

The dating of dipterocarp tree rings: establishing a record of carbon cycling and climatic change in the tropics

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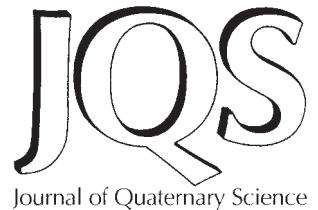
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ABSTRACT: In a first step to obtain a proxy record of past climatic events (including the El Niño–Southern Oscillation) in the normally aseasonal tropical environment of Sabah, a radial segment from a recently fallen dipterocarp (*Shorea superba*) was radiocarbon dated and subjected to carbon isotope analysis. The high-precision radiocarbon results fell into the ambiguous modern plateau where several calibrated dates can exist for each sample. Dating was achieved by wiggle matching using a Bayesian approach to calibration. Using the defined growth characteristics of *Shorea superba*, probability density distributions were calculated and improbable dates rejected. It was found that the tree most likely started growing around AD 1660–1685. A total of 173 apparent growth increments were measured and, therefore, it could be determined that the tree formed one ring approximately every two years. Stable carbon isotope values were obtained from resin-extracted wholewood from each ring. Carbon cycling is evident in the ‘juvenile effect’, resulting from the assimilation of respired carbon dioxide and lower light levels below the canopy, and in the ‘anthropogenic effect’ caused by increased industrial activity in the late-nineteenth and twentieth centuries. This study demonstrates that palaeoenvironmental information can be obtained from trees growing in aseasonal environments, where climatic conditions prevent the formation of well-defined annual rings. Copyright © 2004 John Wiley & Sons, Ltd.



KEYWORDS: dipterocarp; canopy; tropical; radiocarbon dating; wiggle matching.

Introduction

In recent years, climatologists have realised the importance of tropical phenomena being statistically and perhaps mechanistically teleconnected to worldwide climatic conditions. In particular, the El Niño–Southern Oscillation (ENSO) causes significant climatic anomalies and changes in storm trajectories over much of the tropics and subtropics. In ENSO years, the trade winds over the Pacific weaken and the upwelling off the South American coast is replaced by warmer waters. At the same time, the associated high pressure over the Indonesian region causes severe droughts on Sabah, northern Borneo (Walsh and Newbery, 1999). As meteorological records in this region are very limited, indirect records are required to reconstruct past ENSO events. One method that has been used to

reconstruct past climates in temperate regions is the analysis of tree rings, both through ring-width measurements and, more recently, through the determination of stable isotope values. The absence of annual growth rings in tropical trees means that this methodology is not typically utilised for climatic reconstruction in tropical regions. However, while the ring formation may not be annual, some tropical species do exhibit clear, defined growth rings. This record holds great potential for reconstructing the ecological history of these forests, particularly for a more definitive determination of the age of tropical rainforests, for the examination of carbon cycling, and for reconstructing climatic events in the tropics.

This study begins to address these concerns by examining the nature of the growth of one of the most prominent families of trees on Sabah, the Dipterocarpaceae. Dipterocarps are particularly prevalent in the aseasonal lowland forests of Sabah and can be found growing up to an elevation of 300 m above sea level, where they constitute 70–80% of the canopy trees. One of the most common trees is Selangan batu daum halus (*Shorea superba* Sym.), which inhabits undulating or hilly

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environments (Wood and Meijer, 1964). In order to derive a reliable proxy of climate change from tree ring analysis it is necessary to verify the relationship between ring formation and time for any given species. While temporal control is an important part of climatic reconstruction, determining the age of long-lived species in the tropical rainforests also helps in estimating the capacity of the forests to assimilate carbon. The age and height distribution of trees in a forest strongly influence the carbon budget. Radiocarbon dating has been used to determine the age of trees (Chambers *et al.*, 1998; Kurokawa *et al.*, 2003) or to assist dating samples that cannot be absolutely dated (Biondi and Fessenden, 1999; Vogel *et al.*, 2001; Hua *et al.*, 2003), but the method is not without problems. Research on the age of long-lived tree species from the tropical forests has generally been inconclusive. This research represents an initial collaborative study to establish a chronological framework for climatic reconstruction in tropical forests.

