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Vegetation greening and its environmental drivers across glacier forefields of the Third Pole

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Abstract. Characterized by low temperatures, low oxygen availability and strong ultraviolet radiation, the Third Pole glacier region is highly sensitive to global change. We integrated multitemporal records for 36,374 glaciers with remote-sensing, reanalysis and environmental datasets to assess forefield vegetation dynamics and their climatic, edaphic and topographic controls. Our results showed that glacier forefields covered 7003.11 km^2, and were concentrated at elevations of 4000–6000 m. From the earliest recorded glacier outlines to 2022, mean retreat area per glacier was clearly greater in the monsoon region than in the westerly region (0.389 versus 0.122 km^2). Across these forefields, the normalized difference vegetation index (NDVI) increased significantly from 2000 to 2022 (slope = 0.013 $decade^{-1}$, $R^2 = 0.607$, $p < 0.001$). Both greening and growing-season lengthening were significantly faster in the monsoon region than in the westerly region (0.018 versus 0.009 $decade^{-1}$ and 3.80 versus 0.20 days $decade^{-1}$, respectively; $p < 0.001$). Our results also revealed that NDVI was associated with thermal conditions and soil properties, including field capacity, soil organic carbon and bulk density. Overall, vegetation succession in Third Pole glacier forefields is a staged process triggered by climate warming and snow-cover change, progressively supported by soil development and constrained over the long term by high-elevation terrain. Together, these findings reveal spatially uneven greening trajectories across Third Pole glacier forefields and suggest that their environmental constraints change as newly exposed landscapes develop, providing a scientific basis for understanding alpine ecosystem responses to climate change in extreme habitats.

Keywords: glacier forefields; vegetation succession; normalized difference vegetation index; mixed-effects model; climate change

1 Introduction

The Third Pole usually refers to the Qinghai-Tibet Plateau and its surrounding high mountain systems, with a total area of more than 5 million square kilometres and a mean elevation of more than 4000 m (Yao et al., 2012). Its high elevation and large cryospheric storage make it regarded as one of the largest concentrations of ice outside the polar regions, and it affects regional and even global climate, water cycling and biodiversity patterns. The Randolph Glacier Inventory (RGI) 7.0 lists approximately 131,762 glaciers in the Third Pole, covering 99,468.5 km^2 (RGI Consortium, 2023). The estimated ice volume is approximately 7,481 km^3 (Zemp et al., 2019). According to hydrothermal conditions and glacier physical properties, they can

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be divided into maritime, subcontinental and extremely continental glaciers (Yang et al., 2015). With global climate warming, mountain glaciers in the Third Pole are undergoing significant mass loss and retreat. Estimates based on ASTER satellite stereo-image digital elevation models covering 92% of the glacier area of the Third Pole show that from 2000 to 2016, the mean annual mass change of Third Pole glaciers was -0.18 +/- 0.04 m w.e. yr^{-1}, with the strongest loss in the Nyainqentanglha Mountains, reaching -0.62 +/- 0.23 m w.e. yr^{-1} (Brun et al., 2017; The GlaMBIE Team et al., 2025).

Global glacier retreat is exposing extensive new terrestrial, lacustrine, wetland and riverine habitats. These emerging ecosystems have distinctive environmental conditions. Projections based on the GloGEM model and CMIP6 scenarios suggest that, outside the Greenland and Antarctic ice sheets, glacier retreat may expose 149,000 +/- 55,000 km^2 of potential new ecosystem area under SSP1-2.6, roughly the area of Nepal, and 339,000 +/- 99,000 km^2 under SSP5-8.5, roughly the area of Finland, by 2100 (Bosson et al., 2023). Such emerging ecosystems provide irreplaceable habitats and natural laboratories for studying vegetation primary succession (Ficetola et al., 2024; Pothula and Adams, 2022). First, they begin from bare moraines, sand, gravel, debris and newly formed glacial lakes. Initial substrates consist of heterogeneous patches of sandy sediments, exposed debris, erosion gullies, floodplains and debris-flow deposits, and are typically poor in organic carbon, nitrogen and other nutrients (Franzetti et al., 2020; Wojcik et al., 2021). Second, these habitats are highly heterogeneous: microtopography, aspect, water content, sediment grain size and distance from the glacier terminus jointly shape vegetation colonization and community composition (Wei et al., 2022; Wojcik et al., 2021). Finally, succession often proceeds from microorganisms, mosses and lichens to herbs, shrubs, forests or alpine meadow communities, accompanied by increases in soil organic carbon, total nitrogen, available phosphorus and microbial community complexity (Fernández-Martínez et al., 2017; Göransson et al., 2011; Schmidt et al., 2008). In the Hailuogou Glacier forefield of Gongga Mountain, for example, a nearly 2 km chronosequence spanning about 120 years of retreat extends from bare ground and sparse pioneer herbs to shrubland, broadleaf forest and mature mixed conifer-broadleaf forest. During this process, soil organic carbon, total nitrogen and microbial community structure change substantially, illustrating the transition from bare substrate to a relatively stable ecosystem (Bai et al., 2020; He and Tang, 2008). Biological legacies from retreating glaciers may also influence the assembly of emerging soil communities (Cantera et al., 2026). Glacier forefields are therefore not only spatial carriers of emerging ecosystems, but also representative settings for analysing colonization, community replacement and ecosystem functional recovery.

Vegetation succession in glacier forefields is not driven simply by time since retreat. It is a dynamic process jointly regulated by initial environmental conditions, geomorphic disturbance, species dispersal and biological interactions (Chapin et al., 1994; Wojcik et al., 2021). Within this framework, theoretical and empirical studies commonly describe three interacting mechanisms: habitat filtering, time and dispersal, and biotic interactions (Hanusch et al., 2022). Habitat filtering emphasizes constraints imposed by low temperature, drought, substrate instability, weak soil development and nutrient poverty. Unmanned aerial vehicle imagery from three glacier forefields in the eastern Pamir Plateau and western Tianshan of the Third Pole revealed a negative relationship between fractional vegetation cover and gravel cover, supporting the importance of habitat filtering (Wei et al., 2022). Time and dispersal emphasize the roles of succession age, dispersal distance and dispersal mode in controlling community assembly rates. In the Baishui No. 1 Glacier forefield of Yulong Snow Mountain, communities were divided into three stages (9-13, 13-102 and 110-400 years), developing from bare ground to sparse vegetation and then alpine meadow.

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Dominant dispersal modes shifted from wind dispersal in early stages to animal dispersal later, indicating the role of dispersal mode in community assembly (Chang et al., 2014). Biotic interactions focus on facilitation, competition and plant-soil feedbacks during succession (Jones and Del Moral, 2009; Jumpponen et al., 1999; Llambí et al., 2021; Song et al., 2019). A joint species distribution modelling study of 117 plant species in four Alpine glacier forefields showed that positive and negative species associations explained up to 34% of spatiotemporal variation in plant communities (Losapio et al., 2021). Positive associations dominated pioneer communities, whereas negative associations strengthened as community age increased, suggesting a shift from early facilitation to later competition (Losapio et al., 2021). These mechanisms do not replace one another. Their relative importance changes through succession: early communities are often controlled by dispersal limitation and strong environmental filtering, whereas soil development, increasing vegetation cover and stronger biological feedbacks gradually increase facilitation, competition and deterministic assembly processes (Chapin et al., 1994; Hanusch et al., 2022; Song et al., 2019).

The heterogeneity of the regional environment of the Third Pole means that studies of one or several glacier forefields cannot fully explain the overall regional state, so regional-scale studies are urgently needed to analyse the vegetation patterns, succession rules and influencing factors of glacier forefields (Zou et al., 2025). The eastern and southern parts of the Third Pole are mainly controlled by the Indian monsoon, whereas the western and northern parts are more affected by westerly circulation, and the two differ significantly in precipitation patterns, water-vapour sources and wet-dry differentiation. In addition, the forefields of maritime, subcontinental and extremely continental glaciers also differ significantly in retreat rate, substrate stability, soil development and vegetation colonization conditions. This may lead to inconsistent succession starting points, succession rates and community assembly mechanisms among different regions, leaving a key gap for fully understanding vegetation succession in Third Pole glacier forefields (Casallas et al., 2025). This study aimed to explore the spatiotemporal patterns of vegetation succession and the climatic and environmental driving factors in the extreme habitats of Third Pole glacier forefields from 2000 to 2022. Specifically, (1) we constructed a Third Pole glacier forefield dataset and analysed the elevational characteristics and spatial differences of its distribution; (2) with NDVI and phenology (green-up date, withering date and growing-season length) as the core indicators, we quantified the spatiotemporal trends of vegetation greening in glacier forefields; and (3) we analysed the effects of multiple types of factors, including climate, soil, topography and glacier attributes, on NDVI change trends, analysed the shift characteristics of driving mechanisms among forefields with different retreat times, and quantitatively identified the dominant controlling factors of vegetation succession.

2 Materials and methods

2.1 Study area

This study focused on glacier forefields within 65-105 degrees E and 25-50 degrees N, covering the Tibetan Plateau and surrounding mountains, including the Himalaya, Hindu Kush, Pamir and Tianshan ranges, in the interior of Eurasia. Elevation in the study area ranges from 3101 to 8848 m. The region has complex tectonic and geomorphic settings and largely retains primary ecological conditions, with cold-, drought- and hypoxia-tolerant periglacial species such as *Saussurea spp.*, *Rhodiola*

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spp. and *Androsace spp.* The Third Pole contains extremely continental, subcontinental and maritime glaciers. Maritime glacier regions have comparatively favourable hydrothermal conditions and can support montane mixed conifer-broadleaf forests and subalpine coniferous forests, whereas continental and subcontinental glacier regions are mostly located in colder and drier alpine environments with slow soil development. The study area has a plateau mountain climate controlled mainly by the Indian summer monsoon and the subtropical westerlies. We therefore divided it into a southeastern monsoon-dominated region and a western westerly-dominated region (Huang et al., 2023).

2.2 Data collection

Glacier forefields are areas exposed after glacier retreat from surfaces formerly covered by ice (Matthews, 1992; Rydgren et al., 2014). Glacier boundary data were obtained from the Global Land Ice Measurements from Space (GLIMS) database (GLIMS Consortium, 2005). We selected glaciers with boundary outlines from at least two mapping years and delineated retreat areas from the spatial differences between successive outlines. The midpoint year between two boundary dates was assigned as the retreat year for each sample, representing the approximate exposure time of the forefield surface. For each glacier retreat polygon, we generated five random sample points under a glacier-level stratified sampling design to balance local heterogeneity and computational efficiency.

To assess the robustness and repeatability of the five-point sampling design, we conducted an independent resampling procedure. Using the same rule, a second set of five random points was generated for the same retreat polygon of each glacier, producing two independent sample sets (A and B). In total, 36,374 glaciers were included, yielding 363,740 sample points, with 10 points per glacier, for multi-angle validation of the sampling design. First, median standardized differences between the two sets (Median |A - B|/SD) were low for most variables, especially temperature, precipitation, soil physicochemical properties and NDVI across different periods, and generally remained below the threshold of 0.2 (Fig. S1). Second, kernel density comparisons showed that the two independent random samples had highly consistent environmental and vegetation distributions at the point scale (Fig. S2). Third, principal component analysis indicated strong overlap between the two samples in multivariate space, with nearly identical point clouds and confidence ellipses (Fig. S3). Finally, sample sets A and B showed similar distributions of Mahalanobis distances to the centroid of sample set A in PCA space (Fig. S4). Together, these four validation approaches show that the random sampling design produced highly consistent univariate differences, distributional structures, multivariate patterns and deviations from the environmental centre, with no obvious systematic bias. The sampling scheme is therefore robust, repeatable and capable of representing environmental and vegetation characteristics of glacier forefields.

The normalized difference vegetation index (NDVI) combines spectral reflectance in red and near-infrared bands and provides a global measure of vegetation greenness (Carlson and Ripley, 1997). NDVI is also positively correlated with annual aboveground net primary productivity and is considered a reliable proxy for estimating vegetation productivity in mountain regions (Paruelo et al., 1997; Rumpf et al., 2022). We therefore used NDVI as an indicator of vegetation greening and succession. Vegetation dynamics were characterized using the MODIS NDVI product MOD13Q1, a 250 m, 16-day composite distributed by NASA's Land Processes Distributed Active Archive Center (Didan, 2021).

