Paddy cultivation during early Holocene: evidence from diatoms in Lahuradewa lake sediments, Ganga Plain

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Lahuradewa lake deposits, adjacent to the Lahuradewa archaeological site were rich in diatoms, going back to about 10 kyrs. The diatoms are grouped into four categories, namely, planktic, benthic, paddy field and anthropogenic-influenced. The variation in planktic and benthic forms reflects changes in the water budget of the lake in response to the change in rainfall, viz. more planktic in humid phases and less planktic in dry phases. These changes correspond to the changes identified by other proxies, namely phytolith. Paddy field diatoms are present in good numbers since about 8 ka along with anthropogenic diatoms; their numbers increase during dry phases and decrease in humid phases. This supports the contention that humans were living in this area since early Holocene and agriculture activity started around 8 ka. Presence of paddy field diatoms in lake sediments is rather unique. It is argued that the lake margin was used for paddy cultivation. Intermittently, sediment and organic remains namely paddy field diatoms, rice phytoliths and grass microcharcoal were washed from lake margin agricultural fields into deeper parts of the lake to be preserved in lake sediments.

Keywords: Agriculture, diatoms, Holocene, Lahuradewa lake, paddy field.

DIATOMS are siliceous microorganisms living in a variety of physico-chemical conditions both in marine as well as in freshwater conditions. They are sensitive to environmental conditions, and are both benthic and planktic in their habit. On land, diatoms occur mainly in rivers and lakes. Further, paddy fields which have water most of the time during the growth of paddy show specific types of diatoms, designated as paddy field diatoms.

The Lahuradewa archaeological site, Sant Kabir Nagar district, Uttar Pradesh is located adjacent to the Lahuradewa lake. The base of the Lahuradewa lake profile is dated about 10 ka BP and has been studied for phytolith and pollens to reconstruct the palaeoclimate, palaeovegetation and agricultural activity of the Holocene time[1–4]. The diatoms, including paddy field diatoms have been recorded[1,2,4]. In the present study, studies on diatoms were carried out and an attempt was made to reconstruct the evolution of the lake, paddy field cultivation and anthropogenic activity (organic pollution) around the Lahuradewa lake during the last 10 ka.

Paddy field diatoms can withstand the highly fluctuating water levels of paddy fields and are considered as indicators of rice cultivation in the past, when present in fossil assemblages[4]. A unique and interesting ecosystem is formed in paddy fields. The paddy field environment undergoes distinct seasonal changes caused by both natural conditions and human manipulations. One of the most important characteristics of the paddy field environment is the seasonal variation in water level[5]. Diatoms survive in paddy fields because they grow in water-logged condition. Most paddy-field diatoms belong to the benthic and tychoplanktonic communities which are tolerant to highly fluctuating water levels[6]. In India, the record of paddy field diatoms from the lake profile section is hitherto unavailable. However, few studies on the present day paddy field diatoms and their distribution in south India have been carried out in the Kuttanadu paddy fields (Kerala)[7] and in Rasipuram area (Tamil Nadu)[8].

The evidence for paddy field cultivation is substantiated by the occurrence of rice phytoliths recorded from the lake profile. In this study, based on rice phytolith, rice cultivation in the Ganga Plain (India) dates back to ~8300 years BP (ref. 1). Tracing the origin of domestication of rice, when, where and how it was brought into domestication and subsequent cultivation are extremely debatable[9–12]. Current findings from archaeology and genetics from Yangtze River valley (South China), suggest that rice was cultivated as early as 8000 years BP (ref. 9). However, recent studies from South East Asia and China argue that rice cultivation in China seems to predate that of India and is the most likely source of rice in Southeast Asia[13].

Area of study

The Ganga Plain makes the central part of the Indo-Gangetic foreland basin. It shows a large variety of alluvial landforms, namely active river channels, abandoned

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channels, meander cut-off, bhur ridges and water bodies (lakes and ponds). The present-day geomorphology of Ganga Plain is a result of climate change, tectonic activity and base level changes in the last 100,000 years[14,15]. Most of the lakes were formed during latest Pleistocene–Holocene due to channel abandonment related to the tectonics and changing climate[15]. Pollen studies, phytolith, geochemistry and C–O isotope study of the lake sediments of the Ganga Plain have helped in the reconstruction of palaeovegetation[3,16–20]. The vegetation of the Ganga Plain witnessed changes in the last few millennia due to climate change. It has been demonstrated that since at least 40,000 years BP the Ganga Plain was a grassland with few thickets[21]. Evidence of anthropogenic activity in the Ganga Plain is available in the form of microcharcoal (evidence of slash-burning activity) and *Cerelia* pollens since about 15,000 years BP (ref. 17).

The Lahuradewa lake (lat. 26°46′N; long. 82°57′E) is located adjacent to the Lahuradewa archaeological site near Lahuradewa village in Sant Kabir Nagar district (Figure 1). It is significant to note that the lake sediments and archaeological site at Lahuradewa both provide information on environmental changes and anthropogenic activity for the last 10,000 years. An attempt has been made to compare the results of the study of the lake sediments and the archaeological site[22].

The Lahuradewa area receives an annual rainfall of about 1400 mm (Figures 2 and 3). The lake is located on the upland interfluve surface and receives its water budget essentially from the monsoon rainfall. During monsoon season the lake expands on its margins. Later it becomes small and in extreme dry months it holds water only in a small part. The western part of the lake holds water in all the seasons, but eastern and northern parts of the lake are shallow and become dry after the monsoon.

Sampling and method of study

A 2.8 m deep trench was dug on the eastern dry part of the lake, where 28 samples at 10 cm interval were collected (Figure 4). Six samples were collected at different depths for radiocarbon dating. The samples were analysed for pollen studies, grain size, phytoliths and microcharcoal[1–4]. Lithologically, the lake profile is divided into three zones. The sediments are mainly silt and clay with

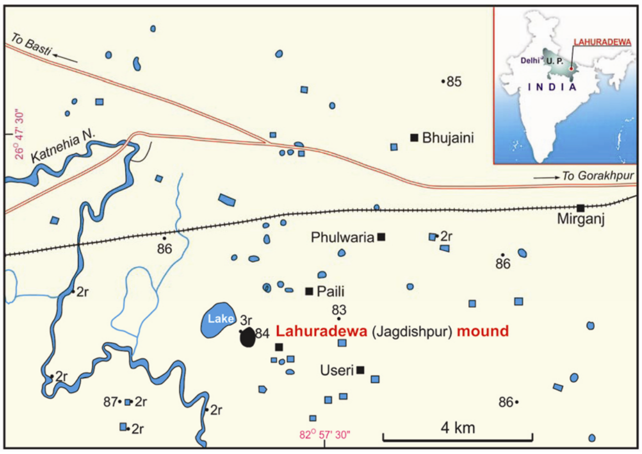

Figure 1. Location map of the Lahuradewa lake[1].

