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ORIGINAL PAPER

Late Holocene palaeovegetational and environmental changes inferred from organic geochemical proxies in sediments from Pookot Lake, southern India

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Abstract
The sediments from Pookot Lake situated in the *Sahyadri* (Western Ghats) of southern India provided a record of palaeovegetation and palaeomonsoon variations during the Late Holocene. The palaeovegetation was reconstructed using the carbon isotopic composition of bulk organic matter ($\delta^{13}C_{org}$) and organic geochemical proxies (C/N ratio, C_{org} %, N % and $CaCO_3$). The vegetation composition (C_3 and C_4 plants) in the Pookot Lake catchment has changed in response to monsoonal variations. Around 2500 cal. years B.P., the lake had a high water level, increased aquatic plankton activity and abundant C_3 vegetation in its catchment, indicating strong monsoonal conditions. From 2500 to 1000 cal. years B.P., the lake had a lower water level, decreased aquatic plankton activity and increased contribution from C_4 land plants, indicating low rainfall conditions. During 1500 to 1000 cal. years B.P., the contributions from C_3 land plants and aquatic plankton increased, suggesting a moderate rainfall. From 1000 cal. years B.P. to the Present, the abundances of C_3 and C_4 vegetation fluctuated, indicating variations in the monsoonal strength. During the Medieval Warm Period (1000 to 600 cal. years B.P.), the monsoon was strong, but it was weak during the Little Ice Age (600 to 350 cal. years B.P.). From 350 cal. years B.P. to the Present, it has been steady. A similar climatic trend is documented in other palaeovegetation records from geographically different parts of India although spatial variability exists. Archaeological lines of evidence suggest a possible climate–culture link in the region.

Keywords Indian summer monsoon · Palaeovegetation · Productivity · Carbon isotopes · Lake sediments · Southern India

Rengaswamy Ramesh is deceased.

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Introduction

The Holocene Epoch, which includes the entire time span of human civilization, is generally considered as an interval of relative climate stability (Marcott and Shakun 2014). However, the Indian Summer Monsoon (ISM) exhibited weak and strong phases during this period (Patnaik et al. 2012). A general trend of strong monsoon during the Early Holocene (Prasad et al. 2014; Rawat et al. 2015a, b), weak monsoon events at ~8.2 ka B.P. and 4.2 ka B.P. (Staubwasser et al. 2003; Dixit et al. 2014a, b) and a relatively dry period from the Mid to Late Holocene (Sarkar et al. 2015) is documented in several palaeomonsoonal records. The monsoonal variability in the region on millennial scale is ascribed to changes in summer insolation at Milankovitch scale, tectonics and changes in atmospheric CO_2 concentration (Kathayat et al. 2016; Patnaik et al. 2012) and/ or changes in oceanic and atmospheric circulation (Zhao et al. 2010). However, short-term climatic variations have been ascribed to changes in monsoon circulation pattern, surface thermal boundary conditions of oceans, North Atlantic Deep Water production and Total Solar Irradiance (Patnaik et al. 2012; Wanner et al. 2008; Tiwari et al. 2015). Although many continental and marine records of palaeomonsoon from the Indian sub-continent exhibit similar trends, some dis-similarities are present (Sandeep et al. 2015).

There exists a decreasing trend of south-west monsoon rainfall over Kerala (Krishnakumar et al. 2009; Soman et al. 1988), which is known as the "Gateway of summer monsoon" over India (Krishnakumar et al. 2009). The reasons ascribed for this are steady decline in the strength of monsoon current and the strength of the Tropical Easterly Jet Stream (Krishnakumar et al. 2009). Though the state of Kerala receives heavy rainfall, the intensity of climatological droughts has been increasing, which impacts agricultural production in the state (Gopakumar 2011). To fully comprehend the behaviour of monsoon system over southern India and to predict future monsoonal trends in the region, it is imperative to determine trends in past rainfall and its spatial variability during the Holocene Period. The Holocene is also the period when humans migrated and adapted in response to abrupt climate changes (deMenocal 2001; Borzenkova et al. 2015; D'Andrea et al. 2011). Hence, it is essential to have a thorough understanding of the Holocene climate change, considering its cultural impacts. Lake sediments provide a continuous and high-resolution record of the past environment. The numerous lakes that are geographically widely distributed and that cover different climatic settings in southern India are useful in reconstructing the spatial variability of monsoon during the Holocene. However, there are only a limited number of continental records of Holocene rainfall for Kerala (Sandeep et al. 2015; Bhattacharyya et al. 2015) and even more so for southern India (Shankar et al. 2006; Warrier et al. 2014; Rajmanickam et al. 2016; Sandeep et al. 2017; Basu et al. 2017).

The organic matter preserved in lake sediments is a direct indicator of environmental conditions prevailing at the time of deposition and thus important in palaeoenvironmental reconstruction (Castañeda and Schouten 2011). It is a complex mixture of lipids, carbohydrates, proteins and other biochemicals produced by organisms that live in the lake and its watershed (Meyers and Lallier-Verges 1999; Meyers and Ishiwatari 1993). It is precipitated in lakes as a result of a variety of biochemical and geochemical processes, and on preservation, becomes a part of palaeolimnological record (Meyers and Ishiwatari 1993). The composition and amount of organic matter vary as the type and abundance of plant life in and around the lake change. The C/N ratio may be used to differentiate between organic matter derived from aquatic algae/plankton and land plants; the $\delta^{13}C$ of organic matter, on the other hand, helps differentiate between contributions from C_3 and C_4 terrestrial plants. The C_{org}/N ratio, together with the carbon isotopic signature of organic matter, helps identify the source and differentiate between contributions from aquatic, C_3 and C_4 terrestrial plants, which in turn, may be used to infer the climatic conditions of the period when these biota lived.

Sandeep et al. (2015) reconstructed three phases of palaeoclimatic history in Pookot Lake region based on rock magnetic data, namely phase 1 (~3100 to 2500 cal. years B.P.): high catchment erosion and detrital influx with strong monsoon; phase 2 (2500 to 1000 cal. years B.P.): low and steady rainfall with low and uniform catchment erosion and detrital influx; and phase 3 (~1000 cal. years B.P. to the Present): high catchment erosion with a shift to strong monsoonal conditions. The rock magnetic data are well supported by particle size and pollen data (Bhattacharyya et al. 2015). However, it is essential to decipher the response of vegetation to these climatic shifts. This will help not only in validating the other proxy reconstructions but also in understanding whether there is any instantaneous (or delayed) response in terms of lake level variations and vegetation (terrestrial and aquatic plant) shifts. In this context, the present study has been undertaken to reconstruct the past vegetation in terms of aquatic and terrestrial (C_3 and C_4) plants to decipher the palaeovegetation conditions during the Late Holocene.