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Climate conditions were represented by 2 m air temperature from ERA5-Land reanalysis and precipitation from the CHIRPS v2.0 dataset (mm month^{-1}) (Funk et al., 2015). The Palmer Drought Severity Index (PDSI) is a standardized drought index based on precipitation, evapotranspiration and soil-water balance, with smaller values indicating drier conditions and negative values usually representing drought (Funk et al., 2015). We used monthly PDSI products from TerraClimate as an indicator of regional drought severity (Abatzoglou et al., 2018).

Soil variables were obtained from SoilGrids 2.0 at 250 m resolution and 0-5 cm depth, including soil pH, soil organic carbon (soc), cation exchange capacity (cec), bulk density (bdod), field capacity (wv0033), total nitrogen (N) and coarse fragment volume (cfvo) (Poggio et al., 2021). These properties characterize soil water and nutrient retention and were treated as static variables (Turek et al., 2023). Topographic parameters included elevation and slope, which were extracted for each sample point from the 30 m SRTM DEM (Farr et al., 2007).

All datasets were spatially registered in the WGS 84 coordinate system to ensure correspondence between samples and environmental variables. Data quality control removed missing or invalid NDVI, temperature and precipitation values and checked the consistency between glacier IDs and coordinates.

2.3 Data analysis

2.3.1 Estimation of NDVI trends and climate sensitivity

We estimated trends in annual maximum NDVI, mean annual temperature (T_mean) and annual total precipitation (Pre_annual) at each sample point during 2000–2022. Trends were estimated using Theil–Sen slopes and evaluated with the Mann–Kendall test (Sen, 1968). The estimator was defined as:

$$\beta_{NDVI} = \text{median}(\frac{NDVI_j - NDVI_i}{t_j - t_i}), i < j \tag{1}$$

$$\beta_T = \text{median}(\frac{T_j - T_i}{t_j - t_i}), i < j \tag{2}$$

$$\beta_P = \text{median}(\frac{P_j - P_i}{t_j - t_i}), i < j \tag{3}$$

where i and j are the values in years i and j, t is time in years, T is mean annual temperature and P is annual total precipitation. This procedure yielded trend slopes for NDVI, temperature and precipitation. The Mann-Kendall non-parametric test was then used to determine whether these temporal trends were statistically significant (Mann, 1945).

To evaluate vegetation responses to climate change, we estimated the sensitivity of NDVI to temperature and precipitation at each sample point. Temperature and precipitation changes were used as denominators to construct Theil-Sen-type sensitivity estimates (S) for NDVI responses to temperature and precipitation:

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$$S_T = \text{median}\left(\frac{NDVI_j - NDVI_i}{T_j - T_i}\right),\ i < j, T_i \neq T_j \tag{4}$$

$$S_P = \text{median}\left(\frac{NDVI_j - NDVI_i}{P_j - P_i}\right), i < j, P_i \neq P_j \tag{5}$$

where S_T and S_P denote the sensitivities of NDVI to temperature and precipitation, respectively; T_i and T_j are mean annual temperatures in years i and j; and P_i and P_j are annual total precipitation values in years i and j. Larger absolute values indicate stronger NDVI responses to the corresponding climate factor. Positive values indicate that NDVI increases with that factor, whereas negative values indicate an inverse relationship. Significance was evaluated using the Mann-Kendall non-parametric test.

2.3.2 Vegetation phenology

We used the MODIS MOD13Q1 NDVI product, with 16-day temporal resolution and 250 m spatial resolution, to construct annual within-year NDVI time series for each sample point from 2000 to 2022 (Didan, 2021). MOD13Q1 is a pixel-based 16-day vegetation index composite product that reliably characterizes vegetation growth dynamics at regional scales (Didan, 2021). The Savitzky-Golay filter has been widely used to reconstruct remote-sensing vegetation time series because it suppresses noise while preserving the shape of seasonal curves (Chen et al., 2004; Jönsson and Eklundh, 2004). To reduce the effects of cloud contamination, observation errors and short-term anomalies on phenological detection, we smoothed the annual NDVI series at each sample point using a Savitzky-Golay filter with polynomial order p = 2 and window width w = 5.

Phenological metrics were extracted from the smoothed annual NDVI curves using a relative-threshold method. This rule-based approach is commonly used in remote-sensing phenology, and amplitude-based thresholds can adapt to seasonal differences among vegetation backgrounds while remaining interpretable and robust for large-scale applications (Zeng et al., 2020). We first calculated the seasonal amplitude for each point and year as the difference between annual maximum and minimum NDVI. A threshold equal to 20% of the amplitude was then used to identify start of season (SOS), end of season (EOS) and length of growing season (LOS). Time-series analyses retained only points with at least 10 valid years. Interannual trends in SOS, EOS and LOS from 2000 to 2022 were calculated and expressed consistently as days decade^{-1}.

2.3.3 Extreme climate indices

Extreme climate events, including drought, extreme precipitation, heat waves and extreme cold, depart from the environments to which vegetation is adapted. They can suppress plant growth or cause mortality and are therefore important variables affecting vegetation succession in glacier forefields (Niu et al., 2014). The Expert Team on Climate Change Detection and Indices (ETCCDI) of the World Meteorological Organization has defined a suite of climate extreme indices to facilitate comparison among studies. We selected 27 indices (Table S1) that are commonly used to evaluate the intensity, frequency and duration of climate extremes (Jiang et al., 2012, 2015; Wartenburger et al., 2017; You et al., 2008).

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2.3.4 Growing degree days

We used growing degree days (GDD) to represent the thermal resources available for vegetation growth in glacier forefields. GDD accumulates the positive difference between daily mean temperature and a biological base temperature and is an important metric for characterizing thermal limitation on plant growth in alpine regions (Löffler and Pape, 2020; Wang, 1960).

Daily GDD was calculated as:

$$GDD_i = \max(TM_i - T_b, 0) \tag{6}$$

where TM_i is daily mean temperature and T_b is the base temperature. When daily mean temperature exceeds the base temperature, the excess is counted; otherwise GDD is set to 0. Daily values were then accumulated to monthly and annual scales. Because alpine plant growth is highly sensitive to low-temperature thresholds, we used 0 degrees C and 5 degrees C as base temperatures to construct GDD0 and GDD5 (Lukasová et al., 2025).

2.3.5 Mixed-effects modelling

To identify the dominant climatic and environmental controls on vegetation succession in glacier forefields, we used linear mixed-effects models (LMMs) (Kuhn et al., 2025; Pinheiro and Bates, 2000). LMMs estimate fixed effects of environmental predictors while including random effects associated with repeated observations or spatial heterogeneity among sample points. This approach accounts for non-independence among observations and improves the robustness and ecological interpretability of parameter estimates (Dormann et al., 2007).

The general model structure was:

$$NDVI_{\max} = \beta_0 + \sum_{k=1}^{n} \beta_k X_k + (1 \mid samp) + \varepsilon \tag{7}$$

where $NDVI_{\max}$ is growing-season maximum NDVI and represents vegetation productivity at sample point i in year t. β_0 is the model intercept, β_k is the fixed-effect coefficient for predictor X_k, $(1 \mid samp)$ is the random intercept for sample point i and ε is the residual error. The random intercept controls for non-independence caused by repeated observations at the same point and unobserved spatial heterogeneity among points.

Fixed effects included environmental predictors representing climate, soil, terrain and glacier conditions. Climate variables included daytime land surface temperature (LSTD), night-time land surface temperature (LSTN), mean 2 m air temperature (T_mean), total precipitation (Pre), growing-season precipitation (Pre_grow_sum), non-growing-season precipitation (Pre_nongrow_sum) and snow-cover duration (SCD). Soil variables included field capacity (wv0033), soil organic carbon (soc), cation exchange capacity (cec), bulk density (bdod), coarse fragment volume (cfvo), soil pH (pH_H_2O) and total nitrogen (N), which characterize water and nutrient retention. Terrain and glacier predictors included elevation (dem), slope, retreat area (dt_area), glacier status (retreating or advancing) and retreat year (r_year), representing geomorphic constraints

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and glacier-retreat history. Before model fitting, all continuous predictors were standardized using z-scores to compare effect sizes, and variance inflation factors (VIFs) were used to assess multicollinearity. Variables with VIF > 5 were removed. LMMs were fitted in R version 4.5.0 using the lme4 and lmerTest packages (Bates et al., 2015; Kuznetsova et al., 2017). Model performance was evaluated using Akaike information criterion (AIC) and marginal and conditional R^2 values calculated with the performance package. Fixed-effect significance was determined using Wald chi-square tests and 95% confidence intervals.

2.3.6 Multiple factor analysis

To summarize environmental differentiation among glacier forefields at different succession stages, we used multiple factor analysis (MFA) to jointly reduce the dimensionality of climate, soil and terrain variables. MFA was developed for data structures in which the same observations are described by multiple groups of variables. It is appropriate when variables have explicit group membership but need to be analysed in a unified framework (Escofier and Pagès, 1994; Pages et al., 1991). MFA preserves group structure within an overall ordination, thereby extracting the main shared environmental gradients among samples while retaining the information organization within each variable group (Peres-Neto et al., 2006). It is therefore suitable for analysing composite environmental space under the joint influence of climate, soil and terrain (Abdi et al., 2013).

Environmental variables used in MFA were divided into three groups corresponding to the climate, soil and terrain groups in the fixed-effect models. We extracted the variance explained by the main axes, the contribution of each variable group to each dimension, and the coordinates, contributions and cos2 values of individual variables on the first two axes. These metrics were used to interpret the main environmental gradients and the positions of different succession stages in environmental space.

2.3.7 Structural equation modelling

To test direct and indirect relationships among climate change, soil chemical conditions and vegetation succession in glacier forefields, we constructed a structural equation model (SEM) (Rosseel, 2012). The SEM was used mainly to analyse direct effects of temperature and precipitation change on NDVI trends and whether climate factors indirectly affected vegetation recovery through changes in soil chemistry. NDVI trends represented the intensity of vegetation succession from 2000 to 2022, temperature and precipitation trends represented regional climate change, and soil pH represented the soil chemical environment. Because this analysis focused on the mediating mechanism linking climate, soil and vegetation, rather than on a complex path network including all environmental variables, not all soil, terrain and glacier attributes were included simultaneously. Final variable selection was based on random forest importance ranking, mixed-effects modelling results, ecological meaning and path-model interpretability, thereby avoiding model redundancy and overfitting.

Before modelling, all continuous variables were standardized to remove dimensional differences and improve comparability among path coefficients. Model fit was evaluated using the chi-square test, comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR) (Rosseel, 2012). Variables and paths that did not improve model fit, were not significant or lacked clear ecological meaning were excluded from the final model. The final SEM reported standardized path coefficients and significance levels to quantify direct climate effects on NDVI trends and indirect effects mediated by soil pH (Rosseel, 2012).

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2.3.8 Statistical analysis

All statistical analyses were performed in R version 4.5.0 and Python version 3.14.0. ArcMap 10.8 (Esri Inc., Redlands, CA, USA) was used for geometric correction, band compositing and study-area clipping of remote-sensing images, and maps were produced in the WGS 1984 coordinate system. Pairwise relationships among variables were tested using Pearson correlation analysis. Hierarchical clustering was used to visualize the correlation matrix and identify groups of closely related drivers. All variables were standardized before analysis. Statistical significance was set at $p < 0.05$.

3 Results

3.1 Elevational differentiation and spatial heterogeneity

We identified 36,374 glacier forefields across the Tibetan Plateau and surrounding high mountains and constructed a Third Pole glacier-forefield NDVI dataset for 2000-2022. The glacier distribution extended from 67.48 to 101.90 degrees E and from 27.50 to 45.30 degrees N, covering major glacierized regions such as the Himalaya, Karakoram, Kunlun, Tanggula and mountains along the southeastern margin of the Tibetan Plateau. This study mainly focused on forefields formed since 1959, with retreat years ranging from 1959 to 2014. Elevations of Third Pole glacier forefields ranged from 3101 to 8048 m. Most occurred between 4000 and 6000 m, which contained 73% of observed forefields, and the median elevation was 5224 m. Forefield area increased overall, and 72.7% of glaciers showed retreat, exposing additional forefield terrain. Mean retreat area was 0.19 km^2, with strong spatial heterogeneity. Exposure of glacier forefields across the Third Pole was relatively slow, averaging 0.139 km^2 of newly exposed forefield area per decade by 2022 (Fig. 1).