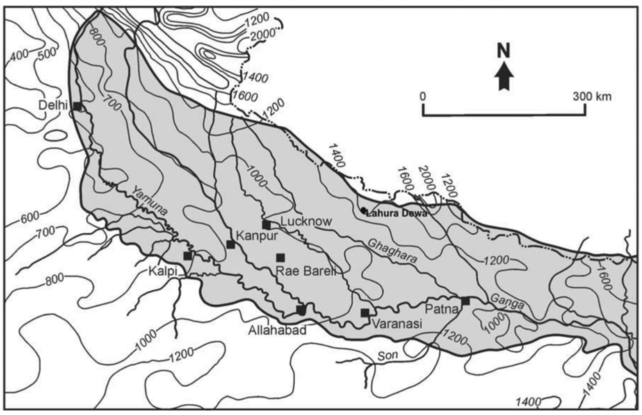

Figure 2. Distribution pattern of annual rainfall in the Ganga Plain[21].

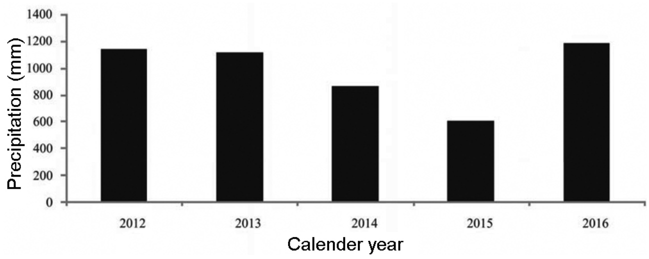

Figure 3. Mean annual precipitation of Sant Kabir Nagar district (in mm)

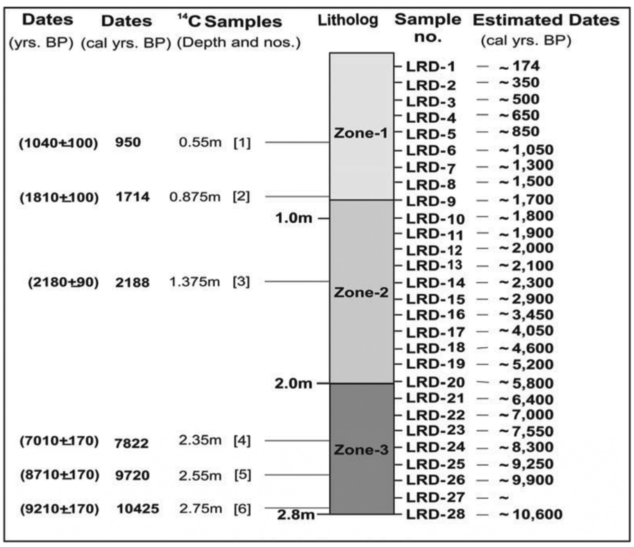

Figure 4. Lithological profile of Lahuradewa lake deposit along with ^{14}C dates and estimated ages (on the basis of sedimentation rate)[2].

Table 1. Distribution of diatoms in Lahuradewa lake profile

Smp no	*Cyclotella*	*Aulacoseira*	*Sellaphora*	*Eunotia* (lake form)	*Achnanthidium*	*Anomoeneis*	*Tabellaria*	*Bacillaria*	*Brachysira*	*Epithemia*	*Neidium*	*Diploneis*	*Psammothidium*	*Eunotia* (paddy field)	*Navicula*	*Nitzschia*	*Achnanthes*	*Frustulia*	*Craticula*	*Caloneis*	*Cocconeis*	*Amphora*	*Encyonema*	*Pinnularia*	*Surirella*	*Tryblionella*	*Stauroneis*	*Cymbella*	*Hantzschia*	*Gyrosigma*	*Gomphonema*	*Synedra*
LRD-1	0	0	32	81	23	2	65	6	6	0	0	0	0	40	65	17	1	0	15	0	0	20	15	52	1	8	5	0	3	0	131	3
LRD-2	0	0	7	45	2	0	7	2	1	0	0	0	0	22	53	3	0	3	2	0	0	1	10	32	0	0	3	2	2	0	48	0
LRD-3	0	0	0	47	1	0	13	0	0	0	0	0	0	23	7	7	0	0	0	1	0	0	7	6	0	0	5	0	0	0	21	0
LRD-4	0	5	0	53	12	0	8	0	0	0	0	0	0	26	6	10	0	0	0	1	0	0	8	1	0	0	1	0	0	0	11	0
LRD-5	0	5	0	83	17	0	12	0	0	2	0	0	0	53	17	20	0	0	10	0	0	0	10	10	0	0	3	0	0	0	40	0
LRD-6	5	0	0	107	22	0	15	0	0	6	10	1	0	92	21	0	0	0	10	6	0	0	6	5	0	0	3	0	1	0	66	0
LRD-7	1	0	0	183	16	0	15	0	0	0	3	22	0	92	7	3	0	0	3	0	0	0	12	15	0	0	0	0	0	0	57	0
LRD-8	0	0	0	91	13	0	8	0	1	0	10	3	0	46	2	0	0	0	2	0	0	0	3	1	0	0	5	0	0	0	57	0
LRD-9	0	0	5	94	12	0	5	0	0	0	0	3	0	47	17	5	0	0	6	0	0	2	7	5	1	0	2	0	0	0	85	7
LRD-10	5	6	0	41	1	0	0	0	0	0	0	16	0	20	1	2	0	0	1	0	0	0	0	0	0	0	0	0	2	0	6	1
LRD-11	10	80	2	74	2	0	0	0	0	1	0	47	0	37	4	2	0	7	3	0	0	2	0	3	3	0	2	0	3	0	92	0
LRD-12	5	57	1	98	2	0	0	0	0	0	0	70	0	49	3	2	0	10	0	0	0	2	1	0	0	0	10	0	0	0	98	16
LRD-13	17	187	0	58	6	0	0	0	0	0	0	37	1	29	10	5	0	11	2	1	0	1	1	2	0	0	1	0	1	0	32	7
LRD-14	2	16	5	29	11	0	0	1	0	0	0	0	0	14	102	5	20	21	0	0	0	1	0	3	0	0	11	0	0	0	10	7
LRD-15	20	22	7	229	53	0	0	0	0	0	0	10	0	114	45	5	7	5	2	0	0	11	10	2	0	0	16	0	0	0	45	15
LRD-16	10	40	0	199	30	0	0	0	0	0	0	0	0	99	0	15	0	10	5	0	0	13	0	10	0	10	0	0	0	0	142	50
LRD-17	10	57	0	267	27	0	10	0	0	0	0	30	0	133	10	12	2	5	12	9	60	5	0	10	0	10	0	0	5	0	115	0
LRD-18	10	82	0	210	20	0	2	0	0	15	0	0	0	105	15	7	0	0	0	0	20	8	0	5	0	5	0	0	0	0	140	0
LRD-19	0	42	0	97	2	0	0	0	0	0	0	0	0	48	10	12	0	2	7	0	23	12	0	4	0	0	0	0	10	0	40	7
LRD-20	10	25	0	173	5	0	15	0	0	0	0	0	0	87	21	2	0	0	2	2	20	2	0	0	0	0	0	0	0	0	8	0
LRD-21	15	175	0	100	5	0	3	0	0	0	0	0	0	50	25	10	0	2	15	10	0	0	2	2	0	0	0	0	0	0	50	0
LRD-22	45	80	0	117	5	0	7	0	0	0	0	15	0	58	70	10	0	10	25	22	0	0	1	57	0	0	15	0	0	0	55	0
LRD-23	50	185	0	23	0	0	0	0	0	0	0	0	0	12	7	0	0	0	0	5	0	0	0	0	0	0	5	0	0	0	30	0
LRD-24	42	182	0	13	1	0	2	0	0	0	0	0	0	7	5	1	0	7	0	6	0	0	0	0	0	0	0	0	0	0	15	0
LRD-25	65	155	0	20	0	0	0	0	0	0	0	0	0	10	0	7	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0
LRD-26	1	0	0	11	0	0	0	0	0	0	0	0	0	6	5	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRD-27	2	0	0	13	0	0	0	0	0	0	0	0	0	7	20	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LRD-28	0	0	0	10	0	0	0	0	0	0	0	0	0	5	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

