Late Quaternary vegetational and climatic changes from tropical peats in southern India – An extended record up to 40,000 years BP

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Stable carbon isotope ratios of peats dated (by ^{14}C) back to 40 kyr BP from the montane region (> 1800 m asl) of the Nilgiris, southern India, reflect changes in the relative proportions of C3 and C4 plant types, which are influenced by soil moisture (and hence monsoonal precipitation). From prior to 40 kyr BP until 28 kyr BP, a general decline in $\delta^{13}C$ values from about – 14 per mil to – 19 per mil suggests increased dominance of C3 plants concurrent with increasingly moist conditions. During 28–18 kyr BP there seems relatively little change with $\delta^{13}C$ of – 19 to – 18 per mil. At about 16 kyr BP a sharp reversal in $\delta^{13}C$ to a peak of – 14.7 per mil indicates a clear predominance of C4 vegetation associated with arid conditions, possibly during or just after the Last Glacial Maximum. A moist phase at about 9 kyr BP (the Holocene Optimum) with dominance of C3 vegetation type is observed, while arid conditions are re-established during 5–2 kyr BP with an overall dominance of C4 vegetation. New data do not support the occurrence of a moist phase coinciding with the Mediaeval Warm Period (at 0.6 kyr BP) as suggested earlier. Overall, the climate and vegetation in the high altitude regions of the southern Indian tropics seem to have responded to past global climatic changes, and this is consistent with other evidences from India and other tropical regions.

STUDIES on tropical climatic and vegetational history from a variety of continental deposits are gaining importance in recent years. Snow-line reconstructions[1], carbon isotope analyses of peats[2], oxygen isotope analyses of ice cores[3] and noble gases dissolved in groundwater[4] suggest significant climatic changes on land at low latitudes, especially during the Last Glacial Maximum (LGM) (ca. 20–16 kyr BP). A better understanding of the past climatic and vegetational changes in the tropics from proxy data sets becomes essential in view of anticipated future global climatic changes.

Palaeoclimatic reconstruction, using stable carbon isotope analyses of organic matter, is based on the well-known difference in $^{13}C/^{12}C$ ratios of C3 and C4 plants, which are separated on the basis of their photosynthetic pathways of carbon fixation. C3 plants (dicot plants and temperate grasses) and C4 plants (mainly tropical grasses and sedges) have mean $\delta^{13}C$ values in the range of – 26 to – 28 per mil and – 11 to – 13 per mil respectively[5]. They also show distinctive ecological preferences, with C3 plants preferring regions of higher precipitation and soil moisture and C4 plants dominating in regions of low soil moisture and aridity[6,7]. Based on this, $\delta^{13}C$ values from soil organic matter[6,9], lake sediments[10] and peats[2] have been used as palaeoclimatic indicators.

We have earlier reported changes in vegetation and climate up to 9 kyr BP in the Sandynallah basin of the Nilgiri hills, southern India, based on $^{13}C/^{12}C$ ratios of peats from a single core[2]. In this article we extend the $\delta^{13}C$ record up to 40 kyr BP through further sampling of peats from three cores in two basins in the Sandynallah region.

Study area

The Nilgiri hills is located between 11°0′–11°30′N and 76°0′–77°20′E in the Western Ghats of southern India. The natural vegetation of the montane region (1800–2500 m asl) is a mixture of stunted evergreen forest and grassland. Annual precipitation from the southwest (summer) and northeast (winter) monsoons over the plateau averages 1300–3000 mm. Further details of the vegetation and climate are found elsewhere[2,11–13]. The Sandynallah region from where peats were collected is located at about 2200 m asl in the Nilgiri hills. Mean annual rainfall at Sandynallah is 1400 mm.

Peat deposits are generally found in the valleys or basins of the montane regions (> 1800 m asl) of the Western Ghats. Low temperature, anaerobic conditions and frequent water-logging favour the formation of peats in the higher altitude regions of the tropics. The vegetal matter of peat is derived from C3 and C4 plants growing in the valleys and the surrounding hill slopes of the basin. This can be expected to preserve the vegetational and climatic record of the region, as diagenic alteration of stable carbon isotopes in organic peats does not occur[14].

