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A 8400-year pollen records of vegetation dynamics and Indian Summer Monsoon climate from central India: Signatures of global climatic events

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Pollen analytical study of a 2.1-m deep lacustrine sedimentary profile from central India has demonstrated that between ~ 8400 and 1200 cal yr BP, open, mixed tropical, deciduous forest occurred in the region under a warm and moderately humid climate, probably indicating moderate monsoon precipitation. Subsequently, between ~ 1200 and 500 cal yr BP (AD 750-1450), with the spread of most of the existing forest constituents, the open, mixed tropical, deciduous forest was succeeded by dense mixed, tropical, deciduous forest owing to the prevalence of a warm and humid climate with increased monsoon precipitation, coinciding with the Medieval Warm Period (MWP)/ Medieval Climate Anomaly (MCA) (AD 750-1200). Finally, during ~ 500 cal yr BP (AD 1450) to the Present, mixed, tropical, deciduous forest has been replaced by a relatively denser, mixed, tropical, deciduous forest around the study area under a warm and relatively more humid climate with further increase in monsoon precipitation, which falls within the time-frame of the Current Warm Period (CWP) (AD 1800 to the Present). Moreover, the varying degrees of warming since ~8.4 ka to the Present could be correlatable with the Holocene Climate Optimum (HCO)/Holocene Thermal Maximum (HTM). The present study provides insights into the vegetation dynamics and Indian Summer Monsoon (ISM)-influenced climate since the last ~8.4 ka to the Present from one of the poorly understood areas of the tropics where rainfall is essentially controlled by the monsoon [especially the southwest (summer) monsoon; SWM/SM] variability.

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INTRODUCTION

Vegetation dominates the carbon and water energy cycle of terrestrial ecosystems and has a pivotal position in global changes (Pielke Sr. *et al*., 1998; Zhong *et al*., 2010). The influence of vegetation change on climate system is mainly reflected in the surface albedo, aerodynamic resistance and regional evapotranspiration (Suzuki *et al*., 2007; Neigh *et al*., 2008; Chen *et al*., 2009; Liu *et al*., 2011). Further, climate largely controls the global distribution and composition of the vegetation and the vegetation, in turn, impacts the climate locally through influence on the hydrological cycle (Bouimetarhan *et al*., 2014). Vegetation produces large amounts of pollen gains and spores and the widespread transport and mixing of pollen grains by wind or water generally form pollen assemblages, which represent characteristics of vegetation, climatic conditions or sedimentary environment at a specific time or area (Faegri *et al*., 1989). Lake sediments serve as important repositories for pollen grains and spores (Faegri *et al*., 1989; Sun and Wu, 1987; Chen *et al*., 2006) and pollen grains retrieved from lacustrine environments act as an important proxy evidence for palaeovegetation and palaeoclimate reconstructions. Pollen-derived vegetation records from any area will reflect variations in monsoon (here the Indian Summer Monsoon; ISM/Southwest Monsoon; SWM) precipitation (Bonnefille *et al*., 1999; Quamar, 2021 a, b; Quamar and Chauhan, 2012, 2014; Quamar and Bera, 2014, 2017, 2020; Quamar and Kar, 2020a; Quamar *et al*., 2017, 2021; Kar and Quamar, 2019, 2020 and references cited therein).

The ISM provides ~80% of the total rainfall to South Asian countries (Gadgil, 2003) and simultaneously influences the agriculture and socio-economic development of about two-thirds of the world population (Benn and Owen, 1998). The ISM is driven by the movement of the Inter Tropical Convergence Zone (ITCZ) over the equatorial region (Ghosh *et al*., 1978). More specifically, the summer rains associated with the South West monsoon (SWM) are initiated by the northward movement of the ITCZ due to warming of the Asian continents during summer (Wright *et al*., 2008). Further, the ITCZ is driven by the energy fluxes and not just by heating

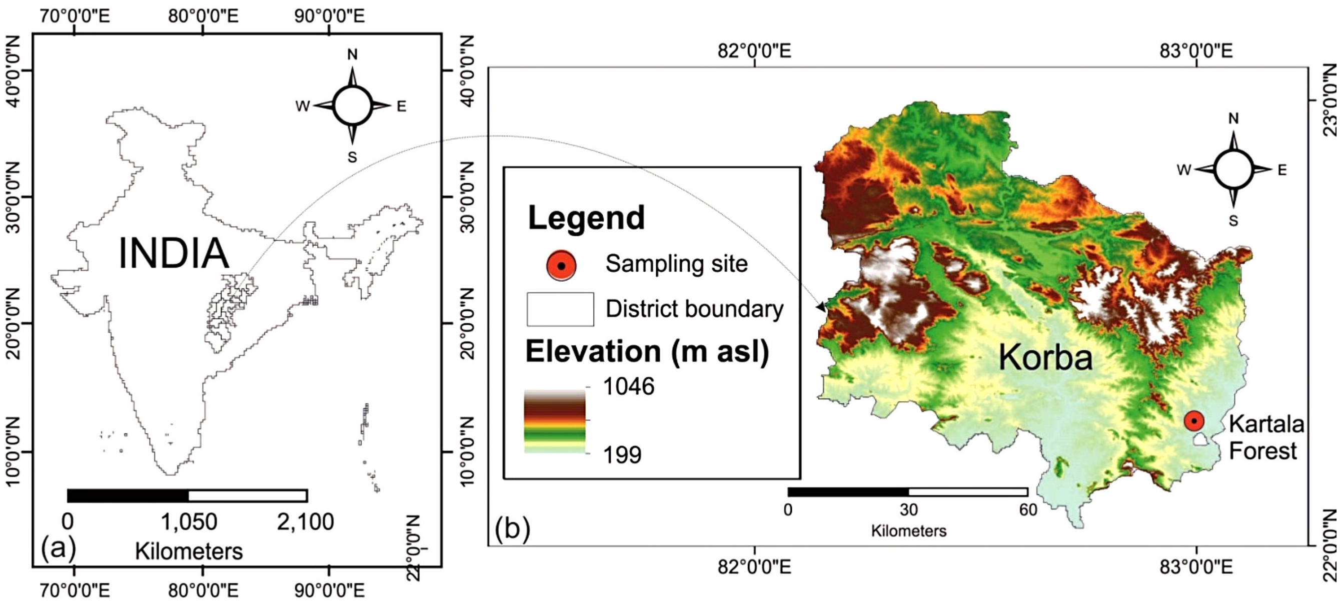

Fig. 1a. Map of India showing Chhattisgarh State. **1b.** Shuttle Radar Topographic Mission (SRTM) and Digital Elevation Map (DEM) of the investigation site at the Kartala Forest Range in the Korba district of Chhattisgarh State, central India. Source of Figure. 1a, b: The figures 1a, b are created using ArcGIS 10.3.

of the landmasses. Keeping in view the importance of the monsoon, especially in agriculture-based socio-economic development of the country, the present study was carried out from the Korba District of Chhattisgarh State (central India) to help understand the variation in the SWM around the region. Efforts have also been made to look into the initiation of agricultural practices and their subsequent pace, as well as the changes in lake level during different climatic phases, which were also possibly governed by variations in monsoonal precipitation.