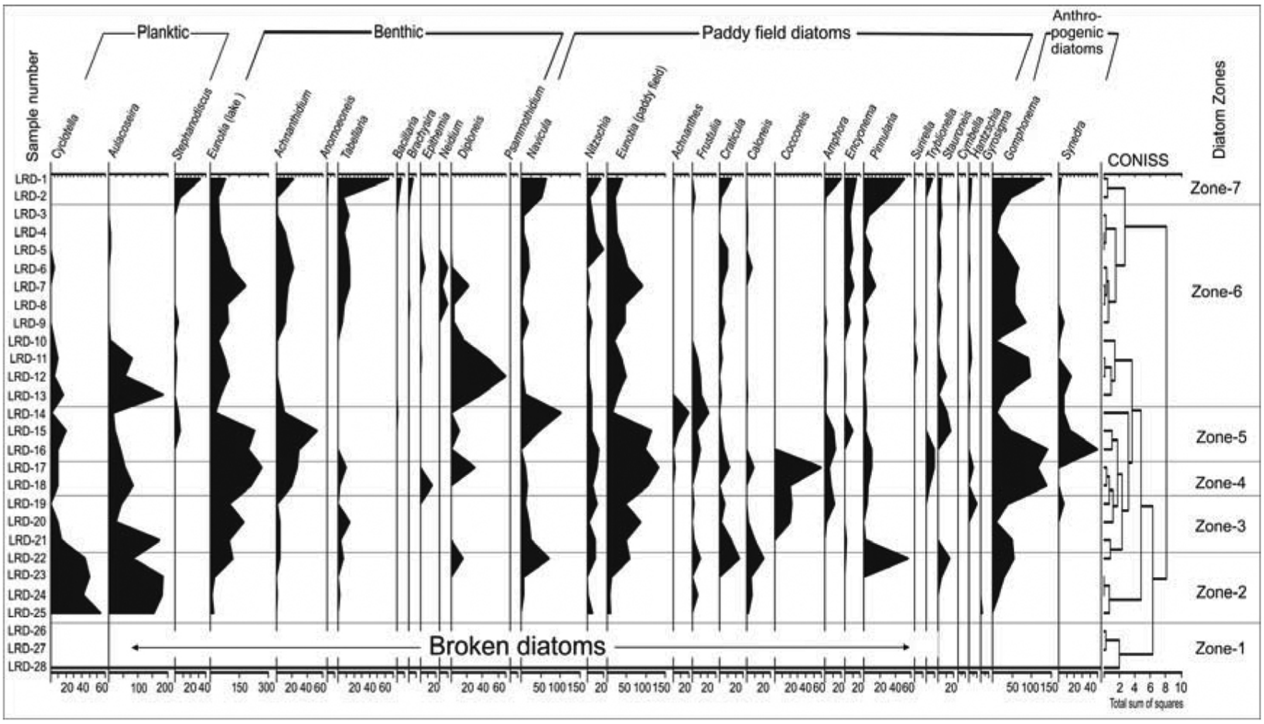

Figure 5. Range chart of the diatoms.

very little sand[2]. The three zones are: Zone 1 (0.00–0.90 m) – dark mud with rootlets; zone 2 (0.90–2.00 m) – dark mud; zone 1 (2.00–2.80 m) – black organic mud.

In the present study the diatoms of all the 28 samples were analysed. For diatom study, sediment samples were prepared using standard digestion procedures[23–25]. The identification was carried out using light microscopy (Olympus BH-2) with ×100 oil immersion objective. In total, 300–500 diatom frustules per sample were counted for statistical and graphical representations (Table 1). The identification, classification and counting of diatom frustules were as per standard procedure[26–28].

Diatom analysis

The diatoms are categorized into four groups namely:

(i) Planktic (centric): They are free floating and thrive in lake waters. *Cyclotella meneghiniana*, *Aulacoseira granulate.*

(ii) Benthic (pennate): They live on the top surface of lake sediments. *Eunotia*, *Achnanthidium*, *Anomoeoneis*, *Tabellaria*, *Bacillaria*, *Brachysira*, *Epithemia*, *Neidium*, *Diploneis*, *Psammothidium.*

(iii) Paddy field diatoms: They occur in the paddy fields. In case of Lahuradewa lake profile they are transported from lake margin paddy fields into the deeper part of the lake. *Navicula*, *Nitzschia*, *Eunotia*, *Achnanthes*, *Frustulia*, *Caloneis*, *Cocconeis*, *Amphora*, *Encyonema*, *Pinnularia*, *Surirella*, *Stauroneis*, *Tryblionella*, *Cymbella*, *Hantzschia*, *Gyrosigma*.

(iv) Anthropogenic diatoms: They occur in lakes where organic pollution is high. They are benthic in nature. *Gomphonema*, *Synedra*.

In the present study TILIA ver. 1.7 was used for preparation of graph and cluster analysis (CONISS) using square root transformation with dissimilarity coefficient (Edwards and Cavalli-Sforza's chord distance) to delineate zones for the diatoms. The CONISS cluster analysis was applied on the raw counts rather than percentages in order to get a holistic view of the diatoms in the study site. The distributions of different types of diatoms in the lake profile are shown in Figure 5. In all, 7 zones were identified for the 28 samples and 32 diatom datasets (Figure 5). The diatom diversity recovered from the Lahuradewa lake profile is shown in Figure 6.

Zone-1 (LRD-28-LRD-26, ~10,600–9900 cal years BP) – In this zone broken diatoms were recorded but in very low frequencies. These diatom frustules cannot be precisely identified. In addition, a significant proportion of freshwater sponge spicules was also recorded in this zone.

Zone-2 (LRD-25-LRD-22, ~9250–7000 cal years BP) – The zone was characterized by high frequencies of planktic (centric) diatoms dominated by *Cyclotella meneghiniana* and *Aulacoseira granulata*. However, their frequency reduced considerably in the topmost part of this zone. Few benthic forms and paddy field diatoms were also identified but with low counts.