Methods

Peat samples were collected from two adjacent valleys or basins, less than 1 km apart, in the Sandynallah

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Table 1. Radiocarbon ages from peat samples in the Sandynallah region of the Nilgiri hills, southern India

Depth (cm)	Lab no.	Radiocarbon age ± 1SD (yr BP)	$\delta^{13}C$ (per mil)
Basin A (Pit 1)			
5–10	BS-874*	Modern	– 18.0
120–125	BS-1083	380 ± 140	– 17.9
140–145	BS-1085	660 ± 180	– 15.5
150–155	BS-873*	2230 ± 130	– 17.4
160–165	BS-968*	2550 ± 90	– 16.9
170–175	BS-871*	3040 ± 80	– 14.7
180–185	BS-967*	4050 ± 110	– 15.0
190–195	BS-872*	4680 ± 120	– 14.9
233–240	BS-869*	8680 ± 140	– 20.2
Basin A (Pit 2A)			
70–75	BS-1097	2600 ± 120	– 14.8
90–95	BS-1165	4490 ± 90	– 14.5
110–113	BS-1166	6270 ± 170	– 17.4
120–125	BS-1094	9440 ± 220	– 16.5
150–153	BS-1099	11300 ± 440	– 16.0
Basin A (Pit 2B)			
158–161	BS-1098	10230 ± 280	– 15.9
173–176	BS-1066	12540 ± 230	– 16.2
183–186	BS-1067	12620 ± 790	– 16.5
192–195	BS-1070	9640 ± 790	– 18.2
198–201	BS-1101	15890 ± 1230	– 14.7
210–213	BS-1068	13810 ± 1040	– 16.8
Basin B (Pit 1A)			
35–37	BS-1076	2120 ± 90	– 16.6
55–58	BS-1075	4010 ± 100	– 17.0
Basin B (Pit 1B)			
62–64	BS-1073	3730 ± 100	– 15.3
78–80	BS-1074	4560 ± 100	– 16.0
95–98	BS-1064	5370 ± 150	– 16.2
110–113	BS-1060	11820 ± 180	– 17.1
115–118	BS-1185	18440 ± 510	– 18.5
121–124	BS-1186	28150 ± 2180	– 19.2
129–132	BS-1092	25190 ± 660	– 19.0
141–144	BS-1093	28410 ± 890	– 18.5
153–156	BS-1058	22450 ± 410	– 18.3
159–162	BS-1091	31790 ± 1180	– 18.1
165–168	BS-1090	31380 ± 1140	– 17.7
171–174	BS-1059	35560 ± 2480	– 18.0
180–183	BS-1095	39690 ± 2700	– 17.1
189–192	BS-1096	> 40000	– 16.6
201–204	BS-1057	> 40000	– 16.2
217–220	BS-1062	> 40000	– 15.5
241–244	BS-1063	> 40000	– 16.6

Two pits each of 2.4 m (pit 1) and 2.55 m (pit 2) depth in basin A and one pit of 2.44 m (pit 1) in basin B were dug. Peat samples, each of 5 cm depth at 10 cm interval, were collected from pit 1 of basin A. From pit 2 of basin A continuous sampling was carried out from 100 cm to 159 cm (referred to as pit 2A), while sampling was slightly shifted to an adjacent section of the pit (referred to as pit 2B), from 156 cm to 255 cm because of wall collapse in pit 2A. From basin B peat samples each of 2 cm depth were collected at 9 cm ntervals until 61 cm and continuously beyond this (each sample of 3 cm depth) up to 78 cm depth (referred to as pit 1A). As the wall collapsed beneath this depth, we shifted to an adjacent portion and sampled continuously from 62 cm depth until 244 cm (referred to as pit 1B). All ^{14}C ages are based on a half-life of 5730 ± 40 years. The reference year for BP is AD 1950.

*The radiocarbon dates of these peat samples from basin A (pit 1) are based on Sukumar *et al.*[2]. A $\delta^{13}C$ value of – 13.8 per mil was obtained at a depth of 235–238 cm in basin B (pit 1B). This has not been dated but can be expected to be > 40000 yr BP.

region. Two pits in basin A and one pit in basin B were dug (for further details refer to Table 1). Samples were collected from the walls of the pits. Care was taken to avoid any contamination. These were packed in polythene bags and stored at 7°C to minimize deterioration.

