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 *Syzygium* 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 system having their own internal drainage pattern[1]. The formation of these water bodies has occurred due to the disruption of fluvial channels around 9–8 ka in response to tectonic activity and base-level changes[2,3]. These lakes are potential source for palaeoclimatic and palaeovegetation studies; however, not many sincere efforts have been made to understand the palaeoclimatic shifts, floristic antiquity and inception of agrarian activities in this vast alluvial tract, barring sketchy pollen-based information from the Central Ganga Plain[4–6]. Recently, studies pursued on some lakes from this region have deciphered the palaeovegetation, palaeoclimatic changes, lake-level fluctuations and anthropogenic activities during the Late Quaternary Period based on pollen, geological and isotopic evidences[3,7–12]. Now, it has become desirable to extend the pollen studies to other areas so that a comprehensive picture of the changing vegetation scenarios and contemporary climatic events during the Late Quaternary Period could be reconstructed in the regional perspective. Further, emphasis is to be given to deduce the anthropogenic activities leading to the Holocene domestication of plants and the subsequent course of agricultural practice with respect to monsoon variability. To address all these issues, a 2.8 m deep sediment profile has been analysed for its pollen composition and organic–inorganic carbon distribution from Jalesar Tal, Unnao District, Uttar Pradesh, to generate and refine the database on palaeovegetation and palaeoclimate in the Central Ganga Plain during the Late Pleistocene–Holocene.

The Jalesar Tal, an ancient lake, is situated in the vicinity of Sanchankot between lat. 26°58′44.48″N and long. 80°19′11.31″E in the Safipur Tehsil, Unnao District on the Sandila–Bangarmau metalled road on the right bank of Sai River, a tributary of the Gomti River (Figure 1). It is about ~ 40 km northeast of Safipur and ~ 67 km northwest of Unnao township following the road route. The lake measuring about 1 km in circumference is oval in shape. It gets filled with water during monsoon season and remains almost dry during rest of the year, except a little water towards the centre. Most of the adjoining areas are under paddy cultivation by the local populace. The area is level plain with average elevation of 117.82 m amsl. The lake is in close proximity of the Neolithic–Chalcolithic settlement site – Sanchankot, where extensive excavations have been carried out by the Department of Ancient Indian History and Archaeology, Lucknow University, in order to know the cultural history of the Ganga Plain through the retrieval of artefacts. These excavations have yielded a cultural sequence of five periods, viz. Painted Grey Ware (PGW), Northern Black Polished Ware (NBPW), Shunga–Kushana, Gupta and Rajputa. However, the recovery of red-ware and large number of terracotta human figurines from the trench excavated at Jalesar mound suggests that the Kushana Culture flourished in the vicinity of the lake during AD 100–200 (D. P. Tiwari, unpublished information).