Study area

Location, geology and climate

Pookot Lake (PK; also known as *Pookode*) is a rain-fed freshwater lake situated in the *Sahyadri* (Western Ghats; elevation ~775 m) near Vythiri village of Wayanad District, Kerala State (Fig. 1). It is 6.5 m deep, and it covers an area of ~0.085 km^2. The climate (India Meteorological Department 2008) is generally moist with an average rainfall of 4200 mm/year. The lake is situated in a mountainous terrain with dense forest. The forest around Pookot Lake belongs to the category of western tropical wet evergreen forests of low elevation (Champion and Seth 1968; Bhattacharyya et al. 2015). Hence, abundant organic matter is supplied to the lake along with sediments from the catchment area, which is characterized by ferruginous forest loamy type of soil (Geological and Mineral Map of Kerala 1995; Soman 1997).

Chronology of PK sediments

The chronology of two undisturbed sediment cores (2.4-m-long PK1; 2.2-m-long PK2) collected from the Pookot Lake was established using ^{14}C dating by accelerator mass spectrometry

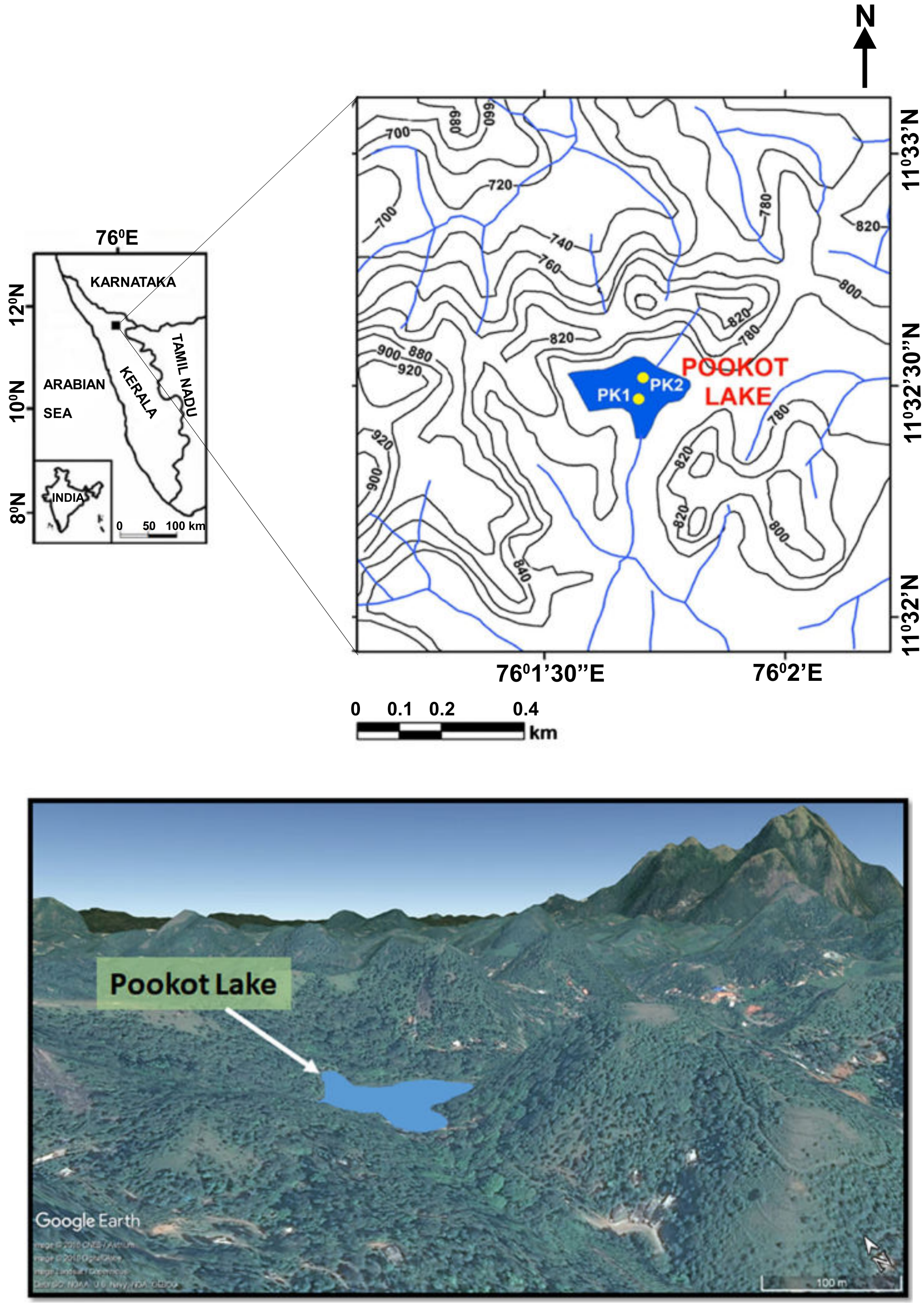

Fig. 1 Location map showing the topography of the Pookot Lake and its surrounding area. Topographic contours are in metres. The locations of cores PK1 and PK2 are shown. Google Earth image of the lake is also shown

(AMS). The age-depth model obtained suggests a mean sedimentation rate of 0.02 to 0.49 cm/year. Further details of sampling, ^{14}C analysis and age-depth model are given by Sandeep et al. (2015). This paper is based on the results obtained for core PK1, which was sampled at 0.5 cm interval. Using the R (R Development Core Team 2010) code package "clam" (v. 2.3.2; Blaauw 2010), the age-depth model was generated from the ^{14}C ages and IntCal13 calibration curve (Reimer et al. 2013). The maximum ^{14}C age obtained was 2003 $\pm$ 28 years for a depth of 194–194.5 cm.

Methods

Organic geochemical analysis

The carbon, nitrogen and $CaCO_3$ contents were determined for 26 bulk sediment samples. The samples were dried in a hot air oven at 40 °C and finely ground and homogenized using an agate pestle and mortar. About 2 g of the sediment sample was taken in a beaker and 1 N dilute HCl added in small increments until effervescence stopped (Schumacher 2002). It was kept overnight at room temperature to facilitate complete removal of carbonates. The sample was washed 3–4 times with deionised water and dried in the hot air oven at 100 °C. Weight loss after the HCl treatment gives the weight of $CaCO_3$ or inorganic carbon and is expressed as percentage. The organic carbon and nitrogen contents in the decarbonated samples were determined using a CHNS analyzer (Model: Elementar Vario EL III) at the Sophisticated Test and Instrumentation Centre, Cochin University of Science and Technology, Cochin. From the carbon and nitrogen percentages, C/N ratio was calculated and expressed as atomic ratio by multiplying the mass ratio with 1.167 (Meyers and Teranes 2001).