Methods

Sample preparation

In March 2001, a radial segment was obtained from a recently fallen dipterocarp tree (*Shorea superba*) growing close to the Danum Valley Field Centre on Sabah, Malaysia (5° 01'N; 117° 49'E). In the laboratory, the segment was sanded with progressively finer grades of abrasive paper to reveal any visible growth rings or banding (Stokes and Smiley, 1963). Any ring-widths identified were measured to an accuracy of 0.001 mm using a Velmex measuring stage and binocular microscope.

Radiocarbon dating

To provide a time-frame, five samples (each covering 2–12 'rings') from the same radial segment were selected for high-precision ^{14}C analysis at the Quaternary Dating Research Unit, Pretoria, South Africa. In the high-precision gas proportional counting system, ^{14}C is measured indirectly by detecting the β particles emitted when ^{14}C decays. To reduce the influence of cosmic radiation on the counting procedure, the laboratory is located in a specially constructed underground room covered by 12 m of earth. The counters themselves are shielded with lead and complex electronics further minimise the influence of cosmic radiation (Vogel and Marais, 1971). Samples from throughout the Holocene may be dated at a precision of better than ± 20 years, rather than the typical ± 40 years obtained for conventional radiocarbon dating. The atmospheric testing of nuclear weapons up to the signing of the Partial Test Ban Treaty in AD 1963 elevated the ^{14}C value of atmospheric CO_2 . Although this ^{14}C has been incorporated into other reservoirs of the carbon cycle, the ^{14}C value of atmospheric CO_2 is still above the natural levels and hence samples can be dated to the nearest year from AD 1955 to the present (Vogel *et al.*, 2002).

The wood samples (ca. 20 g) were split into matchstick size pieces and pre-treated with dilute acid, alkali and dilute acid respectively to remove soluble organic components (Tans and Mook, 1980). The relatively small sample sizes precluded the isolation of specific chemical components. Combustion and subsequent purification yielded carbon dioxide for gas proportional counting (Vogel and Marais, 1971).

Carbon isotope analysis

In order to explore carbon isotope variations across the entire radial segment, individual samples from each growth increment were ground in a coffee grinder and the mobile constituents removed using an ethanol/toluene extraction to yield resin-extracted wholewood (Loader *et al.*, 1997). Resin-extracted wholewood was selected for carbon isotopic analysis as it may contain a stronger climatic signal than α -cellulose or lignin alone (Loader *et al.*, 2003). The carbon isotopic values were measured using a Thermoquest EA1110 elemental analyser interfaced to a VG Isogas SIRA 24 stable isotope ratio mass spectrometer at the Quaternary Dating Research Unit, Pretoria, South Africa. Results are expressed using the conventional notation as deviations from the Vienna Pee Dee belemnite (VPDB) standard (Coplen, 1995). Each sample was measured at least twice. The average precision on replicate results was 0.19‰, which reflects sample preparation and measurement errors.

Results

Establishing an approximate time-frame

Approximately 173 apparent growth increments were measured (Fig. 1). Owing to variations in atmospheric ^{14}C values, it is unreliable to base radiocarbon dates of samples from the 'modern plateau' (AD 1650–1955) on single measurements as ambiguous calibrated dates can arise (Fig. 2). Therefore, five ^{14}C values were determined at intervals throughout the radial segment. Initial analysis of the high-precision radiocarbon dates confirmed that more than one calibrated date exists for the samples from rings 1–12 (PTA 8561), 53–54 (PTA 8623), 94–95 (PTA 8847) and 132–133 (PTA 8572). The sample from rings 158–159 (PTA 8641) had elevated ^{14}C levels caused by the atmospheric testing of nuclear weapons.

The climate of northern Borneo is influenced primarily by the Indo-Australian monsoonal system, with northerly winds from December to March (northern hemisphere winter), which is the 'peak' rainfall part of the year, and south-westerly winds from May to October (Walsh, 1996). On balance, therefore, Danum may be classed as a northern hemisphere site with a significant seasonal influence from the southern hemisphere. Using a northern hemisphere radiocarbon calibration curve (Hua *et al.*, 1999), the ^{14}C value of 132.6 pMC (per cent modern carbon) for sample rings 158–159 (PTA 8641) was found to have two intercepts, with the bomb carbon curve corresponding to the years AD 1978 \pm 1 or AD 1962 \pm 1 (Table 1).