STUDY AREA

The site of investigation, Kodamsar Lake (KL), is situated about 45 km east of Korba Township near Timanbhauna village of the Kartala Forest Range (82º 59.389' E : 22 º 16.681" N; ~300 m a.s.l.) in the Korba District (Fig. 1). The lake basin is almost circular in outline and has a rough diameter of about 200 m^2. The depth of lake under investigation is 5 m. The eastern part of the lake basin is dried up and is presently under cultivation by the local people. However, the northern, western and southern flanks of the lake retain some water and are marked by a perpetual swampy margin. According to the local populace, this lake is being used for fishing purpose by the local residents of the region. A low-energy and quiet sedimentary depositional environment could be prevailing around the sampling provenance (Brown, 1985; Catto, 1985; Fall, 1987). Physiographically, the study area falls under Korba Basin, which is formed by the Hasdeo River and its tributaries. The average altitude of the area ranges from 250-350 m above the mean sea level. Red yellow soil, laterite soil and sandy clay soil are the chief soil types of the area in question which originated from a wide variety of parent materials formed under different geological formations of Cuddapah, resting on Archean Rocks (Verghese *et al*., 2014). The plain area is under agricultural activity by the local inhabitants including tribal peoples.

VEGETATION AND CLIMATE

The vegetation of the region is characterized by tropical, deciduous forests (both moist and dry types), dominated by teak (*Tectona grandis*) and sal (*Shorea robusta*) (Champion and Seth, 1968; Quamar and Kar, 2020). However, 16 different types of vegetation are found in India (Champion and Seth, 1968). These are Tropical wet evergreen forests (also called tropical rain forests), Tropical semi-evergreen forests, Tropical moist deciduous forests, Littoral and swampy forests, Tropical dry deciduous forests, Tropical dry evergreen forests, Tropical thorny/scrub forests, Sub-tropical broad-leaved hill forests, Sub-tropical pine forests, Sub-tropical dry evergreen forests, Montane wet temperate forests, Himalayan wet/moist temperate forests, Himalayan dry temperate forests, Sub-alpine forests, Moist alpine forests and Dry alpine forests. Nonetheless, the common and typical associates of the forests around the study area are shown in Table 1.

The study area experiences both the tropical savannah-type climate (Aw) and mesothermal-Gangetic Plain type climate (Cwg), according to the Köppen's system of classification of climate (1936), which is based upon annual and monthly means of temperature and precipitation (Quamar and Kar, 2020). Nearest Climate Research Unit Timeseries (CRU TS) 4.01, 0.5 x 0.5 gridded climate data points, 1901-2016, showing mean monthly precipitation and temperature around the KL sedimentary profile of the Korba District,

Table 1. Common associates of the forest around the study area.

Name of Taxa	Habits	Name of Families
Madhuca indica J. F. Gmelin	Tree	Sapotaceae
Terminalia chebula Retz	Tree	Combretaceae
T. bellerica (Gaertn.) Roxb.	Tree	Combretaceae
T. arjuna (Roxb. ex DC.) Wight et Arn.	Tree	Combretaceae
T. tomentosa Wight et Arn.	Tree	Combretaceae
Azadirachta indica A. Juss.	Tree	Meliaceae
Diospyros melanoxylon Roxb.	Tree	Ebenaceae
Schleichera oleosa (Lour.) Oken.	Tree	Sapindaceae
Syzygium cumini (L.) Skeels	Tree	Myrtaceae
Buchanania lanzan Spreng.	Tree	Anacardiaceae
Acacia catechu (L. f.) Willd.	Tree	Mimosaceae
Dalbergia sissoo Roxb.	Tree	Fabaceae
Boswellia serrata Roxb. ex.- Colebr	Tree	Burseraceae
Holoptelea integrifolia Planch.	Tree	Ulmaceae
Gmelina arborea Roxb.	Tree	Lamiaceae
Aegle marmelos (L.) Correa	Tree	Rutaceae
Emblica officinalis Gaertn.	Tree	Euphorbiaceae
Anthocephaleous cadamba (Roxb.) Miq.	Tree	Rubiaceae
Lagerstroemia parviflora Roxb.	Tree	Lythraceae
Mitragyna parvifolia (Roxb.) Korth.	Tree	Rubiaceae
Adina cordifolia (Roxb.) Hook. f. ex.- Bedd.	Tree	Rubiaceae
Eucalyptus sp. L'Hér.	Tree	Myrtaceae
Butea monosperma (Lam.) Taub.	Tree	Fabaceae
Ficus benghalensis L.	Tree	Moraceae
Semecarpus anacardium L.f.	Tree	Anacardiaceae
Ziziphus mauritiana Lam.	Shrub	Rhamnaceae
Strobilanthes sp.	Shrub	Acanthaceae
Acacia spp.	Shrub	Mimosaceae
Holarrhena antidysenterica (L.) Wall.	Shrub	Apocynaceae
Ricinus communis L.	Shrub	Euphorbiaceae
Grasses (Members of Poaceae)	Terrestrial herb	Poaceae
Ageratum conyzoides L.	Terrestrial herb	Asteraceae
Sida rhombifolia Roxb. ex Fleming	Terrestrial herb	Malvaceae
Hyptis suaveolens (L.) Poit	Terrestrial herb	Lamiaceae
Blumea spp.	Terrestrial herb	Asteraceae
Leucas aspera (Willd.) Link.	Terrestrial herb	Lamiaceae
Chenopodium album L.	Terrestrial herb	Amaranthaceae
Amaranthus spinosa L.	Terrestrial herb	Amaranthaceae
Achyranthes aspera L.	Terrestrial herb	Amaranthaceae
Xanthium strumarium L.	Terrestrial herb	Asteraceae
Mazus japonicas (Thunb.) Kuntze	Terrestrial herb	Mazaceae
Sonchus spp.	Terrestrial herb	Asteraceae
Oxalis acetocella	Terrestrial herb	Oxalidaceae
Justicia simplex D. Don.	Terrestrial herb	Acanthaceae
Euphorbia hirta L.	Terrestrial herb	Euphorbiaceae
E. thymifolia L.	Terrestrial herb	Euphorbiaceae
Ajuga sp.	Terrestrial herb	Lamiaceae
Commelina benghalensis L.	Terrestrial herb	Commelinaceae
Scirpus sp.	Marshy herb	Cyperaceae
Cyperus rotundifolia L.	Marshy herb	Cyperaceae
Carex sp.	Marshy herb	Cyperaceae
Ammania baccifera L.	Marshy herb	Lythraceae
Rumex sp.	Marshy herb	Polygonaceae
Polygonum plebieum R. Br.	Marshy herb	Polygonaceae
P. serrulatum Lag., *Mentha arvensis* L.	Marshy herb	Polygonaceae
Mentha arvensis L.	Marshy herb	Lamiaceae
Hygrophila auriculata (Schumach.) Heyne.	Marshy herb	Acanthaceae
Pimpinella tomentosa (Dalzell & Gibson) C.B. Clarke	Marshy herb	Apiaceae
Solanum xanthocarpum Schrad et Wendl.	Marshy herb	Solanaceae
Ocimum americanum L.	Marshy herb	Lamiaceae
O. sanctum L.	Marshy herb	Lamiaceae
Typha latifolia L.	Aquatic herb	Typhaceae
Trapa sp.	Aquatic herb	Trapaceae
Nymphoides indica (L.) Kuntze	Aquatic herb	Menyanthaceae
Potamogeton purpurascens Seidi ex J. Presl et C. Presl	Aquatic herb	Potamogetonaceae
Lemna paucicostata Hegelm.	Aquatic herb	Araceae
Dryopteris prolifera (Retz.) C. Chr.	Pteridophytic herb	Dryopteridaceae
Adiantum philippensis L.	Pteridophytic herb	Pteridaceae
Diplazium esculentum (Retz.) Sw.	Pteridophytic herb	Athyriaceae
Selaginella semicordata N. Wall.	Pteridophytic herb	Selaginellaceae
Lycopodium cernuum	Pteridophytic herb	Lycopodiaceae