Radiocarbon dating of a subset of the peat samples was carried out at the Birbal Sahni Institute of Palaeobotany. After removing visible rootlets, the samples were treated with 10% HCl at 95°C to remove carbonates. They were subsequently neutralized, centrifuged and dried at 95°C. The specific activity of ^{14}C in the samples was measured using a gas proportional counter[15]. All ^{14}C ages are based on a half-life of 5730 ± 40 years. Table 1 shows the sample details and the corresponding ^{14}C ages. The calendar dates would be different from the ^{14}C dates, in general being greater by about 10–15% over the ^{14}C dates, for ^{14}C dates of 5–20 kyr BP (see refs 16, 17 for recalibrated dates, and ref. 2 for recalibration of some of the Nilgiri samples).

Stable carbon isotope ratios in peats and in dried leaf samples of modern C3 and C4 plants in the basin were determined by the method of Stump and Frazer[18]. Peat was ground to a fine powder, demineralized with 10% HCl and completely dried. The samples were combusted with CuO at 800°C in sealed quartz tubes. The carbon was quantitatively converted to CO_2 and measured in a VG-Micromass 903 mass spectrometer at the Physical Research Laboratory.

The isotope ratios are expressed as δ values, where

$$\delta^{13}C = [(^{13}C/^{12}C \text{ sample})/(^{13}C/^{12}C \text{ standard}) - 1] \times 1000 \text{ per mil.}$$

The standard was PDB-carbonate, and the overall precision of the isotope analyses was ± 0.1 per mil. The $\delta^{13}C$ of an internal standard UCLA-glucose ($\delta^{13}C = -9.78$ per mil measured at UCLA) was measured along with the peat samples and a mean value of – 9.70 (± 0.14, $n = 7$) was obtained.

Results and discussion

The $\delta^{13}C$ values of dominant C3 and C4 plants found currently in the basin average – 26.6 per mil (± 2.3, $n = 13$) for C3 grasses and herbs and – 10.9 per mil (± 0.97, $n = 8$) for C4 grasses and sedges. Both C3 and C4 species were found within the Poaceae and Cyperaceae. A plot of $\delta^{13}C$ values and the corresponding ^{14}C ages of the peat samples is shown in Figure 1.

The $\delta^{13}C$ values have fluctuated between – 20 per mil and about – 14 per mil during the past 40 kyr, suggesting that these values have been derived from a nearly equal proportion of C3 and C4 vegetation in the former case and from a predominance of C4 plants in the latter. Peat samples with approximately similar dates from the

