

# Regional climate and vegetation interactions in the high-altitude forests of North Sikkim, eastern Himalaya: A palynological approach

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## Abstract

The coupled interfaces of vegetation and climate in forested regions of monsoon-dominated eastern Himalaya are controlled by spatial-temporal changes in various environmental factors. To detect the variation in vegetation through the changing altitudes of this eastern Himalaya region, modern pollen rain records of surface deposits from various localities at North Sikkim were analysed. This study attempts to contribute towards the understanding of empirical changes across this complex vegetation persisting at an altitudinal range of 2500–4400 m a.s.l. in the North Sikkim region of the eastern Himalaya, India. The samples were predominantly gathered from diverse localities spanning a range of altitudes and varying vegetation distributions, leading to distinct variations in the pollen yield across the different sites. The quantitative multivariate statistical analysis, such as Redundancy Analysis and Cluster Analysis, are applied to this palynological data set, effectively elucidate the variations in modern pollen spectra. The mean annual precipitation (MAP) and mean temperature of the warmest month (MTWA) are the climatic variables strongly influencing the modern pollen rain recorded in these high-altitude regions of the eastern Himalaya.

## Keywords

Modern pollen spectra, Climatic variables, Redundancy Analysis, Elevation, Sikkim

## INTRODUCTION

The North Sikkim located in the eastern Himalaya holds some of the largest glaciers and sources of fresh water to the regions down the valley and beyond. These high-altitude terrains are occupied by subtropical, temperate, and alpine plant species towards the end of the tree lines. Any variation in the climate and overall change in the environmental dynamics of this region can cause large amplitude changes in the flora and fauna of the region.

This part of the eastern Himalaya area is also a corridor for the existing flora and fauna towards regions such as the Tibetan Plateau in its north-northwest, mainland China towards its east, and tropical southeast Asia in the southern edges of the northeastern Indian landmass. The vegetation in North Sikkim and across the eastern Himalaya includes many endangered species and endemic taxa. The parallel growth and variation of such taxa in such a high and remote region of Sikkim depend on various environmental factors.

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Modern pollen rain can provide quantitative evidence to understand the modern vegetation distribution across a study area, which helps to establish the past vegetation reconstruction through fossil pollen records (Davis et al., 2013, 2020). This evidence provides viable information regarding rebuilding palaeo vegetation and climate (Birks & Birks, 1980; Davis et al., 2013, 2020; Flenley, 1973; Liu & Lam, 1985; Moore & Webb, 1978; Wright, 1967). The existing floral assortment and regional forest diversification can be assessed through modern pollen rain analysis (Calcote, 1995; Xu et al., 2007; Zhang et al., 2017) and provide a modern analogue to study the palaeoecology of the region. Relative pollen productivities (RPPs) estimates have provided past landcover reconstruction globally through the Regional Estimates of Vegetation Abundance from Large Sites (REVEALS) model (Fyfe et al., 2013; Githumbi et al., 2022; Li et al., 2023; Mazier et al., 2012; Serge et al., 2023; Sugita, 2007; Trondman et al., 2016). The Eurasian modern pollen database (EMPD) comprises 8663 data sets from sites in Europe and northern and eastern Asia (Davis et al., 2020). The regions such as India, Central Asia, northern Asia, and the Middle East have limited modern pollen sites in the EMPD database (Davis et al., 2020). The complex topography, ever-changing altitude, and spatio-temporal impact of environmental factors create a rich biodiversity of flora and fauna in northeastern India. The forest types dominating this region are the tropical deciduous forests, temperate, and sub-alpine forests, creating a biodiversity hotspot in the extreme northeastern region of India. The modern vegetation analysis based on pollen-rain investigations from surface deposits in northeast India have been carried out in studies from Sikkim Himalaya (Dubey et al., 2018), Darjeeling Himalaya (Ghosh et al., 2017), Arunachal Pradesh (Mehrotra et al., 2019), Assam (Basumatary, 2017; Basumatary et al., 2018; Bera, 2000, 2003; Bera et al., 2011, 2012, 2013; Dixit & Bera, 2012; Tripathi & Bera, 2014; Tripathi & Pandey, 2023; Tripathi et al., 2016), Meghalaya (Basumatary & Bera, 2007, 2014; Basumatary, Gogoi, et al., 2017; Basumatary, Narzary, et al., 2017; Basumatary et al., 2013, 2014, 2015, 2018; Gupta & Sharma, 1985; cf. Quamar & Kar, 2019), Manipur (Chauhan & Nautiyal, 2009), Mizoram (Mehrotra et al., 2025) and Tripura (Mehrotra & Shah, 2018; Saha et al., 2007). The recent modern pollen records from the western Himalaya were from regions such as Akhnoor, Jammu district, in Kashmir Himalaya (Quamar, 2020), Bhagirathi valley (Roy et al., 2021), Chopta Tungnath region, Rudraprayag district, Uttarakhand (Mishra et al., 2022), Chorabari glacier region, Kedarnath, Uttarakhand (Kar et al., 2022), Lahul and Spiti valley, Himachal Pradesh (Kar et al., 2015), Baspa valley, Kinnaur,

Himachal Pradesh (Tomar et al., 2024). The central Himalayas also have modern pollen records, such as from Kalla Bank glacier valley, Dhauliganga Basin, Uttarakhand (Ali et al., 2020), in central Nepal (Neupane et al., 2024), and Yadong, Tibet Autonomous Region in the eastern Himalaya (Zhang et al., 2020). In the present study, we analysed 20 surface samples from the upper Teesta basin, which lies in the northern parts of North Sikkim, eastern Himalaya, to understand the modern pollen rain across an elevation gradient of 2600–4300 m a.s.l. and its relationship to vegetation distribution, environmental factors, and altitudinal changes. This eastern Himalaya modern pollen record can further be utilised to understand its potential to reconstruct palaeovegetation and palaeoclimate in this sensitive climate zone of northeastern India.

## STUDY AREA

North Sikkim is a region within the eastern Himalay an sector of India, surrounded by Nepal, Bhutan, the Tibet Autonomous Region, and subtropical parts of India. The region is impacted by the monsoon originating from the Bay of Bengal, causing rainfall from June to September. The North Sikkim region has topographical barriers of the eastern Himalaya, causing the monsoon winds to shed a large amount of precipitation, but eventually diminishing the intensity of these moisture-laden winds. The Tibetan Plateau contributes towards regional and hemispherical circulation patterns and climate (An et al., 2001; Feng et al., 2023), which are impacted by the extreme seasonal variations, including the freezing and thawing of the Plateau grounds (Zhao et al., 2004). The North Sikkim region also records low temperatures along with intense snowfall during the winter season.