Carbon stable isotopic analysis ($\delta^{13}C$)

To determine the $\delta^{13}C$ of organic carbon, a small quantity (~ 1 g) of the sediment sample was treated with 10% HCl for several hours, dried and heated at 900 °C along with CuO powder and silver foil (Northfelt et al. 1981). The CO_2 that evolved was purified cryogenically before injecting it into the mass spectrometer. The isotopic composition is expressed as $\delta^{13}C$ in parts per thousand (‰) relative to the Vienna-Pee Dee Belemnite (V-PDB) standard. ($\delta = ((R_{sam}) - (R_{std}) - 1) \times 1000$, where R_{sam} and R_{std} refer to the $^{13}C/^{12}C$ ratio in the sample and the standard, respectively). The external precision for the laboratory standard was ± 0.12‰ for $\delta^{13}C$ (Yadava and Ramesh 1999). For reproducibility check, a few replicates were run, and they revealed no significant differences (within $\pm$ 0.7‰). The conversion of organic carbon to CO_2 gas and the subsequent $\delta^{13}C$ analysis using an isotope ratio mass spectrometer (Model: PDZ Europa GEO20–20) were carried out at the Physical Research Laboratory, Ahmedabad.

Results and discussion

The source of organic matter and the carbon isotopic signal in PK sediments

In order to appreciate the palaeovegetation/palaeoenvironmental significance of organic proxies, it is essential to determine their origin. The lacustrine organic matter can have different origins in response to aquatic primary production, input (from catchment) of vegetation and particulate and dissolved materials to the lake (Zanchetta et al. 2018). The TOC concentration is influenced by both initial production of biomass and subsequent degree of degradation; so, they integrate the different origins of organic matter, delivery routes, depositional processes and amount of preservation (Meyers and Teranes 2001). At present, the catchment area of the lake is covered with tropical evergreen forest with abundant C_3 woody plants. A description of different plant species in the catchment area is given by Bhattacharyya et al. (2015). However, there are C_4 plants in the lake catchment area too as evidenced by the pollen analysis of the PK sediments (Fig. 2; Bhattacharyya et al. 2015). Although, the organic carbon originates mainly from hydrophytes and terrestrial plant detritus, it may also have been derived from aquatic algae and different species of aquatic bryophytes in PK sediments (Nair et al. 2005).

Non-vascular aquatic plants, such as phytoplankton, contain less fiber but more proteins and, hence, have low atomic C/N ratio values, commonly between 4 and 10. On the other hand, vascular land plants are rich in fiber but low in proteins and have C/N ratio values ≥ 20 (Meyers and Lallier-Verges 1999; Meyers 1997, 2003). Most of the PK sediment samples show C/N ratio values between 10 and 20, indicating a mixed origin. Only a few samples show C/N ratio values less than 10, suggesting a predominantly aquatic origin. The C/N ratio values > 10 may indicate an increased contribution from terrestrial organic matter as a result of enhanced run-off and vegetal cover. This is evidenced by the pollen record (Fig. 2; Bhattacharyya et al. 2015), which suggests that periods of high C_{org} content correspond to high total pollen content (both total pollen count and tree pollen). Values of C/N ratio may also vary due to loss of nitrogen from the decomposition of nitrogen-bearing compounds with time (Lee and Olson 1984; Prasad et al. 1997). However, there was no such systematic loss of nitrogen with passage of time in PK sediments (Fig. 3). Also, the strong correlation between C_{org} and N ($r = 0.93$, $n = 24$, $p = < 0.01$) (Fig. 4a) indicates that both the elements are organically bound. The high content of C_{org} in the sediment samples indicates detrital influx of organic matter from the catchment or a high contribution from aquatic plants. These two scenarios are possible only during strong monsoonal conditions which brings higher amount of organic matter from the catchment area in to the lake and/or higher growth of aquatic plants in lake bed.

The carbon isotopic signal of PK sediments is mainly derived from organic matter, as inorganic carbon is removed during the sample processing itself. The $\delta^{13}C$ of organic matter may reflect the carbon isotopic composition of terrestrial (C_3 and C_4) and aquatic plants. However, the rate of carbon uptake during algal productivity, the isotopic composition of dissolved inorganic carbon (DIC), changes in pH, temperature, nutrient limitation and growth rate can also affect the $\delta^{13}C$ of organic matter produced by phytoplankton (Meyers and Teranes 2001). C_3 plants (dicots and temperate grasses) have $\delta^{13}C$ values in the range of − 31.5 to − 23‰ (average = − 28.57‰) and C_4 plants (tropical grasses and sedges) in the range of − 16 to − 10‰ (average = − 13‰) (Rajagopalan et al. 1997; Cerling et al. 1997; Basu et al. 2015). The difference in their isotopic signatures is due to their different photosynthetic pathways of carbon fixation, with the former using the C_3 Calvin pathway and the latter the C_4 Hatch-Slack pathway (Prasad et al. 1997; O'Leary 1988). The ecological preferences of C_3 and C_4 plants are also different, the former preferring high precipitation and high soil moisture content and

Fig. 2 Pollen diagrams for Pookot Lake sediments (Reprinted with permission from Springer Nature: Springer Nature, Environmental Earth Sciences, Bhattacharyya et al. v.74(4), pp. 3559–3572, Copyright (2015). Note: Based on the changes in pollen assemblage during the past 3100 years, two pollen zones—zone 1 (> 153.5 cm) and zone 2 (0–153.5 cm)—may be recognised. Zone 1 possesses no/hardly any spores/pollen. Zone 2 contains spores/pollen of diverse taxa and in good amounts at that)

the latter aridity and low soil moisture content (Rajagopalan et al. 1997). Aquatic plants can have $\delta^{13}C$ values in the range of − 12 to − 26‰ (Fry and Sherr 1984; Smith and Walker 1980). In general, the organic matter in lake sediments is of mixed origin, because of which isotopic values may be in the continuum defined by these end member values. Organic matter that is produced in lakes by phytoplankton (algae) using dissolved CO_2 in isotopic equilibrium with the atmosphere is usually isotopically indistinguishable from that produced by C_3 plants in the surrounding watershed (Meyers and Teranes 2001; Meyers and Lallier-Verges 1999). Algal organic matter, nonetheless, usually has a distinctly different carbon isotopic composition than the material produced by C_4 plants growing either on land or lake bottom. In such cases, C/N ratio may be used in combination with $\delta^{13}C$ values, as the value for the former is < 10 for planktonic algae. According to Silliman et al. (1996), as there is considerable overlap in the $\delta^{13}C$ of various plants, C/N ratio may help identify the source.

