Late Pleistocene–Holocene vegetation and climate change in the Central Ganga Plain: a multiproxy study from Jalesar Tal, Unnao District, Uttar Pradesh

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Pollen and organic–inorganic carbon analyses of a 2.8 m deep sediment profile from Jalesar Tal, Unnao District, Uttar Pradesh reveal that just prior to and between 42,490 and 13,560 cal yrs BP, this region supported grassland vegetation largely comprising grasses with scanty trees of *Szyszgium* and *Prosopis* under a cool and dry climate. The coarser sand sediments deposited from 13,560 to 5,260 cal yrs BP are palynologically barren and may be linked to the upwarping phase of the Ganga Plain, resulting into rapid reworking of the sediments, including calcrete formation. Between 5,260 and 4,760 cal yrs BP with the invasion of more trees, viz. *Holoptelea*, *Acacia*, *Bombax ceiba*, *Aegle marmelos*, etc. groves of forest interspersed with grassland got established due to amelioration of climate. Interestingly, the appearance of Cerealia pollen denotes the initiation of cereal-based agricultural practice in the region. Around 4,760 to 3,200 cal yrs BP, the invasion of a large number of trees, viz. *Madhuca indica*, *Emblica officinalis*, *Sterculia* and *Adina cordifolia*, besides those existing earlier coupled with high organic carbon values implies that the forest groves became diversified with the onset of a warm and humid climate in response to active SW monsoon. The rising trend of Cerealia pollen reflects the acceleration of agricultural practice in the region. Between 3,200 and 1,200 cal yrs BP, the forest groves turned sparse owing to reduced monsoon precipitation leading to prevalence of a less humid climate in the region. Since 1,200 cal yrs BP, the further diminishing trend of arboreals and aquatic plants signifies decline in rainfall witnessing a warm and dry climate.

Keywords: Carbon analysis, cerealia pollen, climate change, vegetation.

The Ganga Plain, which is the middle part of the Indo-Gangetic foreland basin, has a large number of lakes and ponds of various dimensions in the interfluve region and located far away from the present-day active drainage
In general, this region enjoys a humid climate, which is largely influenced by the southwest monsoon. Winter season from November to February is marked by average minimum and maximum temperatures of 7.6°C and 21°C respectively. The temperature seldom descends to 0°C during the extreme cold months of December and January. Summer season from March to June is characterized by the blowing of hot winds known as loo, with average minimum and maximum temperatures of 27°C and 32.5°C respectively. The temperature shoots up to 46°C in the hottest month of June. Monsoon season commences in mid-June and continues till mid-September. The weather gets sultry during July–September. The average annual rainfall recorded for the region is 1,020–1,140 mm.

The area in the vicinity of the lake has patchy occurrence of stands or groves of forest interspersed with herbaceous vegetation, dominated by grasses. Thus, the landscape imparts a view of scrub forests. The trees, viz. *Acacia arabica*, *Holoptelea integrifolia*, *Cordia dichotoma*, *Syzygium cumini*, *Madhuca indica*, *Butea monosperma*, *Mimosa sp.*, *Pithecellobium dulce*, *Terminalia*, *Dalbergia sissoo* and *Acacia nilotica* together with thickets of *Ziziphus mauritiana*, *Carissa spinarum*, *Adhatoda vasica*, *Indigofera sp.* and *Nyctanthes arbor-tritris* occur sparsely distributed in the scrub forests. *Tamrindus indica*, *Mangifera indica*, *Syzygium cumini*, *Ficus benghalensis* and *Azadirachta indica* are the common avenue trees.