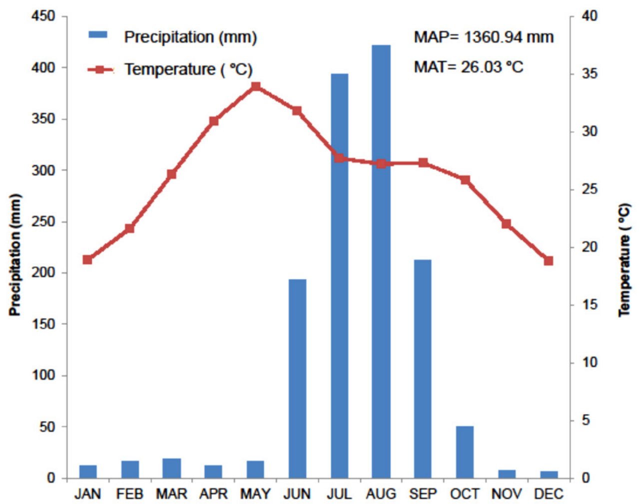

Fig. 2. Nearest Climate Research Unit Timeseries (CRU TS) 4.01, 0.5 x 0.5 gridded climate data point, 1901-2016, showing mean monthly precipitation and temperature around the KL of the Korba District. These data are 116-year climate averages for the period 1901-2016; MAP= Mean Annual Precipitation; MAT= Mean Annual Temperature.

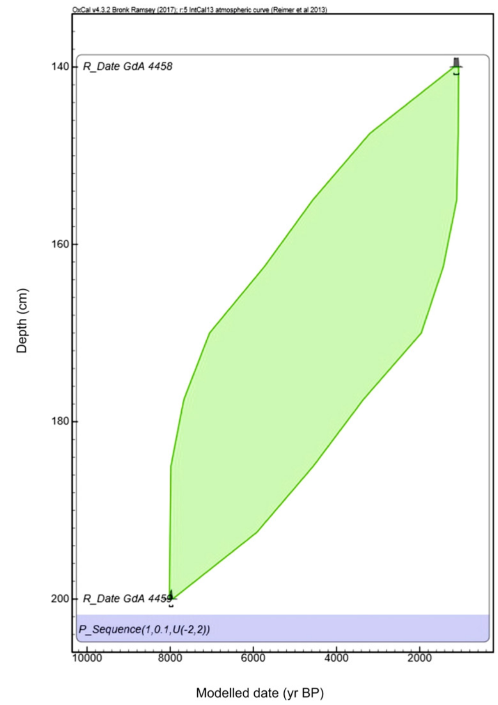

Fig. 3. Modelled age and their respective depths for the KL sediment pollen profile using OxCal v4.2.3. Calibration was done using IntCal13 (Reimer *et al.* 2013) calibration curve and calibrated dates are expressed as 95% probability ranges (following, Scott *et al.* 2007; Rull *et al.* 2015; Demske *et al.* 2016).

Chhattisharh State have been represented in Fig. 2 (Harris *et al*., 2014). The mean annual temperature (MAT) is 26.03 °C and the mean annual precipitation (MAP) is 1360.94 mm around the KL, Korba District.

MATERIALS AND METHODS

For the present study, a 2.1m deep sedimentary profile was dug out with the help of spade and mattock from the eastern part of Kodamsar Lake (KL), which falls under the Kartala Forest Range of the Korba District in Chhattisgarh State in 2014. In total, 21 samples were collected at 10 cm intervals each from this profile for pollen analysis. Besides, seven samples were also taken at different intervals for radiocarbon dating. Three prominent lithozones are apparent from top to bottom in this profile also, based on the dissimilarity in sediment texture at various depths. The topmost lithozone is comprised of blackish clayey soil with rootlets and charcoal pieces followed by dark brownish clayey soil. The bottommost stratum is made up of blackish clayey soil (Troels-Smith, 1955).

For KL sedimentary pollen profile, three samples, out of the seven samples collected, were AMS ^{14}C dated (7160 ± 30 yr BP at 200 cm depth, 1190 ± 20 yr BP at 140 cm depth and 6640 ± 35 yr BP at 50 cm depth) at the Institute of Physics, Gliwice Radiocarbon Laboratory (GdA), Poland. As one of dates (6640 ± 35 yr BP at 50 cm depth) is inverted, which could be due to some sort of contamination while packing the samples in the field, methodological flaw and/or other reasons, we had removed that one and considered the dates 7160 ± 30 yr BP at 200 cm depth and 1190 ± 20 yr BP at 140 cm depth for further study. Meanwhile, effect of tectonic activity around the study area cannot be denied as Singh (2004) suggested active tectonism in the Ganga Plain foreland basin, which is mostly in the form of contractional system in the piedmont zone, and prominent extensional system in the southern part of the basin. The tectonics of 8-5 kyr BP (encompassing the reverse age of 6640± 35 yr BP around the study area) in Ganga Plain produced areas of centripetal drainages and changed the fluvial landscape into a landscape of ponds and lakes with few high grounds and was helped by the climate change from humid to dry around 5 ka BP. Earlier, Srivastava *et al***.** (2003) also suggested a prominent tectonic activity at 7-5 ka and dry climate at 5 ka, which produced undulatory topography and high siltation rates in the lakes and ponds. Further, they suggested that the peripheral bulge, southern Ganga Plain has been tectonically active, causing deep incision of rivers and a 40 ka seismic event, and Mid-Late Holocene tectonic activity can be inferred.

