes vegetation browning rather than greening [12,14,15].

Declining juniper recruitment trends and stationary shrublines over the past 60 years across the subnival range of the central Himalayas under a warming and drying climate, thus, do not support the vegetation expansion reported by a recent remote sensing-based study [6]. Our study reveals a pressing need to evaluate how shrinking subnival vegetation green biomass affects the hydrological cycle and biodiversity in the Himalayas. *In-situ* experiments, including combinations of extreme temperature and moisture regimes, nutrient additions, altered biotic interactions, and snow manipulations are warranted to advance our understanding of alpine vegetation responses to warming climate.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Eryuan Liang and Josep Peñuelas designed the study. Shalik Ram Sigdel and Jayram Pandey performed field plot survey, and Sher Muhammad did remote sensing analysis. All authors contributed to the data analysis, interpretation and manuscript writing.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2021.06.005.

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