Glacier forefields showed marked differences between climatic regions. Although glaciers were more numerous in the westerly-dominated region, glaciers in the monsoon-dominated region retreated faster and exposed larger forefield areas per glacier, so cumulative forefield area was greater in the monsoon region. The cumulative exposed area of glacier forefields exceeded 7003.11 km^2. A total of 26,752 glaciers, or 73.5% of the dataset, were located in the westerly-dominated region, compared with 9622 glaciers (26.5%) in the monsoon-dominated region. The number of glaciers in the westerly region was 2.8 times that in the monsoon region, but total forefield area was smaller. Forefield area in the monsoon region was about 3742.50 km^2, accounting for 53.4% of the total, whereas cumulative forefield area in the westerly region was about 3260.61 km^2, or 46.6%. In terms of temporal change, 73% of glacier forefields in the monsoon region showed increasing area, whereas 59% of glaciers in the westerly region showed decreasing forefield area. By 2022, the mean exposed area formed by glacier retreat was about 0.389 km^2 per glacier in the monsoon region, substantially higher than the 0.122 km^2 per glacier in the westerly region.

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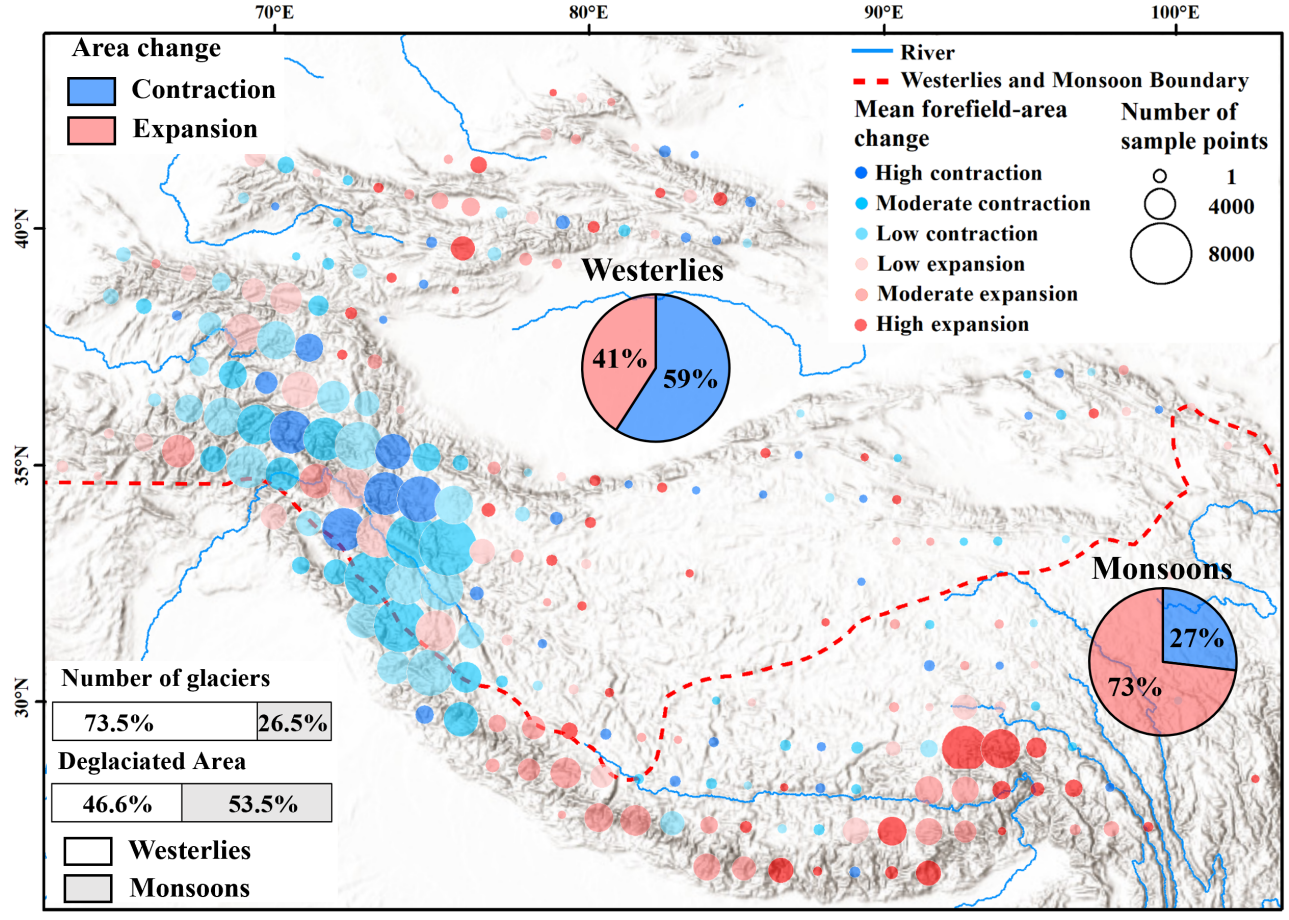


Figure 1. Spatial distribution and area changes of glacier forefields across the Third Pole. Circle size represents the number of sample points, whereas circle colour indicates the direction and relative magnitude of mean forefield-area change. Blue and red shades denote contraction and expansion, respectively. The dashed red line separates the westerly- and monsoon-dominated regions, and blue lines indicate rivers. Pie charts show the proportions of expanding and contracting forefields within each climatic region. The lower-left inset compares the regional shares of sampled glaciers and total deglaciated area, with white indicating the westerly region and grey the monsoon region.

3.2 Persistent greening and lengthening growing seasons

From 2000 to 2022, vegetation in Third Pole glacier forefields showed a significant greening trend (Fig. 2a). Regional mean NDVI increased linearly and significantly, with a slope of 0.013 decade^{-1} ($R^2 = 0.607$, $p < 0.001$). Overall, 76.5% of forefields showed positive NDVI trends, indicating continued vegetation succession during the past two decades. NDVI trends were spatially heterogeneous, with significant increases concentrated in the eastern and southeastern Tibetan Plateau and along some mountain margins. Greening was weaker in the westerly-dominated region, where mean NDVI increased by 0.0092 decade^{-1} (Fig. 2b). In contrast, 80.3% of forefields in the monsoon-dominated region exhibited positive NDVI trends, with mean NDVI increasing at twice the westerly rate (0.0184 decade^{-1}).

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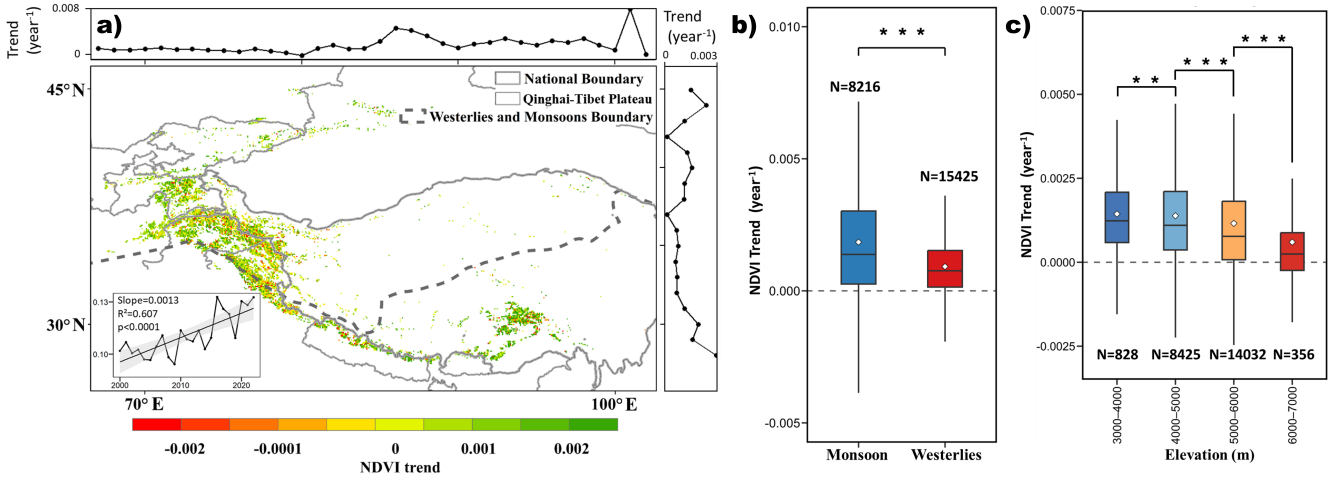


Figure 2. NDVI trends in Third Pole glacier forefields. (a) Spatial pattern of NDVI trends in glacier forefields from 2000 to 2022. (b) Comparison of NDVI trends between monsoon-dominated and westerly-dominated regions. (c) NDVI trends across elevation bands. Asterisks indicate significance levels: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

Phenological changes showed that lengthening growing seasons provided an important window for vegetation greening in glacier forefields. SOS and EOS were mostly stable, with 70.2% and 68.2% of forefields showing no significant trend, respectively. LOS showed a weak overall lengthening trend (slope = 1.53 days decade^{-1}), but with strong heterogeneity. More than half of forefields showed no significant LOS trend, 26.7% showed significant lengthening, and only 18.97% showed significant shortening (Figs S5-S7). Spatially, earlier SOS occurred mainly from the eastern Himalaya to the Tanggula Mountains, whereas delayed SOS was concentrated near the boundary between the westerlies and southwest monsoon and around the western Himalaya. Delayed EOS was more pronounced in the monsoon region, whereas parts of the southern Karakoram showed earlier EOS. LOS lengthening was concentrated mainly along the southeastern margin of the Tibetan Plateau. LOS lengthening was significantly stronger in the monsoon region (n = 4767) than in the westerly region (n = 8079). The mean slope was 3.80 days decade^{-1} in the monsoon region, with 35.7% of forefields showing positive trends, compared with only 0.20 days decade^{-1} and 20.8% positive trends in the westerly region. Thus, growing-season lengthening was most evident in southeastern Tibetan Plateau glacier forefields, and phenological responses were more sensitive in the monsoon region than in the westerly region.

3.3 A shift from warming-triggered recovery to soil and elevational constraints

From 2000 to 2022, the study area experienced significantly increasing precipitation and weak warming, with pronounced spatial heterogeneity under the influence of the westerlies and South Asian monsoon (Figs. 3a,b). Annual total precipitation and mean growing-season precipitation increased significantly, by 56.35 and 37.95 mm decade^{-1}, respectively. By contrast, trends in mean annual temperature and mean growing-season temperature were not significant, although values increased from -8.48 °C to -7.80 °C and from 1.57 °C to 2.20 °C, respectively. Both warming and wetting trends were stronger in

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the monsoon region than in the westerly region. Precipitation increased significantly in both climatic regions: annual total precipitation increased by 86.10 mm decade^{-1} in the monsoon region, 1.9 times the rate in the westerly region (45.66 mm decade^{-1}). Mean growing-season temperature trends were not significant in either region (Figs. 3c,d). Snow-cover duration decreased significantly in the monsoon region, at -9.29 days decade^{-1} (Fig. 3e), providing a longer potential window for vegetation succession.