These two AMS ^{14}C dates were calibrated in the OxCal v. 4.3 package (Bronk Ramsey, 2001) with the standard IntCal 13 calibration curve (Reimer *et al*., 2013) (Table 2). To establish the age–depth relationship, a Poisson process deposition model (Bayesian age-depth modeling; Bronk Ramsey, 2008) was followed. The model showed all agreement indices and convergence indices higher than the critical values; thus, both the AMS ^{14}C samples were kept in the model. The final age–depth model is presented in Fig. 3, with a 95% probability for the age of every depth.

The two calibrated dates were interpolated and extrapolated in this case also to decode the vegetation dynamics and coeval climate change in the region in a definite time-frame. The two calibrated dates i.e. 7978 cal yr BP at 200 cm depth and 1118 cal yr BP at 140 cm depth were used to calibrate the sedimentation rate of the profile, which were not uniform in this case also owing to the

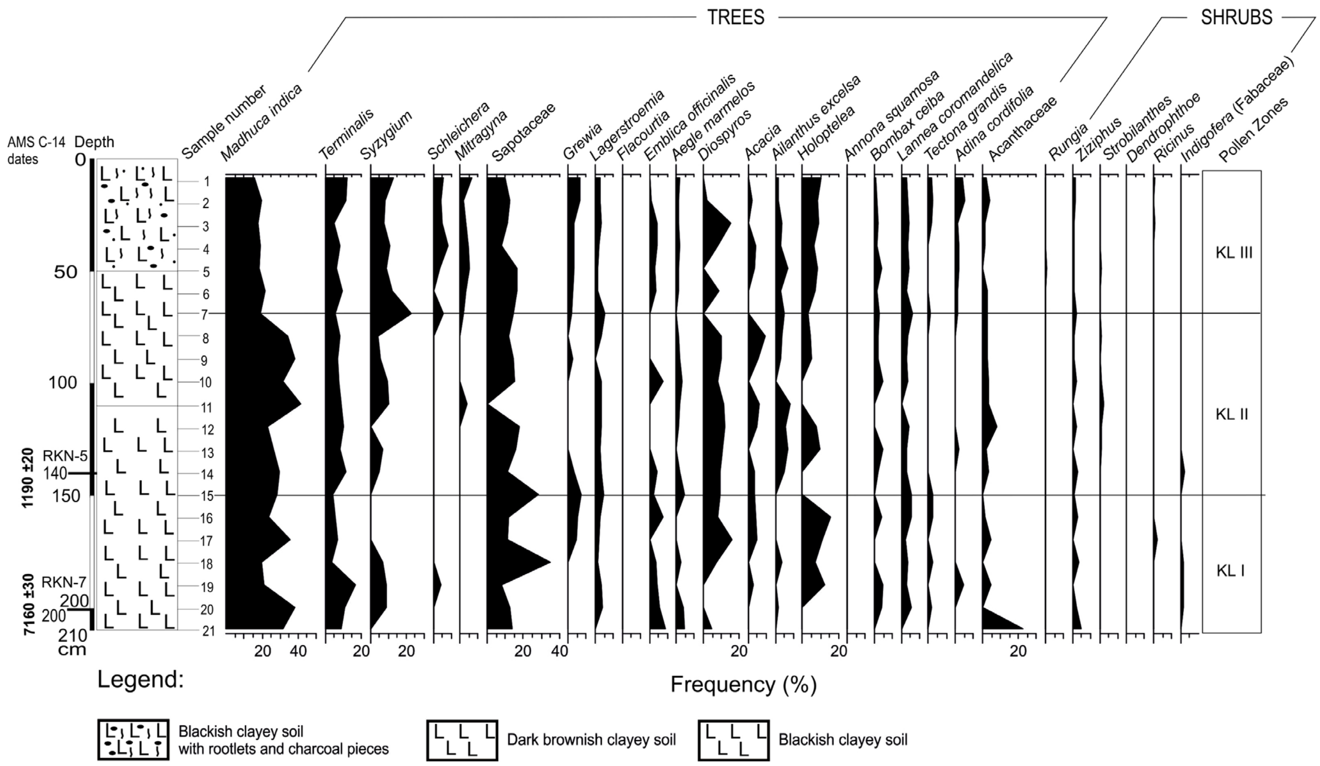

Fig. 4. Pollen diagram of tree taxa and shrubs from the KL sediment profile, Korba District. The pollen zones are designated with the initials 'KL' after the name of the site of investigation Kodamsar Lake.

Table 2. Calibration of the AMS ^{14}C dates as well as extrapolation and interpolation of the dates at different depths of the pollen zones of KL sediment profile.

Depth (cm)	Lab code	AMS ^{14}C age (yr BP)	Calibrated AMS ^{14}C age ranges with error (cal yr BP)	Calibrated AMS ^{14}C age (Mean data) (cal yr BP)	Dates of different Pollen Zones (cal yr BP)
200	GdA 4459	7160±30	8019-7978±41	7978	**Pollen Zone I**: 210-150 cm = ~8378 (8400)-1198 (1200) **Pollen Zone II**: 150-70 cm = ~1198 (1200)-478 (500)
140	GdA 4458	1190±20	1178-1118±59	1118	**Pollen Zone III**:70-0 cm = ~478 (500)-Present

difference in sediment composition throughout the profile. The two calibrated sedimentation rates of the profile were 40 years/cm (considering the date 7978 cal yr BP at 200 cm depth) and 8 years/cm (considering the date 1118 cal yr BP at 140 cm depth and assuming the surface as modern). These two sedimentation rates have facilitated to interpolate and extrapolate the dates at the point of zone boundaries made in the pollen diagram i.e. 8378 (~8400) cal yr BP at 210 cm depth, 1198 (~1200) cal yr BP at 150 cm depth and 478 (~500) cal yr BP at 70 cm depth to describe the temporal changes in the vegetation and coeval climate in the region.

Extraction of pollen and spores from the sediment samples follows sample processing method of Faegri *et al*. (1989). Chemical treatments successfully removed humus and (also deflocuulate the pollen and spores from the sediment samples), silica and cellulose using 10% KOH, 40% HF and an acetolysis mixture, consisting of concentrated sulphuric acid (H_2SO_4) and acetic anhydride ($C_4H_6O_3$) in 1:9 ratio, respectively. The samples were finally prepared in 50% glycerine solution for microscopic examination. A few drops of phenol were also added to avoid any microbial contamination.