The herbaceous vegetation of terrestrial habitats comprises *Ageratum conyzoides*, *Euphorbia hirta*, *E. thyrsifolia*, *Mazus japonicus*, *Evolvulus alsinoides*, *Justicia simplex*, *Rungia pectinata*, *Osalis acetosella* and *Chenopodium album*. In most of the reclaimed land *Tribulus terrestris*, *Portulaca oleracea*, *Launaea nudicaulis*, *Solanum xanthocarpum*, *Alternanthera sessilis* and *Eragrostis tenella* are frequent. The wetland along the bank of lakes and rivers is inhabited by *Cyperus rotundus*, *Scirpus maritimus*, *Polygala chinensis*, *Rotala rotundifolia*, *Hygrophi/a auriculata* and *Polygonum plebeium*. The aquatic vegetation includes *Lemna polyrriza*, *Typha angustata*, *Trapa natans*, *Jussiaea perennis*, *Nelumbo nucifera*, *Potamogeton cristatus* and *Nymphoides cristata*.

A 2.80 m deep trench was dug on the eastern dry flank of the lake (26°58'44.78"N, 80°19'12.37"E), located about 150 m north of the Sanchankot excavation site for the collection of sediment profile. Twenty-eight samples at 10 cm interval each were picked up from this trench profile for analysis. Beyond 2.8 m depth, further collection of samples was not done due to the presence of organic carbon deficient coarse sand as well as oozing out of subterranean water. In addition, five bulk radiocarbon dating samples, at larger intervals, were also taken from the trench.
The sediment composition is characterized by the presence of sand, silt and clay in variable fractions (Figure 2). The topmost lithounit consists of sticky, yellowish silty-clay with sand. Underlying this is blackish, sticky silty-clay intercalated with sand layers. This is followed by blackish, sticky silty-clay with minor amount of sand. Subsequent lithounit is marked by the increasing fraction of sand with silt and clay, and it overlies the yellow sandy silt with minor clay zone, which is the thickest lithounit in the trench profile. The bottommost stratum is composed of coarse sand (Table 1).

Five radiocarbon dates have been determined for the trench profile at broader intervals (Table 2). For the lowermost zone the sedimentation rate has been calculated as 1,564 year/cm using the calibrated ages 42,490 ± 3,550 yrs BP at 268.5 cm depth and 25,290 ± 1,690 yrs BP at 257.5 cm depth, whereas it is 14.19 yrs/cm for the intermediate zone lying just above the barren zone taking into account the cal ages 4,960 ± 520 yrs BP at 195 cm depth and 3,860 ± 400 cal yrs BP at 117.5 cm depth. For the upper part of the profile, sedimentation rate has been calculated as 30.22 yrs/cm using the dates 3,860 ± 400 cal yrs BP at 117.5 cm depth and 3,180 ± 220 cal yrs BP at 95 cm depth. These sedimentation rates have facilitated in the extrapolation of more dates, i.e. 13,560 cal yrs BP at 250 cm depth, 5,260 cal yrs BP at 210 cm depth, 4,760 cal yrs BP at 185 cm depth and 1,200 cal yrs BP at 30 cm depth in order to define the temporal changing vegetation pattern and corresponding climatic episodes in the region prior to 42,490 cal yrs BP.

Ten grams of sample was treated with 10% aqueous KOH and 40% HF solutions to deflocculate the pollen/spores and to remove silica from the sediments respectively. Thereafter, the standard technique of acetylation using acetylation mixture (9 : 1 ratio of acetic anhydride and concentrated sulphuric acid) was followed. The samples for microscopic examination were prepared in 50% glycerin solution.

The trench samples analysed from Jalesar Lake were found potential in pollen/spore content (Figure 3). The pollen sums vary from 200 to 300 depending on the productivity of the samples. They exclude the pollen of aquatic plants and fern spores due to their local origin. The percentage frequencies of the retrieved taxa have been calculated in terms of the total terrestrial pollen only. The retrieved pollen taxa grouped as trees, shrubs, herbs, ferns, algal remains and drifted are put in the same order in the pollen diagram.