Although it has been stated that samples from the modern plateau cannot be unambiguously radiocarbon dated (Worbes, 2002; Worbes and Junk, 1999), it may be possible to date samples using a technique known as wiggle matching. Where the precise age differences between ^{14}C -dated samples are known independently, radiocarbon dates may be matched to the variations in the calibration curve caused by atmospheric ^{14}C activity. This procedure can be used to obtain very accurate dates, despite the coarse nature of the calibration curve. Although wiggle matching can be performed visually, quantification of the relationship improves the confidence of the calibration procedure. Wiggle matching has been achieved using classical statistical techniques (Pearson, 1986; Vogel *et al.*, 2001) or, more recently, a probabilistic approach (Bayliss *et al.*, 1999; Bronk Ramsey *et al.*, 2001; Slusarenko *et al.*, 2001).

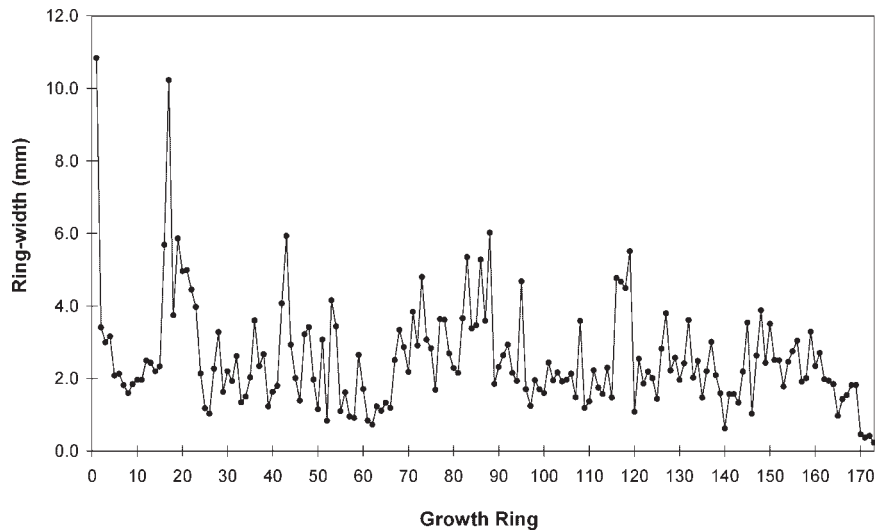


Figure 1 Growth increment variations in the *Shorea superba* sample growing at Sabah, Malaysia (radius = 439.1 mm; 173 rings; mean ring width = 2.5 mm)

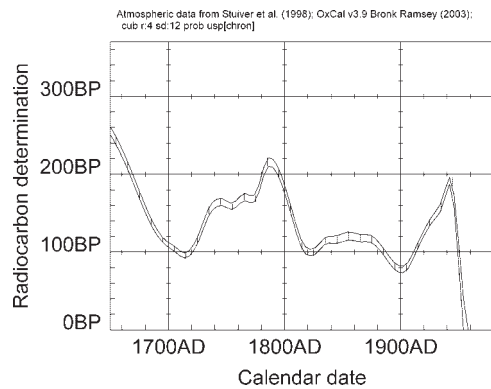


Figure 2 Northern hemisphere radiocarbon calibration curve for the period AD 1650–1955 (Bronk Ramsey, 2003; Stuiver *et al.*, 1998)

The radiocarbon calibration program OxCal (Bronk Ramsey, 2003) employs Bayes' theorem to quantify the relationship in the light of chronological information (Bronk Ramsey, 1995, 1998). This probabilistic program was selected to calibrate radiocarbon dates using the INTCAL98 northern hemisphere dataset (Fig. 2; Stuiver *et al.*, 1998). The calibration process generated the prior probability distributions (Fig. 3) that were used in the wiggle matching procedure. OxCal uses a Markov chain Monte Carlo (MCMC) sampling algorithm to calculate the posterior distribution based upon the chronological constraints and probability distributions (Fig. 4). The extent that the final (posterior) distribution overlapped with the original (prior) distribution was assessed by calculating the agreement index (A). For most samples, where the number of constraints is small, values below the threshold (A'c) of 60% indicate unreliable chronological models.