Counting of pollen and spores were made under a transmitted light microscope (Olympus BX50) using 40 X objective lens at the Quaternary Palynology Laboratory of the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow. Identification of the pollen and spores was assisted by published reference material (Chauhan and Bera, 1990; Nayar, 1990; Quamar and Chauhan, 2011, 2012; Quamar and Bera, 2017; Quamar and Kar, 2020a) and the reference collections

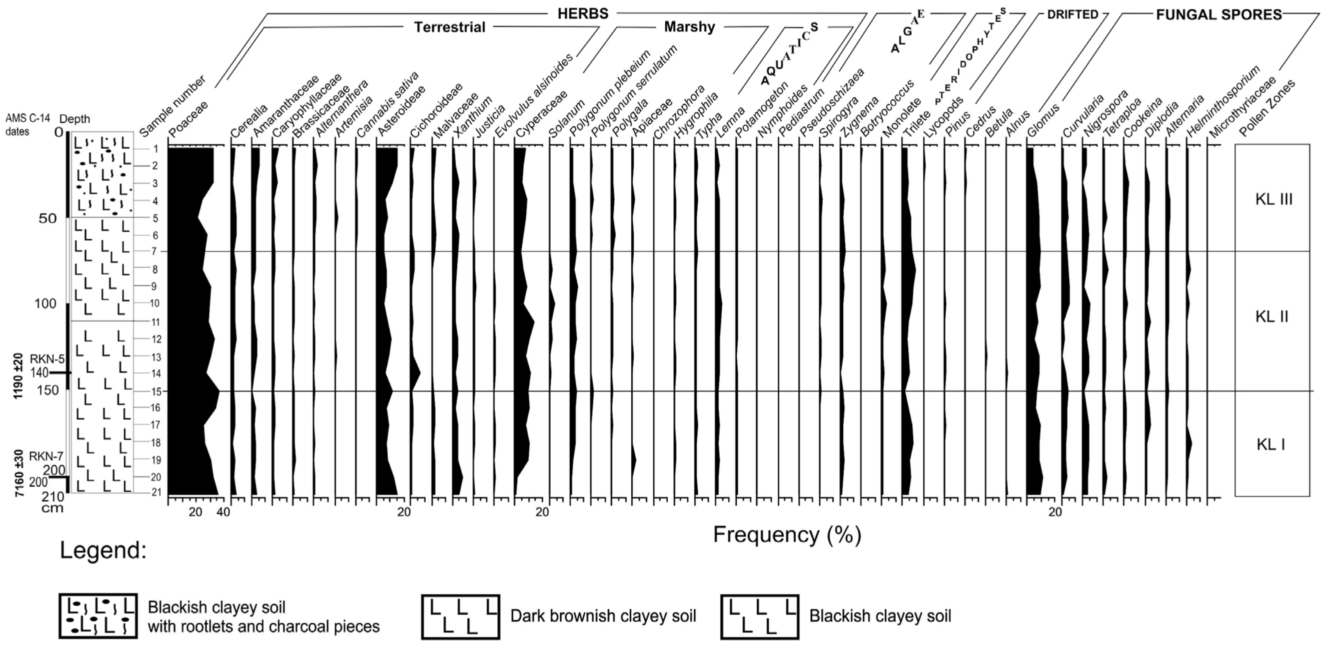

Fig. 5.. Pollen diagram of herbaceous taxa from KL sediment profile, Korba District. The pollen zones are designated with the initials 'KL' after the name of the site of investigation Kodamsar Lake.

held at the Birbal Sahni Institute of Palaeosciences (BSIP) Herbarium, Lucknow. More than 300 terrestrial pollen grains were counted per sample. Pollen percentages were calculated using the Total Pollen Sum (TPS) of terrestrial plants pollen only. Pollen of aquatic plants, marshy taxa, as well as spores of algae, ferns, drifted (transported from higher reaches; the Himalaya) and fungi were excluded from the TPS, however, their percentages were calculated using the TPS. The pollen diagrams (Figs. 4 and 5) were constructed using TILIA and TG View software (Grimm, 1991). Taxa were arranged in the pollen diagrams as trees, shrubs, herbs, marshy taxa, aquatics, algal remains, ferns, drifted and fungal spores.

RESULTS

The pollen diagrams (Figs. 4 and 5) have been divided into three distinct pollen zones (KL-I, KL-II, & KL-III) on the basis of the changing frequencies of the important arboreals and non-arboreal taxa in order to discuss the sequential vegetation succession and contemporary climatic changes in a chronological order in the region. The pollen zones numbering from bottom to top are described as below:

Pollen Zone KL-I (210-150cm)

This pollen zone with a single AMS ^{14}C date of 7160±670 cal yr BP (190-210 cm depth) and covering the time bracket of ~ 8400 to 1200 cal yr BP is characterized by the presence of open, mixed tropical deciduous forest. Among the arboreals, the trees constitute an average value of 14% pollen in the TPS, whereas the contribution of shrubs is meagre with an average value of 0.79% pollen only. The important tree taxa are *Madhuca indica*, *Terminalia*, *Syzygium*, Sapotaceae, *Schleichera*, *Diospyros*, *Aegle marmelos, Emblica officinalis*, *Acacia*, *Lannea coromandelica*, *Bombax ceiba*, whereas *Ziziphus*, Fabaceae and Acanthaceae are the principal shrubby taxa. Poaceae, among the non-arboreals, represents an average value of 26.78% pollen of the TPS. Cerealia and other cultural plant pollen taxa, such as Amaranthaceae, Caryophyllaceae, Brassicaceae, *Artemisia*, *Alternanthera* and *Cannabis sativa* contribute with an average value of 6.23% pollen in the TPS. Asteroideae (Tubuliflorae; Asteraceae, average 8.52% pollen) is followed by other terrestrial herbs, such as Cichorioideae/Lactucoideae (Liguliflorae; Asteraceae), Malvaceae, *Justicia*, *Xanthium*, *Evolvulus alsinoides* and *Convolvulus* have an average contribution of only 6.19% pollen in the TPS. Cyperaceae (average 5.97% pollen), *Solanum* sp., *Polygonum plebeium*, *P. serrulatum*, *Polygala*, Apiaceae, *Chrozophora*, and *Hygrophila* (average 4.54% pollen) are the marshy taxa in the pollen-rain. *Typha*, *Lemna* and *Potamogeton* are the aquatic taxa, which have also lower values (2.06%), whereas *Zygnema*, *Spirogyra* (zygospores) and *Botryococcus* are algal spores and are represented in lower values (average 1.97%). Monolete and trilete fern spores have moderate values (4.02%), whereas the drifted pollen taxa (*Pinus*, *Cedrus*) have less values (<1% pollen). The fungal spores such as *Glomus*, *Curvularia*, *Nigrospora*, *Tetraploa, Cookeina, Diplodia*, *Alternaria, Helminthosporium* and Microthyriaceae are recorded in variable frequencies in this pollen zone.