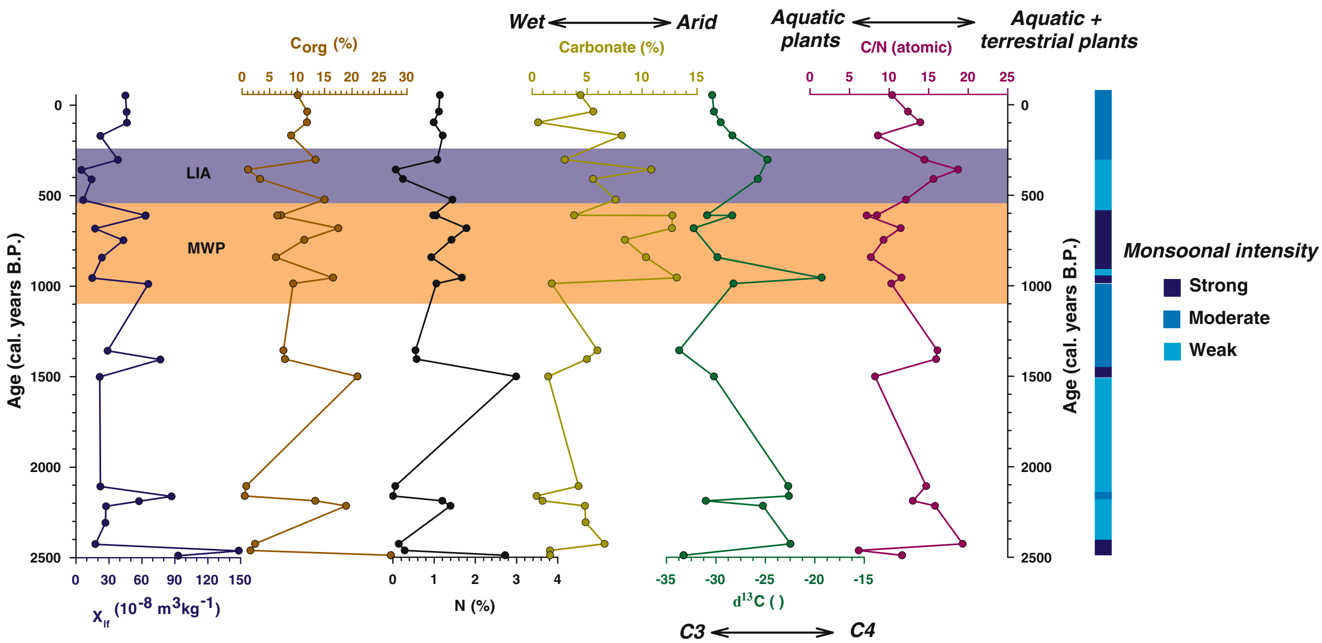

Fig. 3 Down-core variations of magnetic susceptibility (χ_{lf}), organic carbon (C_{org}), nitrogen, carbonate %, $\delta^{13}C$ and C/N ratio of Pookot Lake sediments. *Note*: C_{org} and N do not exhibit any significant relationship with χ_{lf} whereas carbonate, C/N ratio and $\delta^{13}C$ exhibit a negative correlation (LIA, Little Ice Age; MWP, Medieval Warm Period)

However, two extreme conditions may also exist. According to Meyers (2003), when the availability of dissolved atmospheric CO_2 ($\delta^{13}C = -7‰$) is limited (during conditions of high productivity or alkaline pH) and lake algae begin to use dissolved bicarbonate ($\delta^{13}C = 1‰$) as their source of carbon, algal isotopic composition becomes heavier compared to that of land plants. Algal $\delta^{13}C$ values may be as high as −9‰ (close to that of C_4 plants). This will lead to an increase in the $\delta^{13}C$ of organic matter (Leng and Marshall 2004) and a remarkably high primary productivity in lakes may result in high $\delta^{13}C$ values of the organic matter (Xu et al. 2006). At the other extreme, delivery of large amounts of isotopically lighter soil (dissolved inorganic carbon with $\delta^{13}C$ around −12‰) may lead to isotopically lighter algal organic matter ($\delta^{13}C$ around −32‰). In addition, the oxic degradation and diagenetic alteration of organic matter can also lead to a decrease in the carbon isotopic values (Lehman et al. 2002). Production of methane and its oxidation also lead to variations in the carbon isotopic values of methane and the residual organic matter (Jedrysek et al. 2014).

The fluctuating values of C_{org} % (Fig. 3), with no systematic decrease towards the core-bottom, indicate the absence of diagenetic alteration of organic matter (Anusree et al. 2017;

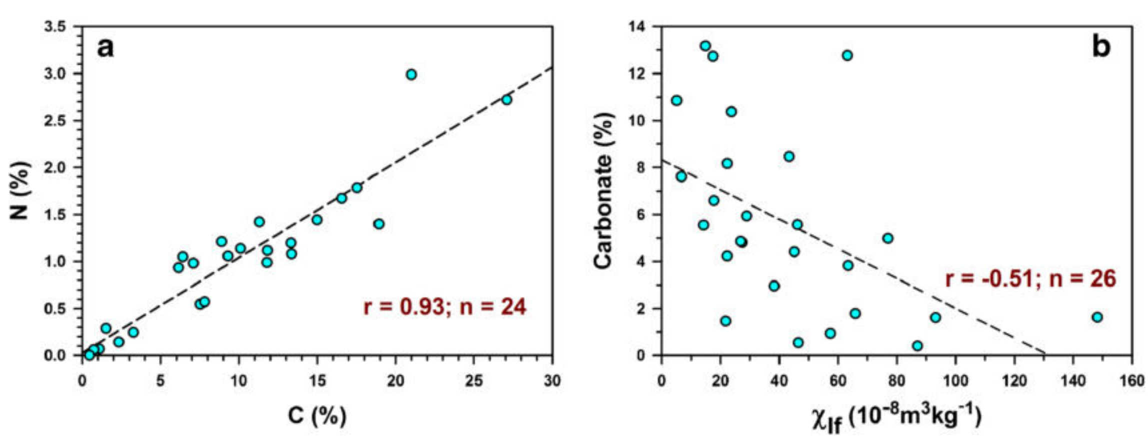

Fig. 4 (**a**) C vs. N biplot for Pookot Lake sediment samples. *Note*: The strong positive correlation indicates that the two parameters are organically bound. (**b**) Magnetic susceptibility (χ_{lf}) vs. carbonate (%) for PK sediments. *Note*: The two parameters exhibit a negative correlation

McArthur et al. 1992; Muzuka and Hillaire-Marcel 1999). The rock magnetic data (Sandeep et al. 2015) also indicate the absence of diagenetic alteration of magnetic minerals.

Organic geochemical and carbon isotopic data

Organic carbon (C_{org}), nitrogen, $CaCO_3$, C/N ratio and $\delta^{13}C$ values exhibit considerable down-core variations (Fig. 3). The C_{org} content varies from 0.47 to 27.08% (average = 10%), the nitrogen content from 0 to 3% (average = 1%), the $\delta^{13}C$ values from − 33.72 to − 17.08‰ (average = − 27.9‰) and the $CaCO_3$ content from 0.4 to 13.2% (average = 5.6%).