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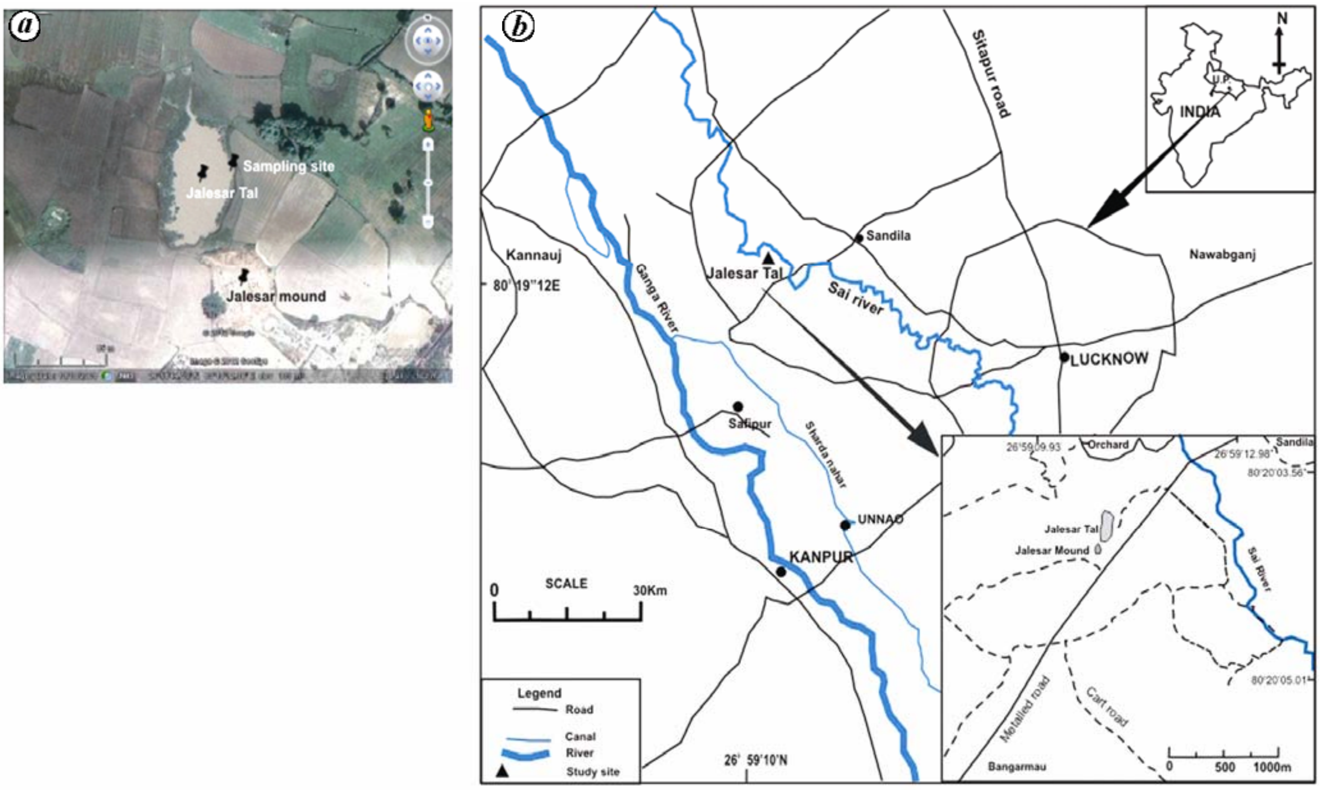

Figure 1. ***a***, Google map showing the location of Jalesar Tal. ***b***, Map showing a part of Unnao District in Uttar Pradesh. Inset shows exact location of Jalesar Tal.

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[13]. 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-tritis* occur sparsely distributed in the scrub forests. *Tamirandus 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. thymifolia*, *Mazus japonicus*, *Evolvulus alsinoides*, *Justicia simplex*, *Rungia pectinata*, *Oxalis 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 mucronatus*, *Polygala chinensis*, *Rotala rotundifolia*, *Hygrophila auriculata* and *Polygonum plebeium*. The aquatic vegetation includes *Lemna polyrriza*, *Typha angustata*, *Trapa natans*, *Jussiaea perennis*, *Nelumbo nucifera*, *Potamogeton cristatum* 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.