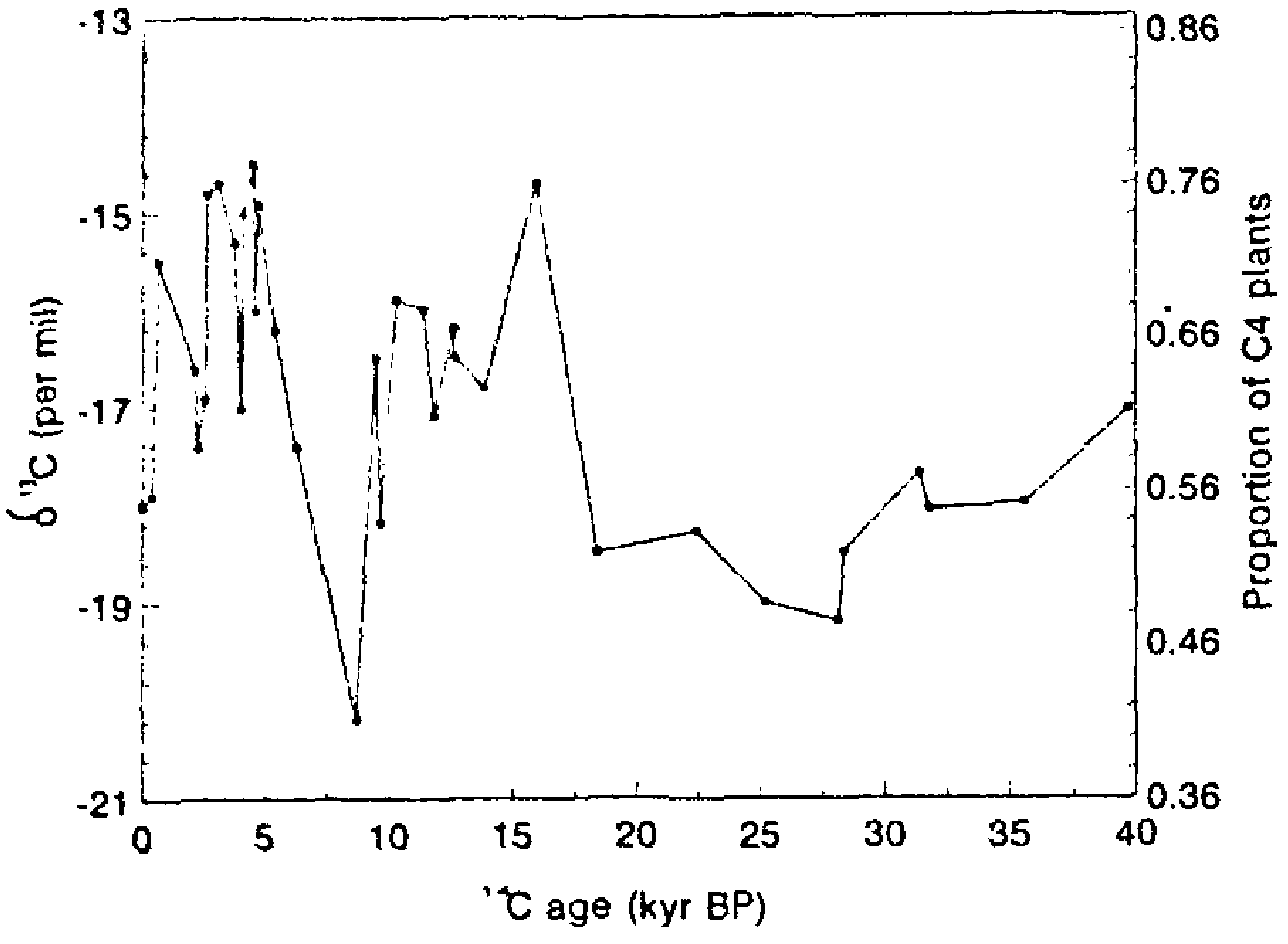

Figure 1. δ^{13}C values (in per mil, with respect to PDB) versus ^{14}C age (kyr BP) of peats from Sandynallah region, Nilgiri hills, southern India. The scale on the right gives the proportion of C4 plants based on upper and lower limits of − 26.6 and − 10.9 per mil for exclusively C3 and C4 plants respectively.

two basins show a 0.3 to 2.1 per mil variation in their δ^{13}C values. This difference could be attributed to local site variation in moisture conditions and proportions of the C3 and C4 plants.

The δ^{13}C profile of peats > 40 kyr BP generally shows a progressively negative trend up to 40 kyr BP, indicative of a decrease in the proportion of C4 plants, or increasing moisture conditions. While the δ^{13}C value reaches a peak value of − 13.8 per mil (almost complete C4 dominance) at a depth of 235–238 cm, it is − 17.1 per mil (significant C3 contribution) at a depth of 180–183 cm which has been dated at 39.7 kyr BP. We are unable to determine the time period over which this change took place because samples older than 40 kyr BP could not be dated by the conventional ^{14}C method. This overall change in the δ^{13}C value continues from 40 kyr to about 28 kyr BP reaching − 19.2 per mil (at 28.2 kyr BP), suggesting increasingly moist conditions, and changing marginally to − 18.5 per mil at 18.4 kyr BP.

In their work on Quaternary climatic changes in the desert regions of Gujarat and Rajasthan, Allchin and co-workers[19] have also proposed a dry phase prior to 40 kyr BP and a wet phase after 40 kyr BP. Similar results were obtained from tropical Africa where high lake levels have been observed prior to 25 kyr BP (ref. 20). Street and Grove[21] also show evidence for higher lake levels in Africa for the period between 30 kyr and 21 kyr BP. In southern Australia, higher lake stands during 40–20 kyr BP have been reported[22]. For the first time evidence for relatively moist conditions between 40 kyr and 20 kyr BP is demonstrated in southern India.

The LGM is believed to have extended anywhere from about 22 kyr to 14 kyr BP, with a mean of 18 kyr (ref. 14). At Sandynallah a δ^{13}C signature of − 14.7 per mil suggesting an expansion of C4 vegetation is seen around 16 kyr BP. This C4 signature is based on a single sample from basin A (pit 2B) of Sandynallah (Table 1). It is likely that peat formation is reduced or nearly absent during periods of extreme aridity, as Sandynallah basin B showed an abrupt change from about 12 to 18 kyr with no peats dated in between (Table 1). An arid phase, with almost purely C4 vegetation, between 20 kyr and 17 kyr BP in the Nilgiri hills had been earlier demonstrated from peats collected from other basins in the Nilgiri hills[2]. Evidence from other data such as lake level fluctuations in Africa[23] and lacustrine pollen deposits in north-western India[24] supports the late glacial arid conditions during this time period. δ^{18}O ratios in pollen[25] and foraminifera[26] from ocean sediments also suggest arid conditions and weaker summer monsoon during this time period. Similarly, climatic model simulations[27–29] point to a period of weak Asian south-west (summer) monsoon during the LGM. The C4 signature in montane southern India may be a response to a weaker summer monsoon and lower soil moisture in the region during the LGM.