## MODERN VEGETATION

The modern vegetation of Sikkim is divided into three major botanical zones based on the elevation occupied and vegetation characteristics, that is, tropical, Temperate, and alpine (Chettri et al., 2010; Srivastava, 1996). The vegetation of Sikkim can be distinguished as low, middle, and upper hill forests, preceded by the Rhododendron-Conifer zone, alpine scrubs, and grassland (Srivastava, 1996). We give a summarised account of these forests as explained by Srivastava (1996). In the sub-mountainous tracts at an elevation of 244–900 m, tropical to subtropical dense broad-leaved semi-evergreen taxa occupy the low hill forests. *Schima wallichii*, *Bauhinia purpurea*, *Toona ciliata*, *Stereospermum tetragonum*, *Bombax ceiba*, *Dillenia pentagyna*, *Lagerstroemia*

*parviflora*, *Sterculia villosa*, *Terminalia myriocarpa*, *T. tomentosa*, and *Albizia* spp. are some of the dominant trees of these forests, along with *Castanopsis indica*, *Syzygium formosum*, and *Magnolia champaca*, and elements such as *Phoebe lanceolata*, *P. hainesiana*, *P. attenuata*, *Litsea polyantha*, and *Cinnamomum tamala* (Srivastava, 1996). In these Lower Hill forests, canes, climbers, tree ferns, several species of *Artocarpus* such as *A. chaplasha*, along with *Bischofia javanica*, epiphytes such as orchids, aroids etc., are also found, interspersed with *Ficus semicordata* and dense undergrowth along the banks of the Teesta and Rangit rivers.

The subtropical middle hill forest found at an elevation of 750–1,000 m is occupied by evergreen species and a few deciduous trees. Dense forests of large evergreen trees of *Quercus glauca*, *Q. spicata*, *Q. serrata*, and *Q. griffithii* are found at 1,200 and 1,600 m or above. Tree taxa such as *Castanopsis tribuloides*, *C. indica*, *Schima wallichii*, and *Phoebe hainesiana* are commonly found between 750 and 1,200 m, along with occasionally occurring *Magnolia champaca* and *Stereospermum tetragonum*. In these forests, epiphytes, climbers, and an undergrowth of several herbaceous and shrub species are common (Chettri et al., 2010).

There are other known taxa, such as *Drimycarpus racemosus*, *Juglans regia*, *Engelhardia spicata*, *Spondias lutea*, *Exbucklandia populnea*, *Magnolia cathcartii*, *Talauma hodgsonii*, *Saurauia nepaulensis*, *Ficus oligodon*, *F. semicordata*, *Betula alnoides*, *Alnus nepalensis*, *Terminalia* spp., *Macaranga* sp., *Litsea polyantha*, *Phoebe lanceolata*, *P. attenuata*, and members of the family Meliaceae occupying these forests.

The upper hill forests found between 1,500 and 2,700 m are the warm or wet temperate types, having many altitude zones occupied by oaks, laurels, epiphytes, mosses, herbs, shrubs, ferns, and a few woody climbers. Some laurels grow between 1,800 and 2,100 m, followed by oaks such as *Quercus lamellosa* between 2,100 and 2,400 m and *Q. pachyphylla* between 2,400 and 2,700 m, overlapping each other. In the elevation range of 2,100–2,400 m, *Castanopsis tribuloides*, *Acer campbellii*, *Magnolia excelsa*, *M. cathcartii*, *Q. lamellosa* are prevailing, along with frequently occurring *Q. lineata*, *Betula alnoides*, *Symplocos theifolia*, and *Alnus nepalensis*.

These oak forests also have *Castanopsis tribuloides*, *Acer Campbell*, *Mangolia Campbell*, *Symplocos theifolia*, and *Taxus wallichiana* between 2,400 and 2,700 m. Above 2,700 m, *Q. pachyphylla* solely occupies the forest, where *Rhododendron griffithianum* is found as an undergrowth along with dwarf bamboos.

The cold temperate or sub-alpine forests found around 2,700 m to 3,600 m mainly comprise *Rhododendrons* and

conifers. In this *Rhododendron*-Conifer zone, other species such as *Q. pachyphylla*, *Q. lineata*, extend up to altitudes of 2,700 m and with infrequent occurrence of *Acer campbellii*, *A. caudatum*, *Betula utilis* and *Magnolia campbellii*. These oaks are gradually substituted by *Rhododendron arboreum*, *R. campanulatum* and *R. grande* and other species of the genus one proceeding towards higher altitudes. At the edges of the Lachen valley (3,300 m) or above Samdong, *Betula utilis* is found in these *Rhododendron* forests (Chettri et al., 2010).