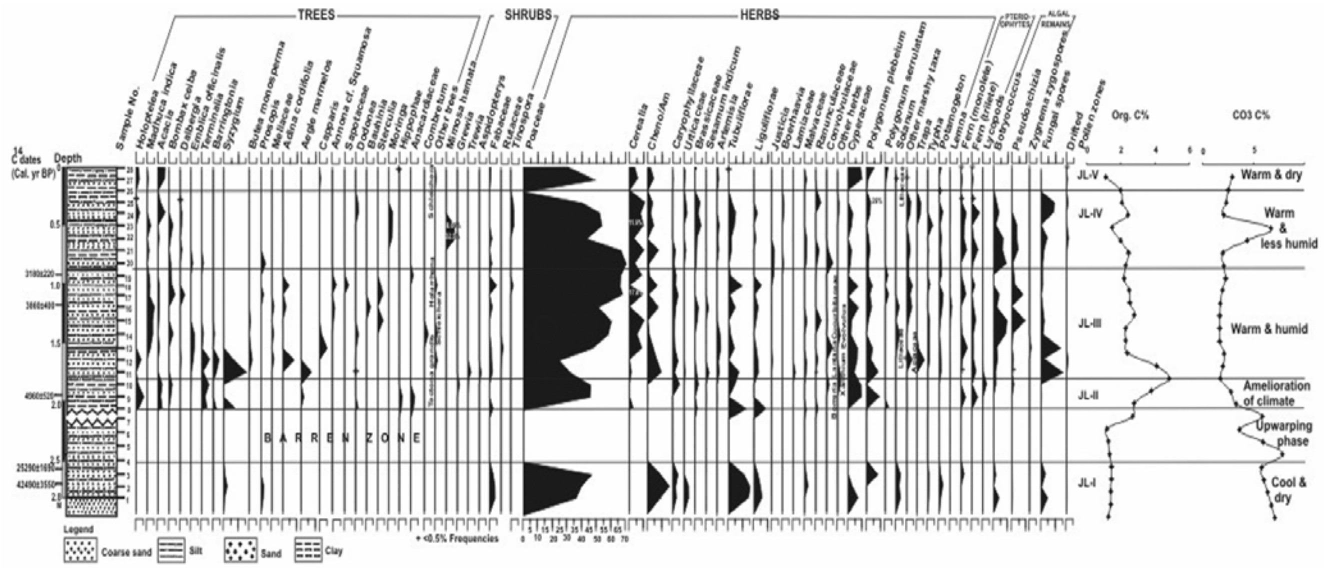

Figure 2. Pollen and organic–inorganic carbon distribution diagram from Jalesar Tal, Unnao District.

Table 1. Lithological details of the trench profile

Depth (m)	Lithology
0.0–0.30	Sticky, yellowish silty-clay with sand
0.40–0.90	Blackish, sticky, silty-clay with intercalated sand layers
0.90–1.85	Blackish silty-clay with minor sand
1.85–2.10	Blackish silty-clay with sand
2.10–2.80	Yellowish sandy silt with minor clay
2.80–3.00	Coarse sand

Table 2. Radiocarbon date for the trench profile

Depth (cm)	Lab. ref. no.	Cal age yrs BP
95	BS-3075	3,180 ± 220
117.5	BS-3071	3,860 ± 400
195	BS-3076	4,960 ± 520
257.5	BS-3069	25,290 ± 1,690
268.5	BS-3070	42,490 ± 3,550

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 acetolysis[14] using acetolysing 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