Following the LGM, there is a trend towards moist conditions with δ^{13}C values in the range of − 16 to − 17 per mil during 13.8 to 10.2 kyr BP. During the early to mid-Holocene (10–5 kyr BP) there is a peak moist period around 9 kyr BP (δ^{13}C = − 20.2 per mil at 8.7 kyr BP) as indicated by a substantial contribution of C3 vegetation. During this period, annual precipitation is believed to have been much higher than today in Southern Asia and in Africa north of the equator[30]. The increased isolation at high latitudes may also have resulted in enhanced monsoon in north-western India[31], with precipitation being about 200 mm/yr above present values as calculated from pollen profiles[32]. Thus, increased monsoon and soil moisture, perhaps coinciding with warmer temperatures, and supporting a higher proportion of C3 vegetation may have prevailed around 9–8 kyr BP in the montane regions of the Nilgiri hills.

Arid periods with an overall dominance of C4 grasses are clearly established from about 5 kyr BP to 2 kyr BP, although there is fluctuation in the δ^{13}C values during this period. Pollen profiles from lake sediments in north-western India[32] and monsoon upwelling record from the Arabian Sea[33] also support a weakening of the summer monsoon over the Indian sub-continent during this period. Reduction in humid conditions and increase in grassland pollen ca. 3.5 kyr BP have also been observed from two marine cores in western India at latitude 14–15°N (ref. 34).

Earlier dating of peats from pit 1 in Sandynallah basin A had suggested that samples at a depth of 50–85 cm, showing a predominantly C3 signature, could be dated through a best-fit regression at about 0.5–0.7 kyr BP (ref. 2). This had indicated that a rapid shift in vegetation to C3 type at Sandynallah may have corresponded to the Mediaeval Warm Period, dated at

AD 1200–1400, of Europe and North America[14]. New radiocarbon dates of samples at depth 120–125 cm (380 yr BP) and 140–145 cm (660 yr BP) from this pit (Table 1) do not support the earlier view. The predominance of C3 vegetation is either much more recent or an anomaly due to human-induced disturbance to the upper layers of the peat bog in recent decades.

The pattern of changes in vegetation (C3/C4 plant types) in the montane regions of southern India seems synchronous with changes in the strength of the monsoon and in soil moisture. A number of climate models have also shown a positive correlation between the temperature and the strength of the Asian summer monsoon[27–29]. Higher temperatures (due to variations in the earth's orbit or greenhouse gases such as CO_2) could result in increased precipitation and soil moisture and favour the spread of C3 vegetation type. Conversely, lower precipitation and soil moisture as a consequence of lower mean temperatures would favour the spread of C4 grasslands.

Moreover, Robinson[35] has shown that atmospheric CO_2 levels since the LGM as measured in the Antarctic ice cores[36] are remarkably correlated with the proportion of C3/C4 vegetation as revealed from carbon isotope analyses of peats in montane southern India[2]. She has suggested that under low atmospheric CO_2 concentrations the C4 plants, which are known to have a physiological advantage over C3 plants, may also have enjoyed a competitive edge over C3 plants during the LGM.

This is actually not inconsistent with the well-known positive correlation between atmospheric CO_2 and temperature and of the model-derived relationship, between temperature and Indian summer monsoonal precipitation. Thus, soil moisture (or strength of the monsoon) and atmospheric CO_2 levels could both play a role in determining the relative dominance of C3 and C4 vegetation in a region. However, there has to be a much better understanding of the relationship between atmospheric CO_2 levels, temperature, monsoonal precipitation, evapotranspiration, soil moisture and competitive abilities of C3 and C4 plants before tropical climatic changes during the Quaternary can be reconstructed with higher resolution and certainty from stable isotopic analyses of the peats.

The broad changes in climate and vegetation observed in montane southern India support the contention that tropical climatic change is significantly in tune with global climatic changes described in greater detail for the higher latitudes. Sampling from several basins along the Western Ghats in southern India can be expected to provide a clearer picture of late Quaternary climate change.

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