Pollen Zone KL-II (150-70 cm)

This pollen zone with a single AMS ^{14}C date of 1190±20 cal yr BP (130-150 cm depth), and encompassing a time span of ~ 1200 and 500 cal yr BP shows the dense mixed tropical deciduous forest. The results show that tree and shrubby taxa, among the arboreals, have an average values of 18.95% and 1.01% pollen, respectively, in the TPS. *Madhuca indica*, *Terminalia*, *Syzygium*, *Lannea*, *Bombax ceiba*, *Holoptelea*, *Ailanthus excelsa*, *Acacia*, *Diospyros*, *Emblica officinalis*, *Aegle marmelos*, *Lagerstroemia* and Sapotaceae are the noted tree taxa, whereas *Ziziphus*, *Strobilanthes* and Acanthaceae are the shrubby taxa in this pollen zone, which have slightly increased values in comparison to the preceding pollen zone. Among the non-arboreal taxa, Poaceae (average 23.15% pollen), as well as Cerealia and other cultural plant pollen taxa (average 5.92% pollen in the TPS), though, have almost equal values as in the preceding zone, but a bit decreased comparatively. Asteroideae (average 5.82%) and other terrestrial herbs (average 4.76%) decreased comparatively. Cyperaceae (average 6.81%) and Solanaceae, *Polygonum plebeium*, *P. serrulatum*, *Polygala*, Apiaceae, *Chrozophora* and *Hygrophila*, the marshy taxa, have an average value of 4.85% pollen in this pollen zone, showing increased values. *Typha*, *Lemna* and *Potamogeton* are the aquatic taxa, whereas *Zygnema* and *Spirogyra* (zygospores), the algal remains, as well as monolete and trilete fern spores have comparatively increased values (average 3.43%, 2.07% and 5.73%, respectively) in this pollen zone. *Pinus*, *Cedrus*, *Betula*, and *Alnus* are the drifted plant pollen taxa which are sparse (average 0.57% pollen). The fungal spores such as *Glomus*, *Curvularia*, *Nigrospora*, *Tetraploa*, *Cookeina*, *Diplodia*, *Alternaria*, *Helminthosporium and* Microthyriaceae are recorded in variable high to low values in this pollen zone.

Pollen Zone KL-III (70-0 cm)

This pollen zone enveloping a time interval of ~ 500 cal yr BP to the Present demonstrates the presence of a relatively denser, mixed tropical deciduous forest. The tree taxa amongst the arboreals, have an increased average values of 30.78% pollen in the TPS as compared to the preceding pollen zones. *Madhuca indica*, *Syzygium*, *Terminalia*, *Holoptelea*, *Grewia*, Sapotaceae, *Schleichera*, *Mitragyna*, *Adina*, *Ailanthus excelsa*, *Emblica officinalis*, *Aegle marmelos*, *Lannea coromandelica*, *Acacia* and *Diospyros* are the prominent tree taxa, whereas *Zizyphus*, Acanthaceae, *Strobilanthes* and *Ricinus communis* are the shrubby taxa recorded with average low value of 1.13% pollen in this zone. Among the herbaceaous elements, Poaceae shows comparatively decreased values and represents an average of 18.67% pollen in the TPS. Cerealia and other cultural plant pollen taxa increased comparatively and are encountered with average values of 7.76% pollen. Asteroideae (average 6.73% pollen) have increased values as compared to the preceding pollen zone, however, the other terrestrial herbaceous taxa (average 4.40% pollen) have lesser values in comparison to the preceding pollen zone. Cyperaceae (average 4.57% pollen) and *Polygonum plebeium*, *P. serrulatum*, *Polygala*, Apiaceae and *Hygrophila* (average 3.53% pollen), amongst the marshy taxa, have moderate values, though, comparatively lesser than the preceding pollen zone. *Typha*, *Lemna* and *Potamogeton* are the aquatic taxa (average 3.16% pollen), whereas Zygospores of *Zygnema* and *Spirogyra* and *Botryococcus* are the algal remains (average 1.67% spore) as well as monolete and trilete fern spores and lycopods (3.43%), though, have moderate to lesser values, but decreased comparatively. The drifted pollen of *Pinus*, *Cedrus* and *Betula* is meagre (<1% pollen). *Glomus*, *Curvularia*, *Nigrospora*, *Tetraploa*, *Cookeina Diplodia*, *Alternaria*, *Helminthosporium* and Microthyriaceae and are the prominent fungal spores recorded in variable high to low values in this pollen zone.

DISCUSSION

The palynological study of a 2.1m deep lacustrine sediment profile samples from KL provides three-fold temporal vegetation dynamics in response to the contemporary climate (change), as well as human activities, its subsequent pace, and lake-level changes from the Kartala Forest Range of the Korba District in Chhattisgarh State during the last ~8.4 kyr. The pollen sequence has demonstrated that between the time interval of ~ 8400 and 1200 cal yr BP (Pollen Zone KL-I), open, mixed tropical, deciduous forest comprising *Madhuca indica*, Sapotaceae, *Holoptelea*, *Diospyros*, *Terminalia*, *Syzygium*, *Emblica officinalis*, *Ailanthus excelsa* and *Bombax ceiba* occupied the region under a warm and moderately humid climate probably indicative of moderate monsoon precipitation. This phase is partly correlated with the second phase of the Amjhera Swamp (AJ-II, ~ 6000-5400 cal yr BP) and third phase of the Nitaya Lake (NL-III, ~ 4657-2807 cal yr BP), Hoshangabad District (Chauhan and Quamar, 2012b; Quamar and Chauhan 2012); the first phase of the Kachia Jhora-Lake (KJ-I, ~3350-2250 cal yr BP), Sehore District (Quamar and Chauhan, 2015), the second phase of the Nakta Lake (NL-II, ~8500 cal yr BP to the Present), Mahasamund District of Chhattisgarh State (Quamar and Kar, 2020a), as well as the first phase of Chaudhary-Ka-Tal (CKT-I, ~ 8500-6400 cal yr BP), Raibareli District of Uttar Pradesh (Saxena *et al*., 2015), central Ganga Plain (India), wherein similar palaeovegetation and palaeoclimate were reconstructed. Inception of cereal-based agricultural practice and other human activities around the study site is clearly manifested by the steady presence of *Cerealia* and other cultural plant pollen taxa, such as Amaranthaceae, Brassicaceae, Caryophyllaceae, *Artemisia*, *Alternanthera*, and *Cannabis sativa*. The presence, though inadequately, of freshwater algae, *Zygnema* and *Spirogyra* (zygospores), *Botryococcus*, as well as aquatic taxa, *Typha*, *Lemna* and *Potamogeton,* is suggestive of the existence of a lake. The presence of sedges (Cyperaceae) and other stray wetland taxa, such as *Polygonum plebeium*, Solanaceae, *P. serrulatum*, *Polygala*, Apiaceae, *Chrozophora*, and *Hygrophila* indicate the presence of swampy condition. Trilete and monolete fern spores during this phase grew locally in the moist and shady situations close to the lake.