Table 1 Calibration of radiocarbon dates using OxCal (Bronk Ramsey, 2003; Stuiver *et al.*, 1998). The initial calibration using OxCal generated the prior probability distributions (Fig. 3) that were subsequently used in the 'wiggle matching' procedure. The dates were calibrated using the V_Sequence routine in OxCal, which utilised the defined chronological constraints and probability distributions (Fig. 4). The dates are normalised to $\delta^{13}C = -25.0\%$ and reported with the conventional one sigma error ($\pm 1\sigma$) based upon counting statistics, where there is a 68.2% chance that the values will fall within the quoted range (Stuiver and Polach, 1977). Based upon the defined constraints, there is a 39.0% chance that rings 1–12 (PTA8561) correspond to the period AD 1660–1685 (denoted A) and a 29.2% chance that they correspond to the period AD 1735–1765 (denoted B). Rings 158–159 (PTA 8641) were found to correspond to the year AD 1978 ± 1 or AD 1962 ± 1 depending upon which intercept with the bomb carbon peak was appropriate. Several rings were combined to provide sufficient material for radiocarbon dating. The relative area of each ring was used to calculate the midpoint subsequently used to calculate the number of rings between samples

Sample (PTA)	8561	8623	8847	8572	8641	(Outer)
<i>Initial data</i>						
Rings	1–12	53–54	94–95	132–133	158–159	173
Uncalibrated date	180 \pm 20 BP	220 \pm 20 BP	120 \pm 20 BP	160 \pm 20 BP	(132.6 pMC)	—
$\delta^{13}C_{VPDB}$ (‰)	-29.56	-29.23	-28.77	-28.52	-29.57	—
<i>Posterior probability distribution calibrated dates</i>						
1 σ range (AD)	(A) 1660–1685 (39.0%)	1781–1797 (68.2%)	1825–1885 (68.2%)	1924–1940 (68.2%)	(C) 1977–1979	2000
	(B) 1735–1765 (29.2%)				(D) 1961–1963	
<i>Difference between samples</i>						
Rings	—	47	41	38	26	15
Years	—	116 (A) 39 (B)	66	77	46 (C) 30 (D)	22 (C) 38 (D)
Rings/year	—	0.41 (A) 1.21 (B)	0.62	0.49	0.57 (C) 0.87 (D)	0.68 (C) 0.39 (D)

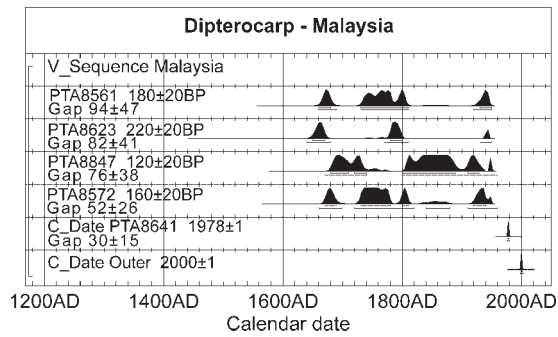


Figure 3 Calibration of radiocarbon dates using OxCal (Bronk Ramsey, 2003; Stuiver *et al.*, 1998). The prior probability distributions are illustrated. The gap between samples is based upon the ring count (see text). The horizontal lines below the probability distributions represent one-sigma and two-sigma ranges of calibrated dates

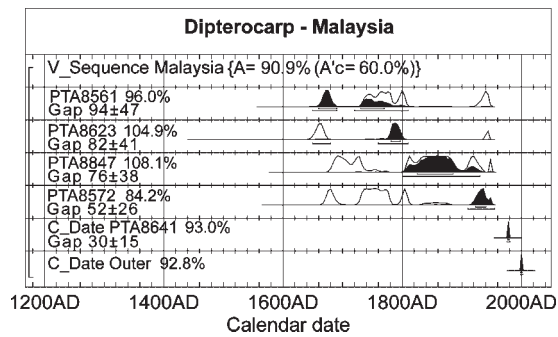


Figure 4 The posterior probability distribution of calibrated radiocarbon dates (solid shading) taking into account the specified constraints. The horizontal lines below the probability distributions represent one-sigma and two-sigma ranges of calibrated dates. The agreement indices (A) provide a measure of how well the posterior distribution agrees with the prior distribution. The threshold for accepting the agreement as good (A'c) is 60% (Bronk Ramsey, 1995, 2003; Stuiver *et al.*, 1998)