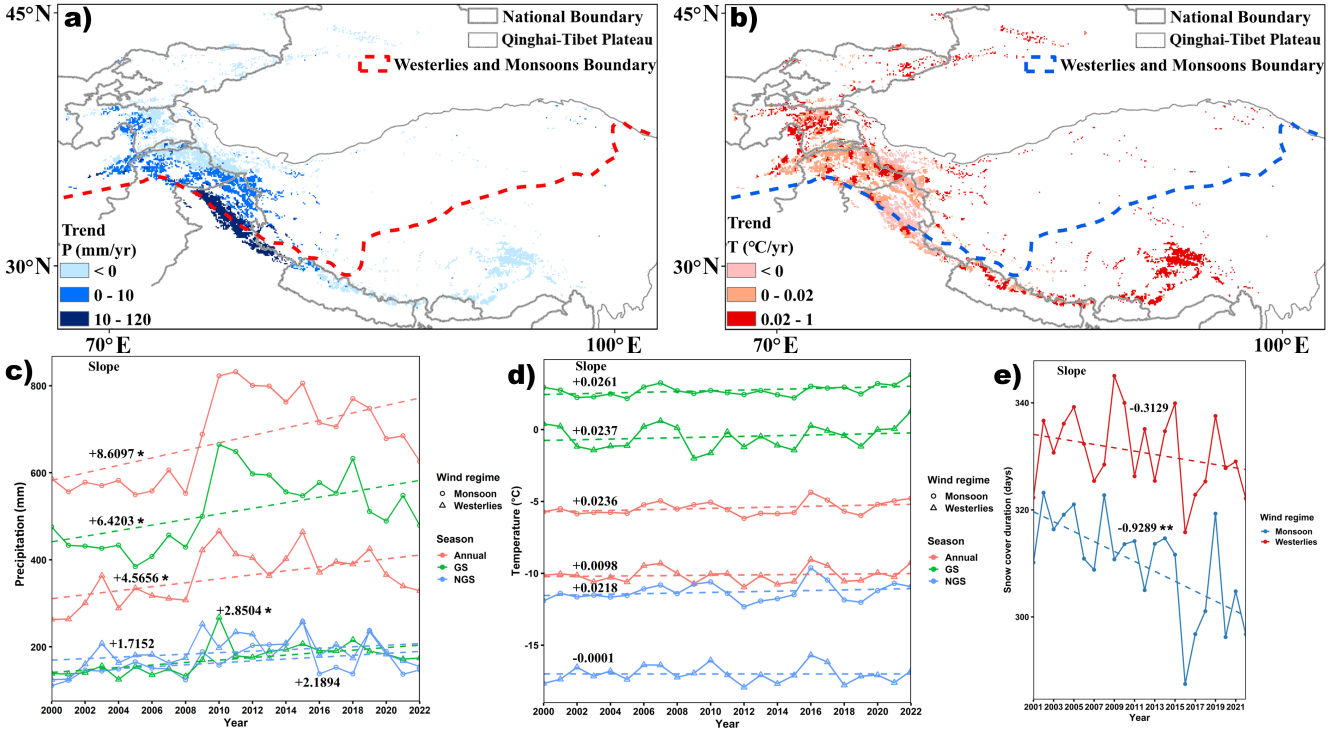


Figure 3. Spatiotemporal trends in precipitation and temperature in Third Pole glacier forefields from 2000 to 2022. (a) Spatial distribution of precipitation trends in glacier forefields; colours indicate annual precipitation change rate (mm yr^{-1}), and the dashed line marks the boundary between westerly-dominated and monsoon-dominated regions. (b) Spatial distribution of mean temperature trends in glacier forefields; colours indicate temperature change rate (degrees C yr^{-1}). (c) Temporal changes in annual precipitation, growing-season (GS) precipitation and non-growing-season (NGS) precipitation under different wind regimes. Dashed lines indicate fitted linear trends. (d) Temporal changes in annual mean temperature and corresponding GS and NGS temperatures under different wind regimes. Dashed lines indicate fitted linear trends. (e) Interannual changes in snow-cover duration in glacier forefields under different wind regimes. Symbols and colours indicate wind regimes.

Sensitivity analysis showed that temperature was the main climatic factor affecting NDVI changes in glacier forefields, with NDVI being significantly more sensitive to temperature than to precipitation. The mean NDVI–precipitation sensitivity coefficient was close to zero (-8.23×10^{-5}), and NDVI responded negatively to increased precipitation in 51.23% of the region (Figs. 4a,b). The mean NDVI–temperature sensitivity coefficient was 0.0105, with forefields exhibiting significant and slight

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increases accounting for 63.46% and 19.00%, respectively, or 82.46% combined (Figs. 4c,d). By climatic region, both the monsoon region and the westerly region were dominated by positive temperature responses, with the proportions of forefields showing significant increase being 64.14% and 63.21%, respectively. However, the proportions of forefields with significantly decreased and slightly decreased NDVI sensitivity to precipitation were higher in the monsoon region than in the westerly region.

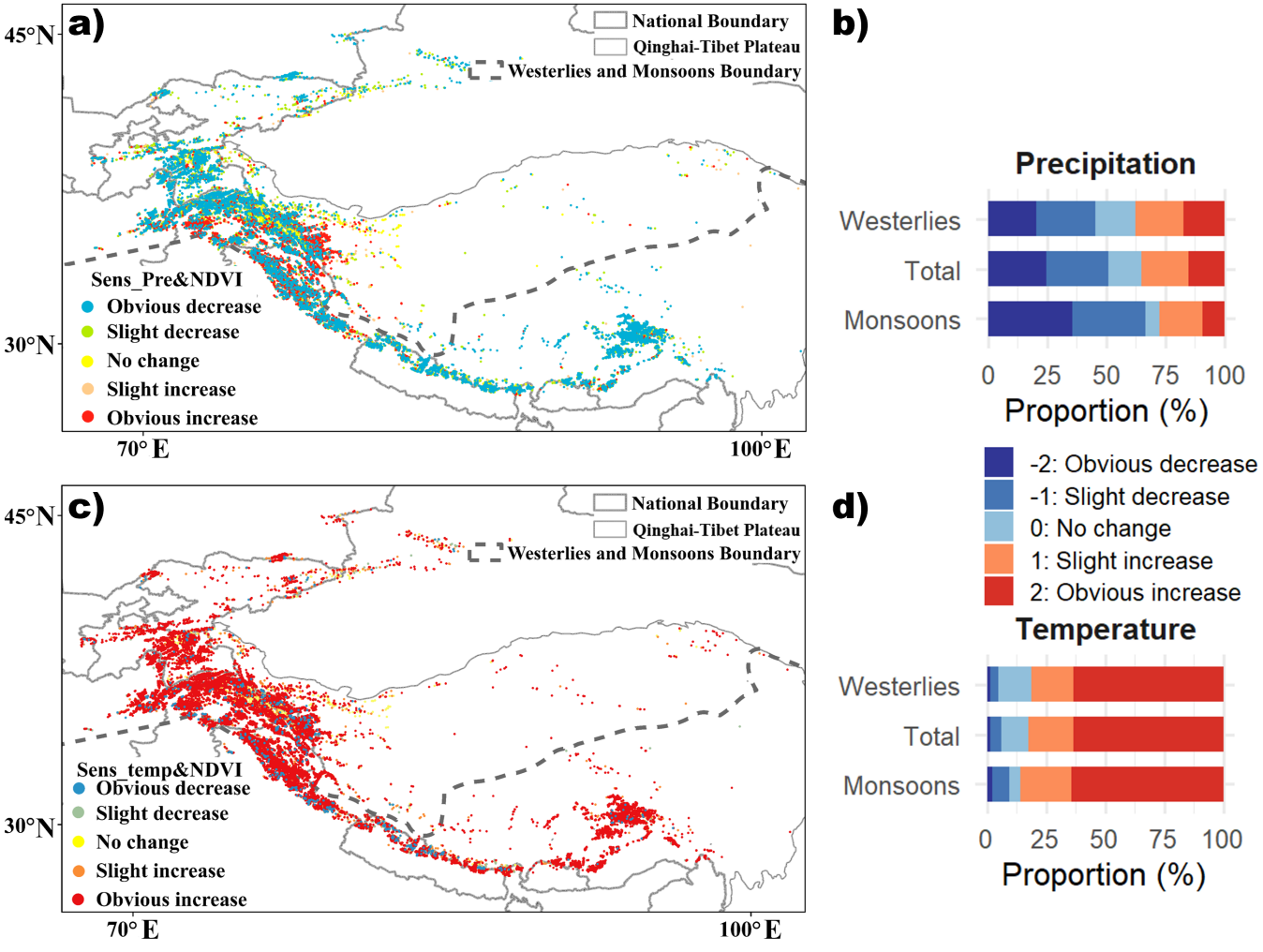


Figure 4. Sensitivity of NDVI to temperature and precipitation across the Third Pole from 2000 to 2022. (a,b) Sensitivity of NDVI to precipitation and category proportions in the westerly-dominated and monsoon-dominated regions. (c,d) Sensitivity of NDVI to temperature and category proportions in the westerly-dominated and monsoon-dominated regions.

Extreme climate analysis further indicated a consistent warming signal and asymmetric diurnal warming across the study area, with declining diurnal temperature range and fewer cold events. These changes suggest weakening low-temperature

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stress and more favourable thermal conditions for vegetation succession in glacier forefields (Fig. S8). For precipitation, the frequency and intensity of extreme precipitation increased significantly, and heavy precipitation events were more frequent and intense in the monsoon region than in the westerly region, reflecting differences in moisture structure and precipitation processes between the two climatic backgrounds (Figs S9-S10). Median PDSI was 0.713, while the westerly-dominated region showed a drying trend of -0.051 yr^{-1} (Fig. S11). GDD0 and GDD5 indicated increasing thermal resources, particularly in the monsoon region (Fig. S12). NDVI was positively correlated with GDD and negatively correlated with PDSI, suggesting that vegetation succession in Third Pole glacier forefields was driven mainly by increasing heat supply, whereas moisture fluctuation and drought acted as general limiting factors (Fig. S13).

Climate was not the only control on vegetation succession. Succession age, elevation, soil structure and nutrients also played important roles at the regional scale. As succession age increased, vegetation succession strengthened significantly (Fig. S14). Forefields older than 32 years (group A) had significantly higher NDVI trends than younger sites in groups B and C, with succession ages of 16-32years and less than 16 years, respectively. Terrain also affected vegetation succession (Figs. 6d,e). Vegetation status declined significantly with increasing elevation, indicating that harsh high-elevation environments constrain succession in glacier forefields.

MFA quantified the roles of environmental factors across succession stages and showed a stage-dependent transition in drivers of vegetation succession in Third Pole glacier forefields (Fig. S15). In forefields younger than 16 years (group C, retreated after 2006), vegetation succession was mainly controlled by hydrothermal windows and showed strong positive correlations between NDVI and temperature and precipitation (Fig. S16). As succession age increased (group B, retreated during 1990-2006), the system entered a transitional stage in which climate and soil were both strongly correlated with vegetation, suggesting that plant colonization and expansion began to modify soil structure and nutrients (Fig. 5a). In forefields older than 32 years (group A, retreated before 1990), the control exerted by topographic factors, especially elevation and slope, increased progressively to 58.8%, compared with 30.4% in group C (Fig. 5b). The influence of climate declined from 31.9% in group C to 13.0% in group A. These results indicate a shift from regional climate control to local constraints associated with elevation, soil structure and nutrients.

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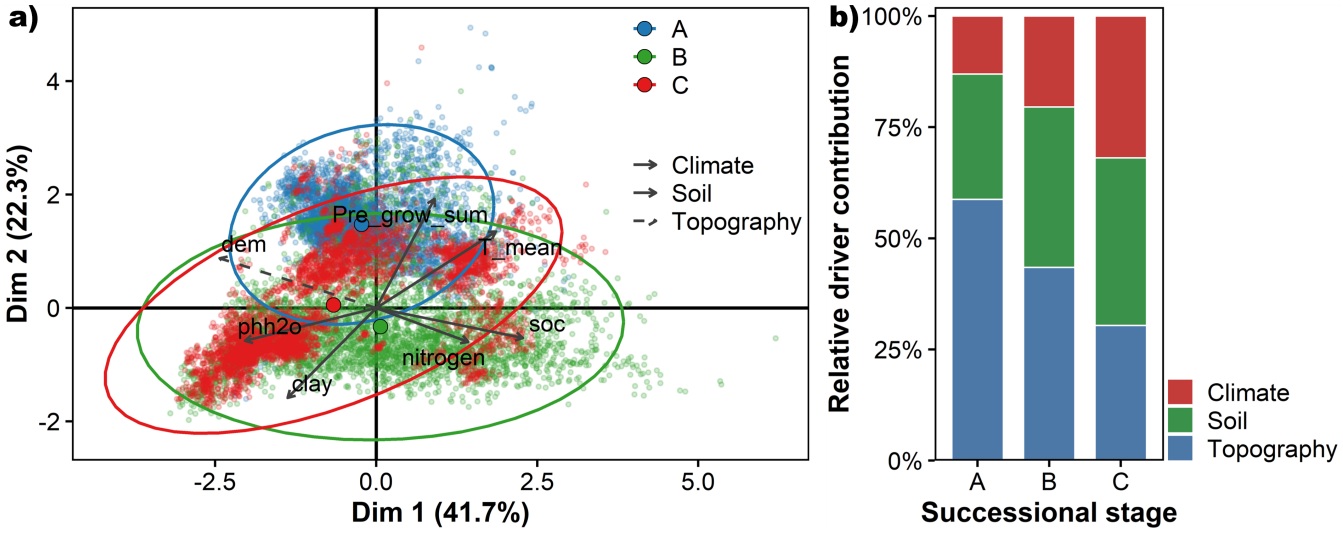


Figure 5. Environmental differentiation and relative contributions of drivers in glacier forefields of different retreat ages. (a) Environmental differentiation among forefields of different retreat ages based on multiple factor analysis (MFA). Group A: glacier retreat before 1990; group B: glacier retreat during 1990-2006; group C: glacier retreat after 2006. Arrows indicate the direction of major environmental factors, and ellipses indicate 95% confidence regions for each group. Arrow length reflects the relative contribution of climate, soil and terrain variables to the ordination structure on the first two MFA axes. (b) Relative contributions of climate, soil and terrain factors to NDVI change across retreat-age groups. Bars show standardized relative contributions of the three factor classes in each stage.