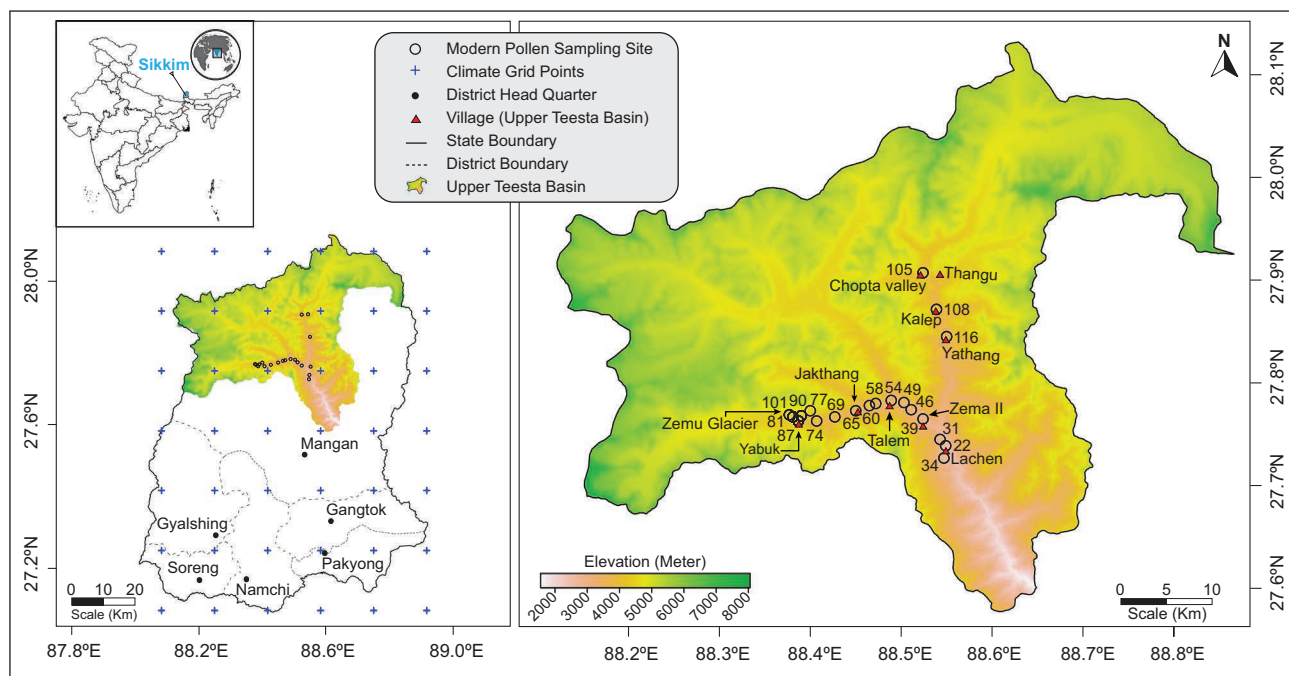
The dominant tree taxa in the Lachen valley between the altitudes of 2,700 and 3,000 m are *Tsuga dumosa*, which are also found in Chokka in western Sikkim. *Picea spinulosa* is also found with *Tsuga dumosa*, but below 3,000 m. *Taxus wallichiana* is found in forests above Lachung, growing with *Abies densa*. In eastern Sikkim, between Karponang and Chhangu, and in western Sikkim, between Simdong and Thangu up to 3,000 m, are pure formations of *Abies densa*. Scrubs of *Rhododendron arboreum* grow along steep slopes at about 3,000 m. Past the tall tree line, the vegetation comprises *Rhododendron campanulatum*, *R. wightii*, *R. thomsonii*, *R. cinnabarinum*, and *R. decipiens* existing together. Various species of *Aconitum* commonly occupy the forest floors below the *Rhododendron* at high altitudes, mainly in Thangu. *Salix wallichiana* trees are also growing along streams near the Thangu valley.

The alpine Scrub and Grassland vegetation grows at an altitude of 3,600–4,300 m and above. Then, above 3,600 m along the termination of the tree line, *Juniperus pseudosabina*, *J. recurva*, grow as bushes on sunny hill slopes in North and East Sikkim, especially around Thangu valley (4,200 m) and Chhangu (4,300 m). Above 3,600 m on exposed rock crevices, the *Rhododendron lepidotum* grows up to 30 cm are found growing. *Ephedra gerardiana* are seen only on the hill tops around Thangu valley. Few species belonging to genera such as *Ranunculus*, *Anemone*, *Delphinium*, *Rhus*, *Potentilla*, *Primula*, *Fragaria*, *Cassiope*, and *Allium* spp. are found along the gentler slopes of open meadows.

## MATERIALS AND METHODS

### Sample collection and processing of the palynological samples

The 20 surface samples of moss cushions collected across the various sampling sites from the upper Teesta basin, North Sikkim (Figure 1), are listed in Table 1 along with site details such as location names, coordinates, elevation, and vegetation types. These samples were collected



**Figure 1.** Map showing the modern pollen sampling site from Upper Teesta Basin, North Sikkim, eastern Himalaya. The left panel of the diagram shows the state of Sikkim along with the climate grid points and modern pollen sites. The right panel of the diagram is an enlarged view of the Upper Teesta Basin with detailed locations of the sampling sites.

in sampling bags (Figure 2), sealed, and labelled with sampling code SKM (No). These sites were located in the north-west transect from Lachen to Zemu glacier and the adjoining region. The elevation at these sites ranged from 3,600 to 4,300 m a.s.l. The samples collected from the elevation 2,600–3,200 m a.s.l. at six sites, namely around Zema, near Lachen, Chaten, Dozom Khola, while five sites at 3,300–3,621 m a.s.l. were around Talem and Jakthang. The following elevation levels were between 3,800 and 4,000 m a.s.l. five samples were collected around the Yabuk and Zemu glacier region. At another site, Yathang, the elevation was 3,608 m a.s.l., and one sample was collected towards the northern parts of the study area, along with three samples at elevations between 4,000 and 4,300 m a.s.l. These samples are collected in different forests and vegetation types (Figure 2). To comprehend the changes in modern pollen abundance along such high-elevation transects of eastern Himalaya, these samples were collected and further processed for palynological analysis.

These samples were processed in the Laboratory at Birbal Sahni Institute of Palaeosciences, Lucknow, and prepared for further palynological analysis. Standard methodology was followed to process and prepare the palynological samples for the present study (Erdtman, 1943; Faegri & Iversen, 1964).

## Palynological assemblage analysis

For each palynological sample, a minimum of 300 pollen-spores was counted and further expressed as relative percentages. The total pollen count was based on the number of arboreal and non-arboreal pollen taxa and aquatic/marshy and fern spores. The ‘Pollen Sum’ was calculated by only including the arboreal and non-arboreal pollen taxa counts. The computer program TILIA version 2.0.2 (Grimm, 2004) was used to make the pollen percentage diagram. Furthermore, the pollen taxa with more than 0.5% were included in the CONISS analysis (CONISS, Grimm, 1987) in the TILIA computer program. This modern pollen data set of each sampling site was grouped using the CONISS analysis, based on unconstrained chord-distance clustering on square root transformed palynological percentage data.