In lacustrine sediments, inorganic carbon occurs in allochthonous and autochthonous carbonates (Luo et al. 2008; Chen et al. 2002). The $CaCO_3$ content in PK sediments does not exhibit any significant correlation with C_{org} and C/N ratio values. In addition, carbonate rocks are absent in the Pookot Lake catchment (Geological and Mineral Map of Kerala 1995). Hence, the carbonates in PK sediments seem to be authigenic in origin. The carbonates can be precipitated authigenically by photosynthetic utilisation of CO_2 and the resultant calcium carbonate supersaturation in the water column (Leng and Marshall 2004). In the tropics, carbonate precipitation is related to increased production of phytoplankton with annual lake-water mixing and nutrient availability (Lamb et al. 2002). Temperature also favours the production of autochthonous carbonate by enhancing the algal productivity of the lake and depleting the dissolved CO_2 content of lake water (Warrier and Shankar 2009). The inorganic carbonates are precipitated in-situ during warm and dry conditions (high evaporation) (Wetzel 2001) which are deposited in the lake bed. Hence, the presence of carbonate in the PK sediments

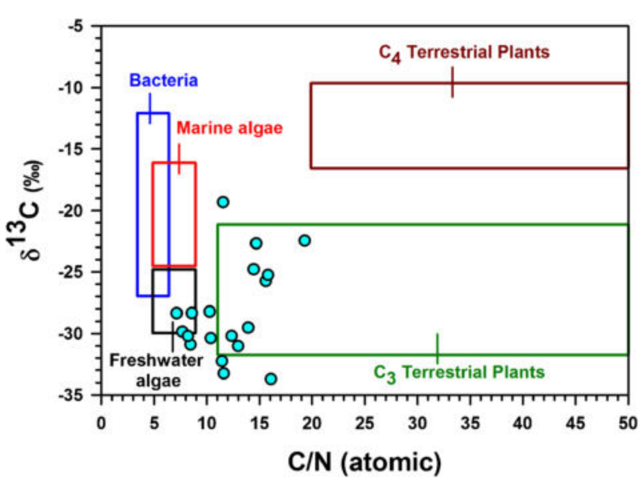

Fig. 5 Fields of C/N ratio and $\delta^{13}C$ values for freshwater algae, marine algae and C_3 and C_4 plants (after Meyers 1994). Data for Pookot Lake sediment samples are also shown (blue circles)

may be indicative of relatively dry and low-rainfall conditions (Luo et al. 2008). This is substantiated by the negative correlation ($r = -0.51$; $n = 26$; $p < 0.01$) between χ_{lf} values of PK sediments (Sandeep et al. 2015) and carbonate % (Fig. 4b). A negative correlation between carbonate content and rainfall is documented in many other studies as well (Warrier et al. 2014; Jenny et al. 2002; Luo et al. 2008).

According to Meyers (1994, 2003), the distinctive $\delta^{13}C$ values of C_3 and C_4 plants may be used in conjunction with characteristic C/N values of algal and land-derived organic matter to identify the sources of organic matter in lake sediments. A bi-plot of C/N ratio vs. $\delta^{13}C$ was used to distinguish the sources of organic matter in Pookot Lake sediments (Fig. 5). The C/N ratio and $\delta^{13}C$ values suggest that the organic matter is predominantly of mixed origin (terrestrial and aquatic), with C_3 land plants being the main terrestrial source. Although organic matter sources may easily be identified using these parameters, climatic interpretation of the C/N ratio is rather complex. Two interpretations exist in literature. An increase in terrigenous organic matter may be viewed as either an increased terrrigenous contribution or a decreased aquatic contribution, both of which have different climatic implications. Many workers interpreted high C/N ratio values as due to an increased contribution from land plants due to a high terrigenous influx, resulting from high rainfall conditions and vice versa (Xu et al. 2006; Chakraborty et al. 2006; Wohlfarth et al. 2004; Kaushal and Binford 1999). However, other studies attributed the low C/N ratio values to deep water conditions because of abundant planktonic growth, implying a wet climate (Rühland et al. 2009; Prasad et al. 1997; Krishnamurthy et al. 1986). During dry/low-rainfall conditions, lake level decreased, leading to shallow water conditions which, in turn, resulted in a decreased contribution from plankton and an increase in C/N ratio values (Krishnamurthy et al. 1986; Wang et al. 2001; Prasad et al. 1997; Meyers and Lallier-Verges 1999). Hence, the high relative contribution from allochthonous sources was ascribed to a decrease in the autochthonous contribution (due to a reduction of aquatics and shrinkage of lake area). A relative decrease of allochthonous contribution may be attributed to an increase of autochthonous contribution (due to abundance of aquatics and rise in lake level) (Wang et al. 2001). For Pookot Lake sediments, the second interpretation appears more reasonable on two counts. First, the C/N ratio exhibits a negative correlation with χ_{lf} ($r = -0.43$, $n = 24$, $p = 0.04$), i.e., periods of high χ_{lf} were associated with low values of C/N and vice versa. If the data are interpreted in terms of an increasing terrigenous contribution (= increasing rainfall), a negative correlation between C/N ratio and χ_{lf} is not tenable. Moreover, there is no significant relationship between χ_{lf} and C_{org} (Table 1). Second, there is no positive relationship between C/N ratio and organic carbon. If the C/N ratio was due to an increased terrigenous contribution, there should have been a parallel increase in organic carbon

Table 1 Correlation matrix for magnetic susceptibility (χ_{lf}), $\delta^{13}C$, carbonate and organic geochemical parameters. Numbers marked in bold are significant at 1% level and those with an asterisk significant at 4% level

	χ_{lf} (10^{-8} m^3 kg^{-1})	N %	C%	C/N	Carbonate %	$\delta^{13}C$ (‰)
χ_{lf} (10^{-8} m^3 kg^{-1})	1.00					
N %	− 0.08	1.00				
C %	− 0.10	**0.93**	1.00			
C/N	− 0.43*	− 0.43*	− 0.17	1.00		
Carbonate %	**− 0.51**	0.00	− 0.05	− 0.03	1.00	
$\delta^{13}C$ (‰)	− 0.27	− 0.42	− 0.37	0.37	0.13	1.00

during high-rainfall periods. Hence, it may be argued that the increase in C/N ratio was not due to an increase in terrigenous contribution, but due to a relative decrease in planktonic contribution (due to the lowering of water level).

Meyers and Lallier-Verges (1999) proposed that a wetter climate generally enhanced aquatic productivity as a consequence of greater in-wash of soil nutrients. This enhanced algal production was recorded as a lower C/N ratio. This model may aptly explain the organic matter delivery to the Pookot Lake, i.e., during high-rainfall periods there was enhanced aquatic productivity due to a greater in-wash of soil nutrients and vice versa.