The benthic forms were comprised of *Eunotia*, *Achnanthidium*, *Frustulia*, *Pinnularia*, *Stauroneis*,

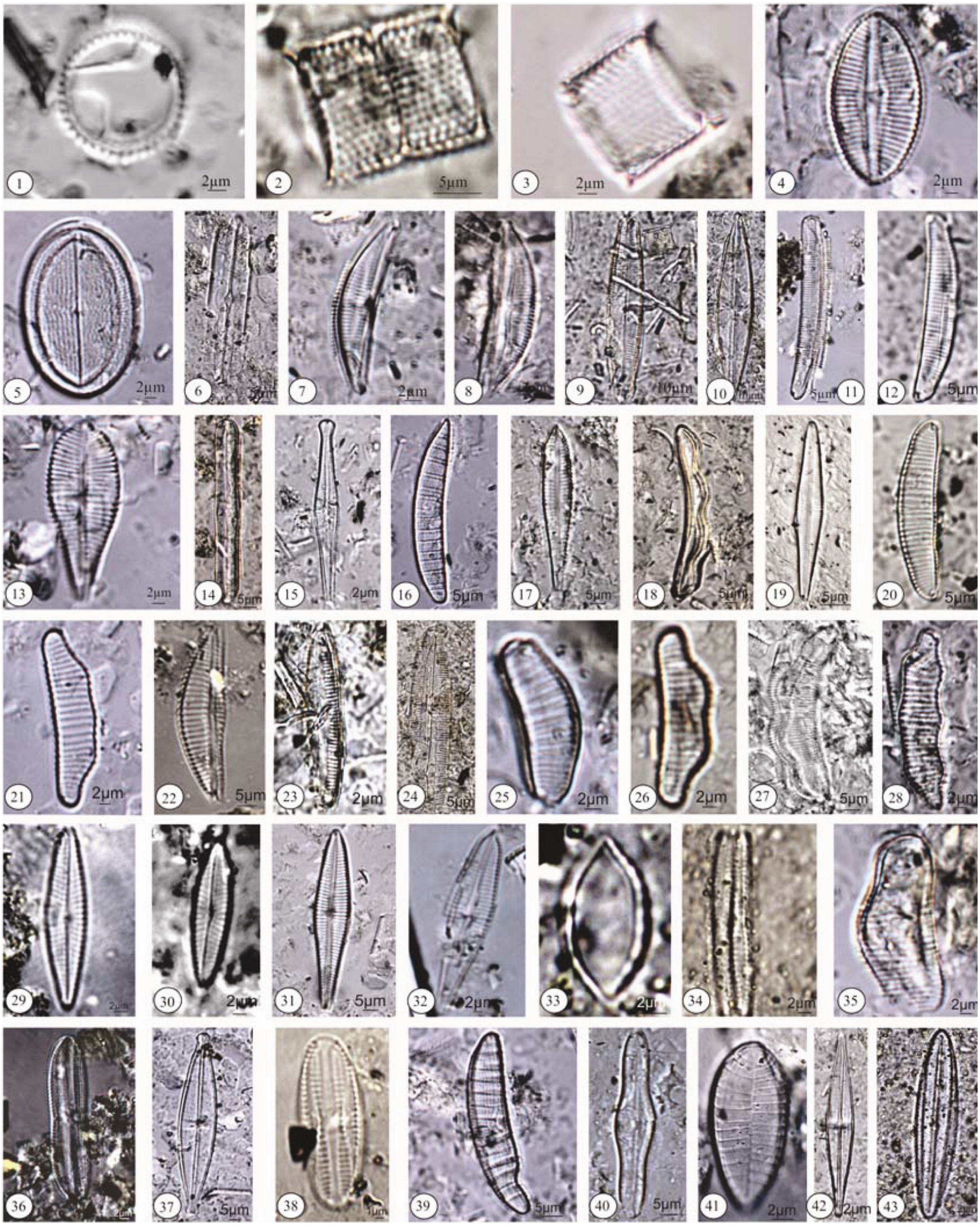

Figure 6. Diatom diversity recovered from the sediments of the Lahuradewa lake profile. 1, *Cyclotella meneghiniana*; 2, A*ulacoseira granulata* (chain form); 3, *Aulacoseira granulata* (girdle view); 4, *Diploneis smithii*; 5, *Cocconeis placentula*; 6, *Caloneis* sp.; **7**, *Amphora exigua*; 8, *Amphora coffeaeformis*; 9, *Pinnularia acrosphaeria*; 10, *Craticula cuspidate*; 11, *Eunotia soleirolii*; 12, *Eunotia curvata*; 13, *Gomphonema augur*; 14, *Pinnularia acrosphaeria*; 15, *Gomphonema subtile*; 16, *Eunotia duplicoraphis*; 17, *Gomphonema augur*; 18, *Eunotia*; 19, *Gomphonema angustum*; 20, *Eunotia duplicoraphis*; 21, *Eunotia praerupta*; 22, *Encyonema minutum*; 23, *Pinnularia*; 24, *Pinnularia acrosphaeria*; 25, *Eunotia*; 26, *Eunotia diodon*; 27, *Eunotia zygodon*; 28, *Eunotia* sp.; 29, *Navicula viridula*; 30, *Navicula cincta*; 31, *Gomphonema affine*; 32, *Gomphonema*; 33, *Nitzschia* sp.; 34, *Achnanthes* sp.; 35, *Eunotia praerupta*; 36, *Nitzschia accuminatum*; 37, *Stauroneis anceps*; 38, *Amphora praelata*; 39, *Epithemia* sp.; 40, *Gomphonema* sp.; 41, *Surirella gemma*; 42, *Craticula subhalophila*; 43, *Frustulia* sp.

Gomphonema. Amongst the paddy field diatoms, *Navicula*, *Nitzschia*, *Eunotia*, *Frustulia*, *Cocconeis*, *Stauroneis*, *Gyrosigma* were also recorded in this zone but with low frequencies. The anthropogenic diatom *Gomphonema* appeared in sample no. LRD-24 (~8300 cal years BP) and thereafter it was represented in all the samples. In the lower part of this zone the benthic and paddy field diatoms were recorded in very low frequencies but their diversity and frequency increased at the top (LRD-22) during ~7000 cal years BP.

Zone-3 (LRD-21-LRD-19, ~6400–5200 cal years BP) – In this zone only one sample recorded slightly high planktic diatoms (LRD-21); however, in the rest of the samples (LRD-20 and LRD-19) their counts were reduced to a great extent. The planktic diatoms in this zone were represented by *Cyclotella meneghiniana* and *Aulacoseira granulata*. However, there was a steady increase in benthic diatoms particularly *Eunotia*. The other benthic forms present in this zone were *Tabellaria*, *Achnanthidium* and *Diploneis*. This zone recorded increased diversity and frequency of the paddy field diatoms namely, *Navicula*, *Nitzschia*, paddy field *Eunotia*, *Achnanthes*, *Frustulia*, *Craticula*, *Caloneis*, *Cocconeis*, *Amphora*, *Encyonema*, *Pinnularia*, *Surirella*, *Tryblionella*, *Stauroneis*, *Cymbella*, *Hantzschia* and *Gyrosigma*. The anthropogenic diatom *Gomphonema* and *Synedra* were present in varying proportions.