## Modern Climate records

The climatic data (temperature and precipitation) from meteorological stations are needed to establish modern pollen-climate relationships. The regional climate records were collected from standard resources for further estimation. The India Meteorological Department (IMD), Pune, and Global Historical Climate Network version 2 (GHCN



**Table 1.** Sampling site details of the modern pollen data along with climatic variables and dominant forest and vegetation type.

| SC     | LAT           | LONG          | ELEV | LN                              | MAT   | MTCO  | MTWA  | MAP    | Dominant forest type/<br>vegetation                                                |
|--------|---------------|---------------|------|---------------------------------|-------|-------|-------|--------|------------------------------------------------------------------------------------|
| SKM022 | 27° 45' 44.6" | 88° 33' 06.9" | 2600 | Zema I                          | 10.57 | 2.58  | 16.35 | 145.48 | <i>Abies densa</i> - <i>Tsuga dumosa</i> - <i>Hippophae</i>                        |
| SKM031 | 27° 44' 19.6" | 88° 32' 51.2" | 2741 | Between Lachen and Zema I       | 9.82  | 1.77  | 15.74 | 138.93 | <i>Picea spinulosa</i> - <i>Hippophae</i>                                          |
| SKM034 | 27° 43' 35.5" | 88° 32' 48.9" | 2814 | Above Chaten                    | 9.42  | 1.34  | 15.40 | 136.71 | <i>Picea spinulosa</i> - <i>Abies densa</i> - <i>Rhododendron</i> spp              |
| SKM039 | 27° 45' 55.4" | 88° 31' 26.8" | 2843 | Zema II                         | 9.23  | 1.15  | 15.21 | 138.43 | <i>Abies densa</i> - <i>Tsuga dumosa</i> - <i>Hippophae</i>                        |
| SKM046 | 27° 46' 28.1" | 88° 30' 39.6" | 3057 | Between Zema II and Dozom Khola | 8.08  | -0.10 | 14.29 | 128.64 | <i>Abies densa</i>                                                                 |
| SKM049 | 27° 46' 50.3" | 88° 30' 12.1" | 3166 | Dozom Khola                     | 7.50  | -0.73 | 13.82 | 123.52 | <i>Abies densa</i>                                                                 |
| SKM054 | 27° 46' 57.9" | 88° 29' 19.3" | 3303 | Talem                           | 6.77  | -1.53 | 13.24 | 116.52 | <i>Abies densa</i> - <i>Juniperus indica</i>                                       |
| SKM058 | 27° 46' 48.1" | 88° 28' 20.3" | 3501 | 1 km after Talem                | 5.72  | -2.68 | 12.42 | 105.01 | <i>Abies densa</i> - <i>Juniperus indica</i>                                       |
| SKM060 | 27° 46' 40.9" | 88° 27' 54.0" | 3510 | 1 km before Jakthang            | 5.67  | -2.74 | 12.39 | 103.77 | <i>Abies densa</i> - <i>Juniperus indica</i>                                       |
| SKM065 | 27° 46' 22.6" | 88° 27' 00.4" | 3504 | Jakthang                        | 5.70  | -2.72 | 12.45 | 101.47 | <i>Abies densa</i> - <i>Juniperus indica</i>                                       |
| SKM069 | 27° 46' 08.9" | 88° 26' 01.1" | 3621 | 1 km after Jakthang             | 5.06  | -3.30 | 11.75 | 109.72 | <i>Abies densa</i> - <i>Juniperus indica</i>                                       |
| SKM074 | 27° 45' 47.5" | 88° 24' 40.7" | 3793 | Between Jakthang and Yabuk      | 4.15  | -4.28 | 11.01 | 101.91 | <i>Abies densa</i> - <i>Juniperus indica</i>                                       |
| SKM077 | 27° 45' 49.7" | 88° 24' 06.0" | 3915 | 1 km before Yabuk               | 3.51  | -4.99 | 10.49 | 95.91  | <i>Abies densa</i> - <i>Juniperus indica</i> - <i>Rhododendron</i>                 |
| SKM081 | 27° 46' 06.8" | 88° 22' 50.2" | 4253 | Zemu glacier                    | 1.75  | -7.02 | 9.30  | 62.56  | <i>Juniperus squamata</i>                                                          |
| SKM087 | 27° 46' 06.0" | 88° 23' 09.2" | 4132 | Yabuk                           | 2.39  | -6.34 | 9.84  | 66.68  | <i>Abies densa</i> - <i>Rhododendron</i>                                           |
| SKM090 | 27° 45' 59.1" | 88° 23' 21.9" | 4050 | Yabuk                           | 2.82  | -5.87 | 10.18 | 71.03  | <i>Abies densa</i> - <i>Rhododendron</i>                                           |
| SKM101 | 27° 46' 07.1" | 88° 22' 33.9" | 4311 | Sona Camp                       | 1.44  | -7.35 | 9.03  | 60.94  | <i>Juniperus squamata</i>                                                          |
| SKM105 | 27° 54' 27.0" | 88° 31' 28.8" | 4016 | Chopta valley                   | 3.02  | -5.71 | 10.27 | 79.04  | <i>Betula utilis</i> - <i>Juniperus</i> - <i>Rhododendron</i>                      |
| SKM108 | 27° 52' 20.8" | 88° 32' 35.2" | 4019 | Thangu                          | 3.01  | -5.76 | 10.29 | 76.32  | <i>Betula utilis</i> - <i>Juniperus</i> - <i>Rhododendron</i> - <i>Abies densa</i> |
| SKM116 | 27° 50' 40.2" | 88° 33' 00.2" | 3608 | Yathang                         | 5.17  | -3.33 | 11.97 | 99.92  | <i>Betula utilis</i> - <i>Juniperus</i> - <i>Rhododendron</i> - <i>Abies densa</i> |

**Note:** SC = Sample code; LAT = Latitude °N; LONG = Longitude = °E; ELEV = Elevation in metre; LN = Locality name; MAT = Mean annual temperature (°C); MTCO = Mean temperature of coldest month (°C); MTWA = Mean temperature of warmest month (°C); MAP = Mean annual precipitation (mm).

v2) and hydropower reports of National Hydroelectric Power Corporation (NHPC) had climate data available from the study area. However, there were a few meteorological stations with both temperature and precipitation records, mostly at lower elevation sites. The meteorological stations of Gangtok and Tadong had records from 1968 and 1978, respectively. However, the remaining stations are mostly rain gauge stations with records for approximately 4–25 years (Samui, 1994). The meteorological data

from higher elevation sites were discontinuous and had the maximum missing data in the climate records. Only the station at Gangtok had a climate record of more than 30 years with a few missing values (Seetharam, 2008), but it was far from the present study area. The interpolation of climate records from numerous homogenous climate stations at each pollen site is a prerequisite for the analysis aimed at the present study. However, due to a lack of such robust climate records in these remote locations of North



**Figure 2.** (a) Moss cushions on rock surface used to collect to study modern pollen rain, (b) collection of moss cushions, (c) *Abies densa* forest near to Jakthang, (d) *Betula utilis* forest below Yabuk, (e) *Juniperus recurva* forest below Yabuk, (f) mixed broad leaved forest near to Lachen, (g) *Betula-Juniperus* mixed forest, (h) *Rhododendron* in Kelep, (i) a view of Zemu glacier in North Sikkim, showing rock surface with moss cushion, (j) rock surface with moss cushion above the Zemu glacier, (k) anthropogenic activity in the forest area and (l) anthropogenic activity by local village inhabitants in North Sikkim.