Between ~ 1200 and 500 cal yr BP (AD 750-1450) (Pollen Zone KL-II), with the spread of most of the existing forest constituents particularly *Madhuca indica*, *Terminalia*, *Syzygium*, Sapotaceae, *Diospyros*, *Holoptelea*, *Ailanthes excelsa* and *Bombax ceiba* and immigration of some more arboreals**,** such as *Acacia*, *Mitragyna,* etc., dense mixed, tropical, deciduous forest succeeded the open, mixed tropical, deciduous forest owing to the prevalence of a warm and humid climate with increased monsoon precipitation, which falls with the time-interval of the Medieval Warm Period (MWP)/Medieval Climate Anomaly (MCA) (AD 750-1200; Lamb, 1977; Anderson *et al*., 2002). This phase partially matches with the first phase of the Kachar Lake (KL-I, ~ 2050-1600 cal yr BP), Sehore District (Quamar and Chauhan, 2011); second phases of the Kachia Jhora-Lake (KJ-II, ~ 2250- 800 cal yr BP), Sehore District (Quamar and Chauhan, 2015) and the Sapna Lake (SL-II, ~ 2250-1260 cal yr BP), Betul District (Chauhan and Quamar, 2012a); fourth phase of the Amjhera Swamp (AJ-IV, ~ 2178 cal yr BP- Present), Hoshangabad District (Chauhan and Quamar, 2012b), first phase of the Khedla Quila Lake (KQLI, ~1416-506 cal yr BP; AD 534—1444), Betul District (Quamar and Chauhan, 2014), southwestern Madhya Pradesh, as well as second phase of the Matijharia Lake (ML-II, ~ 4250-1000 cal yr BP), Koriya District (Quamar and Bera, 2014), Chhattisgarh, central India, third phase of the Manjarkui Lake (ML-III, ~3762 cal yr BP to Present), Sehore District (Quamar and Nautiyal, 2016), southwestern Madhya Pradesh, India. The agricultural practice and other human activities remained almost static, as Cerealia and other cultural plant pollen taxa remained unchanged. The lake level increases a bit which is reflected by the increased values of freshwater alga- *Zygnema* (zygospores), as well as aquatic taxa, *Lemna*, *Typha* and *Potamogeton*. However, swampy conditions continued to exist as is suggested by the presence of Cyperaceae and other marshy taxa. Fern spores (trilete and monolete) during this phase also grew locally in the moist and shady places close to the lake.

The climate elucidation of the pollen zones I and II (KL I & II) partially matches with the climatic interpretation during ~2941-2390 cal yr BP; Zone I and ~1782-1299 cal yr BP; Zone III) from Sri Lanka (Gayantha *et al*., 2017), wherein warm and humid climate with intense monsoonal (SWM) precipitation was inferred.

Since ~ 500 cal yr BP (AD 1450) to the Present (Pollen Zone KL-III), a relatively denser, mixed, tropical, deciduous forest replaced the dense mixed, tropical, deciduous forest as a result of increase in the number and frequencies of the existing taxa, such as *Madhuca indica*, Sapotaceae, *Syzygium*, *Terminalia*, *Diospyros*, *Schleichera*, *Holoptelea*, *Ailanthes excelsa*, *Bombax ceiba* and *Lannea coromandelica* of the preceding phase under a warm and relatively more humid climate with further increase in monsoon precipitation, falls within the time-frame of the Current Warm Period (CWP; AD 1800 to the Present). The findings of this phase coincides to a certain extent with the inferences drawn from the Matijharia Lake (ML-III, ~ 1000 cal yr BP to Present), Koriya District (Quamar and Bera, 2014) and Amjhera Swamp (AJ-IV, ~ 2178 cal yr BP to Present), Hoshangabad District (Chauhan and Quamar, 2012a). The pace of agricultural practice and other anthropic activities increased in this phase, as Cerealia and other cultural plant pollen taxa show increased values in comparison to the preceding phases, as a consequence of increased monsoonal precipitation. The lake level remained almost static during this phase, as the frequencies of freshwater algae, such as zygospores of *Zygnema* and *Spirogyra*, as well as aquatic elements, such as *Typha*, *Potamogeton* and *Lemna* remained almost similar as in the preceding phase. The swampy conditions, though, continued in this phase but reduced their dimensions as indicated by the comparatively lower values of swampy taxa, such as Cyperaceae, *Polygonum plebeium*, *P. serrulatum*, *Polygala*, Apiaceae, among others. Trilete and monolete fern spores, as well as the Lycopods during this phase grew locally in the moist and shady conditions close to the lake.

Varying degrees of warming during the Holocene, such as warm and moderately humid climate with moderate monsoon precipitation, warm and humid climate with increased monsoon precipitation and finally warm and relatively more

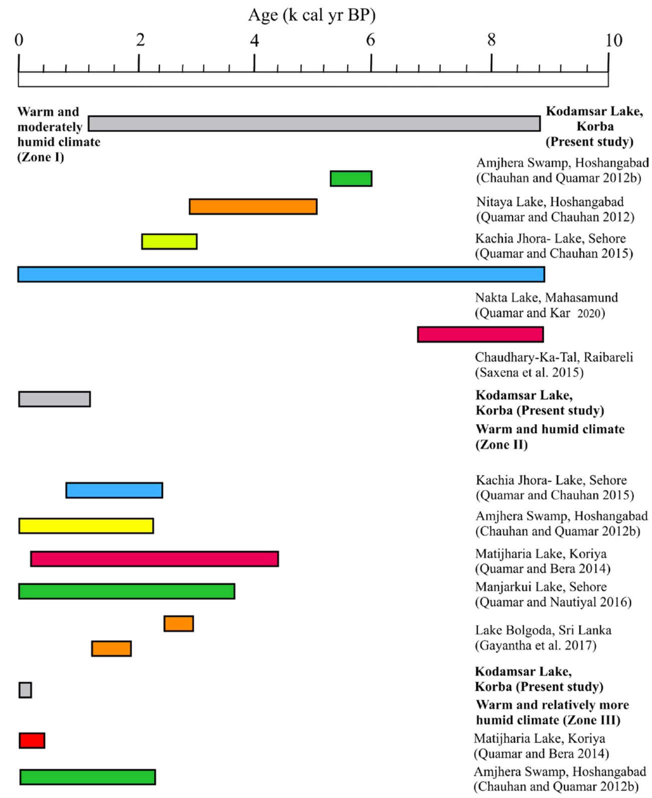

Fig. 6. Summary diagram showing the correlation of the present study with the studies carried out in India and South Asia (especially Sri Lanka).