For loss on ignition determination ~ 5 g, −200 mesh sample powder was taken in quartz crucibles and kept in
oven for 12 h at 110°C for removal of moisture present in the samples. Weight loss was measured at 550°C and 950°C respectively, so as to determine the organic carbon and carbonate carbon present in the sample. This technique is rapid and provides fairly consistent results comparable to those obtained using carbon analyser and therefore widely used.15,16

To delineate the sequential changes in the vegetation and corresponding climate events in the region, the pollen diagrams have been divided into five distinct zones (JL-I to JL-V). The pollen zones are designated with the initials ‘JL’, i.e. name of the investigation site ‘Jalesar Tal’ and are described as below (Figure 2).

Pollen zone JL-I (280–250 cm) with a radiocarbon date of 42,490 ± 3,550 cal yrs BP and 25,290 ± 1,690 cal yrs BP, covering a time-span of prior to 42,490 to 13,560 cal yrs BP is characterized by the dominance of non-arboreals over arboreals. A few tree taxa, viz. Syzygium (1.4–1.32%) and Prosopis (1.4–3.12%) are recorded sporadically in low frequencies. Fabaceae (3.0–4.24%) representing the shrubbery vegetation is consistently recorded.

The non-arboreals are marked by much higher values of Poaceae (36.0–47.7%) followed by Chenlo/Am (8.3–16.4%), Tubuliflorae (10.6–14.8%), Liguliflorae (2.27–5.66%), Caryophyllaceae (1.56–3.03%), Urticaceae (3.12–3.5%) and Malvaceae (1.5–3.12%) in moderate to high frequencies. The wetland taxa, viz. Cyperaceae (1.52–8.33%), Solanum (2.2–2.8%) and P. plebeium (6.06% in one sample only) are recovered in appreciable values, though sporadically. Potamogeton (1.4–2.3%), Typha (1%) and Botryococcus (0.75–2.83%) represent the aquatic flora. Fern monolete spores (2.27%) are met with in one sample only. Fungal sporads, viz. Curvularia, Nigrospora and Alternaria are also encountered in moderate amounts. The organic carbon values are almost consistent; however, the carbonate carbon shows a decreasing trend.

The Barren zone (250–210 cm) covering the time-span of 13,560 to 5,173 cal yrs BP has not yielded enough pollen, probably due to their non-preservation in the sediments. The sediment composition is almost the same as in zone-I; however, the decreasing organic carbon trend continues in this zone, except in the upper part from where the trend shows gradual increase. The carbonate carbon has increased, showing a fluctuating trend. The intermittent presence of calcrite and non-preservation of pollen may have some other implications, as discussed in the subsequent sections.

Pollen zone JL-II (210–185 cm) with solitary radiocarbon date of 4,960 ± 520 cal yrs BP and encompassing the period 5,260 to 4,760 cal yrs BP also demonstrates the relatively higher frequencies of non-arboreals. However, a large number of trees turn up in this zone. Syzygium (8.0%) shoots up in the beginning only. Terminalia (3.47–5.35%), Holoptelea (1.78–2.64%), Anacardiaceae (1.73–1.89%), Dodonea, Barringtonia, Bombax ceiba (1.78% each), Acacia, Aegle marmelos (1.73% each) and Hippophae (0.81%) appear for the first time in variable frequencies. Fabaceae (2.6%) and Grewia (0.67%) represent the shrubs.

Among the non-arboreals, Poaceae (44.6–46.4%), Tubuliflorae (4.46–17.4%), Liguliflorae (8.0%), Caryophyllaceae (5.36%), Chenlo/Am, Malvaceae, Brassicaceae (1.78–3.57%), Chrozophora, Xanthium and Borreia (1.78% each) are in moderate to high frequency. Cerealia (2.67%) appears for the first time. Marshy taxon, Cypreae (8.9%) is met with in high frequencies, whereas P. plebeium (7.13%) and P. serrulatum (2.73%) are retrieved intermittently. Potamogeton (1.7%) is the sole representative of aquatic vegetation. Freshwater algae–Botryococcus and Pseudoschizia (0.89% each) are scantly. Fern spores (monolete 2.6% and trilete 4.4%) are sporadic. The significant and consistent increase in organic carbon with a complementary reduction in carbonate carbon is also supporting the vegetational pattern of the region.