To enable the dipterocarp sample to be dated by wiggle matching, the incremental growth rate was assumed to be uniform. However, it should be noted that the growth process may well be continuous (Sass *et al.*, 1995) with differing growth rates between juvenile and mature trees (Ng, 1979). Initial inspection of the calibrated radiocarbon dates indicated that the rings were not annual in nature. If the sample obtained from rings 158–159 corresponded to the year AD 1978 ± 1 (C in Table 1), the 15 rings to the last year of growth in AD 2000 covered approximately 22 years and hence the tree laid down 0.68 rings/year. If the alternative date of AD 1962 ± 1 was selected (D in Table 1), the 15 rings covered approximately 38 years and the growth rate was 0.39 rings/year. Whatever date is correct for this sample, it is clear that the rings cannot be annual.

In light of this information, the number of years between rings ('gap' in OxCal) was defined as 2 ± 1 years (Figs 3 and 4; Table 1). This wide margin of variability ensured that the chronological model used by OxCal was constrained by the fact that the tree uniformly produced between 0.3 rings/year (i.e. 1 ring every 3 years) and 1 ring/year. The V_Sequence routine in OxCal was used to calculate the calibrated dates with the highest overlap with the prior distribution with respect to the specified chronological information (Fig. 4). It was found that the highest overall agreement index (90.9%) was calculated when the sample from the innermost rings, 1–12 (PTA 8561), had the most probable calibrated date of AD 1660–1685 or AD 1735–1765 (Table 1).

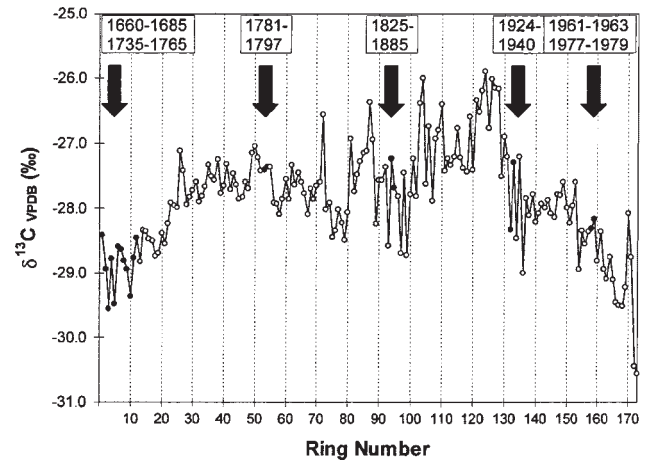


Figure 5 Carbon isotope values determined on resin-extracted wholewood from the 173 growth increments, where increment 1 is located at the centre of the tree. Closed circles represent the number of rings combined to provide sufficient material for radiocarbon dating. The most probable radiocarbon dates are illustrated. The mean $\delta^{13}\text{C}$ value is $-27.85 \pm 0.19\text{‰}$. The tree died in AD 2000

Carbon isotope values

The carbon isotope values determined on resin-extracted wholewood obtained from the 173 growth increments reveal evidence of carbon cycling in the rainforests of Sabah (Fig. 5). The widely reported 'juvenile effect' primarily reflecting lower irradiance levels below the canopy and the 'anthropogenic effect' caused by the increased burning of ^{13}C -depleted fossil fuels are clearly evident in the $\delta^{13}\text{C}_p$ values of the *Shorea superba* sample.