Linear mixed-effects modelling identified dominant factors affecting vegetation succession in glacier forefields. Overall, succession was jointly controlled by soil, terrain, glacier attributes and climate, and most factors were highly significant (Figs. 6a-c). Among soil factors, field capacity and soil organic carbon had the strongest positive effects on NDVI, with beta values of 0.321 and 0.090, respectively. By contrast, bulk density and coarse fragment content had strong negative effects, with beta values of -0.022 and -0.014, indicating that compact and coarse substrates constrain vegetation recovery. Among other attributes, elevation and retreat year had clear negative effects, with beta values of -0.033 and -0.025, suggesting that high elevation and younger forefields remain important constraints. Among climatic factors, annual daytime land surface temperature was the strongest positive factor (beta = 0.024), followed by growing-season maximum temperature (beta = 0.011), indicating that heat availability promotes vegetation recovery. Overall, these results suggest that vegetation recovery in glacier forefields is shaped by the combined effects of thermal promotion, topographic-elevational limitation and soil substrate regulation. Warming and favourable conditions in the southeastern monsoon region support vegetation succession, whereas high elevation, short exposure age, high bulk density and high coarse-fragment content jointly constrain it.

The structural equation model further indicated that soil conditions improved significantly with increasing succession age and promoted vegetation succession, but this process remained constrained by high elevation (Fig. 6d). Increasing succession age significantly reduced soil bulk density (-0.59, $p < 0.001$) and promoted soil organic carbon accumulation (0.28, $p < 0.001$). Elevation constrained soil formation: higher elevations had lower SOC (-0.45, $p < 0.001$), lower soil water-holding capacity

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(-0.35, $p < 0.001$) and slightly higher bulk density (0.11, $p < 0.001$). Among direct pathways affecting vegetation succession, precipitation change had the strongest direct effect, and it was negative (-0.21, $p < 0.001$). Warming had a positive effect on NDVI (0.06, $p < 0.001$), but the effect was weaker. Soil-mediated pathways also contributed to vegetation recovery. Soil water-holding capacity had a significant positive effect (0.176, $p < 0.001$), whereas higher bulk density significantly suppressed NDVI increase (-0.117, $p < 0.001$). SOC was weakly but significantly positively related to NDVI (0.04, $p < 0.05$). Elevation also directly suppressed NDVI (-0.174, $p < 0.001$), while the direct positive effect of succession age on NDVI was relatively weak (0.028, $p < 0.05$).

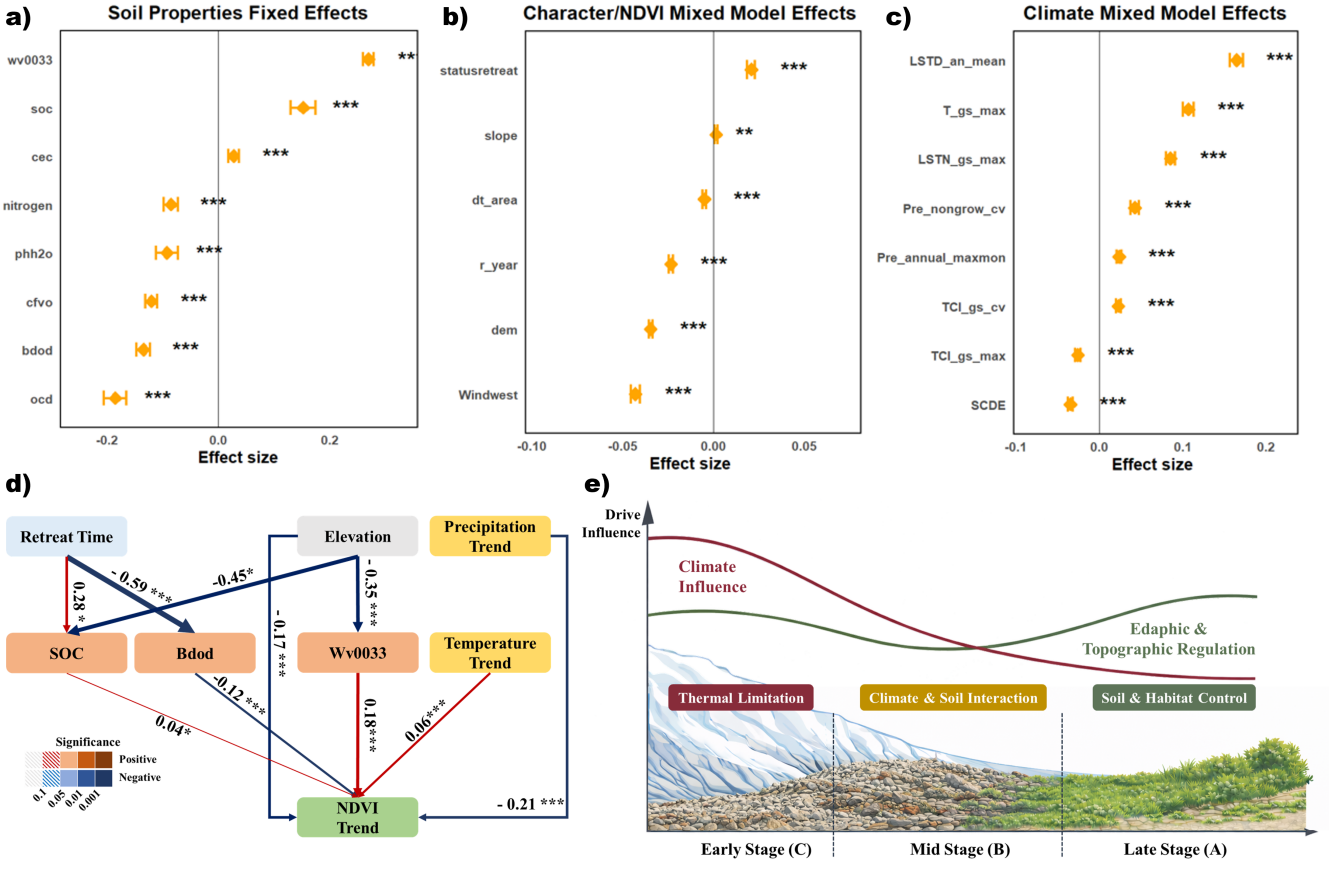


Figure 6. Mixed-effects model, structural equation model and conceptual framework for vegetation succession in Third Pole glacier forefields. (a) Fixed effects of soil properties related to water and nutrients. (b) Mixed-effects results for terrain, glacier and NDVI-related characteristics. (c) Mixed-effects results for climate variables. (d) Structural equation model (SEM). Arrows indicate directions of effects among variables, and colours indicate different pathway types. (e) Conceptual framework for drivers of vegetation succession in Third Pole glacier forefields. Error bars indicate 95% confidence intervals of standardized coefficients; asterisks indicate significance levels ($p < 0.05$*, $p < 0.01$**, $p < 0.001$***).

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4 Discussion

4.1 Persistent greening and monsoon-westerly differentiation in Third Pole glacier forefields

Our results show that NDVI increased significantly across Third Pole glacier forefields from 2000 to 2022. The regional mean NDVI trend was 0.013 decade^{-1}, and 76.5% of forefields showed positive trends, indicating regional-scale vegetation colonization and increasing productivity. Studies of global glacier retreat have reported comparable ecological responses, as continued retreat exposes new land in mountain regions and promotes the formation of new ecosystems consisting of soil, vegetation and microorganisms (Bosson et al., 2023; Ficetola et al., 2024; Wojcik et al., 2021). Research in the European Alps has shown that reduced snow cover and increased vegetation productivity jointly drive alpine greening (Rumpf et al., 2022). Studies in the Gran Paradiso glacier forefields, the retreating environments on the eastern slope of Gongga Mountain and Svalbard have similarly reported increases in NDVI, vegetation cover or vegetation productivity through time, suggesting that greening is a common signal in glacier-forefield succession (Gennaro et al., 2023; Ingrosso et al., 2025; Yang et al., 2025).

Within the Third Pole, NDVI increased by 0.0184 decade^{-1} in the monsoon-dominated region, about twice the rate in the westerly-dominated region (0.0092 decade^{-1}). Thus, although glacier forefields were greening overall, greening intensity was strongly heterogeneous. The higher NDVI increase in the monsoon region can be interpreted as the combined result of more favourable hydrothermal conditions, longer potential growing windows and faster exposure of bare terrain. Work in Gongga Mountain, a monsoon-influenced region, has shown that warm and humid conditions favour rapid vegetation establishment in glacier forefields, consistent with the stronger greening observed here (Yang et al., 2025). Reviews of glacier forefields emphasize that climate background, terrain, hydrology and soil conditions jointly regulate succession rates. The Third Pole should therefore not be described as greening uniformly. A more defensible interpretation is a hierarchical pattern of overall greening, regional differentiation and local regulation (Siegfried et al., 2023; Wojcik et al., 2021). NDVI increases can reflect changes in vegetation cover, growth or phenology without necessarily indicating shifts in species composition (Bayle, 2026). Phenological results further support this spatial heterogeneity: LOS lengthening was much stronger in the monsoon region (3.80 days decade^{-1}) than in the westerly region (0.20 days decade^{-1}). In alpine ecosystems, growing-season length is jointly controlled by snowmelt, low-temperature thresholds and heat accumulation. The stronger LOS lengthening in the monsoon region may therefore reflect the combined release of growing-season windows by shorter snow-cover duration and greater thermal resources (Rumpf et al., 2022; Schmidt et al., 2008; Zeng et al., 2020).

4.2 Thermal improvement as a trigger, with precipitation effects mediated by local terrain

Although mean temperature trends were not significant from 2000 to 2022, the study area showed signs of thermal improvement, including weaker low-temperature stress, fewer cold events, declining diurnal temperature range and increasing GDD. NDVI was also highly sensitive to temperature: 82.46% of forefields showed increasing NDVI with rising temperature. These results indicate that improved thermal conditions are an important external trigger for vegetation recovery in glacier forefields. Studies of temperature extremes in the eastern and central Tibetan Plateau show close links between elevation and temperature extremes, suggesting that changes in cold processes at high elevation can alter ecosystem thermal settings (You et al., 2008).

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Research on alpine plant thermal niches indicates that near-surface temperature and thermal thresholds explain plant occurrence and distribution, confirming heat availability as a key constraint on alpine plant growth and colonization (Löffler and Pape, 2020). Reviews of plant responses to climate extremes also show that cold, heat waves, drought and extreme precipitation affect plant growth and mortality, and that thermal improvement under climate change can expand growth windows in Third Pole glacier forefields (Niu et al., 2014). Studies in alpine and glacier-retreat environments commonly interpret increasing heat resources as favourable for pioneer plant colonization, microbial activity and nutrient turnover during early ecosystem development (Jiang et al., 2019; Kumar et al., 2022; Schmidt et al., 2008).

Mean NDVI sensitivity to precipitation was close to zero, and 51.23% of forefields showed reduced NDVI with increasing precipitation, indicating that more precipitation does not necessarily promote greening. The SEM also showed that precipitation change had the strongest direct negative effect on NDVI, suggesting that precipitation may inhibit NDVI through indirect processes such as increased cloudiness, lower radiation, colder and wetter conditions, or waterlogging (Lizaga et al., 2019; Niu et al., 2014). Reviews of plant responses to climate extremes indicate that excessive precipitation, cold-wet environments and extreme rainfall can affect plant growth through hypoxia, mechanical disturbance, disease risk or insufficient radiation (Niu et al., 2014). Work on covariation of summer NDVI between the eastern Tibetan Plateau and the Lake Baikal region has also shown that NDVI-climate relationships depend on atmospheric circulation and regional hydrothermal background, meaning that precipitation effects can change among regional contexts (He et al., 2020).