Sikkim and adjoining regions, we utilised the global land areas ‘-resolution climate data set by New et al. (2002) to estimate modern pollen site-specific climate. This climate data set (New et al., 2002) is based on the Climate Research Unit (CRU) gridded climate dataset and had a resolution of 10 arc-minutes/minutes/~18 km/~0.17° and was spatially interpolated for regions with no data. A set of 42 grid points covering the entire Sikkim and adjoining areas was selected

to extract the temperature and precipitation records (Figure 1). Various climatic variables such as mean annual temperature (MAT), mean temperature of coldest month (MTCO), mean temperature of warmest month (MTWA), and mean annual precipitation (MAP) based on gridded temperature and precipitation records (New et al., 2002) were compiled. The extent of overall distribution of the selected climate variables across Sikkim and adjoining



regions is represented in Figure 1. The weighted distance interpolation method was followed to interpolate the modern pollen site-specific values for each climate variable (MAT, MTCO, MTWA, and MAP) after reducing all stations to sea level (Guiot & Goeury, 1996). This procedure takes into consideration all climate stations (here, 10-minute latitude/longitude grid points) within the interpolation radius around the pollen sampling sites. It finally yields an estimate of temperature variables (MAT, MTCO, and MTWA) with an  $R^2$  of  $> 0.996$  and precipitation variables (MAP) with an  $R^2 = 0.955$ .

## Ordination Analysis

Ordination techniques through linear-based or unimodal-based statistical methodologies were applied to decipher the complex relationship of modern pollen assemblage along the climate gradients in the study area. The detrended correspondence analysis (DCA) was applied to the complete percentage-square root transformed pollen dataset to determine the gradient length. Here, the square root transformation of the assemblage data was done to stabilise the variance and to minimise the 'signal to noise' ratio in the data (Prentice, 1980; Seppä et al., 2004). These estimates of the environmental variable gradient length determine the variations of the pollen taxa along the entire length of these gradients and are expressed in standard deviation units. Accordingly, an ordination model best expressing the relationship among the modern pollen taxa and climatic variables is selected through their gradient lengths. Based on the gradient length having  $> 2.5$  standard deviations, unimodal responses are considered suitable (Birks, 1995), and canonical correspondence analysis (CCA) can be applied. However, if the gradient length  $< 2.5$ , linear-based methods, principal component analysis (PCA) or redundancy analysis (RDA) can be applied. The linear ordination done for the present studies applies constrained analysis PCA to understand the basic data structure. RDA

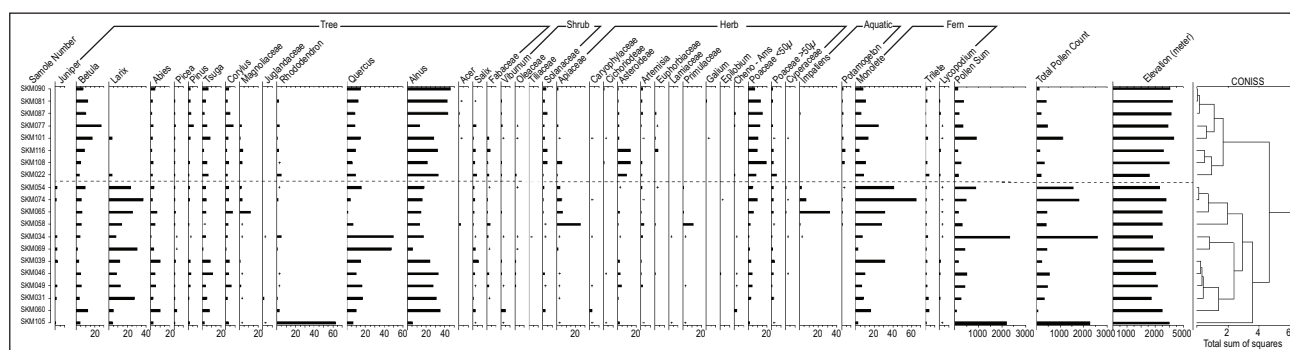
is applied along with the climatic variable to analyse the quantitative influence on the datasets. The degree of variation in the modern pollen assemblage expressed through the constrained RDA explained climatic datasets in this ordination analysis. The Monte Carlo permutation tests (using 999 random permutations) were applied to understand statistical significance in the ordination. The CANOCO, version 5 (ter Braak & Šmilauer, 2012), a computer programme, was used to carry out all the ordination analysis.

## RESULTS

### Modern pollen spectra of North Sikkim, eastern Himalaya

An assemblage of ~34 pollen taxa was recorded in these surface samples, with around 27 taxa which were  $> 0.5\%$  found in at least two samples. The modern pollen spectra (Figure 3) represented the distribution of the abundant taxa within the sample set. The CONISS results had two major cluster groups, further forming subgroups, based on the percentage of modern pollen data, and the modern vegetation variations in the region are defined accordingly.