Zone-4 (LRD-18-LRD-17, ~4600–4050 cal years BP) – This zone comprised of only two samples. A decrease in the planktic diatoms, i.e. *Cyclotella meneghiniana* and *Aulacoseira granulata* was recorded. The benthic diatoms showed enhancement in their occurrences mainly of *Eunotia* forms. The other benthic diatoms recorded were *Achnanthidium*, *Tabellaria*, *Diploneis*, etc. The paddy field diatoms were recorded maximum in terms of frequencies and species diversity. The rise in paddy field diatoms was noted by *Navicula*, *Nitzschia*, *Eunotia*, *Cocconeis*, *Craticula*, *Amphora*, *Pinnularia*, *Tryblionella*, *Caloneis* and others. In this zone the anthropogenic diatom indicator *Gomphonema* showed high frequency.

Zone-5 (LRD-16-LRD-14, ~3450–2300 cal years BP) – This zone represented differential diatoms recorded in the samples. The planktic diatom *Cyclotella meneghiniana* showed an overall decrease in frequency whereas *Aulacoseira granulata* showed very low counts. The benthic diatoms showed low diversity and were represented mainly by *Eunotia* and *Achnanthidium*. *Diploneis* and *Bacillaria* (Benthic forms) were encountered in one sample only. The diversity of paddy field diatoms was high, represented by *Navicula*, *Eunotia*, *Achnanthes*, *Frustulia*, *Craticula*, *Caloneis*, *Cocconeis*, *Amphora*, *Encyonema*, *Pinnularia*, *Surirella*, *Tryblionella*, *Stauroneis*, *Cymbella*, *Hantzschia*. Among these, *Navicula* and *Eunotia* were prominent. The anthropogenic indicator diatom *Gomphonema* and *Synedra ulna* also became prominent in this zone.

Zone-6 (LRD-13-LRD-3, ~2100–500 cal years BP) – This zone showed variable counts of various types of diatoms. The planktic diatoms *Cyclotella meneghiniana*, *Aulacoseira granulata* and *Stephanodiscus* were recorded in low frequency. The benthic diatom assemblage comprised chiefly of *Eunotia* and *Diploneis* with variable frequencies of *Achnanthidium*, *Anomoeneis*, *Tabellaria*, *Bacillaria*, *Brachysira*, *Epithemia*, *Neidium*, *Diploneis* and *Psammothidium*. The benthic diatoms showed variable proportions from the base to the top of this zone. The paddy field diatoms showed increase in this zone, represented mainly by *Navicula*, *Eunotia* and *Nitzschia*, with frequent but low counts of *Craticula*, *Encyonema*, *Pinnularia*, *Stauroneis* and occasionally occurring *Caloneis*, *Amphora*, *Surirella*, *Frustulia*, *Amphora*, *Encyonema*, *Stauroneis* and *Hantzschia*. However, the diversity of the paddy field diatoms was reduced in this zone. The frequency of anthropogenic diatoms *Gomphonema* and *Synedra ulna* was also fluctuating throughout this zone.

Zone-7 (LRD-2 - LRD-1, ~500 cal yrs BP – present) – In this zone the planktic diatoms showed a weak but fair rise towards the top. The benthic diatoms also rose in this zone towards the top and the major forms recorded were *Eunotia*, *Achnanthidium*, *Anomoeneis*, *Tabellaria*, *Bacillaria* and *Brachysira*. The paddy field diatoms in this zone were represented primarily by *Navicula*, *Nitzschia* and *Eunotia*. However, low occurrences of *Achnanthes*, *Frustulia*, *Craticula*, *Amphora*, *Encyonema*, *Pinnularia*, *Surirella*, *Tryblionella*, *Stauroneis*, *Cymbella* and *Hantzschia* were recorded. The anthropogenic diatom records also showed increase at the top with *Gomphonema* and *Synedra ulna* species.

Discussion

Change in diatom population and climate change

Planktic diatoms thrive in the lake waters while benthic diatoms are present on the sediment bottom of the lake. If the lake expands, planktic forms become more common, while reduction in lake causes increase in the benthic forms[29]. The anthropogenic influenced diatoms thrive in the lake, if organic pollution of the lake increases[30,31]. The paddy field diatoms are present in lake margins which are agricultural fields in several places in eastern India. They are washed into deeper parts of the lake along with sediment and organic matter of the paddy fields. Changes in the proportion of paddy field diatoms are essentially linked to the agricultural activity of the humans living in the area. The changes in the frequency and nature of diatoms through the lake profile during last 10 kyrs is a reflection of climate change affecting the water budget of the lake and anthropogenic activity, especially paddy field cultivation (Figure 7).

During ~10,600–9900 cal years BP (Zone 1) the lake was shallow, but possibly perennial in nature. The diatom