Based on the C/N ratio and carbon isotopic data of Pookot Lake sediments, three scenarios of environmental conditions were inferred (Fig. 6):

Scenario 1. C/N < 10 and $\delta^{13}C$ = − 32 to − 23‰: These values indicate the predominance of aquatic plankton, indicating deep water conditions, a higher lake level and a strong monsoon (wet phase). The C_3 land plants were predominant in the catchment; however, their contribution is overshadowed by that of aquatic plants (Fig. 6a). This scenario indicates high rainfall conditions.

Scenario 2. C/N = 10 to 20 and $\delta^{13}C$ = − 31 to − 23‰: The ranges of values indicate a mixed vegetation (plankton + more C_3 land plants + less C_4 land plants), suggesting a reduced contribution from aquatic plankton, relatively shallower water and moderate monsoonal conditions. Even in this isotopic range of − 23 to − 31‰, the more depleted values indicate relatively higher rainfall conditions (Fig. 6b). A moderate rainfall is indicated by this scenario.

Scenario 3. C/N = 10 to 20 and $\delta^{13}C$ = − 23 to − 19‰: These ranges of values also suggest a scenario of mixed vegetation (plankton + more C_4 land plants + less C_3 land plants), reduced contribution from aquatic plankton and relatively shallower water and lower rainfall conditions compared to scenarios 1 and 2. This scenario has a lower rainfall compared to scenarios 1 and 2 because carbon isotopic values veer towards less negative values (= C_4 vegetation). Although none of the samples approached the − 11 to − 13‰ range (characteristic of C_4 land plants), some exhibited values in the range of − 25 to − 19‰, which indicate a mixture of both C_3 and C_4 types, but a higher contribution from the latter. This scenario had relatively weak monsoonal conditions (arid) compared to scenarios 1 and 2 as C_4 plants are characteristic of low-rainfall conditions (Fig. 6c).

This model is bolstered by the negative correlation (r = − 0.27) between χ_{lf} (Sandeep et al. 2015) and $\delta^{13}C$ data (Table 1). Although the correlation is statistically not significant, it, nevertheless, indicates that periods with higher χ_{lf} values (= higher rainfall) were associated with more depleted $\delta^{13}C$ values. When precipitation was high (low), the $\delta^{13}C$ values of the plants in the catchment decreased (increased) (Xu et al. 2006; Wei et al. 2010). The negative correlation of χ_{lf} data (Sandeep et al. 2015) with C/N ratio (r = − 0.43) and $\delta^{13}C$ (r = − 0.27) and the positive correlation of $\delta^{13}C$ with C/N (r = 0.37) indicate a common underlying forcing or control on the lake system, which is climate.

C_3–C_4 vegetation dynamics and its climatic implications during the Late Holocene

The $\delta^{13}C$ values show that the Pookot Lake catchment had a mixture of C_3 and C_4 vegetation during the Late Holocene. Around 2500 cal. years B.P., C_3 vegetation was dominant. The aquatic plankton were also predominant, indicating deep water conditions and a high lake level. All these data indicate high rainfall (scenario 1: strong monsoon; Fig. 6a). This period is also characterized by high magnetic susceptibility (χ_{lf}) values and sand content (Sandeep et al. 2015) and devoid of pollen grains (Fig. 2; Bhattacharyya et al. 2015), which indicates a high detrital influx (including organic matter) to the lake.

From 2500 to 1000 cal. years B.P., there was increased contribution from C_4 land plants. Also, there was a reduced contribution from aquatic plankton, indicating relatively shallower water conditions. This implies low rainfall conditions (scenario 3: weak monsoon; Fig. 6c). However, from 1500 to 1000 cal. years B.P., rainfall was relatively high with contributions from C_3 land plants and aquatic plankton, indicating moderate rainfall and intermediate lake level (scenario 2: moderate monsoon; Fig. 6b). However, there was a brief return to strong monsoonal conditions during this period. The