Pollen zone JL-III (185–95 cm) with two radiocarbon dates 3,860 ± 400 and 3,180 ± 220 cal yrs BP and with a time bracket of 4,760 to 3,200 cal yrs BP demonstrates further increase in trees. M. indica (1.16–5.23%), Adina cordifolia (1.7–6.4%), Capparis (1.28–5.26%), Emblica officinalis (0.64–1.92%), Sterculia (1.74–4.13%) and B. monosperma (0.64–1.7%) are the new entrants with increased values together with Annona cf. squamosa (0.58–1.75%), Dalbergia (0.64–3.41%), Tectona grandis (1.29%), Holarrhena and Schleichera (1.28% each), Meliaeaceae (0.81–1.21%) and Bauhinia (0.6%) which are scanty. Terminalia (0.64–6.4%), Barringtonia (1.28–4.5%), Bombax ceiba (0.58–3.47%), Syzygium (1.6–7.74%) and A. marmelos (7.21) are recorded in good amounts. Acacia (0.5–0.9%) and Combretum (1.92%) are in moderate to low frequencies, whereas Holoptelea (3.22%), Prosopis (1.73%) and Anacardiaceae (0.5%) are sporadic. The shrubby taxon, Fabaceae (0.585–5.45%) reveals a rising trend. Rutaceae (1.75%), Aspidopterys (1.09%) and Trewia (0.73%) are infrequent.

The non-arboreals Poaceae (24.5–68.6%) and Cerealia (0.73–11.03%) are met within higher frequencies than in the previous zone, whereas the culture pollen taxa, Chenlo/Am (0.917–9.12%), Artemisia (0.73–4.67%), Caryophyllaceae (1.09–3.47%), Brassicaceae (0.68–2.72%), Cucurbitaceae (1.92%) and Sesamum indicum (0.73–0.87%) are also recovered in variable frequencies. Others, viz. Tubuliflorae (0.87–9.09%), Liguliflorae (0.87–3.64%), Ranunculaceae (0.36–3.44%), Malvaceae (0.73–2.63%) and Convolvulaceae (0.68–3.5%) have improved values. Lamiaceae and Lantana (0.73% each) are extremely low. Marshy taxa, viz. Cyperaceae (0.5–6.1%), Polygonum plebeium (1.16–6.5%), Solanum (1.16–1.92%) and Polygonum serratulatum (1.62–1.73%) are frequent. Apiaceae (4.51%) and Liliaceae (0.64%) emerge for the first time with aquatic element–Trapa (5.1%) in one sample each. Typha (0.68–6.65%) and
Potamogeton (0.73–4.13%) have higher frequencies than in the pollen zone JL-II, except for meagre presence of Lemna (0.87%). Fern spores (monolete 0.36–4.67% and trilete 0.64–12.2%) together with Botryococcus (1.7–9%) and Pseudoschizia (3%) show improved values. The maximum organic carbon and minimum inorganic carbon values also support relatively favourable conditions.

Pollen zone JL-IV (95–30 cm) covering the time-span of 3,200 to 1,200 cal yrs BP shows reduction in numbers and frequencies of arboreals and corresponding improvement in non-arboreals. M. indica (1.2–2.17%), Holoptelea (0.42–1.96), Dodonea (1.4–1.96%), E. officinalis (0.97%) and Terminalia (0.64%) decline sharply compared to the preceding zone. However, Acacia (0.813–4.9%) and Bombax ceiba (0.81–2.17%) are found with increased values. Prosopis (2.75%) is encountered in one sample only. Moringa (0.81–2.17%) appears in good values for the first time. Shrubby element, Mimosahamata (8.6–32.52%) appears abruptly with increased value in the middle with Tinospora (1.49–2.17%) in the upper half. Fabaceae (0.87–0.91%) is infrequent.