Discussion

Although the maximum age of tropical broadleaved trees is required to provide a time-scale for the reconstruction of carbon fluxes in a tropical rainforest, there are still widely differing estimates. Age determinations based upon radiocarbon dating seem to exceed ring-width counts by a factor of three (Worbes, 2002). Radiocarbon dating for this type of determination is fraught with difficulties as many dates can exist for ambiguous points on the calibration curve; of particular concern is the 'modern plateau' between AD 1650 and AD 1955 (Fig. 2). Chambers *et al.* (1998) dated trees from the tropical rainforest trees in Amazonia, but it is unclear exactly how they overcame these problems. In a similar study in Borneo, however, Kurokawa *et al.* (2003) explicitly state that they rejected any samples less than 400 years old. In our study, a Bayesian approach was used to wiggle match several high-resolution radiocarbon dates from a sample covering this period that has proved so difficult to date. Upon initial inspection, results of the age determination from the sample at the tree's centre appear to be inconclusive, as the most probable calibrated date for the innermost rings can be either AD 1660–1685 or AD 1735–1765 (Table 1). However, as juvenile dipterocarps are relatively slow-growing trees that wait for an opportune gap in the canopy to exploit, the most likely of the two potential dates for the tree would be AD 1660–1685. This date determination is also supported by the calculated growth rate of the tree (Table 1). If the innermost rings are dated to AD 1660–1685, the overall growth rate until the next dated sample is

0.41 rings/year. The next sample from rings 53 and 54 is firmly anchored at AD 1781–1797 owing to the particular intercept on the radiocarbon calibration curve. If the alternative date for the innermost rings of AD 1735–1765 is selected, the growth rate over the same period is 1.21 rings/year. This unusually high rate is contrary to the generally accepted theory that growth rates of seedlings and saplings growing below the canopy are usually very slow (Kurokawa *et al.*, 2003). Therefore, the innermost rings can be tentatively dated to the years AD 1660–1685, although the alternative date of AD 1735–1765 cannot be totally excluded.

The absence of climatic seasonality is the main reason for the lack of well-defined cyclical growth rings for tropical trees (Jacoby, 1989). However, an annual dry season of 2–3 months with less than 60 mm rainfall/month is sufficient to induce the formation of annual rings in tropical trees (Worbes, 1995). This is not the case at Danum, where the climate is far from seasonal (Walsh and Newbery, 1999). Corner (1952) observed that rings in Malaysian trees often correspond with the appearance of a new crop of leaves. However, the flushing of leaves can be difficult to detect as there can be a lack of synchronisation between branches even on the same tree (Ng, 1988) and both leaf flushing and fall can occur at the same time (Killman and Thong, 1995). In Peninsular Malaysia, two annual growth rings might be expected as dipterocarps can exhibit two flushes of leaves/year (Ng, 1988). If the date of AD 1660–1685 is accepted for the innermost rings, the overall growth rate determined for this tree from Malaysian Borneo is 0.53 rings/year, i.e. the tree forms one ring every 2 years. As Ng (1981) reported that flushing can occur from anything between 6 months and 2 years for mature trees, this rate is within the reported limits. Worbes (1989) also observed a biennial growth pattern for Costa Rican oaks (*Quercus costaricensis*), which he attributed to the irregular periodicity of precipitation.

The carbon isotope value of trees rings is controlled by the isotopic composition of atmospheric CO₂ and the ratio of the internal to external concentration of CO₂, which reflects the balance between stomatal conductance and photosynthetic rate (McCarroll and Loader, 2004). Over the past few decades, the carbon isotope value of tree rings has been used successfully to reconstruct past environmental conditions at a wide range of sites throughout the world. They have been demonstrated to have a higher degree of coherence than other growth proxies and therefore fewer samples are required to produce time-series with an adequate degree of replication (Loader *et al.*, 2003).

The source of carbon for trees is atmospheric CO₂. Isotopic fractionation occurs during diffusion of gases through the boundary layer and stomata to and from the sites of photosynthesis and during carboxylation by the enzyme used to fix carbon, which for C₃ plants is ribulose-1,5-bisphosphate. The magnitude of the fractionation varies with photosynthetic type, environment, genotype and many other factors (O'Leary, 1993).