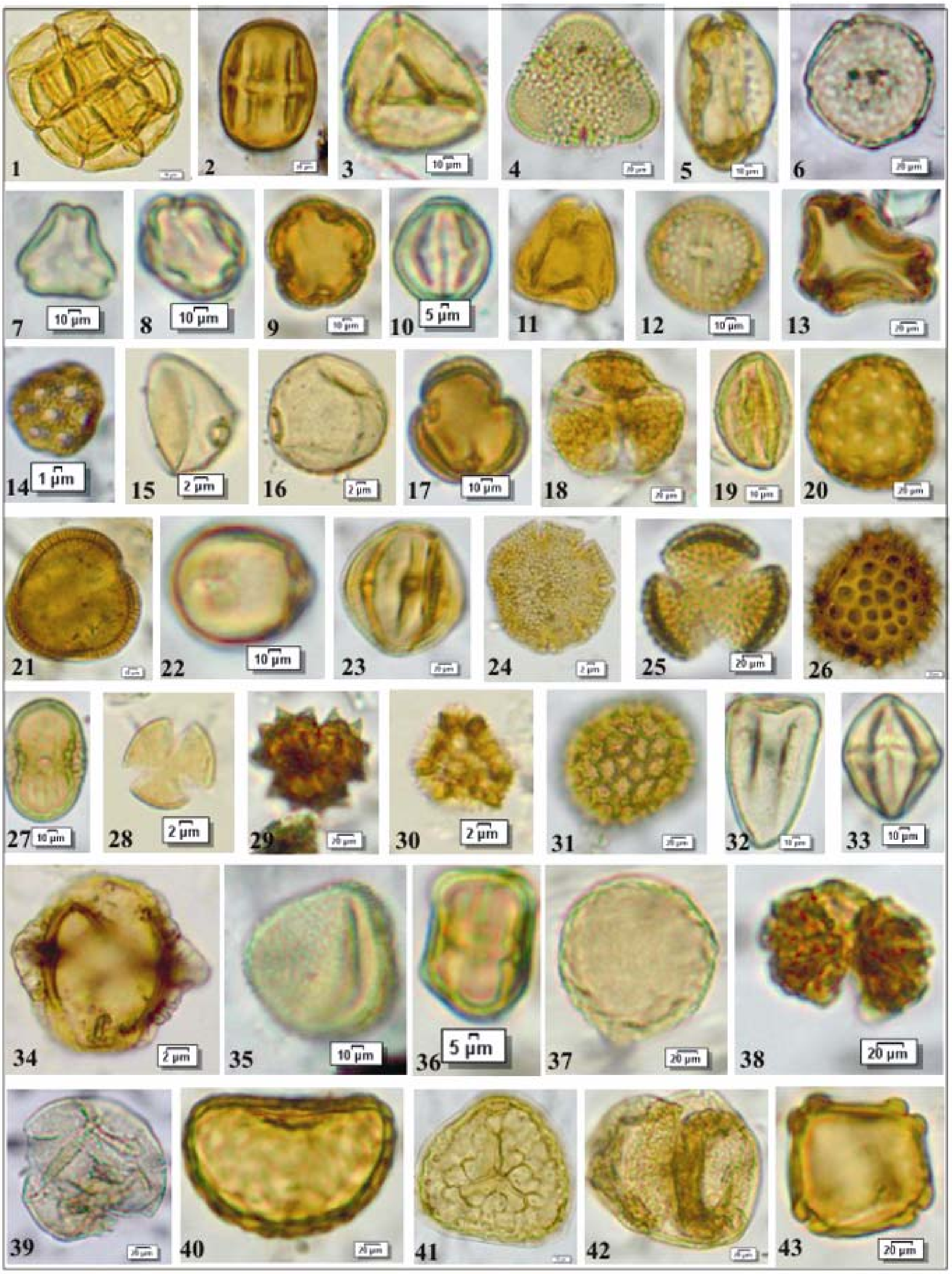

Figure 3. Various pollen grains recovered after maceration from samples of different zones. 1. *Acacia*, 2. *Madhuca indica*, 3. *Schleichera*, 4. *Bombax ceiba*, 5. *Barringtonia*, 6. *Holoptelea*, 7. *Syzygium*, 8. *Terminalia*, 9. *Emblica officinalis*, 10. *Adina cordifolia*, 11. *Symplocos*, 12. *Aegle marmelos*, 13. *Combretum*, 14. Caryophyllaceae, 15. Cerealia, 16. Poaceae, 17. *Artemisia*, 18, 19. *Prosopis*, 20. Cheno/Am, 21. Convolvulaceae, 22. *Trewia*, 23. *Moringa*, 24. *Sesamum*, 25. Brassicaeae, 26. Malvaceae, 27. *Justicia*, 28. Ranunculaceae, 29. Tubuliflorae, 30. Liguliflorae, 31. *Polygonum serrulatum*, 32. Cyperaceae, 33. *Solanum*, 34. *Trapa*, 35. *Typha*, 36. *Polygonum plebeium*, 37. Zygospore *Zygnema*, 38. *Botryococcus*, 39. *Potamogeton*, 40. Fern (monolete), 41. Fern (trilete), 42. *Pinus*, 43. *Alnus*.

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 to13,560 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 shrubby vegetation is consistently recorded.

The non-arboreals are marked by much higher values of Poaceae (36.0–47.7%) followed by Cheno/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 spores, 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 calcrete 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%), Cheno/Am, Malvaceae, Brassicaceae (1.78–3.57%), *Chrozophora*, *Xanthium* and *Borreria* (1.78% each) are in moderate to high frequency. Cerealia (2.67%) appears for the first time. Marshy taxon, Cyperaceae (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 scanty. 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), Meliaceae (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, Cheno/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 serrulatum* (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, *Mimosa hamata* (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 Cheno/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 monolete spores (0.47–4.58%) are consistent with moderate values, whereas triletes (1.41–4.9%) are recovered in low frequencies. The relatively decreasing trend in organic carbon and complementary increase in carbonate carbon further support the changing vegetation pattern in the region.