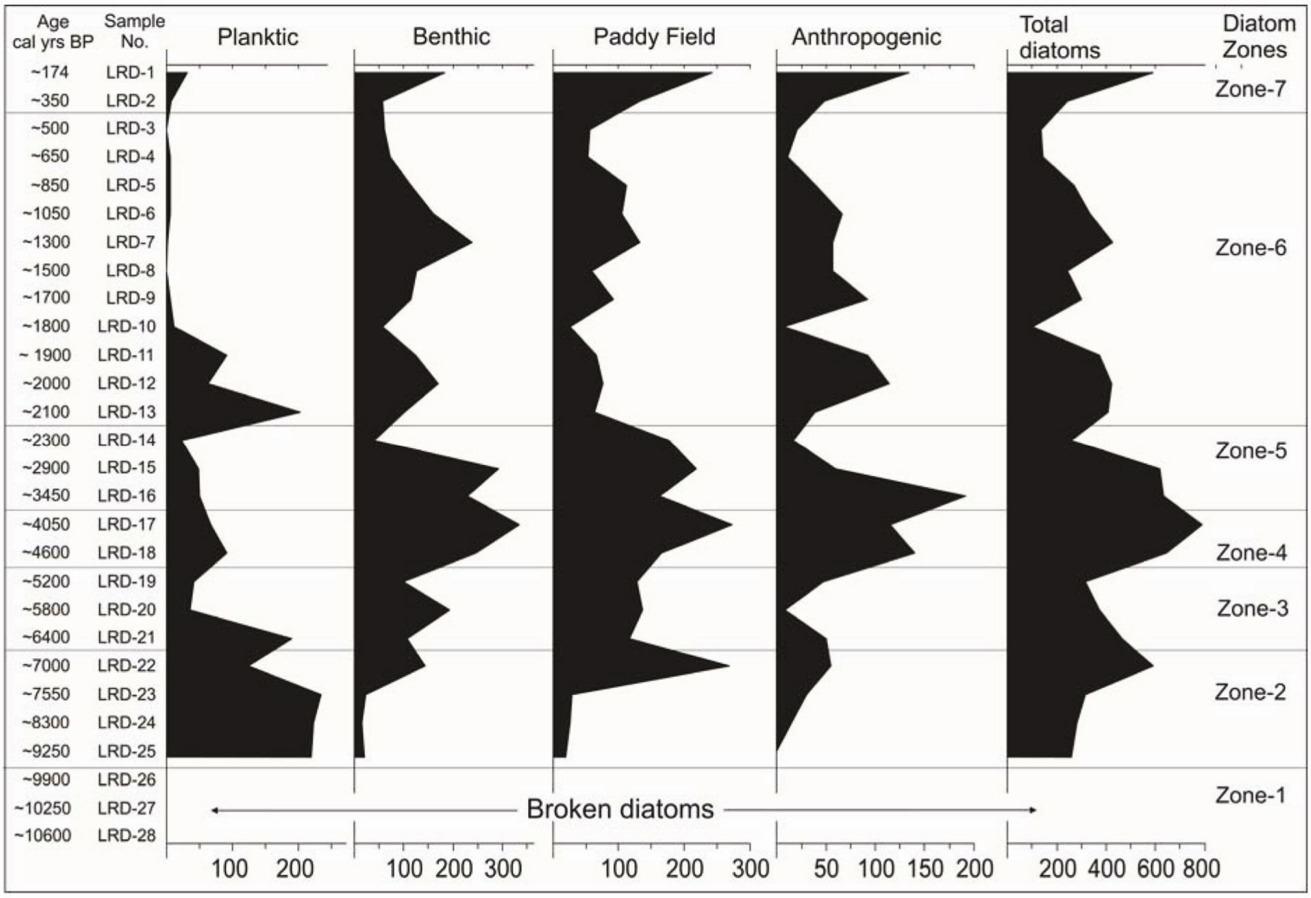

Figure 7. Variation of planktic, benthic, paddy field and anthropogenic diatoms in the Lahuradewa lake sediments.

population was relatively poor during this period but the sponge spicules were found to be dominating in this zone. In several other studies as well, the diatom poor samples were often rich in freshwater sponge spicules[32–34]. It appears that if the lake is shallow and rich in organic matter the sponge spicules dominate and diatoms are poor[33].

Planktic diatoms were high during ~9250–7000 cal years BP (Zone 2) indicating that the water in the lake was high. It was probably due to high rainfall during the time[2,29]. Evidence of agricultural practice was present since ~9250 cal years BP in the form of paddy field diatoms. The anthropogenic activity was supported by the presence of anthropogenic influenced diatoms, i.e. *Gomphonema* species around ~8300 cal years BP. The favourable climate with high rainfall was also indicated by increase in diatom population. Pollen records of Lahuradewa lake profile suggest the appearance of Cheno/Am pollen since 7822 cal yrs BP and Cerelia pollen since ~7500 cal years BP. Similarly, the phytolith records of Lahuradewa lake also indicate the period of strong monsoon ~7000 cal years BP (ref. 2). The multiproxy study of Sanai Tal deposits of Ganga Plain has also reported strengthened monsoon during the Early Holocene around 7000 cal years BP (refs 35, 36). Correlatable records of strengthened monsoon during this period are observed in the Ganga Plain based on lacustrine multiproxy studies[17,20,37]; eastern margin of the Thar Desert[38] and from other parts of the Indian subcontinent[39,40]. This period broadly corresponds to the early Holocene Climatic Optima observed in most monsoon affected regions[41].

The period from ~6400 to 5200 cal years BP (Zone 3) showed reduction in planktic diatoms which may be due to lower rainfall. It caused reduction in the lake, but expansion of lake margin used as paddy fields. Though total diatom count showed a decline; the paddy field diatoms showed a prominent increase in number and species diversification. The anthropogenic diatoms showed variable frequencies during this period.

The time span of ~4600 to 4050 cal years BP (Zone 4) showed a prominent decrease in the frequency of planktic diatoms, but on the contrary the benthic diatoms increased in number, though the diversity was not increased. The paddy field diatoms showed enhanced diversity. The pattern of frequency changes in paddy field diatoms corresponds to the frequency changes of anthropogenic diatoms.

A decline in rainfall related to SW monsoon showed prominent reduction in ~5800–3000 cal years BP (ref. 41).

This caused reduction in the volume of Lahuradewa lake, but provided more area for paddy cultivation along the lake margin. However, in our study, effect of reduced rainfall was reflected in diatoms during 4600–4050 cal years BP and became very prominent during 3400–2300 cal years BP (Zone 5) when both planktic and benthic diatoms decreased. Palynological records of the studied lake also reveal increase in arboreal pollen taxa and decrease in the marshy elements around 5000 years BP (ref. 3). A similar climatic trend was observed in the phytolith records which suggest the prevalence of aridity around 5000–4000 cal years BP (ref. 2). Oxygen isotope analysis of teeth enamel recovered from the archaeological sites of Ganga Plain revealed a less humid trend from 3600–2800 cal years BP (ref. 36).

The period from ~2300 to 500 cal BP (Zone 6) was a period of centennial scale rainfall variation[42]. The diatoms during this time showed a fluctuating pattern of decline and rise in their frequency and diversity. Around 2100–1800 cal years BP, the paddy field diatoms showed an overall declining trend followed by an increase around 1300 cal years BP. This suggests changes from more humid monsoon to weaker monsoon conditions. The oxygen isotopic records of bovid tooth enamel from Ganga plain also indicate more humid trend between 2800 and 1500 cal years BP followed by less humid conditions[36].

After 1800 cal years BP there was an increase in the count of diatoms, particularly the paddy field diatoms. However, the count of planktic forms was low. This indicates weaker monsoon and reduced lake level. The phytolith records of Lahuradewa lake also show reduced monsoon during 1650–1200 cal years BP as indicated by high value of Phytolith index (I_{ph}), followed by a small humid event 1200–950 years BP which is evident by low I_{ph} values. In addition, the presence of *Eunotia* in abundance around 2300 cal years BP, suggests relatively pristine lake water conditions, which strongly deteriorated later on, as made evident by increased frequencies of *Navicula* and *Nitzschia* species. It seems that lake size decreased and increased in response to the century-scale changes in rainfall. Human activity increased in the area, which is reflected in the increase in the count of anthropogenic influenced diatoms[18]. Around 1200–950 cal years BP, increased monsoon precipitation was observed from the pollen record of Mesa Tal[42].

The period from ~500 cal years BP to present (Zone 7) showed some enhancement in rainfall and there was a rise in diatom counts. This rise was noticed in both planktic and benthic diatoms which occurred naturally in the lake environment. The paddy field diatoms also showed increased diversity along with increase in anthropogenic diatoms. Similar trends of enhanced monsoon were also observed ~400 years BP (1420–1620 AD) inferred on the basis of pollen records of Nikhari Tal, Eastern Ganga Plain[18].