Ground vegetation shows some enhanced values of Poaceae (70.6–68.7%) in the lower part; however, it declines thereafter. Cerealia (3.6–12.12%) followed by Brassicaceae (0.91–4.7%) and Urticaceae (0.94–2.94%) denote much improvement, whereas Chenio/Am (0.91–6.6%) remains static. Caryophyllaceae (0.97–1.8%) and Artemisia (0.98–3.36%) are sporadic. The heathland taxa, viz. Tubuliflorae (1.6–4.9%) and Liguliflorae (1.62–2.32%), Malvaceae (0.60–3.26%) and Ranunculaceae (0.60–2.94%) are marked by increased frequencies compared to Justicia (0.60–2.17%) and Boerhavia (0.98%). Marshy taxon, Cyperaceae (0.47–2.94%) declines much compared to preceding pollen zone, whereas P. plebeium (0.81–26.02%) increases considerably. Aquatic elements, namely Typha (1.21–3.26%) and Potamogeton (0.47–1.96%) are as before. Trapa (0.96%) is recorded poorly towards the top of this zone. Botryococcus (1.08–5.6%) exhibits lower values in contrast to the preceding zone. Fern monolet spores (0.47–4.58%) are consistent with members of Asteraceae, Chenopodiaceae/Amaranthaceae, Caryophyllaceae and Urticaceae in variable proportions. A few trees such as Syzygium and Prosopis coupled with thickets of Fabaceae were sparsely distributed upon the open grassland vegetation under a regime of cool and dry climate. The meagre record of the aquatic elements, viz. Typha, Potamogeton and freshwater alga – Botryococcus suggests the prolonged existence of the lake with small dimension. The lake was probably encircled with an ill-developed marsh all around, which is well portrayed by the retrieval of wetland taxa such as sedges (Cyperaceae), P. plebeium and Solanum. The relatively low organic carbon values also suggest limited vegetation in the lake vicinity; however, the higher inorganic carbon values could be linked to large residence time allowing sedimentary digenetic processes to precipitate carbonates. The presence of coarse sand at the bottom, i.e. beyond the depth of 2.80 m in lithocolumn reveals that earlier the Sai River was an active channel at the present Jalesar Tal site, which later shifted eastwards as seen today. The coarser sediment (river channel sediment) at the base of the lake sequences has been reported from several other locations by many workers, which testifies that the lakes were formed in a result of neotectonic activity responsible for river migration. Thus, it could be surmised that the abandonment of the river course paved the way for the development of the lake basin.
age. Interestingly, an increasing trend in carbonate carbon along with reduction in organic carbon suggests favourable conditions for oxidation (calcrete formation) due to fluctuating water table as it is also a product of climate amelioration and adequately addressed by earlier workers. The time bracket of the barren zone also coincides with the period of neotectonic activity (~9–5 ka) in the region which resulted in interruption in the normal depositional regime. This hiatus in the sequence might have resulted due to regular/intermittent washing away of the sediments over a larger time interval as stated above. The sediment deposition since 5,173 cal yrs BP in the lake basin has been restored under a ponding environment, initially bringing the reworked sediment from the catchment region as a result of increasing precipitation. Similar evidence of discontinuity in the lithological sequence has also been recorded from Karewa deposits of Kashmir Valley.