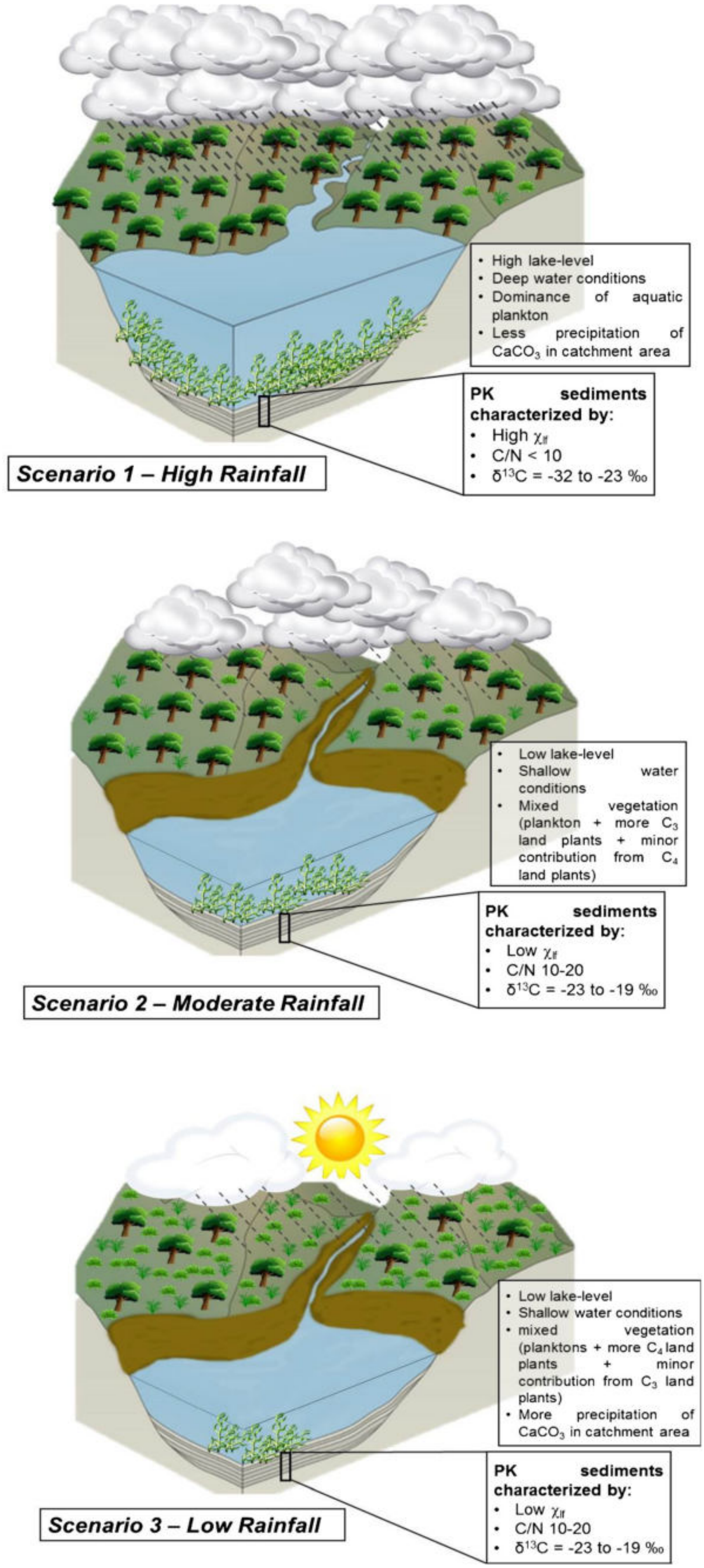

Fig. 6 Schematic model of C_3–C_4 vegetation dynamics in Pookot Lake catchment and PK sediment characteristics under three scenarios: (**a**) high, (**b**) moderate and (**c**) low rainfall

magnetic susceptibility (χ_{lf}) values and sand content were low during this period (Sandeep et al. 2015). The period is devoid of pollen except during 1500–1200 cal. years B.P. when some mangrove pollen are recorded (Bhattacharyya et al. 2015). This indicates low detrital and organic matter influx to the lake.

From 1000 cal. years B.P. to the Present, there were fluctuations from abundant C_3 vegetation under high-rainfall (deep water) conditions to dominant C_4 vegetation under arid (shallow water) conditions. During the Medieval Warm Period (1000 to 600 cal. years), the monsoon was strong with abundance of C_3 vegetation. By contrast, during the Little Ice Age (600 to 350 cal. years B.P.), it was weak with abundance of C_4 vegetation. From 350 cal. years B.P. to the Present, there was a gradual shift from C_4 to C_3 vegetation, indicating a steady strengthening of the monsoon. This period is characterized by fluctuating χ_{lf} values, with a general increasing trend towards the present (Sandeep et al. 2015). The pollen percentage was high when compared to earlier periods, the pollen % being high during ~1000–600 cal. years B.P. and low during ~600–300 cal. years B.P. (Fig. 2; Bhattacharyya et al. 2015). Fluctuations notwithstanding, there was an overall high detrital and organic influx to the lake.

Periods of low detrital influx are characterized by magnetically coarse grains whereas those of high detrital influx periods contain magnetically fine grains (Sandeep et al. 2015). This is also evident from variations in the sedimentation rate. The average sedimentation rate is 0.26 cm/year from ~1000 cal. year B.P. to the Present, whereas it is 0.03 cm/year prior to 1000 cal. years B.P. (Sandeep et al. 2015).

Comparison with other palaeovegetation/palaeomonsoonal records

Figure 7 compares the carbon isotopic data of the Pookot Lake sediments (Fig. 7a) with other palaeovegetation/palaeomonsoonal records from far-flung regions like southern, central and western India and northwestern and northeastern Himalaya to determine the Late Holocene spatial variability of the Indian monsoon. Studies of the Banni grassland in Gujarat (Anusree et al. 2017) show that the period between ~2500 and ~1000 cal. years B.P. was dominated by C_4 plant community, indicating aridity (Fig. 7b). The trend reversed with an increase in C_3 vegetation from ~1000 cal. years B.P. alongside a slight increase in rainfall. The region received high rainfall had a predominance of C_3 vegetation prior to ~2500 cal. years B.P. This is consistent with the trend documented in Pookot Lake sediments (Fig. 7a). However, studies on Nalsarovar lake of western India indicate more enriched $\delta^{13}C$ values from ~3.2 cal. ka B.P.