Isotopic fractionation in C₃ plants is represented by the equation:

$$\delta^{13}\text{C}_p \approx \delta^{13}\text{C}_a - a - (b - a)(c_i/c_a)$$

where $\delta^{13}\text{C}_p$ and $\delta^{13}\text{C}_a$ represent the carbon isotope values of the plant and atmosphere respectively; a represents the fractionation factor due to the difference in the rate of diffusion between ¹³CO₂ and ¹²CO₂ in air; b is fractionation due to carboxylation and c_i and c_a represent the intercellular and ambient concentrations of CO₂ (Vogel, 1980; Farquhar *et al.*, 1982a).

As the heavier isotopic species diffuse more slowly, the diffusivity of ¹³CO₂ in free air has been calculated to be 4.4‰ less than that of ¹²CO₂ (Farquhar *et al.*, 1982a). Although this simplistic approach is usually adopted, the actual situation is far more complex, with isotopic fractionation also occurring in the laminar boundary layer surrounding the leaf, during collisions with the guard cells, in the intercellular air spaces and with water vapour (Farquhar and Lloyd, 1993).

Once the CO₂ has reached the sites of carbon fixation, fractionation occurs during carboxylation. Roeske and O'Leary (1984) determined the isotopic fractionation of gaseous CO₂ caused by carboxylation with the enzyme ribulose-1,5-bisphosphate to be approximately 30‰. From direct measurements of $\delta^{13}\text{C}_p$ and c_i/c_a in leaves of plants growing under varying conditions, Farquhar *et al.* (1982b) calculated this value to be approximately 27‰, which is the value used in most palaeoenvironmental studies.

In principle, it has to be assumed that any environmental variable that exerts stress on plants, and therefore affects the rate of assimilation (A) and/or the stomatal conductance (g) will have some influence on $\delta^{13}\text{C}_p$ via changes in c_i/c_a . If A is the assimilation rate of CO₂ and g is the stomatal conductance of the plant for CO₂, then

$$c_i = c_a - \frac{A}{g}$$

Factors that reduce A through effects primarily on the mesophyll capacity for photosynthesis (such as very low light intensities and deficiencies of certain mineral nutrients) will increase c_i/c_a and hence decrease $\delta^{13}\text{C}_p$. Alternatively, factors which reduce the supply of CO₂, primarily through the reduction of the stomatal aperture, will decrease c_i/c_a and increase $\delta^{13}\text{C}_p$. These factors include environmental parameters such as temperature, humidity, changes in precipitation and hence soil moisture, pollution, and the concentration and isotopic composition of atmospheric CO₂.

In the early years of life when the tree is struggling to grow below the dense canopy of a tropical rainforest, the $\delta^{13}\text{C}_p$ value of leaves and the corresponding tree rings are usually depleted in ¹³C. If relatively uniform growth commenced in AD 1660–1685, the 'juvenile effect' is evident in the time-series up to approximately AD 1740 (Fig. 5). The trend of depleted ¹³C values for leaves growing at lower levels of the forest canopy (Medina *et al.*, 1986; Sternberg, 1989; Sternberg *et al.*, 1989; Schleser, 1990; Broadmeadow *et al.*, 1992; Garten and Taylor, 1992; Broadmeadow and Griffiths, 1993) was initially attributed to the recycling of ¹³C-depleted CO₂ from soil respiration and the degradation of organic matter (Vogel, 1978; Medina and Minchin, 1980). It is generally accepted that, when the mixing of respired CO₂ with the atmosphere is restricted, ambient CO₂ can become substantially depleted in ¹³C, resulting in a decrease of $\delta^{13}\text{C}_p$ values (Tieszen, 1991). Such environments include the dense stands of tropical forests, where vertical mixing usually occurs as a result of temperature differences between the canopy and the forest floor (Medina *et al.*, 1986). van der Merwe and Medina (1991) found that, for trees growing in the Amazon basin, a substantial amount of the ¹³C-depleted CO₂ was recycled.