The pollen record of 5,260 to 4,760 cal yrs BP (pollen zone JL-II) shows an appreciable number of moist tree elements, viz. Holoptelea, Terminalia, Barringtonia, Hippophae and Dodonea along with drought-tolerant trees such as Acacia, B. ceiba and Aegle marmelos immigrated to the area contiguous with the lake, in addition to those which occurred earlier. This enrichment in the vegetation mosaic implies that the restricted groves of the forests, interspersed with open grasslands, got established in the region in response to amelioration of climate with the onset of moderate monsoon precipitation. By this time the development of organic-rich edaphic condition might have also favoured the incursion of a good number of trees in the region. Interestingly, the debut of Cerealia along with associated cropland weeds, viz. Chenopodiaceae/Amaranthaceae, Brassicaceae, Cannabis sativa, Artemisia and Rumex reflects the acceleration in agrarian practice and other human activities owing to favourable climate in the region. Further, the first encounter of Trapa (water chestnut) pollen at the level dated to ca 4,700 cal yrs BP reveals that the lake extended up to the present dried investigated part, studded to the excavated mound. The Trapa fruits would have been consumed by the settlers in their subsistence. The expansion of the lake is also manifested by the steady presence of aquatic elements, viz. Typha and Potamogeton as well as the improvement in the freshwater algae, viz. Botryococcus and Pseudoschizia. The presence of pollen of Pinus and Cedrus in the sediments denotes their transportation largely by water from the Himalayan region. Between 3,200 and 1,200 cal yrs BP (pollen zone JL-IV) the diminishing trend of the prominent trees, viz. M. indica, Terminalia, Sapotaceae and Holoptelea and disappearance of a large number of the earlier existing tree taxa depict the depletion in floristic set up of the forest groves. They became further sparse as well as less varied and were confined into much restricted pockets separated by the wider grassland. A gradual but decreasing trend in organic carbon percentage and the complementary increase in inorganic carbon also support the changing vegetation pattern in the lake vicinity. Hence, this substantial change in the vegetation scenario is inferred to be the outcome of the prevalence of a warm and relatively less humid climate due to the weak SW monsoon. However, the agricultural practices continued at almost the same pace because the Cerealia and other concomitant cropland weeds do not demonstrate any change. The steady decline in the aquatic plants signifies that the lake became shallower, attributed to deteriorating climatic condition.

Since 1,200 cal yrs BP (pollen zone JL-V), the rapid dwindling frequencies of trees allowed the ground flora to flourish. This change in the vegetation and inverse organic–inorganic carbon curves depict that the region...
was mainly supported by the grassland indicating further reduction in monsoon precipitation and the region experienced a warm and dry climate. In the recent past, the excessive anthropogenic interference has made the topsoil vulnerable to erosion and ultimately inhibiting the forest elements to propagate. However, the improvement in *Acacia* is attributed to its recent plantation under the afforestation programme initiated by the Government. The lake has become almost dry and ephemeral; nevertheless, the agricultural practice has been maintained almost with the same magnitude, probably to cope with the food security of the escalating human population during the last millennium. This is evidenced from the steady presence of Cerealia and the concomitant cropland weeds.

Thus, from the present study it is inferred that the presence of coarse sand at the lake base, including other geomorphological evidences suggest that the Jalesar Tal was formed prior to 42,490 cal yrs BP, most likely in an abandoned channel of Sai River presently flowing about 1.5 km northeast of the study site, due to river migration in the interfluve region. The pollen sequence and organic–inorganic carbon curves deduce that around 42,490–13,560 cal yrs BP, this region supported grassland with scanty trees under a cool and dry climate with reduced monsoon precipitation. However, the paucity of pollen during 13,560–5,260 cal yrs BP is linked to the upwarping phase of the Ganga Plain owing to rapid erosion and reworking of the sediments. Between 5,260 and 4,760 cal yrs BP, the groves of forest interspersed with grassland got established with the incursion of a large number of trees in response to amelioration of climate attributed to moderate monsoon rain and the increase in organic carbon and moisture content coupled with the influx of fine-grained sediment in the lake. The first encounter of Cerealia pollen signifies the onset of low-paced, cereal-based agricultural practice in this part of the Central Ganga Plain. The forest groves became dense and diversified around 4,760–3,200 cal yrs BP with the invigoration of the SW monsoon and consequently a warm and humid climate prevailed in the region. Between 3,200 and 1,200 cal yrs BP depletion of the arboreals allowing the coarser sediments to creep into the lake suggests that the climate changed to warm and less humid owing to weakening of the SW monsoon. Since 1,200 cal yrs BP, a warm and dry climate prevailed in the region due to further reduction in monsoon as testified by the sharp decline in arboreals and aquatic plants. However, agricultural practices continued with same pace to sustain the increasing human population.


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