Pollen zone JL-V (30 cm) with the temporal range of 1,200 cal yrs BP to Present depicts the reduction in the number and frequencies of arboreals. *Acacia* (5%) and *Holoptelea* (1.5–2%) are recorded in moderate values. *Capparis*, *Schleichera* (1% each) and *Hippophae* (0.46%) are extremely low. Fabaceae (1%) represents the shrubby vegetation. The non-arboreals, Poaceae (30–48%) together with Cheno/Am (2–3%), *Artemisia* and *Cannabis sativa* (1–1.5% each) are found in good frequencies. Cerealia (2–5%) is consistently present as in the preceding pollen zone. Brassicaceae, Malvaceae (1% each) and Tubuliflorae are meagre. Marshy element, Cyperaceae (8–10%) have higher values in contrast to *P. plebeium* (2–8%), *P. serrutatum* (1–2%), *Solanum* and Liliaceae (0.46% each), which have reduced values. *Potamogeton* (1%), the only aquatic element, is feeble. Fern (monolete and triletes 0.46–1%) decline sharply. The pollen of *Cedrus* (1%) and *Pinus* (0.46%) are scarce. The complementary inverse trend in organic–inorganic carbon is maintained in this zone too.

The pollen and organic–inorganic carbon trend of the sediment profile from Jalesar Tal has unravelled the sequential alterations in the vegetation pattern, coeval climatic episodes and lake-level fluctuation since 42,490 cal yrs BP as well as the commencement of incipient agrarian practice during the mid-Holocene and its later course in the Central Ganga Plain, which could most likely be the aftermath of monsoon variability.

The pollen sequence demonstrates that prior to 42,490 and up to 13,560 cal yrs BP (pollen zone JL-I), this region of the Central Ganga Plain was largely occupied by vast stretches of open herbaceous vegetation largely comprising grasses together 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 sparingly 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 as a result of neotectonic activity responsible for river migration[1–3]. Thus, it could be surmised that the abandonment of the river course paved the way for the development of the lake basin.

The sandy clay sediment lying between the depths of 2.50 and 2.10 m in the lithocolumn covers a time-span of 7,387 years. However, the palaeovegetational inference could not be drawn due to paucity of pollen in the sediments; hence termed as barren zone. The sediment nature does not show any marked change from zone-I, except some reduction in grain size and organic carbon percentage. 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[1]. 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[2,3]. 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[17].

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 pollen suggests the initiation of incipient cereal-based agricultural practice in the region at low pace. Contrary to this, the pollen[8] and phytoliths[18] evidence obtained from the Lahuradewa Lake in eastern Uttar Pradesh denotes the inception of the agrarian practice ~ 7,000 cal yrs BP, probably due to early setting up of the favourable climate. The ground vegetation was still dominated by grasses together with members of Asteraceae, Malvaceae and Ranunculaceae. The marshy fringe along the lake margin became wider as indicated by the rise in wetland taxa, namely sedges *P. plebeium* and *P. serrulatum*, in contrast to the preceding phase. However, the lake did not undergo any major change in its status, because the aquatic flora remained almost as before. The organic–inorganic carbon curves (Figure 2) further support gradual increase in the favourable conditions supporting enhanced and diversified vegetation during this phase.

Subsequently, around 4,760 to 3,200 cal yrs BP (pollen zone JL-III) owing to further invasion of moist trees such as *M. indica*, *A. cordifolia*, *Dalbergia*, *E. officinalis*, *Annona* cf. *squamosa*, *Butea monosperma*, *Capparis*, *Sterculia*, *Combretum* and Meliaceae in a progressive manner as well as spurts in *A. marmelos*, *Syzygium*, *B. ceiba* and *Terminalia* the forest groves became dense and diversified. However, these forest groves were still interspersed with stretches of open herbaceous vegetation dominated by grasses together with Asteraceae, *Convolvulus* and Ranunculaceae. This significant change in the floristics and highest/lowest values of organic/inorganic carbon clearly elucidates that the region experienced a warm and humid climate in response to intensification of the southwest monsoon. An equivalent climate with identical vegetation scenario has also been inferred from Lahuradewa Lake[8], located about 200 km east of the present site between 5,000 and 2,000 cal yrs BP. This temporal variability of ca 300 years could be attributed to the early advent of the active SW monsoon in eastern Uttar Pradesh, as also seen today. This phase of suitable climatic condition falls to a larger extent within the Period of Climatic Optimum[19], which has been noticed globally between 8,000 and 4,000 cal yrs BP. The rising trend 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 top-soil 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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