4.3 Soil substrate conditions control the stable progression of vegetation succession

The mixed-effects model showed that field capacity and SOC had strong positive effects on NDVI, whereas bulk density and coarse fragment content had negative effects. Vegetation succession in glacier forefields therefore depends not only on climate, but also on whether soil substrates can provide water retention, nutrient supply and rooting space (He and Tang, 2008; Jiang et al., 2019). These findings are consistent with studies of alpine and Arctic glacier forefields, where fine-textured and nutrient-rich soils accelerate primary succession and biomass accumulation (Lulakova et al., 2023; Szymanski et al., 2019). Early glacier forefields generally lack mature soils, and low organic matter, low nitrogen supply and coarse substrates constrain plant colonization (Göransson et al., 2011; He and Tang, 2008; Kumar et al., 2022; Schmidt et al., 2008). The SEM showed that increasing succession age reduced bulk density and promoted SOC accumulation, indicating that succession age is not merely a temporal variable but also an integrated indicator of soil development and increasing resource-retention capacity (He and Tang, 2008; Khedim et al., 2021). Along the Hailuogou Glacier chronosequence, soils developed from coarse gravelly bare ground to forest soils with clear profile differentiation over about 180 years. Mineral soil pH declined from about 8.5 to 4.2, bulk density decreased from about 1.42 to 0.95 g cm^{-3}, and organic carbon and total nitrogen accumulated to about 3.5 and 0.6 kg m^{-2}, respectively (He and Tang, 2008). The positive effect of field capacity on NDVI also increased with succession age, and global studies of glacier forefield topsoil have shown that organic matter usually accumulates through succession and is regulated by climate (Khedim et al., 2021). Research in Svalbard further shows that parent material, vegetation cover and site wetness strongly affect soil properties in glacier forefields (Szymanski et al., 2019).

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Elevation had a significant negative effect on NDVI and indirectly constrained vegetation recovery by reducing SOC and soil water-holding capacity and increasing bulk density. Elevation is therefore not simply a background variable, but a key constraint linking heat, soil and vegetation recovery (Löffler and Pape, 2020; You et al., 2008). The negative elevation effect is usually explained by the combined influence of low temperature, short growing seasons and slow soil development. Temperature and heat availability fundamentally limit alpine plant distribution and growth (Löffler and Pape, 2020). Studies along Scandinavian elevation gradients have shown that high-elevation environments generally have lower heat availability and shorter growth windows, and that near-surface root-zone and canopy temperatures constrain alpine plant occurrence, with species-specific thermal niches (Löffler and Pape, 2020).

4.4 Drivers of vegetation succession after glacier retreat

Considering spatial patterns, correlation structure and multivariate ordination together, our results further show that the drivers of vegetation succession in Third Pole glacier forefields shift with succession age (Ficetola et al., 2021; Wojcik et al., 2021). Existing reviews describe glacier-forefield succession as a continuum from an initial stochastic phase to an allogenic, or abiotic, phase, then a biogeomorphic phase and finally an autogenic phase. Allogenic factors are more important early in succession and subsequently decline in relative importance, whereas organic matter accumulation, species interactions and vegetation-soil feedbacks become stronger (Wojcik et al., 2021). A meta-analysis of 95 glacier-forefield studies showed that vegetation cover, vascular plant richness, non-vascular plant richness and lichen richness all increased significantly with succession age. Some microbial and soil animal groups increased rapidly during the first 50 years and declined thereafter, indicating that succession involves not only species accumulation but also taxon replacement driven by competition and changing habitat suitability (Ficetola et al., 2021). Soil properties also change with succession age. In the Urumqi Glacier No. 1 forefield, soil organic carbon, total nitrogen and vegetation cover did not show a simple linear relationship; instead, they increased with vegetation expansion and then fluctuated as rapid plant growth and nutrient consumption intensified (Wei et al., 2021).

In forefields younger than 16 years, soils are insufficiently developed and vegetation succession is controlled mainly by thermal conditions, precipitation, snowmelt and seed dispersal. In recently deglaciated terrain near Puca Glacier in the Peruvian Andes at about 5000 m elevation, the earliest stage of ecosystem development (0-4 years) began with microorganisms, pioneer plants and initial nutrient cycling. Environmental filtering was strong, and plant establishment lagged behind microbial processes (Schmidt et al., 2008). Work on pioneer plant colonization in the Lyman Glacier forefield emphasized that concave surfaces, coarse substrates and proximity to large rocks significantly increased pioneer plant occurrence. These microsites create wind shadows, trap seeds, slow surface runoff, reduce drought stress and improve seed burial and radicle penetration (Jumpponen et al., 1999). A seeding experiment in the Coleman Glacier forefield showed that sowing significantly increased seedling numbers for most species, but seedling densities remained low, indicating that both seed limitation and establishment limitation operate during early succession in glacier forefields (Jones and Del Moral, 2009).

As succession age increases to 16-32 years, the relative importance of climate declines and plant colonization and litter input begin to improve soil conditions. Soil water retention, SOC accumulation and microbial nutrient cycling then become stronger (He and Tang, 2008; Jiang et al., 2019; Khedim et al., 2021). Increasing soil age can shift plant interactions from facilitation to

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competition. In an intraspecific and interspecific neighbour experiment involving *Populus purdomii* and *Salix rehderiana* in the Gongga Mountain glacier forefield, interspecific combinations increased dry matter accumulation in 20-year forefields, whereas *Populus purdomii* dry matter declined under interspecific combinations in 40-year forefields. Microbial communities were also closely associated with soil nitrogen forms, indicating that this transition involves not only aboveground plant competition but also soil nitrogen, microbial processes and plant-soil feedbacks (Song et al., 2019). Pioneer plant strategies and positive interactions can influence primary succession. In a Venezuelan glacier forefield, as succession age increased from about 10 to 21 years, establishment of pioneer plants was no longer controlled only by bare-ground environmental filtering but became more spatially associated with early colonizers such as mosses and lichens. Mosses were significantly enriched within 30 cm neighbourhoods of *Poa petrosa* (Llambí et al., 2021). Thus, in middle-stage forefields (16-32 years), vegetation change is increasingly regulated by climate, soil development, microbial nutrient cycling and plant interactions together (Ficetola et al., 2021; Llambí et al., 2021; Song et al., 2019; Wojcik et al., 2021).

In older forefields (>32 years), the direct explanatory power of regional climate for vegetation succession declined, whereas local processes associated with elevation, slope, bulk density, soil water retention and biological interactions became more important. This pattern is consistent with a stage of stronger local environmental constraints and autogenic feedbacks (Ficetola et al., 2021; Wojcik et al., 2021). Long-term studies of glacier-forefield succession show that community structure, soil development and biological interactions strengthen as succession proceeds, so direct sensitivity to short-term climate variability may decrease in late-stage forefields (Chapin et al., 1994; Ficetola et al., 2021; Song et al., 2019). Research on the synergistic effects of microtopography and succession on fungal spatial diversity in glacier moraines also indicates that local geomorphic structure can continue to influence ecological processes over longer successional time scales (Masumoto et al., 2023). In eight glacier forefields of the southwestern European Alps, some forefields had 80% of pixels colonized by vegetation after 30 years, whereas others had about 30% or less, demonstrating that recovery rate should not be predicted from succession age alone but must also account for terrain and soil substrate conditions (Bayle et al., 2023).

Taken together, vegetation succession in Third Pole glacier forefields can be summarized as a staged process: early control by hydrothermal windows and colonization limitation, middle-stage strengthening of soil development and plant feedbacks, and later regulation by terrain constraints and autogenic processes. Continued glacier retreat will keep generating new early-stage forefields, whereas older forefields will remain constrained by soil development and terrain background. Future vegetation change in the Third Pole may therefore combine rapid responses in newly exposed forefields with persistent local constraints in older forefields. By 2100, the continuing emergence of newly deglaciated terrain may also show greater climate sensitivity, increasing ecological pressures on new glacier forefield ecosystems (Bosson et al., 2023).

5 Conclusions

Based on 36,374 Third Pole glacier forefields from 2000 to 2022, this study revealed spatial heterogeneity in glacier-forefield formation, vegetation change and driving mechanisms. Glacier forefields were widely distributed across major alpine glacierized regions, including the Himalaya, Karakoram, Kunlun and Tanggula mountains and the southeastern margin of the Tibetan

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Plateau. They were generally high-elevation and spatially heterogeneous. Most forefields were concentrated between 4000 and 6000 m, which accounted for 73% of observed forefields. Since 1959, cumulative glacier-forefield area in the Third Pole has exceeded 7003.11 km^2. Although the monsoon region contained fewer glaciers than the westerly region, it had greater total forefield area and larger mean retreat area per glacier, indicating that forefield formation is jointly controlled by glacier number, regional climate background and retreat intensity.

From 2000 to 2022, vegetation in Third Pole glacier forefields showed significant overall greening, with regional mean NDVI increasing at 0.013 $decade^{-1}$ and 76.5% of forefields showing positive trends. Greening was spatially heterogeneous: NDVI increased by 0.0184 $decade^{-1}$ in the monsoon region, about twice the rate in the westerly region (0.0092 $decade^{-1}$). Phenological change was also heterogeneous, with much stronger growing-season lengthening in the monsoon region (3.80 days $decade^{-1}$) than in the westerly region (0.20 days $decade^{-1}$). These results indicate that vegetation recovery in Third Pole glacier forefields is characterized by increasing greenness overall, while phenological responses and greening intensity are regulated by the monsoon-westerly division and local environmental conditions.

Vegetation succession in Third Pole glacier forefields was controlled jointly by thermal improvement, precipitation change, soil development, terrain constraints and succession age. Sensitivity analysis showed that NDVI responded more strongly and positively to temperature than to precipitation, with 82.46% of forefields showing positive temperature responses. This suggests that reduced low-temperature limitation, increasing GDD and shorter snow-cover duration jointly provide a more favourable thermal window for vegetation recovery. Soil and terrain factors determine whether this thermal window is converted into stable vegetation succession. Mixed-effects models showed that field capacity and soil organic carbon promoted NDVI increase, whereas bulk density, coarse fragment content, elevation and shorter succession age significantly constrained recovery. The structural equation model further indicated that increasing succession age reduces bulk density and promotes SOC accumulation, thereby improving substrate conditions. High elevation still reduces SOC and water-holding capacity, increases bulk density and directly suppresses NDVI, producing persistent constraints on vegetation recovery.

Vegetation succession in Third Pole glacier forefields showed clear stage-dependent controls. Early-stage forefields younger than 16 years were controlled mainly by hydrothermal windows. Middle-stage forefields aged 16-32 years were jointly regulated by climate and soil, as plant colonization and soil development began to interact. In older forefields (>32 years), the relative contribution of climate declined, whereas local factors such as elevation, slope, soil structure and nutrient conditions became more important. Overall, vegetation succession in Third Pole glacier forefields is a staged process triggered by thermal improvement and fewer snow-cover days, progressively supported by soil development and increasingly constrained by high-elevation terrain and substrate conditions. As glaciers continue to retreat, these successional patterns and shifts in controls may expand spatially and accelerate under continued warming. This understanding is important for predicting future ecosystem development in Third Pole glacier forefields and for clarifying how plateau mountain ecosystems reorganize under climate change.

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Data availability. The data that support the findings of this study are derived from the following resources. The Global Land Ice Measurements from Space (GLIMS) database is available at https://www.glims.org/maps/glims. The MODIS NDVI product MOD13Q1, a 250 m, 16-day composite data are available at https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod13q1-061. The Palmer Drought Severity Index (PDSI) data are available at https://www.psl.noaa.gov/data/gridded/data.pdsi.html. The CHIRPS v2.0 dataset data are available at https://www.chc.ucsb.edu/data/chirps. SoilGrids 2.0 dataset data are available at https://soilgrids.org/. SRTM DEM dataset data are available at https://www.earthdata.nasa.gov/data/instruments/srtm. The ERA5Land reanalysis data are available at https://earthengine.google.com. MODIS land surface temperature data are available at https://ladsweb.modaps.eosdis.nasa.gov.

Author contributions. QC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing-original draft and editing; XW: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing- original draft and editing; ZY: Visualization and Writing-original draft.

Competing interests. The authors declare that they have no conflict of interest.

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References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., and Hegewisch, K. C.: TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015, Sci. Data, 5, 170191, https://doi.org/10.1038/sdata.2017.191, 2018.

Abdi, H., Williams, L. J., and Valentin, D.: Multiple factor analysis: principal component analysis for multitable and multiblock data sets, WIREs Comput. Stat., 5, 149–179, https://doi.org/10.1002/wics.1246, 2013.

Bai, Y., Xiang, Q., Zhao, K., Yu, X., Chen, Q., Ma, M., Jiang, H., Zhang, X., Penttinen, P., and Gu, Y.: Plant and Soil Development Cooperatively Shaped the Composition of the phoD -Harboring Bacterial Community along the Primary Succession in the Hailuogou Glacier Chronosequence, mSystems, 5, e00475-20, https://doi.org/10.1128/mSystems.00475-20, 2020.