humid climate with further increase in monsoon precipitation during ~ 8400–1200 cal yr BP, ~ 1200–500 cal yr BP and ~ 500 cal yr BP to the Present, as manifested by the open mixed-tropical deciduous forest, mixed-tropical deciduous forest and dense mixed-tropical deciduous forest, respectively, have been observed from the studied area, which could be correlatable with the global Holocene Climate Optimum (HCO), which falls broadly within the time interval of 7000-4000 BP (Benarde, 1992). The HCO or Holocene Thermal Maximum (HTM) (also known as Hypsithermal, Altithermal, Holocene Megathermal, Holocene Optimum, Climate optimum) has also been reported from other parts of the central India, such as from the Hoshangabad District of Madhya Pradesh (7150–4657 yr BP; Quamar and Chauhan, 2012), the Koriya District of Chhattisgarh (9035– 4535 yr BP–Present; Quamar and Bera, 2017; Kar and Quamar, 2019; and the Koriya District (~7340–1961 cal yr BP; Quamar and Bera, 2020). Quamar and Kar (2020) synoptically reviewed the occurrence of HCO from central India and from abroad as well. A warm and humid climate with increased monsoon precipitation was observed between ~ 1200 and 500 cal yr BP (AD 750-1450), supporting mixed-tropical deciduous forest around the study area. This ameliorating climate falls with the time-frame of the Medieval Warm Period (MWP) or Medieval Climate Anomaly (MCA), which is globally known between AD 750 and 1200 (Lamb, 1977; Andersen *et al*., 2002). The MCA has also been observed in other palaeoclimate records from central India (Sinha *et al*., 2011), NW Himalaya (Dutt *et al*., 2018; Pillai *et al*., 2018; Singh *et al*., 2020), western Arabian Sea (Gupta *et al*., 2005), the Ganga basin (Singh *et* *al*., 2015), the Bay of Bengal (BoB) (Naidu *et al*., 2020). Li *et al*. (2014), based on the AMS ^{14}C dating and the analysis of LOI, TOC, TN, grain size and MS in the sediments from Basomtso Lake, southeastern Tibetan Plateau, suggested that the higher values of LOI, TOC, TN, coarse silt, sand and the MS in the sediment indicated higher sediment input probably owing to warmer climatic conditions and higher glacial melt water input during AD 1080-1140, corresponding well with the MCA. Further, the signatures of the Current Warm Period (CWP; AD 1800 to the Present; Wu *et al*., 2012; Fleury *et al*., 2015 Gupta *et al*., 2020) since ~ 500 cal yr BP (AD 1450) to the Present is observed, suggesting dense, mixed, tropical, deciduous forest the around the study area under a warm and relatively more humid climate with further increase in monsoon precipitation. Chauhan (2005) also suggested the signatures of the Current Warm Period (CWP; AD 1800 to the Present) since 400 yr BP (AD 1550) onwards from the Sidhi District of Madhya Pradesh State, central India, wherein the monsoon arrived timely and was strong also, supporting tropical deciduous sal (*Shorea robusta* Gaertn. f.) forest under a warm and more moist climate. Li *et al*. (2014), based on the AMS ^{14}C dating and the analysis of LOI, TOC, TN, grain size and MS in the sediments from Basomtso Lake, southeastern Tibetan Plateau, suggested that the higher values of LOI, TOC, TN, coarse silt, sand and the MS in the sediment indicated higher sediment input probably owing to warmer climatic conditions and higher glacial melt water input during AD 1790-2012, corresponding well with the CWP. Singh *et al* (2020), based on grain size, $\delta\ ^{13}C$ and $\delta\ ^{15}N$, as well as TOC and TN studies from Himachal Pradesh (NW Himalaya), India also recorded CWP during ~1600-2000 AD. The strengthening of the monsoon during the CWP is due to an increase in global temperature coinciding with the industrial revolution and other anthropogenic factors, as well as the associated increase in surface evaporation and convection in the Indian Ocean (Anderson *et al*., 2002; Wang *et al*., 2005 a, b; Sinha *et al*., 2011; Masson-Delmotte *et al*., 2013). Solar insolation and El Niño intensity have been the major forcing factors influencing the ISM strength during the last 1300 years (Cook *et al*., 2010; Sinha *et al*., 2011).

A summary diagram (Fig. 6), showing the correlation of the present study with the studies carried out from India and South Asia, especially Sri Lanka has been presented to have insights into the variations of the Indian Summer Monsoon (ISM/South West Monsoon (SWM).

CONCLUSIONS

The pollen records of a lacustrine sedimentary profile samples from the Korba District of Chhattisgarh State provides three-fold vegetation succession and Indian Summer Monsoon-influenced climate change during the last 8.4 cal kyr. Between ~8.4 and 1.2 cal ka, open, mixed tropical, deciduous forest occupied the region under a warm and moderately humid climate (with moderate monsoon precipitation), which developed into dense mixed, tropical, deciduous forest under a warm and humid climate (with increased monsoon precipitation) between 1.2 ka and 500 cal yr BP. Finally, a relatively denser, mixed tropical, deciduous forest occupied the landscape since 500 cal yr BP (AD 1450) onwards under a warm and relatively more humid climate with further increase in monsoon precipitation. The signatures of global climatic events, such as HCO (~8.4 ka to the Present), Medieval Warm Period (MWP)/ Medieval Climate Anomaly (MCA) (~1200-500 cal yr BP; AD 750-1450) and CWP [since ~ 500 cal yr BP (AD 1450) to the Present] have also been observed around the study area. Cereal-based agricultural practice increased with the increase in monsoonal precipitation around the study area during ~1200 to 500 cal yr BP and ~500 cal yr BP onwards. The existing lake-level increased in latter phases (during ~1200 to 500 cal yr BP and ~500 cal yr BP onwards), which could be a result of increased monsoon precipitation. The swampy conditions existed, but the swamp shrunk and became narrow in dimension in the last phase, as indicated by the comparatively lower values of swampy taxa, which could be due to human pressure, which might have encroached the area for the purpose of practicing agriculture.

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