The first group of samples based on the CONISS results included SKM022, SKM031, SKM034, SKM039, SKM046, SKM049, SKM054 and SKM058. Identifying from the site distribution, these samples were from locations at an altitude range between 2,500 and 3,000 m a.s.l. Tree taxa such as *Juniper* (1%–2%), *Betula* (3%–9.5%), *Larix* (3%–27%), *Abies* (1%–10%), *Picea* (0.60%–1%), *Pinus* (0.50%–2%), *Tsuga* (3%–11%), and *Corylus* (1%–6%), Magnoliaceae (2%), Juglandaceae (0.60%–1.50%), *Rhododendron* (5%), *Quercus* (7%–16%) about 50% in SKM034, *Alnus* (13%–33%), *Acer* (2%), *Salix* (1%–5%) and Fabaceae (0.5%–3%) were recorded in these samples. Some of the tree taxa have higher percentages in a couple of the samples, creating a group or clustering in smaller



**Figure 3.** Pollen spectra showing modern pollen distribution from North Sikkim, eastern Himalaya, along elevation and cluster analysis based on CONISS.

sets or arms instead. The lower forest level comprised about 0.5%–1% of taxa such as *Viburnum*, *Oleaceae*, *Tiliaceae*, and *Solanaceae*, and herbs *Apiaceae* (0.50%–3%), *Asteroidae* (0.5%–10%) and *Artemisia* (0.60%–3%), as recorded in many of the samples. However, SKM058 has 25% *Apiaceae* and 11% *Primula*, which separates it out distinctly in this cluster. The other elements, namely *Caryophyllaceae*, *Epilobium*, and *Euphorbiaceae*, were mainly 0.50%, along with *Cyperaceae* (0.50%–0.70%), *Chenopodiaceae/Amaranthaceae* (0.70%), grass pollen, such as *Poaceae* <50  $\mu$ , are between 2% and 8%, whereas larger *Poaceae* >50  $\mu$  are 2%–5%. *Monolete* (6%–40%), *Trilete* (1%–3%), and *Lycopodium* (1%) were some of the fern spores recorded in these samples. *Monolete* fern spore is found in high percentages in samples SKM039 (31%) and SKM054 (40%). The aquatic taxa such as *Potamogeton* and *Impatiens* are recorded as about 1%–2% in the assemblages of these samples.

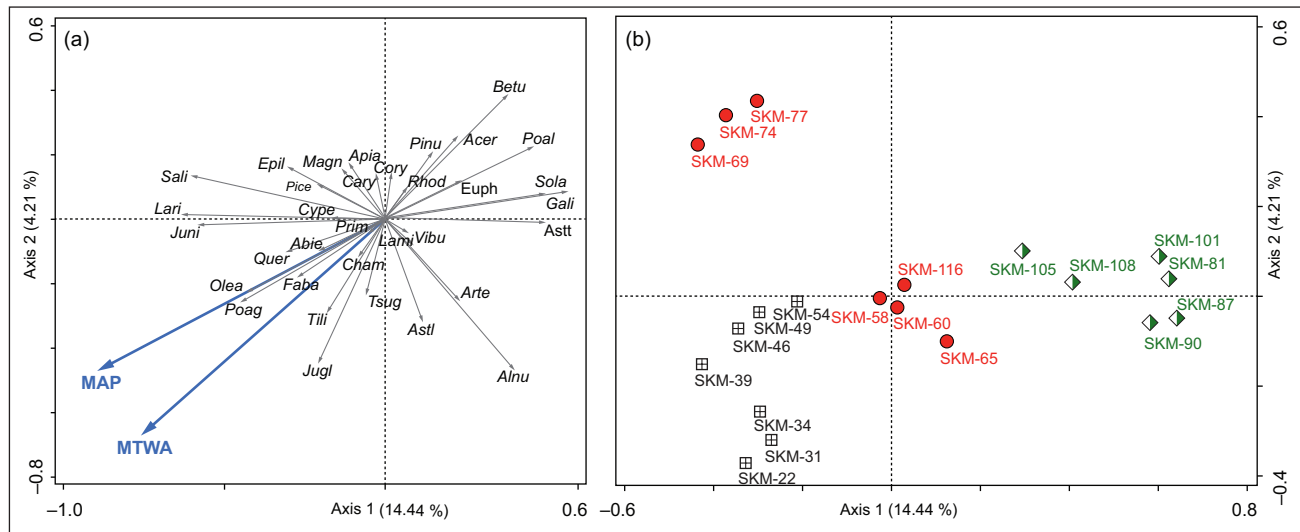
The next group of samples clustering together was obtained from a 3,300 to 4,000 m a.s.l. altitudinal range, which were SKM060, SKM065, SKM069, SKM074, SKM077 077 and SKM116. *Juniper* (1%), *Betula* (1%–12% mostly) which was about 26% in SKM077, *Larix* (5%–37%) (highest, i.e., 37% in SKM077), *Abies* (1%–10%), *Pinus* (1%–5%), *Tsuga* (1%–7.5%), *Corylus* (1%–8%), *Magnoliaceae* (1%–11%), *Rhododendron* (1%–2.5%), *Quercus* (1%–10%) but 47% in SKM069, *Alnus* (5%–3%), with high percentages in samples SKM060 (35%) and SKM116 (32.5%) were some of the tree taxa recorded in these samples. *Acer* was only found in SKM077 at about 1% along with other trees such as *Salix* (1%–3%), and *Fabaceae* (0.50%–3%) in these samples. The next level taxa found in the region included *Viburnum*, which was about 0.5%–1% in most samples but about 5% in SKM060, *Oleaceae* (0.50%) and *Solanaceae* (0.5%–4%). *Apiaceae* (1%–6%), *Caryophyllaceae* (0.5%–2.5%), *Artemisia* (0.5%), *Euphorbiaceae* (3% only in SKM116), *Primulaceae* (0.7% only in SKM065), *Asteroidae* (1%–2%), about 14% in SKM116, were the lower elements of the forests. *Cyperaceae* (0.70%), *Chenopodiaceae/Amaranthaceae* (0.61%–2.5%), *Poaceae* <50  $\mu$  (5%–12%) and *Poaceae* >50  $\mu$  (1%–2%) were present in these sample sets. Aquatic taxa were extremely high (7%–32.5%) in these samples, namely *Potamogeton* (1%–4%) and *Impatiens* (1%–32.5%), with about 32% in the SKM065 sample. This sample was collected near Jakthang, which had marshy lands leading to the presence of excess aquatic. *Lycopodium* was about (0.5%) along with *Monolete* (3%–31%) and *Trilete* (0.5%–4%) fern spores, which were significant in these samples, but mostly recorded in SKM065, that is, *Monolete* about 31%.