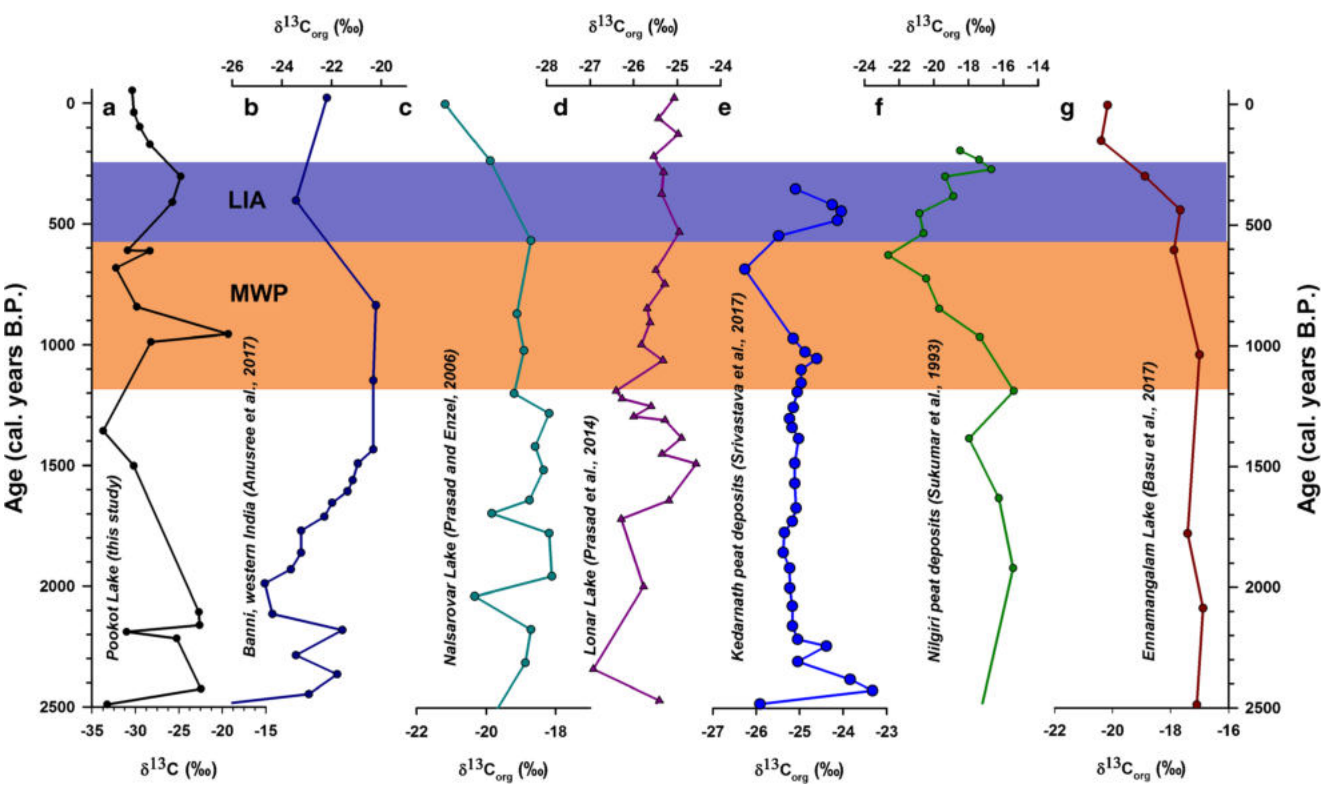

Fig. 7 Comparison of Pookot Lake sediment $\delta^{13}C$ data with other palaeoclimatic records: (**a**) Pookot Lake sediments (present study); (**b**) Banni grassland, Gujarat (Anusree et al. 2017); (**c**) Nalsarovar lake, western India (Prasad and Enzel 2006); (**d**) Lonar Lake, Central India (Prasad et al. 2014); (**e**) Peat from Kedarnath (Srivastava et al. 2017); (**f**) Nilgiri peat deposits, southern India (Sukumar et al. 1993); and (**g**) Lake Ennamangalam, Tamilnadu, southern India (Basu et al. 2017)

onwards, indicating a progressive shift to drier conditions as seen in the present times (Prasad and Enzel 2006; Fig. 7c).

The high-resolution sedimentary carbon isotopic and multi-proxy investigations of Lonar Lake, Central India, provide evidence for a prolonged drought between 2000 and 600 cal. years B.P. (Prasad et al. 2014; Fig. 7d). Menzel et al. (2014) also deciphered relatively dry conditions based on high C_4 land plant contribution and low lake level for the Lonar Lake. The sedimentary $\delta^{13}C$ record from Sanai Lake, Central Ganga Plain (Sharma et al. 2004) exhibits lighter isotopic values, indicating arid conditions from 5000 to 2000 ^{14}C years B.P. The heavier isotopic values from 1700 ^{14}C years B.P. onwards indicate a wetter climate.

Agrawal et al.'s (2015) carbon isotopic data for a lake sediment profile from Anini, Dibang Valley, northeast Himalaya, show an increasing trend in $\delta^{13}C$ values from 2700 to 1300 cal. years B.P., suggesting a change in vegetation pattern from C_3 to C_4 plants as the climate changed from wetter to drier conditions. After 1300 cal. years, however, there was an increasing abundance of C_3 plants, implying wetter climatic conditions. The C_3–C_4 vegetation dynamics reconstructed from palaeolake deposits from Kinnaur, Himachal Pradesh, points to a reduction in precipitation between 4310 and 1800 years B.P., fluctuating dry and wet phases during 1800–1000 years B.P. and desiccation of lake around 1000 years B.P. (Chakraborty et al. 2006). The carbon isotopic and other lines of evidence from the Kedarnath peat record (Srivastava et al. 2017; Fig. 7e) suggest a warm period between ~1250 and 800 cal. years B.P. corresponding to the Medieval Climate Anomaly, a dry and cold phase between ~3000 and ~1400 cal. years B.P. and a wet phase from ~3800 to ~3000 cal. years B.P.

A short, wet phase recorded in the Nilgiri peat deposits from southern India corresponding to the Medieval Warm Period, is documented as a sudden shift in $\delta^{13}C$ values to C_3 vegetation (Sukumar et al. 1993; Fig. 7f). Prior to that period, C_4 plants were dominant, indicating an arid climate. The trend is similar to that shown by the $\delta^{13}C$ record of Pookot Lake sediments. The palaeovegetational record from Ennamangalam Lake, southern India (Basu et al. 2017; Fig. 7g), indicates a steady increase in C_3 vegetation from 3000 to 1000 cal. years B.P.; from 1000 cal. years B.P. to the Present, there was a drastic increase, indicating strong monsoonal conditions.

Possible linkage between climate and human activity?

According to archaeological lines of evidence and rock engravings found in Edakkal Cave, about 40 km away from Pookot Lake, the forests in Wayanad were inhabited for more than 3000 years (Ajithkumar 2013). Although the exact timing of this human migration and settlement is not known, the copious rainfall prior to ~2500 cal. years B.P. might have aided the settlement of Megalithic people in the region. The earliest date ascribed to the petroglyphs in Edakkal Cave is 5th to sixth century B.C. (Iron Age/Megalithic/Early Historic period in Kerala) (Ajithkumar 2013; 2014). The large number of anthropomorphic figures in Edakkal Cave indicates a calamity (like drought and/or forest fire) besieging the region (Ajithkumar 2014). It is likely that due to the sudden weakening of the monsoon post-2500 cal. years B.P., the inhabitants abandoned the place and carved out the figures at Edakkal to tide over the drought and to derive divine benefactions (Ajithkumar 2013; 2014). One such engraving is that of a "human figure with a hand shaped like a jar", which could represent storage of water due to the drought-like conditions prevailing then (Ajithkumar 2013; 2014). After the 2500–1000 cal. years B.P. dry episode, the climatic conditions turned favourable, supporting the growth of trees/shrubs that are the typical assemblage of evergreen and semi-evergreen vegetation of *Sahyadri* (Western Ghats) around 1000 cal. years B.P. (Bhattacharyya et al. 2015; Veena et al. 2014). Palynological evidence also suggests increasing human occupation and agricultural activities around the Pookot Lake from ~1500 cal. years B.P. onwards (Veena et al. 2014). The later set of inscriptions in the caves dating to ~2nd-third century AD to 5th–sixth century A.D. indicates later human settlements at the cave site (Mahadevan 1998).

Conclusions

Our study has documented the shift in the composition of the lacustrine sediments in the Pookot Lake region in response to Late Holocene monsoonal variations. Around 2500 cal. years B.P., C_3 vegetation dominated the region. The lake level was high, with predominant aquatic plankton, indicating strong monsoonal conditions. From ~2500 to 1000 cal. years B.P., there was an increased contribution from C_4 land plants and a reduced contribution from aquatic plants with a lower lake level. This indicates low rainfall conditions. During 1500–1000 cal. years B.P., contributions from C_3 land plants and aquatic plankton increased, suggesting a moderate lake level and a moderate rainfall. From 1000 cal. years B.P. to the Present, the relative abundance of C_3 and C_4 plants fluctuated, indicating varying rainfall conditions. During the Medieval Warm Period (1000 to 600 cal. years), the monsoon was strong but during the Little Ice Age (600 to 350 cal. years B.P.), it was weak. From 350 cal. years B.P. to the Present, the monsoon steadily strengthened. Palaeovegetational/palaeomonsoonal records from different geographical regions of India suggest several similarities in the general trend of monsoonal variations. There is, however, spatial variability among the records. The timing of the engraving of anthropomorphic figures in a nearby archaeological site suggests a fair correlation with the climatic inferences we made from the Pookot Lake data presented here. Therefore, there appears to be a linkage between climate and culture in the region.

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