Paddy field identification in Lahuradewa

Several studies at global scales on paddy field ecology using diatoms have been conducted[5,6,43–45]. In India studies on the day paddy field diatoms have been carried out from Kuttanadu Paddy fields (Kerala)[7]. Usually, paddy field diatoms are restricted to the paddy fields and are preserved in their sediments. Paddy field diatoms in archaeological sites occur in areas identified as ancient paddy fields[5,6,43,44]. The paddy field diatoms and anthropogenic diatoms in conjunction provide evidence of human activity in the Lahuradewa area since ~9250 cal years BP.

Occurrence of large number of paddy field diatoms in the Lahuradewa lake sediment is quite unique. The question is how paddy field diatoms were deposited in large numbers in lake sediments?

The Lahuradewa lake, like most lakes of Ganga Plain is very shallow, mostly few metres deep and possesses flat extensive lake margins. Lake margins are mostly used as agricultural fields[21]. The lakes receive their water budget during monsoon season. During early monsoon (July) season, due to increase in water budget, the lake water expands on the margins. The lake margins with 10–20 cm deep water are used as paddy fields and paddy is transplanted in these areas. During monsoon months with availability of rain water the paddy grows without any artificial irrigation. The paddy is harvested in the month of October when lake margins become dry. Most of these lakes also grow wild rice (the *Tinni* rice), which is carefully harvested by the local population[46]. During floods, sediments along with microcharcoal, rice phytolith and paddy field diatoms are transported into the deeper part of the lake. Hence, the sediments of deeper parts of the lake contain microcharcoal, phytolith and paddy field diatoms in large number.

We would like to argue that the population living at the Lahuradewa archaeological site used the lake margin as a paddy field since about 9000 years BP. The paddy field cultivation showed increase and decrease with changing climate during Holocene. The human activity near the lake led to organic pollution of lake water. Hence anthropogenic-influenced diatoms flourished and increased through time. The anthropogenic diatoms showed increase during ~8300–7000 cal years BP and thereafter a decrease at ~5800 cal years BP. They increased from ~5200 to 3450 cal years BP reaching their maximum in the entire profile. The anthropogenic diatoms became low around ~2300 cal year BP and exhibited an increasing trend from ~2100 to 1900 cal years BP. They decreased during ~1800 cal year BP and increased around ~1700 cal year BP. A prominent decrease was noticed from ~650–500 cal years BP and increase from ~350 till present day. The increasing and decreasing trends of anthropogenic diatoms correspond broadly to that of the paddy field (Figure 7).

The study of rice phytoliths, pollen studies in the lake sediments and the presence of cultivated rice in Lahuradewa archaeological site also strongly indicate agricultural activity in the area since about 9000 years BP (refs 1 and 22). Early domestication and rice cultivation activity in China was discussed earlier. Identification of paddy fields indicating rice cultivation in China has been dated 8000 years BP in Yangtze Valley, South China[9] and in East China since ~7000 years BP (5000 BC)[47]. The oldest rice field in China has been identified in lower Yangtze valley dated about 8400 years BP (ref. 48).