Bates, D., Mächler, M., Bolker, B., and Walker, S.: Fitting Linear Mixed-Effects Models Using lme4, J. Stat. Softw., 67, 1–48, https://doi.org/10.18637/jss.v067.i01, 2015.

Bayle, A.: Satellite Remote Sensing of Alpine Vegetation Dynamics: Challenges and Perspectives, Glob. Change Biol., 32, e70968, https://doi.org/10.1111/gcb.70968, 2026.

Bayle, A., Carlson, B. Z., Zimmer, A., Vallée, S., Rabatel, A., Cremonese, E., Filippa, G., Dentant, C., Randin, C., Mainetti, A., Roussel, E., Gascoin, S., Corenblit, D., and Choler, P.: Local environmental context drives heterogeneity of early succession dynamics in alpine glacier forefields, Biogeosciences, 20, 1649–1669, https://doi.org/10.5194/bg-20-1649-2023, 2023.

Bosson, J. B., Huss, M., Cauvy-Fraunié, S., Clément, J. C., Costes, G., Fischer, M., Poulenard, J., and Arthaud, F.: Future emergence of new ecosystems caused by glacial retreat, Nature, 620, 562–569, https://doi.org/10.1038/s41586-023-06302-2, 2023.

Brun, F., Berthier, E., Wagnon, P., Kääb, A., and Treichler, D.: A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016, Nat. Geosci., 10, 668–673, https://doi.org/10.1038/ngeo2999, 2017.

Cantera, I., Marta, S., Carteron, A., Guerrieri, A., Giachello, S., Bonin, A., Ambrosini, R., Azzoni, R. S., Caccianiga, M., Pittino, F., Simonicini, A., Valle, B., Gobbi, M., and Ficetola, G. F.: The Biodiversity of Retreating Glaciers Leaves an Ecological Legacy in Emerging Soil Communities, Glob. Change Biol., 32, e71040, https://doi.org/10.1111/gcb.71040, 2026.

Carlson, T. N. and Ripley, D. A.: On the relation between NDVI, fractional vegetation cover, and leaf area index, Remote Sens. Environ., 62, 241–252, https://doi.org/10.1016/S0034-4257(97)00104-1, 1997.

Casallas, L. M. V., Khelidj, N., Moran-Ordonez, A., and Losapio, G.: Global impacts of glacier retreat on ecosystem services provided by soil and vegetation in mountain Regions: A literature review, Ecosyst. Serv., 73, 101730, https://doi.org/10.1016/j.ecoser.2025.101730, 2025.

Chang, L., He, Y., Yang, T., Du, J., Niu, H., and Pu, T.: Analysis of Herbaceous Plant Succession and Dispersal Mechanisms in Deglaciated Terrain on Mt. Yulong, China, Sci. World J., 2014, 1–13, https://doi.org/10.1155/2014/154539, 2014.

Chapin, F. S., Walker, L. R., Fastie, C. L., and Sharman, L. C.: Mechanisms of Primary Succession Following Deglaciation at Glacier Bay, Alaska, Ecol. Monogr., 64, 149–175, https://doi.org/10.2307/2937039, 1994.

Chen, J., Jönsson, Per., Tamura, M., Gu, Z., Matsushita, B., and Eklundh, L.: A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky–Golay filter, Remote Sens. Environ., 91, 332–344, https://doi.org/10.1016/j.rse.2004.03.014, 2004.

Didan, K.: MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V061, https://doi.org/10.5067/MODIS/MOD13Q1.061, 2021.

https://doi.org/10.5194/egusphere-2026-6151
Preprint. Discussion started: 3 November 2026
© Author(s) 2026. CC BY 4.0 License.

Dormann, C. F., McPherson, J. M., Araújo, M. B., Bivand, R., Bolliger, J., Carl, G., Davies, R. G., Hirzel, A., Jetz, W., Kissling, W. D., Kühn, I., Ohlemüller, R., Peres-Neto, P. R., Reineking, B., Schröder, B., Schurr, F. M., and Wilson, R.: Methods to account for spatial autocorrelation in the analysis of species distributional data: a review, Ecography, 30, 609–628, https://doi.org/10.1111/j.2007.0906-7590.05171.x, 2007.

Escofier, B. and Pagès, J.: Multiple factor analysis (AFMULT package), Comput. Stat. Data Anal., 18, 121–140, https://doi.org/10.1016/0167-9473(94)90135-X, 1994.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., and Alsdorf, D.: The Shuttle Radar Topography Mission, Rev. Geophys., 45, RG2004, https://doi.org/10.1029/2005rg000183, 2007.

Fernández-Martínez, M. A., Pérez-Ortega, S., Pointing, S. B., Allan Green, T. G., Pintado, A., Rozzi, R., Sancho, L. G., and De Los Ríos, A.: Microbial succession dynamics along glacier forefield chronosequences in Tierra del Fuego (Chile), Polar Biol., 40, 1939–1957, https://doi.org/10.1007/s00300-017-2110-7, 2017.

Ficetola, G. F., Marta, S., Guerrieri, A., Gobbi, M., Ambrosini, R., Fontaneto, D., Zerboni, A., Poulenard, J., Caccianiga, M., and Thuiller, W.: Dynamics of Ecological Communities Following Current Retreat of Glaciers, Annu. Rev. Ecol. Evol. Syst., 52, 405–426, https://doi.org/10.1146/annurev-ecolsys-010521-040017, 2021.

Ficetola, G. F., Marta, S., Guerrieri, A., Cantera, I., Bonin, A., Cauvy-Fraunié, S., Ambrosini, R., Caccianiga, M., Anthelme, F., Azzoni, R. S., Almond, P., Alviz Gazitúa, P., Ceballos Lievano, J. L., Chand, P., Chand Sharma, M., Clague, J. J., Cochachín Rapre, J. A., Compostella, C., Encarnación, R. C., Dangles, O., Deline, P., Eger, A., Erokhin, S., Franzetti, A., Gielly, L., Gili, F., Gobbi, M., Hågvar, S., Kaufmann, R., Khedim, N., Meneses, R. I., Morales-Martínez, M. A., Peyre, G., Pittino, F., Proietto, A., Rabatel, A., Sieron, K., Tielidze, L., Urseitova, N., Yang, Y., Zaginaev, V., Zerboni, A., Zimmer, A., Diolaiuti, G. A., Taberlet, P., Poulenard, J., Fontaneto, D., Thuiller, W., and Carteron, A.: The development of terrestrial ecosystems emerging after glacier retreat, Nature, 632, 336–342, https://doi.org/10.1038/s41586-024-07778-2, 2024.

Franzetti, A., Pittino, F., Gandolfi, I., Azzoni, R. S., Diolaiuti, G., Smiraglia, C., Pelfini, M., Compostella, C., Turchetti, B., Buzzini, P., and Ambrosini, R.: Early ecological succession patterns of bacterial, fungal and plant communities along a chronosequence in a recently deglaciated area of the Italian Alps, FEMS Microbiol. Ecol., 96, fiaa165, https://doi.org/10.1093/femsec/fiaa165, 2020.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., and Michaelsen, J.: The climate hazards infrared precipitation with stations–a new environmental record for monitoring extremes, Sci. Data, 2, 150066, https://doi.org/10.1038/sdata.2015.66, 2015.

Gennaro, S., Cerrato, R., Salvatore, M. C., Salzano, R., Salvatori, R., and Baroni, C.: NDVI Analysis for Monitoring Land-Cover Evolution on Selected Deglaciated Areas in the Gran Paradiso Group (Italian Western Alps), Remote Sens., 15, 3847, https://doi.org/10.3390/rs15153847, 2023.

GLIMS Consortium: GLIMS Glacier Database, Version 1, https://doi.org/10.7265/n5v98602, 2005.

Göransson, H., Olde Venterink, H., and Bååth, E.: Soil bacterial growth and nutrient limitation along a chronosequence from a glacier forefield, Soil Biol. Biochem., 43, 1333–1340, https://doi.org/10.1016/j.soilbio.2011.03.006, 2011.

Hanusch, M., He, X., Ruiz-Hernández, V., and Junker, R. R.: Succession comprises a sequence of threshold-induced community assembly processes towards multidiversity, Commun. Biol., 5, 424, https://doi.org/10.1038/s42003-022-03372-2, 2022.

He, L. and Tang, Y.: Soil development along primary succession sequences on moraines of Hailuogou Glacier, Gongga Mountain, Sichuan, China, Catena, 72, 259–269, https://doi.org/10.1016/j.catena.2007.05.010, 2008.

https://doi.org/10.5194/egusphere-2026-6151
Preprint. Discussion started: 3 November 2026
© Author(s) 2026. CC BY 4.0 License.

He, K., Liu, G., Zhao, J., and Li, J.: Co-variability of the summer NDVIs on the eastern Tibetan Plateau and in the Lake Baikal region: Associated climate factors and atmospheric circulation, PLoS ONE, 15, e0239465, https://doi.org/10.1371/journal.pone.0239465, 2020.

Huang, L., Chen, J., Yang, K., Yang, Y., Huang, W., Zhang, X., and Chen, F.: The northern boundary of the Asian summer monsoon and division of westerlies and monsoon regimes over the Tibetan Plateau in present-day, Sci. China Earth Sci., 66, 882–893, https://doi.org/10.1007/s11430-022-1086-1, 2023.

Ingrosso, G., Ceccarelli, C., Giglio, F., Giordano, P., Hefter, J., Langone, L., Miserocchi, S., Mollenhauer, G., Nogarotto, A., Sabino, M., and Tesi, T.: Greening of Svalbard in the twentieth century driven by sea ice loss and glaciers retreat, Commun. Earth Environ., 6, 30, https://doi.org/10.1038/s43247-025-01994-y, 2025.

Jiang, Z., Song, J., Li, L., Chen, W., Wang, Z., and Wang, J.: Extreme climate events in China: IPCC-AR4 model evaluation and projection, Clim. Change, 110, 385–401, https://doi.org/10.1007/s10584-011-0090-0, 2012.

Jiang, Z., Li, W., Xu, J., and Li, L.: Extreme Precipitation Indices over China in CMIP5 Models. Part I: Model Evaluation, J. Clim., 28, 8603–8619, https://doi.org/10.1175/JCLI-D-15-0099.1, 2015.

Jiang, Y., Lei, Y., Qin, W., Korpelainen, H., and Li, C.: Revealing microbial processes and nutrient limitation in soil through ecoenzymatic stoichiometry and glomalin-related soil proteins in a retreating glacier forefield, Geoderma, 338, 313–324, https://doi.org/10.1016/j.geoderma.2018.12.023, 2019.

Jones, C. C. and Del Moral, R.: Dispersal and establishment both limit colonization during primary succession on a glacier foreland, Plant Ecol., 204, 217–230, https://doi.org/10.1007/s11258-009-9586-3, 2009.

Jönsson, P. and Eklundh, L.: TIMESAT–a program for analyzing time-series of satellite sensor data, Comput. Geosci., 30, 833–845, https://doi.org/10.1016/j.cageo.2004.05.006, 2004.

Jumpponen, A., Väre, H., Mattson, K. G., Ohtonen, R., and Trappe, J. M.: Characterization of 'safe sites' for pioneers in primary succession on recently deglaciated terrain, J. Ecol., 87, 98–105, https://doi.org/10.1046/j.1365-2745.1999.00328.x, 1999.

Khedim, N., Cécillon, L., Poulenard, J., Barré, P., Baudin, F., Marta, S., Rabatel, A., Dentant, C., Cauvy-Fraunié, S., Anthelme, F., Gielly, L., Ambrosini, R., Franzetti, A., Azzoni, R. S., Caccianiga, M. S., Compostella, C., Clague, J., Tielidze, L., Messager, E., Choler, P., and Ficetola, G. F.: Topsoil organic matter build-up in glacier forelands around the world, Glob. Change Biol., 27, 1662–1677, https://doi.org/10.1111/gcb.15496, 2021.

Kuhn, I., Hecht, C., Herzschuh, U., and Scherler, D.: Introducing a glacier forefield monitoring site network to understand succession in the Northern Limestone Alps, Web Ecol., 25, 157–168, https://doi.org/10.5194/we-25-157-2025, 2025.

Kumar, A., Mukhia, S., and Kumar, R.: Microbial community dynamics from a fast-receding glacier of Western Himalayas highlight the importance of microbes in primary succession, nutrient recycling, and xenobiotics degradation, Ecol. Indic., 144, 109565, https://doi.org/10.1016/j.ecolind.2022.109565, 2022.

Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B.: lmerTest Package: Tests in Linear Mixed Effects Models, J. Stat. Softw., 82, 1–26, https://doi.org/10.18637/jss.v082.i13, 2017.