The samples SKM081, SKM087, SKM090, and SKM101 from high-altitude of Yabuk near Zemu glacier to Sona Camp, respectively and samples SKM105 and SKM108 from Chopta valley and Kalep comprised the third group of samples in the cluster diagram. All these samples were collected within an altitude of 4,000–4,200 m a.s.l. *Betula* (4%–17%), *Abies* (1%–4%), *Larix* (3%–4%), *Picea* (0.5%–1%), *Pinus* (1%–3%), *Tsuga* (2%–8%), *Corylus* (2%–5%), *Magnoliaceae* (0.5%–2%), *Rhododendron* (0.50%–2%), *Quercus* (5%–14%), *Acer* (0.50%), *Salix* (1%–2%), *Fabaceae* (1%–2%) were the tree taxa found in these samples. A few other trees observed in them were *Juniper* (0.70%) found only in SKM105, along with *Betula* (17%) and *Rhododendron* (63%), which were maximum in SKM105, whereas *Alnus*, which was highest in number (~45%), was found in most of these sample sets. *Viburnum* (0.5%–1%), *Oleaceae* (0.5%) and *Solanaceae* (1%–4.5%) along with *Apiaceae* (1%–5%), *Cichorioideae* (1%), *Asteroidae* (1%–14%), *Artemisia* (1%–2%), *Euphorbiaceae* (1%), *Galium* (0.58%) occupied the next levels at these sites. *Poaceae* <50  $\mu$  (7%–20%) were in high numbers along with *Poaceae* >50  $\mu$  (1%–2%) and *Chenopodiaceae/Amaranthaceae* (1%). The taxa, *Impatiens* (0.5%), was recorded specifically in SKM081 and *Potamogeton* (1%–3%) were the aquatic taxa found at these sites. *Monolete* (2%–13%), *Trilete* (1%–2%) and *Lycopodium* (0.5%–1%) were recorded in very low numbers. The existence of fewer lower altitude taxa can be caused by the very high-velocity winds prevailing in these dry, snow-clad glacial terrain from where these samples were collected.

## Ordination analysis

The total variance explained by the first axis is 49.1% where axis 1 was 31.1% and axis 2 was 18% for unconstrained PCA carried out during the ordination analysis. This indicated the importance of the few variables impacting the modern pollen data generated from high-elevation sites under extreme climatic conditions. The pollen data and climate data (MAP and MTWA), when analysed using constrained ordination through RDA (Figure 4), the total variance explained was 77.43% where the first axis and the second axis had eigenvalues of 0.1444 and 0.0421, respectively. The climatic variables MAP and MTWA were also analysed using RDA, yielding 12.23% variance for the first axis in the pollen datasets, having significant correlation with MAP ( $r = 0.696$ ,  $p < .02$ ). On the other hand, the climatic variable MTWA for first axis explains 9.93% of the variance and having a significant correlation ( $r = 0.667$ ,  $p < .046$ ).





**Figure 4.** (a) Ordination analysis based on Redundancy Analysis (RDA) for modern pollen and significant climatic variables (MAP and MTWA), and (b) Distribution of modern pollen sampling sites, as shown by RDA.

**Note:** Abie = Abies, Acer = Acer, Alnu = Alnus, Apia = Apiaceae, Arte = Artemisia, Astl = Asteraceae - Liguliflorae (Cichorioideae), Astt = Asteraceae - (Tubuliflorae), Betu = Betula, Cary = Caryophyllaceae, Cham = Chenopodiaceae/ Amaranthaceae, Cory = Corylus, Cyp = Cyperaceae, Epil = Epilobium, Euph = Euphorbiaceae, Faba = Fabaceae, Gali = Galium, Jugl = Juglandaceae, Juni = Juniper, Lam = Lamiaceae, Lari = Larix, Magn = Magnoliaceae, Olea = Oleaceae, Pice = Picea, Pinu = Pinus, Poag = Poaceae > 50 $\mu$ , Poal = Poaceae < 50 $\mu$ , Prim = Primulaceae, Quer = Quercus, Rhod = Rhododendron, Sali = Salix, Sola = Solanaceae, Tili = Tiliaceae, Tsug = Tsuga, Vibu = Viburnum.

Both the ordination analysis (PCA and RDA) for the climatic variable MAP exhibit similarities, thus highlighting the overall impact of this regional climatic scenario on the pollen rain recorded at various sites.

### Quantitative assessment through signals from regional climatic variable impacting the modern pollen assemblage

The ordination analysis, RDA, clearly brings out the impact of the climatic variable MAP at each modern pollen sampling site. The rate of variation in MAP causes distinct segregation in the RDA in terms of the pollen data recorded at each site. This segregation is demarcated by sites along the rate of MAP (60.9–79.0 mm) towards the first RDA axis, in contrast to sites having MAP 116.5–145.5 mm. Another factor plausibly causing this segregation and also influencing the climatic variable is the altitudinal gradients at these sites. The higher elevation (4,016–4,311 m a.s.l.) and low MAP sites (SKM081, SKM087, SKM090, SKM101, SKM105 and SKM108), which were occupying the alpine climate zones towards the Zemu glacier terrain, concentrated on the right side of axis 1. On the contrary, the lower elevation (2,600–3,303 m a.s.l.) sites (SKM022, SKM031, SKM034, SKM039, SKM046, SKM049 and SKM054)

had high values of climatic variable MAP but were also impacted by colder temperatures during the cooler times of the year. The other sites separate out into two distinct sets, where SKM058, SKM060, SKM065 and SKM116, which occupy intermediate parts and close to the centre of both axes, whereas sites SKM069, SKM074 and SKM077 separate out towards the left of axis 1. These sampling sites fall under the impact of both higher and lower elevation and consequent climatic conditions of the region with moderate MAP (95.9–109.7 mm). The sites occupy sub-alpine climate regions and an altitudinal gradient of 3,501–3,915 m a.s.l., having their positions controlled by the RDA axis 2. Such segregations were also observed when the pollen assemblage data from these sites were analysed using CONISS on square root transformed modern pollen percentages.