1. Saxena, A., Prasad, V., Singh, I. B., Chauhan, M. S. and Hasan, R., On the Holocene record of phytoliths of wild and cultivated rice from Ganga Plain: evidence for rice based agriculture. *Curr. Sci*., 2006, **90**(11), 1547–1551.
2. Saxena, A., Prasad, V. and Singh, I. B., Holocene palaeoclimate reconstruction from the phytolith of the lake fill sequence of the Ganga Plain. *Curr. Sci.*, 2013, **104**, 1054–1062.
3. Chauhan, M. S., Pokharia, A. K. and Singh, I. B., Pollen record of Holocene vegetation, climate change and human habitation from Lahuradewa lake, Sant Kabir Nagar District, Uttar Pradesh, India. *Man Environ*., 2009, **XXXIV**(1), 88–100.
4. Prasad, V., Sharma, M., Saxena, A. and Singh, I. B., Fossil diatom assemblages from Lahuradewa Lacustrine sediments as clues for human activity. National Seminar on the Ganga Plain, Abstr., Directorate of Archaeology, Govt of UP, December 2004, p. 45.
5. Ohtsuka and Fujita. The diatom flora and its seasonal changes in a paddy field in Central Japan. *Nowa Hedwigia*, 2001, **73**(1–2), 97–128.
6. Mori, Y., The origin and development of rice cultivation in Japan based on evidence from insect and diatom fossil. In *The Origin of Pottery and Agriculture* (ed. Yasuda, Y.), International Research Centre for Japanese Studies, YRCP, 2002, pp. 273–296.
7. Vijayan, D. and Ray, J. G., Ecology and diversity of diatoms in Kuttanadu paddy fields in relation to soil regions, seasons and paddy–growth–stages. *J. Plant Stud.*, 2016, **5**(2), 7–21.
8. Nashima, K. and Palanisamy, A., Prevalence and distribution of diatoms in the paddy fields of Rasipuram area, Namakkal Dt, Tamilnadu, India. Int. *J. Curr. Microbiol. Appl. Sci.*, 2016, **5**(8), 402–413.
9. Gross, B. L. and Zhao, Z., Archaeological and genetic insights into the origins of domesticated rice. *Proc. Natl. Acad. Sci.*, 2014, **111**(17), 6190–6197.
10. Sharma, S. D., Origin of cultivated rice. In *Monograh on Genus Oryza* (eds Nanda, J. S. and Sharma, S. D.), Science Publishers, Enfield, USA, 2003, pp. 311–329.
11. Fuller, D. Q. Agricultural origins and frontiers in South Asia: a working synthesis. *J. World Prehist*., 2006, **20**, 1–86.
12. Higham, C., The transition to rice cultivation in Southeast Asia. *Last Hunters—First Farmers* (eds Price, T. and Gebauer, A.), School of American Research Press, Santa Fe, NM, 1995, pp. 127–155.
13. Sharma, S. D. *Rice: Origin, Antiquity and History*, Taylor and Francis, CRC Press, Science Publishers, 2010, p. 580.
14. Singh, I. B., Geological evolution of Ganga Plain: an overview. *J. Palaeontol. Soc. India*, 1996, **41**, 99–137.
15. Singh, I. B., Late Quaternary history of the Ganga Plain. *J. Geol. Soc. India*, 2004, **64**, 431–454.
16. Sharma, S., Joachimski, M. M., Tobschall, H. J., Singh, I. B., Sharma, C. and Chauhan, M. S., Correlative evidences of monsoon variability, vegetation change and human inhabitation in Sanai lake deposit: Ganga Plain, India. *Curr. Sci*., 2006, **90**, 973–978.
17. Saxena, A., Trivedi, A., Chauhan, M. S. and Sharma, A., Holocene vegetation and climate change in Central Ganga Plain: a study based on multiproxy records from Chaudhary Ka-Tal, Raebareli district, Uttar Pradesh, India. *Quat. Int.*, 2015, **371**, 164–174.
18. Saxena, A. and Singh, D. S., Multiproxy records of vegetation and monsoon variability from the lacustrine sediments of Eastern Ganga Plain since 1350 AD. *Quat. Int*., 2016; http://dx.doi.org/10.1016/j.quaint.2016.08.003.
19. Chauhan, M. S., Pokharia, A. K. and Srivastava, R. K., Late Quaternary vegetation history, climatic variability and human activity in the Central Ganga Plain, deduced by pollen proxy records from Karela Jheel, India. *Quat. Int*., 2015, **371**, 144–156.
20. Trivedi, A., Chauhan, M. S., Sharma, A., Nautiyal, C. M. and Tiwari, D. P., Record of vegetation and climate during Late Pleistocene-Holocene in Central Ganga Plain, based on multiproxy data from Jalesar Lake, Uttar Pradesh, India. *Quat. Int.*, 2013, **306**, 97–106.
21. Singh, I. B., Quaternary palaeoenvironments of the Ganga Plain and anthropogenic activity. *Man Environ*., 2005, **XXX**, 1–35.
22. Tewari, R. *et al.*, Second preliminary report of the excavations at Lahuradewa, District Sant Kabir Nagar, U.P. 2002–2003–2004 and 2005–2006. *Pragdhara*, 2006, 16.
23. Battarbee, R. W. and Kneen, M. J., The use of electronically counted microspheres in absolute diatom analysis. *Limnol. Oceanogr*., 1982, **27**, 184–188.
24. Battarbee, R. W., Diatom analysis. In *Handbook of Holocene Palaeoecology and Palaeohydrology* (ed. Berglund, B. E.), Wiley and Sons, New York, 1986, pp. 527–570.
25. Renberg, I., A procedure for preparing large sets of diatom slides from sediment cores. *J. Paleolimnol.*, 1990, **12**, 513–522.
26. Round, E. F., Crawford, R. M. and Mann, D. G., *The Diatom Biology and Morphology of Genera*, Cambridge University Press, Cambridge, England. 1990, p. 747.
27. Jacob, J., *Diatoms in the Swan River Estuary, Western Australia: Taxonomy and Ecology*, Koeltz Scientific Books, 2012, p. 456.
28. Karthick, B., Hamilton, P. B. and Kociolek, J. P. An illustrated guide to common diatoms of Peninsular India. *Gubbilabs*, 2013, 206.
29. Zhang, X., Reed, J., Wagner, B., Francke, A. and Zlatko Levkov, Z., Late glacial and Holocene climate and environmental change in the northeastern Mediterranean region: diatom evidence from Lake Dojran (Republic of Macedonia/Greece). *Quat. Sci. Rev.*, 2014, **103**, 51–66.
30. Sladecek, V., Diatoms as indicator of organic pollution. *Acta Hydrochim. Hydrobiol*., 1986, **14**(5), 556–566.
31. Birkett, K. and Gardiner, S., The use of epilithic and epiphytic diatoms as indicators of organic pollution in the Cheboygan River, Cheboygan County, Michigan, 2005; http://deepblue.lib.umich.edu/handle/2027.42/55043.
32. Volkmer-Ribeiro, C., Motta, J. F. M. and Callegaro, V. L. M., Taxonomy and distribution of Brazilian spongillites. In *Sponge Sciences: Multidisciplinary Perspectives* (eds Wanabe, Y. and Fusetani, N.) Springer-Verlag, Tokyo, 1998, 271–278.
33. Machado, V. S., Volkmer-Ribeiro, C. and Iannuzzi, R., Late pleistocene climatic changes in central Brazil indicated by freshwater sponges. *Int. J. Geosci.*, 2014, **5**(8), 799–815.
34. Machado, V. S., Volkmer-Ribeiro, C. and Iannuzzi, R., Investigation of freshwater sponges spicules deposits in a Karstic Lake in Brazil. *Braz. J. Biol.*, 2016, **76**(1), 36–44.
35. Sharma, S., Joachimski, M., Tobschall, H. J., Singh, I. B., Sharma, C., Chauhan, M. S. and Morgenroth, G., Late glacial and Holocene environmental changes in Ganga Plain, Northern India. *Quat. Sci. Rev.*, 2004, **23**, 145–159.
36. Sharma, S., Joachimiski, M. M., Tobschall, H. J., Singh, I. B., Tewari, D. P. and Tewari, R., Oxygen isotopes of bovid teeth as archive of palaeoclimate variations in archaeological deposits of Ganga Plain, India. *Quat. Res.*, 2004, **62**, 19–28.

37. Tripathi, D. *et al.*, Late Quaternary climatic variability in the Central Ganga Plain: A multi-proxy record from Karela Jheel (Lake). *Quat. Int.*, 2017, **443B**, 70–85.
38. Achyuthan, H., Kar, A. and Eastoe, C., Late Quaternary-Holocene lake-level changes in the eastern margin of the Thar Desert, India. *J. Paleolimnol.*, 2007, **38**, 493–507.
39. Singhvi, A. K. *et al.*, Instrumental, terrestrial and marine records of the climate of South Asia during the Holocene. In: Global environmental changes in South Asia: A regional perspective (eds Mitra, A. P. and Sharma, C.) Springer and Capital Publishing Company, 2010, first edn, pp. 54–124.
40. Singhvi, A. K. and Kale, V. S., Palaeoclimate studies in India: last ice age to the Present, In: IGBP-WCRP-SCOPE-Report Series-4; Indian National Science Academy, New Delhi, 2009, pp. 1–34.
41. Prasad, S. and Enzel, Y., Holocene paleoclimates of India. *Quat. Res*., 2006, **66**, 442–453.
42. Wasson, R. J., Chauhan, M. S., Sharma, C., Jaiswal, M., Singhvi, A. K. and Srivastava, P., Erosion of river terraces as a component of large catchment sediment budgets: a pilot study from the Gangetic Plain. *J. Asian Earth Sci.*, 2013, **67–68**, 18–25.
43. Zong, Y., Chen, Z., Innes, J. B., Chen, C., Wang, Z. and Wang, H., Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. *Nature*, 2007, **449**, 459–462.
44. Innes, J. B., Zong, Y., Wang, Z. and Chen, C., Climatic and palaeoecological changes during the mid- to Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at Pingwang, Yangtze coastal lowlands. *Quat. Sci. Rev.*, 2014, **99**, 164–175.
45. Fijita and Ohtsuka, Diatoms from paddy fields in northern Laos. *Diatom*, 2005, **21**, 71–89.
46. Singh, I. B., Geoarchaeology of the Ganga Plain: relationship between geomorphic-climate change during Late Pleistocene – holocene and history of human settlement. *Puratattva*, 2016, **46**, 21–35.
47. Yunfei, Z., Guoping, S., Ling, Q., Chunhai, L., Xiaohong, W. and Xugao, W., Rice fields and modes of rice cultivation between 5000 and 2500 BC in east China. *J. Arch. Sci.*, 2009, **36**(12), 2609–2616.
48. Zheng, Y., Crawford, G. W., Jiang, L. and Chen, X., Rice domestication revealed by reduced shattering of archaeological rice from the lower Yangtze valley. *Nature Sci. Rep*., 2016, **6**, 1–9; doi:10.1038/srep28136.

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