Lizaga, I., Gaspar, L., Quijano, L., Dercon, G., and Navas, A.: NDVI, 137Cs and nutrients for tracking soil and vegetation development on glacial landforms in the Lake Parón Catchment (Cordillera Blanca, Perú), Sci. Total Environ., 651, 250–260, https://doi.org/10.1016/j.scitotenv.2018.09.075, 2019.

Llambí, L. D., Melfo, A., Gámez, L. E., Pelayo, R. C., Cárdenas, M., Rojas, C., Torres, J. E., Ramírez, N., Huber, B., and Hernández, J.: Vegetation Assembly, Adaptive Strategies and Positive Interactions During Primary Succession in the Forefield of the Last Venezuelan Glacier, Front. Ecol. Evol., 9, 657755, https://doi.org/10.3389/fevo.2021.657755, 2021.

https://doi.org/10.5194/egusphere-2026-6151
Preprint. Discussion started: 3 November 2026
© Author(s) 2026. CC BY 4.0 License.



Löffler, J. and Pape, R.: Thermal niche predictors of alpine plant species, Ecology, 101, e02891, https://doi.org/10.1002/ecy.2891, 2020.

Losapio, G., Cerabolini, B. E. L., Maffioletti, C., Tampucci, D., Gobbi, M., and Caccianiga, M.: The Consequences of Glacier Retreat Are Uneven Between Plant Species, Front. Ecol. Evol., 8, 616562, https://doi.org/10.3389/fevo.2020.616562, 2021.

Lukasová, V., Varšová, S., Mrekaj, I., Bilčík, D., Krempaský, J., and Onderka, M.: False spring disrupted the life cycles of Pinus cembra and Vaccinium myrtillus at the alpine treeline ecotone in the High Tatras (Western Carpathians), Reg. Environ. Change, 25, 142, https://doi.org/10.1007/s10113-025-02477-8, 2025.

Lulakova, P., Santruckova, H., Elster, J., Hanacek, M., Kotas, P., Meador, T., Tejnecky, V., and Barta, J.: Mineral substrate quality determines the initial soil microbial development in front of the Nordenskiöldbreen, Svalbard, FEMS Microbiol. Ecol., 99, fiad104, https://doi.org/10.1093/femsec/fiad104, 2023.

Mann, H. B.: Nonparametric Tests Against Trend, Econometrica, 13, 245–259, https://doi.org/10.2307/1907187, 1945.

Masumoto, S., Mori, A. S., Nishizawa, K., Naka, M., Matsuoka, S., Wong, S.-K., and Uchida, M.: Synergistic effects of succession and microtopography of moraine on the fungal spatial diversity in a glacier forefield, FEMS Microbiol. Ecol., 99, fiad090, https://doi.org/10.1093/femsec/fiad090, 2023.

Matthews, J. A.: The ecology of recently-deglaciated terrain : a geoecological approach to glacier forelands and primary succession, Cambridge ; New York : Cambridge University Press, 420 pp., 1992.

Niu, S., Luo, Y., Li, D., Cao, S., Xia, J., Li, J., and Smith, M. D.: Plant growth and mortality under climatic extremes: An overview, Environ. Exp. Bot., 98, 13–19, https://doi.org/10.1016/j.envexpbot.2013.10.004, 2014.

Pages, J., Escofier, B., and Haury, J.: Multiple Factor Analysis : A Method to Analyse Several Groups of Variables Measured on the Same Set of Individuals, in: Applied Multivariate Analysis in SAR and Environmental Studies, vol. 2, edited by: Devillers, J. and Karcher, W., Springer Netherlands, Dordrecht, 33–83, https://doi.org/10.1007/978-94-011-3198-8_2, 1991.

Paruelo, J. M., Epstein, H. E., Lauenroth, W. K., and Burke, I. C.: ANPP estimates from NDVI for the central grassland region of the United States, Ecology, 78, 953–958, https://doi.org/10.1890/0012-9658(1997)078%5B0953:AEFNFT%5D2.0.CO;2, 1997.

Peres-Neto, P. R., Legendre, P., Dray, S., and Borcard, D.: Variation partitioning of species data matrices: Estimation and comparison of fractions, Ecology, 87, 2614–2625, https://doi.org/10.1890/0012-9658(2006)87%5B2614:vposdm%5D2.0.co;2, 2006.

Pinheiro, J. C. and Bates, D. M.: Mixed-Effects Models in S and S-PLUS, https://doi.org/10.1007/b98882, 2000.

Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty, SOIL, 7, 217–240, https://doi.org/10.5194/soil-7-217-2021, 2021.

Pothula, S. K. and Adams, B. J.: Community assembly in the wake of glacial retreat: A meta-analysis, Glob. Change Biol., 28, 6973–6991, https://doi.org/10.1111/gcb.16427, 2022.

RGI Consortium: Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 7, https://doi.org/10.5067/F6JMOVY5NAVZ, 2023.

Rosseel, Y.: lavaan : An R Package for Structural Equation Modeling, J. Stat. Softw., 48, 1–36, https://doi.org/10.18637/jss.v048.i02, 2012.

Rumpf, S. B., Gravey, M., Brönnimann, O., Luoto, M., Cianfrani, C., Mariethoz, G., and Guisan, A.: From white to green: Snow cover loss and increased vegetation productivity in the European Alps, Science, 376, 1119–1122, https://doi.org/10.1126/science.abn6697, 2022.

Rydgren, K., Halvorsen, R., Töpper, J. P., and Njøs, J. M.: Glacier foreland succession and the fading effect of terrain age, J. Veg. Sci., 25, 1367–1380, https://doi.org/10.1111/jvs.12184, 2014.

https://doi.org/10.5194/egusphere-2026-6151
Preprint. Discussion started: 3 November 2026
© Author(s) 2026. CC BY 4.0 License.

Schmidt, S. K., Reed, S. C., Nemergut, D. R., Grandy, A. S., Cleveland, C. C., Weintraub, M. N., Hill, A. W., Costello, E. K., Meyer, A. F., Neff, J. C., and Martin, A. M.: The earliest stages of ecosystem succession in high-elevation (5000 metres above sea level), recently deglaciated soils, Proc. R. Soc. B Biol. Sci., 275, 2793–2802, https://doi.org/10.1098/rspb.2008.0808, 2008.

Sen, P. K.: Estimates of the Regression Coefficient Based on Kendall's Tau, J. Am. Stat. Assoc., 63, 1379–1389, https://doi.org/10.1080/01621459.1968.10480934, 1968.

Siegfried, L., Vittoz, P., and Lane, S. N.: Hydrological heterogeneity and the plant colonization of recently deglaciated terrain, Arct. Antarct. Alp. Res., 55, 2259677, https://doi.org/10.1080/15230430.2023.2259677, 2023.

Song, M., Yu, L., Jiang, Y., Korpelainen, H., and Li, C.: Increasing soil age drives shifts in plant-plant interactions from positive to negative and affects primary succession dynamics in a subalpine glacier forefield, Geoderma, 353, 435–448, https://doi.org/10.1016/j.geoderma.2019.07.029, 2019.

Szymanski, W., Maciejowski, W., Ostafin, K., Ziaja, W., and Sobucki, M.: Impact of parent material, vegetation cover, and site wetness on variability of soil properties in proglacial areas of small glaciers along the northeastern coast of Sorkappland (SE Spitsbergen), Catena, 183, 104209, https://doi.org/10.1016/j.catena.2019.104209, 2019.

The GlaMBIE Team, Zemp, M., Jakob, L., Dussaillant, I., Nussbaumer, S. U., Gourmelen, N., Dubber, S., A, G., Abdullahi, S., Andreassen, L. M., Berthier, E., Bhattacharya, A., Blazquez, A., Boehm Vock, L. F., Bolch, T., Box, J., Braun, M. H., Brun, F., Cicero, E., Colgan, W., Eckert, N., Farinotti, D., Florentine, C., Floricioiu, D., Gardner, A., Harig, C., Hassan, J., Hugonnet, R., Huss, M., Jóhannesson, T., Liang, C.-C. A., Ke, C.-Q., Khan, S. A., King, O., Kneib, M., Krieger, L., Maussion, F., Mattea, E., McNabb, R., Menounos, B., Miles, E., Moholdt, G., Nilsson, J., Pálsson, F., Pfeffer, J., Piermattei, L., Plummer, S., Richter, A., Sasgen, I., Schuster, L., Seehaus, T., Shen, X., Sommer, C., Sutterley, T., Treichler, D., Velicogna, I., Wouters, B., Zekollari, H., and Zheng, W.: Community estimate of global glacier mass changes from 2000 to 2023, Nature, 639, 382–388, https://doi.org/10.1038/s41586-024-08545-z, 2025.

Turek, M. E., Poggio, L., Batjes, N. H., Armindo, R. A., de Jong van Lier, Q., de Sousa, L., and Heuvelink, G. B. M.: Global mapping of volumetric water retention at 100, 330 and 15 000 cm suction using the WoSIS database, Int. Soil Water Conserv. Res., 11, 225–239, https://doi.org/10.1016/j.iswcr.2022.08.001, 2023.

Wang, J. Y.: A Critique of the Heat Unit Approach to Plant Response Studies, Ecology, 41, 785–790, https://doi.org/10.2307/1931815, 1960.

Wartenburger, R., Hirschi, M., Donat, M. G., Greve, P., Pitman, A. J., and Seneviratne, S. I.: Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework, Geosci. Model Dev., 10, 3609–3634, https://doi.org/10.5194/gmd-10-3609-2017, 2017.

Wei, T., Shangguan, D., Yi, S., and Ding, Y.: Characteristics and controls of vegetation and diversity changes monitored with an unmanned aerial vehicle (UAV) in the foreland of the Urumqi Glacier No. 1, Tianshan, China, Sci. Total Environ., 771, 145433, https://doi.org/10.1016/j.scitotenv.2021.145433, 2021.

Wei, T., Shangguan, D., Tang, X., and Qin, Y.: The role of glacial gravel in community development of vascular plants on the glacier forelands of the Third Pole, J. Arid Land, 14, 1022–1037, https://doi.org/10.1007/s40333-022-0073-1, 2022.

Wojcik, R., Eichel, J., Bradley, J. A., and Benning, L. G.: How allogenic factors affect succession in glacier forefields, Earth-Sci. Rev., 218, 103642, https://doi.org/10.1016/j.earscirev.2021.103642, 2021.

Yang, J.-P., Ding, Y.-J., Liu, S.-Y., and Tan, C.-P.: Vulnerability of mountain glaciers in China to climate change, Adv. Clim. Change Res., 6, 171–180, https://doi.org/10.1016/j.accre.2015.11.003, 2015.

Yang, J., Liu, Q., Luo, Y., Yin, Y., and Lu, X.: Rapid dynamics of paraglacial vegetation under temperate deglaciating environments in Mt. Gongga, southeastern Tibetan Plateau, J. Geogr. Sci., 35, 1979–1997, https://doi.org/10.1007/s11442-025-2399-z, 2025.

https://doi.org/10.5194/egusphere-2026-6151
Preprint. Discussion started: 3 November 2026
© Author(s) 2026. CC BY 4.0 License.



Yao, T., Thompson, L. G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., Xu, B., Yang, X., Joswiak, D. R., Wang, W., Joswiak, M. E., Devkota, L. P., Tayal, S., Jilani, R., and Fayziev, R.: Third Pole Environment (TPE), Environ. Dev., 3, 52–64, https://doi.org/10.1016/j.envdev.2012.04.002, 2012.

You, Q., Kang, S., Pepin, N., and Yan, Y.: Relationship between trends in temperature extremes and elevation in the eastern and central Tibetan Plateau, 1961–2005, Geophys. Res. Lett., 35, 2007GL032669, https://doi.org/10.1029/2007GL032669, 2008.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., and Cogley, J. G.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016, Nature, 568, 382–386, https://doi.org/10.1038/s41586-019-1071-0, 2019.

Zeng, L., Wardlow, B. D., Xiang, D., Hu, S., and Li, D.: A review of vegetation phenological metrics extraction using time-series, multispectral satellite data, Remote Sens. Environ., 237, 111511, https://doi.org/10.1016/j.rse.2019.111511, 2020.

Zou, L., Tian, F., Liang, T., Fensholt, R., He, T., and Schaepman-Strub, G.: Topographic effects on vegetation greening and area expansion in global alpine zones under climate change, Int. J. Appl. Earth Obs. Geoinformation, 142, 104727, https://doi.org/10.1016/j.jag.2025.104727, 2025.