### DISCUSSION

In the present study area were the present-day records of minimum and maximum values for climatic variables such as MAT, –10.3°C to 19.5°C; MTCO, –19.4°C to 12.2°C; MTWA, –1.5°C to 23.6°C and MAP, 215.7–3,341.7 mm indicates the range of environmental variables contributing towards the variability in regional climate of northern Sikkim, eastern Himalaya at an altitudinal gradient of

2,500–4,400 m a.s.l. Each of these variables uniquely influences the distribution of modern vegetation in these complex topographies of the eastern Himalaya. However, the present study highlights the dominant contribution of climatic variables such as MAP and MTWA. The ordination analysis simplifies modern pollen distribution in northern Sikkim, being largely impacted by site-specific pollen assemblages preserved according to the climatic influence on the modern vegetation at regional levels. The strong, significant relationship of MAP and MTWA with the assemblage data implies the strength of the pollen data set representing the modern pollen rain in three distinct groups segregated by both regional climatic influence and altitudinal gradient. This is also observed in the CONISS analysis of the pollen percentage data at each sampling site, where similar taxa dominate particular samples, creating clear segregations within the data set. The tree taxa play a distinct role in specifying the presence of distinct vegetation at these sites within each group. The trees such as *Betula*, *Abies*, *Pinus*, *Tsuga*, *Larix*, *Rhododendron*, along with *Alnus*, *Quercus*, and *Corylus*, are in higher percentages at the samples at lower and intermediate altitudes of the sampling range (2,000–4,000 m a.s.l.) along with lower elements such as Apiaceae, *Artemisia*, Asteroideae, Cichorioideae, Solanaceae etc., with grass pollen such as Poaceae >50  $\mu$  and fern spores. However, the samples from extremely high altitudes (400–4,200 m a.s.l.) have fewer tree taxa, except for *Rhododendron*, *Betula*, *Larix*, and in some instances, *Tsuga* and *Quercus*. These sites record more Asteroideae and Poaceae <50  $\mu$  along with a few other ground elements, with very few fern spores compared to lower elevation regions. Hence, topography and climatic scenarios in these remote regions of eastern Himalaya restructure the distribution of forest types and the observed modern pollen yield in surface samples collected. The anthropogenic impact in lower elevation regions cannot be ruled out due to the higher number of larger grass pollen and increased ground elements. Precipitation and temperature changes across these sites can be acute, along with the presence of very high wind speeds, altering the vegetation distribution patterns. The regional climatic changes with the steady patterns of global climatic conditions and extreme climate variations may lead to further amelioration of the vegetation at these high-altitude sites of northern Sikkim.

The adjoining region of the southeastern Tibetan Plateau, which is one of the highest elevation regions of the world, has also recorded similar taxa in 168 surface sediments collected from four distinctive vegetation types (Wang et al., 2022). The modern vegetation recorded in these samples included arboreal taxa such as *Pinus*, *Picea*,

*Betula*, dominated by Cyperaceae, *Artemisia*, in the alpine shrub and meadow and alpine steppe vegetation. *Artemisia*, Cyperaceae, Asteraceae and Brassicaceae comprised the alpine steppe-shrubs. Some of these taxa are congruent with the taxa observed in the present study area in close proximity to these parts of the Tibetan Plateau. Through these modern pollen assemblages, the vegetation and climate relationship was assessed through redundancy analysis, which indicated that MTCO is the main climatic factor that influences pollen distribution in the Tibetan Plateau (Wang et al., 2022). A relationship with temperature (MTWA) was established in the present study, as well as with climate variables analysed through RDA. Such complex forest models have inherent potential to help recreate and reconstruct palaeo vegetation distribution through fossil pollen records in climate-sensitive areas such as south-eastern Tibetan Plateau (Wang et al., 2022). Another modern pollen study from Yadong County near the southern edge of Tibet Autonomous Region and between North Sikkim and Bhutan at altitudes of 2,000–7,400 m a.s.l. recorded changes in the pollen abundance with the changing elevation across the sampling sites (Zhang et al., 2020). The changing elevation impacts the pollen records where the arboreal pollens are high in occurrences at low elevation sites and the ground elements are high in abundance at the cold and arid parts in this region of eastern Himalaya (Zhang et al., 2020). This is coherent with the present study, where there is a distinct variation of taxa recorded at varying elevations of North Sikkim. The arboreal dominant in the Yadong records, such as *Pinus*, *Betula*, *Larix*, *Picea*, *Quercus*, *Tsuga*, and *Salix*, along with herbs and shrubs such as Cyperaceae, Caryophyllaceae, *Artemisia*, *Salix*, Asteraceae, *Primula* spp. etc., are common taxa observed in the samples analysed in the present study. Thus, variations in modern vegetation in the high-elevation regions of eastern Himalaya are impacted by factors such as environmental changes across the altitude gradient and anthropogenic influences (Figure 2), contributing towards the overall pollen yield in the surface samples. Yet the inferences based on the presence of taxa such as *Pinus*, *Betula*, and *Picea*, must be based after careful consideration of the tendency of these taxa being wind transported from the Himalayan mountain slope across alpine steppe regions (Zhang et al., 2020). The studies related to changes in modern pollen rain and vegetation distribution pattern across elevation gradients have been carried out in regions such as America (Castro-López et al., 2021; Correa-Metrio et al., 2011; De Oliveira Portes et al., 2020; Urrego et al., 2011), Asia (Guo et al., 2020; Huang et al., 2018; Quamar et al., 2021; Zhang et al., 2018), Africa (among others, Bonnefille et al., 1993; Julier et al., 2018; Schüler et al.,

2014; Tabares et al., 2018), and Europe (Connor et al., 2021; Fall, 2012; Finsinger et al., 2007; Furlanetto et al., 2019; Hjelle, 1999; Morales-Molino et al., 2020; Ortu et al., 2010; Senn et al., 2022; Servera-Vives et al., 2022) explaining pollen deposition, changing vegetation patterns and also land-use changes (Fontana et al., 2023).

The present study elaborated on the relationship of regional climate data with the modern pollen rain recorded in the eastern Himalayas. The monsoon in this region brings large amounts of precipitation, but the strength declines as higher elevation regions are reached. The average temperatures for the lower elevation parts are much higher than the high eastern Himalaya peaks, making vegetation diminish in terms of density and distribution. The congruence with regional pollen rain records validates the strength of the present study. Further, it encourages more such future works, also for palaeoclimatic reconstruction based on modelling from fossil pollen data.

## CONCLUSIONS

The elevation changes in this region lead to distinct vegetation changes ranging from tropical to temperate, sub-alpine and alpine taxa occupying dense forests and beyond the tree-line limits of the eastern Himalaya. The modern pollen taxa recorded indicate the impact of regional topography and climatic parameters on the vegetation dynamics of North Sikkim. When subjected to ordination analysis and gridded climate data, the modern pollen rain data reveal the significant climatic variables MAP and MTWA impacting the vegetation distribution along the altitudinal gradient.

More modern pollen rain studies with more samples from extended regions of northern Sikkim and beyond shall contribute towards further understanding of pollen-based regional vegetation and climate studies. Future studies through a larger networks of modern pollen rain sites and high-resolution modern climate records can form a basis for a paleoclimatic reconstruction modelled from fossil pollen data from the eastern Himalaya.

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