The decreased $\delta^{13}\text{C}_p$ values for leaves growing lower in the canopy, however, could also be due to the reduced light levels causing higher c_i/c_a values (Farquhar *et al.*, 1982a). This hypothesis was confirmed by Francey *et al.* (1985), who found that the $\delta^{13}\text{C}_p$ of Huon pine growing in a Tasmanian coniferous forest decreased with canopy depth without a corresponding decrease in $\delta^{13}\text{C}_a$. They attributed the lower $\delta^{13}\text{C}_p$ value of the lower leaves to a direct influence of light on c_i/c_a and not to that of respired CO₂. Schleser and Jayasekera (1985) also

found a similar $\delta^{13}\text{C}$ gradient for an isolated lime tree growing with a constant ^{13}C source for all leaves. Several studies have since reported that low irradiance levels limit photosynthesis and generally lead to lower $\delta^{13}\text{C}_p$ values (Ehleringer *et al.*, 1986, 1987; Mulkey, 1986; Francey and Hubick, 1988; O'Leary, 1988; Broadmeadow and Griffiths, 1993; Heaton and Crossley, 1995; Yakir and Israeli, 1995).

As both the recycling of ^{13}C -depleted CO_2 and lower light levels below the canopy may influence the $\delta^{13}\text{C}$ value of leaves, the interpretation of leaf $\delta^{13}\text{C}$ values has been controversial (Farquhar *et al.*, 1989). The influence of recycling of respired CO_2 on $\delta^{13}\text{C}_p$ is often regarded as of secondary importance to that of the regulation of c_i/c_a by gradients in environmental variables, such as the influence of light (Broadmeadow and Griffiths, 1993; Heaton, 1999).

Increased industrial activity in the late-nineteenth and twentieth centuries has resulted in a substantial increase in the burning of ^{13}C -depleted fossil fuels. Over this period, c_a has increased from a baseline value of about 260–280 $\mu\text{mol mol}^{-1}$ to the current-day value of approximately 370 $\mu\text{mol mol}^{-1}$ (Steele *et al.*, 2002) with a concomitant decrease in $\delta^{13}\text{C}_a$ by about 1.5‰ (McCarroll and Loader, 2004). The decrease in carbon isotope values as a result of increased burning of ^{13}C -depleted fossil fuels in the late-nineteenth and twentieth centuries, known as the 'anthropogenic effect', is also clearly demonstrated in the dipterocarp sample from the start of the twentieth century (Fig. 5). Whilst this trend has been reported for trees growing at sites in both the northern (Feng and Epstein, 1995; Treydte *et al.*, 2001) and southern hemispheres (Leavitt and Lara, 1994; February and Stock, 1999), it is not yet known whether it is a universal response of plants to changes in atmospheric CO_2 (Francey, 1981; Robertson *et al.*, 1997; Anderson *et al.*, 1998).

This complex response of trees to increasing c_a and decreasing $\delta^{13}\text{C}_a$ can be explained by reference to c_i/c_a . Polley *et al.* (1993) found that c_i/c_a is approximately constant as c_a increases and therefore, $\delta^{13}\text{C}_a$ influences $\delta^{13}\text{C}_p$. Alternatively, if c_i is constant when c_a increases, then c_i/c_a decreases and $\delta^{13}\text{C}_p$ may increase (Francey and Farquhar, 1982). From these studies, it is evident that additional high-resolution c_a and $\delta^{13}\text{C}_a$ values are required to enable tree ring $\delta^{13}\text{C}_p$ values to be assessed in light of changes to c_i/c_a (Robertson *et al.*, 1997; McCarroll and Loader, 2004).

The main limitation of this study was that it was based upon one radial segment. As dipterocarps exhibit asymmetrical growth with a lack of circumferential uniformity, replication is the key to future research. It is only when the apparent trends found in this study are replicated successfully that the use of tree rings to study the influence of ENSO on the climate of northern Borneo can be assessed with confidence.

Conclusions

The results presented from this initial study demonstrate the potential of the tropical tree ring record as a proxy environmental measure at sites without a strong seasonal climatic signal. A Bayesian approach to wiggle matching high-precision radiocarbon dates allowed the determination of both the age of a tropical tree sample and the establishment of a chronological framework. Carbon isotope values determined on the individual growth increments demonstrated the presence of both the juvenile and anthropogenic effects in the time-series. This study has placed a well-constrained time-scale on an archive previously thought to be undatable and has demonstrated the

potential of tropical tree rings for the reconstruction of past environmental events.

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